SUPPLY CHAIN COORDINATION AND INTEGRATION UNDER YIELD LOSS

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Changhyun Kim

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LeBow College of Business Administration
Drexel University

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TABLE OF CONTENTS

ABSTRACT .... **Error! Bookmark not defined.**

LIST OF FIGURES 5

LIST OF TABLES 6

LLIST OF BASIC NOTATION 7

CHAPTER 1 Introduction 11

1.1 Motivation 11

1.2 Scope of Dissertation and Research Objectives 19

1.2.1 Supply Chain Coordination and Optimization under Quality Uncertainty with option for Emergency Procurement 21

1.2.2 Supply Chain Optimization and Coordination under Quality Uncertainty with Non-linear Price Sensitive Demand 22

1.2.3 Supply Contract Design for Quality Improvement ...... **Error! Bookmark not defined.**

1.3 Research Contributions 23

1.4 Outline of the Dissertation 25

CHAPTER 2 Literature Review 26

2.1 Introduction 26

2.2 Deterministic two-stage supply chain coordination and optimization under quality uncertainty 29

2.3 Stochastic Two-Stage Supply Chain Coordination and Optimization Model under Quality Uncertainty 36

2.4 Supply Chain Contract Design for Quality Improvement 40

2.5 Research Gaps 43

CHAPTER 3 Coordinating a two-stage supply chain under Yield Loss with emergency prOcurement option 46

3.1 Introduction 46

3.2 Assumptions 50

3.3 Model Formulation 52

3.3.1 Non-coordinated Decision Model 53

3.3.1.1 Retailer driven model 54

3.3.1.2 Supplier driven model 57

3.3.2 Joint Coordination model 61

3.4 Solution Procedure 66

3.4.1 Heuristic algorithm for optimal solution 66

3.4.2 Analysis of the coordinated decision model for optimal sourcing 70

3.5 Model Analysis 71

3.5.1 Optimization 71

3.5.2 Profit Maximization 75

3.5.3 Pricing Strategy for External Procurement 76

3.5.4 Profit Sharing and Compensation Policy 79

CHAPTER 4 Coordinating a two-stage supply chain with imperfect quality items and nonlinear price DEPENDENT demand 81

4.1 Introduction 81

4.2 Assumptions 84

4.3 Model Formulation 85

4.3.1 Non-coordinated Decision Model 85

4.3.1.1 Retailer driven model 86

4.3.1.2 Supplier driven model 89

4.3.2 Joint Coordination model 94

4.4 Solution Procedure ... 101

4.5 Model Analysis ... 105

4.5.1 Optimization ... 105

4.5.2 Profit Maximization ... 107

CHAPTER 5 Numerical Analysis and Sensitivity Analysis ... 110

5.1 Sensitivity Analysis ... 110

5.2 Numerical Example and Sensitivity Analysis of Deterministic Demand Model 111

5.2.1 Sensitivity Analysis for the index of the fraction of the market demand satisfied by supplier (β) ... 112

5.2.2 Sensitivity Analysis the defective rate (r) ... 113

5.2.3 Sensitivity Analysis for the external procurement price (p_0) ... 113

5.3 Numerical Example and Sensitivity Analysis of Price Dependent Demand Model 118

5.3.1 Sensitivity analysis for the price elasticity, C ... 118

5.3.2 Sensitivity analysis for the defective rate r ... 119

5.3.3 Sensitivity analysis for the external procurement price (p_0) ... 120

5.3.4 zSensitivity analysis for the ratio of the supplier's setup cost to retailer's ordering cost (c_v/c_b) ... 120

CHAPTER 6 Conclusion and future directions ... 126

6.1 Summary and Conclusion ... 126

6.2 Managerial Insights ... 129

6.3 Future Directions ... 131

Bibliography ... 134

Appendix ... 150

A. Summary and Conclusion ... 150

B. Summary and Conclusion ... **Error! Bookmark not defined.**

C. Summary and Conclusion 155

VITA 159

LIST OF FIGURES

Figure 3.1 Inventory pattern of retailer and supplier 51

Figure 3.2 Effects on the ratio of emergency procurement k^*, as external procurement price (p_0) and the fixed penalty cost for shortage (g) changes...........................78

LIST OF TABLES

Table 3.1 Differences between Sinha *et al*.(2007) and the proposed model........................49

Table 3.2 Inventory pattern of retailer and supplier............**Error! Bookmark not defined.**

Table 3.3 Summary of optimal policies 65

Table 3.4 Summary of $Q*$ according to the range of $k*$ 69

Table 3.5 Comparison of heuristic approach and simultaneous optimization 72

Table 3.6 Total profit at the optimal k^* and Q^*according to outsourcing price, p_0 (when $p_b = 45$) 73

Table 3.7 Effects on the ratio of emergency procurement k^*, as external procurement price (p_0) and the fixed penalty cost for shortage (g) changes **Error! Bookmark not defined.**

Table 4.1 Summary of optimal policies (I) 98

Table 4.2 Summary of optimal policies (I) 99

Table 4.3 Summary of optimal policies (II)..100

Table 4.4 Comparison of heuristic approach and simultaneous optimization 106

Table 5.1 Model Input Parameters...112

Table 5.2 Sensitivity Analysis for the index of the fraction of the market demand satisfied by supplier (β)..115

Table 5.3 Sensitivity Analysis for the defective rate (r) 116

Table 5.4 Sensitivity Analysis for the external procurement price (p_0)...........................117

Table 5.5 Sensitivity Analysis for the price elasticity (C) 122

Table 5.6 Sensitivity Analysis for the index of the defective rate (r)..............................123

Table 5.7 Sensitivity Analysis for the external procurement price (p_0)............................124

Table 5.8. Sensitivity analysis for the ratio of supplier's setup cost to retailer's ordering cost c_v/c_b, ...125

LIST OF BASIC NOTATION

D = Deterministic rate of market demand (units/year);

Q = Retailer's order quantity (units);

n = Number of delivery batches per production run; a positive integer;

k = Proportion of shortage resulting from the supplier's yield loss that is fulfilled by emergency procurement from an external supplier;

Q_p = Supplier's production lot size, $Q_p = nQ$ (units);

p_b = Retail price charged by the retailer (dollars per unit);

p_v = Wholesale price charged by the supplier to the retailer (dollars per unit);

p = Production cost for the supplier (dollars per unit);

p_0 = Emergency procurement price from an external source (dollars per unit);

c_b = Ordering cost incurred by the retailer ($/order);

c_v = Setup cost incurred by the supplier ($/setup);

h_b = Inventory holding cost for the retailer ($ unit/year);

h_v = Inventory holding cost for the supplier ($ unit/year);

β = Proportion of market demand satisfied at the retail level;

r = Proportion of defects produced at the manufacturing stage of the supplier (yield loss);

g, g_0 = parameters of a linear penalty function for incurring shortages, i.e. the *y*-intercept and the slope, respectively, of a linear shortage cost function;

Π_b= annual profit of the retailer;

Π_v= annual profit of the supplier;

Π_{ch}= annual profit of the entire supply chain system.

ABSTRACT

The primary objective of this dissertation is to develop analytical models for typical supply chain situations to help supply chain decision-makers under supply yield loss. We derive solution procedures for each model and present several managerial insights obtained from our models through numerical examples. Additionally, this research provides decision-makers insights on how to incorporate uncertainty in demand and supply and shortage information into a mathematical model.

This study deals with three forms of integrated cost-profit models under different scenarios including coordination policy and supply yield loss in a two-stage supply chain involving a retailer and a supplier, dealing with a single product under deterministic condition. We compare the profits of the whole supply chain system under the coordinated policy with those of individual decision making approaches and demonstrate the efficiency of coordination. These models attempts to find the optimal solutions for the retailer's order quantity, quality level, amount of emergency procurement, and the production and shipment decisions of the supplier, so that the resulting joint total profit for the entire supply chain is maximized. We illustrate our model and the potential benefits of outsourcing in a supply chain system through a numerical example.

Extending the analyses obtained above, we then develop models for an integrated supplier–retailer supply chain under imperfect production and shortages, with the additional decision variable of market pricing on the part of the retailer. We assume that market demand is sensitive to the retailer's selling price and study the combined operation and pricing decisions in the supply chain. We develop profit maximization models for the cases of independent and joint optimization. The results of obtained from our analyses demonstrate that the individual profit, as well as joint profit can be increased by our suggested model, under a non-linear price dependent demand function. In addition, the results with retailer-supplier coordination tend to be superior, which leads to illustrate that setting appropriately retailer's selling price can increase market demand and the profits of both parties, as well as that of the supply chain.

Finally, numerical examples are presented to illustrate these models, and the sensitivity analyses of a selected set of model parameters on the total profit is conducted. A major finding of this study is that coordination between the retailer and the supplier improves channel profit significantly. Furthermore, the possibility of external procurement tends to improve total system profitability as the price sensitivity of demand increases.

CHAPTER 1

INTRODUCTION

1.1 Motivation

Most companies face quality challenges in their products or services, since quality improvement has been one of the long-term competitive strategies for performance enhancement. Improving quality has been considered an important factor in achieving competitive advantages over business rivals, and is attended to extensively in today's fast-paced and increasingly competitive market (Tellis and Johnson, 2007). Over the past decades, increasing product recalls reveals that manufacturing firms are particularly vulnerable to product quality and safety, especially when goods and materials are sourced globally. The number of recall cases in EU countries due to quality problems has doubled during the period 2005-2010 (RAPEX, 2011). The impact of poor quality can be seen across various industries. Even highly reputable companies well-known for excellent past quality performance cannot be immune from the impact of a major recall. See for the examples. The cases involving Toyota (Kumar and Schmiz, 2011), the food industry in China, and even low-technology toy manufacturing in China (Tse and Tan, 2011). Such of substandard output seriously hurt the reputations and the brands of the companies involved, thus, affecting their bottom-line conditions adversely.

Recent product recalls also suggest that manufacturing firms are particularly vulnerable to product defects where goods and materials have been sourced via a supply chain with poor visibility, i.e. lack of information on the material origins and the quality of suppliers (Tse and Tan, 2011). The rapid increase in product quality incidents in global supply chains brings not only new challenges to the policy makers, but also gives rise to new research issues and opportunities for the academic world, especially in the field of supply chain management. Thus, quality-related research in supply chains provides opportunities for new explorations towards extending existing theories and application frameworks.

Supply chains and networks have increased significantly in complexity due to the involvement of numerous suppliers, service providers, and end customers (Pfohl *et al*. 2010). Recent industry trends in the business world have forced companies to expand their activities into new regions in search of qualified employees, lower production costs, high availability of raw materials, giving rise to wider and more complex supply chains while creating new opportunities for the enhancement of competitive advantages. As customer expectations go up, better quality products with shorter delivery times, more customized products, and extremely high service levels become essential for survival in a highly competitive market place. In addition, such a fierce market competition in the global economy has driven companies in many industries to look for better strategies and methods in optimizing their business processes and practices via a higher levels of coordination, collaboration, and integration within supply chains. (Arshinder *et al*, 2008) This situation also boosts competition between manufacturing firms, which inspires them to work out new strategies and practices towards achieving a better match between their production policies and market demands. This continuously evolving dynamic poses interesting challenges for effective coordination, collaboration, and integration of supply chains.

These changes require the implementation of new organizational models with different suppliers and partners responsible for an important part of final product delivery, yielding a service of excellence for satisfying customers. In order to increase value and enhance profitability, it is fundamental to establish successful partnerships with the supply chain partners that can be achieved via new models of cooperation, improved communication and integration among all the relevant constitutions. The utilization of advanced management practices is essential to accomplish these objectives. In this context, the use of integrated approaches to quality, logistics and supply chain management becomes fundamental. Therefore, it will be important to take advantage of quality management and supply chain management synergies in order to improve customer satisfaction, increase employee motivation and to improve the performance of the organization.

A supply chain consists of numerous stages involved, either directly or indirectly, in fulfilling customer requests. Such a chain includes manufacturers, suppliers, transporters, warehouses, retailers, third-party logistic providers, and customers. The objective of supply chain management is to maximize the overall value generated rather than profit generated in a particular stage (Chopra *et al*, 2007). Throughout the 1980's and 1990's the concept of customer and supplier integrative relationships have attracted renewed attention from researchers, as well as practitioners. Business in general has begun to develop close relationships with selected clients, sometimes termed strategic customers, and significantly more emphasis has been placed on improving working arrangements with critical suppliers.

Supply chain collaboration has been strongly advocated by both industry and academics since the mid 1990's, under the banner of concepts such as Supplier Managed Inventory (VMI) and Collaborative Forecasting Planning and Replenishment (CPFR). It is widely accepted that creating a seamless, synchronized supply chain leads to increased responsiveness and lower inventory costs. The driver behind such collaboration is the desire to extend the control and coordination of operations across the entire supply process, replacing both market and vertical integration as means of managing the flow process (Larsen, 2003).

According to Chopra *et al* (2007), the definition of integration is “the quality of the state of collaboration that exists among departments that are required to achieve unity of effort by the demands of the environment”. While this definition refers to integration internal to a firm or organization, our emphasis here goes beyond the firm and encompasses external entities that are major players in a supply chain.

Supply chain coordination (or channel coordination) aims at improving supply chain performance by aligning the plans and the objectives of individual enterprises. It usually focuses on inventory management and replenishment decisions in distributed inter-company settings. These strategies which were recently developed in supply chain management offer the potential for not just cutting cost but also generating new revenues and higher profits. The remaining challenge is to link those novel approaches together to garner the competitive advantage of a seamless flow throughout the supply chain.

With these supply chain strategies, one of the key decisions that a company has to make while designing a product and producing it involves setting the level of quality of its output. Broadly speaking, “quality" refers to an attribute (or a combination of attributes) more emphasis on which increases the selling price of a product but also its marginal cost. A number of existing papers address this basic question and its variants in different contexts (Jeuland 1983). However, this literature has largely overlooked issues arising from operational considerations.

Quality has been defined as fitness for use, or the extent to which a product successfully serves the purpose of consumers (Juran *et al.,* 1974). Akerlof’s (1970) work “The market for lemons: quality uncertainty and market mechanism”, was a pioneering work introducing the term “quality uncertainty”. It explained; due to prevailing asymmetry of information, how the “lemons”, synonym for bad cars, drives the good cars out of the market. A phenomenon of “market for lemons”, originally used to explain the resale market, must have equal capabilities in analyzing the primary sales market and is deemed exploratory research. Acceptance of a quality product (service) is largely influenced by informational rubric at the market end and hence theories of information economics need to be coalesced in a quality paradigm. One side of the market is better informed than the other, and results in poor selection. Low quality products penetrate the market at the cost of high quality products. Informational asymmetric customers may perceive the product price as an average of low and high, which subsumes the cost of manufacturing of high quality product ensuing in quality uncertainty.

Some studies define the integration of quality in supply chain management as the concept of Supply Chain Quality Management – SCQM (Lin and Gibson, 2011). From this point of view, designing a supply chain can be recognized as providing quality products and services across every organization or stage in the supply chain, to clients' expectations. Robinson and Malhotra (2005) stated that

> *"SCQM is the formal coordination and integration of business processes involving all partner organization in the supply channel to measure, analyze and continually improve products, services, and processes in order to create value and achieve satisfaction of intermediate and final customers in the marketplace."*

SCQM assumes a methodical and integrative approach to managing the operations and relationships among different parties in supply chains, in other words, it integrates all parties along the value chain into one whole organism and manages them as the assets of a wide entity (Simchi-Levi et al., 2000; Mentzer et al., 2001; Kannan and Tan, 2005; Wang et al., 2004).

Improving the quality of all supply chain processes leads to overall cost reduction, improved resource utilization and improved process efficiency (Wang et al., 2004). There are some studies that investigate how quality management can be used to improve the performance of the entire supply chain (Lin and Gibson, 2011; Dowlatshahi, 2011; Flynn and Flynn, 2005; Fynes et al. 2005). Other studies that identify various theoretical and methodological characteristics of the ways in which knowledge management applications are proposed in the supply chain context (Robinson and Malhotra, 2005). However, there still are some issues that remains unexplored (Yeung, 2008; Forker et al., 1997). Some authors suggest that further research is needed to provide a clearer understanding of quality practices along the supply chain and the association between quality practices and a system's overall performance (Marra et al., 2012; Kim, 2007; Cao and Zhang, 2011; Craighead et al., 2009; Bozarth et al., 2009). For example, Terziovski and Hermel (2011) present an exploratory study about the role of quality management practices in the performance of integrated supply chains, concluding, similarly as do Robinson and Malhotra (2005) that traditional quality management programs should be transformed, so that quality initiatives interact and synchronize across the entire network of firms in the supply chain. In this study, Terziovsky and Hermel propose that future research should focus on why quality practices are strong predictors of an integrated supply chain, and that future work on integrated quality and supply chain management need to empirically examine the aforementioned research questions using different methods such as survey and case study approaches with multinational samples.

Lin et al. (2005) concludes that key quality management practices can be integrated into the supplier participation programs to provide needed collaboration, which in turn would result in improved organizational performance and also that such performance can be optimized when the organization considers its suppliers as important trading partners and members of the value chain. They state that more research is needed to extend their conclusions to other countries or regions.

Kannan and Tan (2005) have empirically examined the extent to which just in time (JIT), Supply Chain Management (SCM) and Quality Management (QM) are correlated, and consequently their impact on business performance. Their study demonstrates that at both strategic and operational levels, linkages exist between how these areas are viewed by organizations as a part of their operations strategy. Their results indicate that a commitment to quality and an understanding of supply chain dynamics have the greatest effect on performance. Their empirical study, although interesting, is like others studies, limited in scope, in terms of all the supply chain and quality practices.

In view of the existing research, we can say that the integration between SCM and QM is a natural process, since, traditionally, the emphasis of supply chain is on specific functions such as purchasing, manufacturing and shipping in order to support logistics operations. In a competitive environment, there is a need to improve performance by controlling costs, increasing efficiency and service levels, rapid response and high quality of products and services (Lin et al., 2005).

It is clear that our understanding of how the areas of QM and SCM are related in a particular organization and their impact on organizational performance are still very limited (Ramos et al., 2007; Agus, 2011). Flynn and Flynn (2005) show that organizations that pursue both quality and supply chain goals are likely to achieve a competitive advantage. Nevertheless, other researchers found mixed results of the effect of quality management practice on supply chain performance, suggesting that more research is required in order to provide some guidance to both researchers and supply chain managers on how to distribute resources to issues that are critical for the integration of quality management to improve supply chain performance. Some studies have attempted to ascertain the impact, affect in a limited fashion, of these issues on system perfoemance (Fynes et al., 2005; Flynn and Flynn, 2005; Min and Mentzer, 2000; Forker et al., 1997; Yeung, 2008).

1.2 Scope of Dissertation and Research Objectives

SCM applies a methodical and integrative approach to managing the operations and relationships among different parties in supply chains. In other words, SCM integrates all parties along the value chain into one whole organism and manages them as the assets of a wider entity (Simchi-Levi et al., 2000, Mentzer et al., 2001; Kannan and Tan, 2005; Wang et al., 2004).

There exists a substantial volume of literature on supply chain collaboration, integration, and coordination since Pasternack (1985) first proposed the notion of optimal pricing and return policies for perishable items. When suppliers are the sources of quality problems, prior literature has focused on sustaining a retailer's competitiveness given strong assumptions on production capacity, product quality, quality inspection, and delivery policy. Most of the extent work is based on the critical assumption of perfect product quality. This assumption is, however, often questionable in the real issues, such as in supply yield loss. Surprisingly, the literature has not paid sufficient attention to quality uncertainty from a coordination perspective. On the other hand, the literature on channel coordination has not considered quality problem in designing supply chain partnerships. We bridge the gap between these two streams of literature by explicitly considering yield loss in a coordination framework.

Another deficiency in the current literature pertains to information asymmetry on quality issues. Information asymmetry usually occurs in a supply chain when some entities in the chain are better informed than others. Despite recent advances in information technology and the trend towards sharing information among business partners, information asymmetry remains a key feature of real supply relationships. Since the entities in a supply chain may belong to different firms that have conflicting objectives, they may not have access to private information, a system-wide optimal solution may not be implementable unless it can fully resolve any incentive alignment problems caused by asymmetric information in the system. This observation provides another important motivation for this dissertation in which we will develop optimal supply chain contract structure via exploring the impact of the information asymmetry on price and quality issues.

For simplicity, we combine our attention to a retailer-supplier relationship involving a single product under deterministic condition. Our goal is to develop integrated individual as well as joint optimization coordinated models that consider supplier's yield loss and information asymmetry. In order to achieve these goals, we attempt to

- generalize existing channel coordination mechanisms in the form of yield loss with the objective of profit maximization and the possibility of an emergency procurement option from an external vendor.
- analyze optimal supply contract design mechanisms under supply yield loss,

In the remainder of this introductory chapter, we briefly present the ongoing trends in supply chain management, point out why scientific research is crucial to support the advance of new approaches towards the existing problems in supply chain management, and highlight some challenges for mathematics, operations research, and economics. In order to develop supply chain coordination model and contract design framework that considers cost-profit structure, information asymmetry, and issues; this dissertation investigates the following two sets of areas.

1.2.1 Supply Chain Coordination and Optimization under Y with an option for Emergency Procurement from an External Vendor

Supply yield loss often hampers the ability to satisfy all market demand for any reason, it causes a serious problem. Under this stockout situation, retailers will lose their loyal customers, sales, reputation, and so on. One of the strategies for the supplier to overcome this situation may be to procure the item from an external source and then to supply it back to its customers as quickly as possible. In the marketing perspective in today's business environment, as for the retailer, it is naturally desirable for the supplier to implement complete outsourcing to hold the customers without considering the costs to make up for shortage as quickly as possible. However, the supplier may consider the trade-off between the total costs and the benefits related with emergency supply. Thus, this dilemma makes it inevitable that optimal decisions for external procurement by aligning the business processes and coordinating all the activities of the channel participants for the purpose of improving both the performance of the individual party and the total profits of the entire supply chain. Specifically, the supplier needs to adjust the ratio of external procurement to self-production based on the outsource price and the penalty cost for capacity shortage to reach an optimal solution.

Therefore, motivated by Goyal (1976, 1996), and Sinha and Sarmah (2007), we propose a new scheme using the supply chain coordination models and a framework of supply chain contract design under quality uncertainty in a two-stage supply chain. In this dissertation, we investigate the following problems in this area:

- Formulating supply chain coordination models under quality uncertainty, which maximize the total profit of the supply chain,
- Developing a supply chain coordination model which determines the optimal ratio of external procurement.

1.2.2 Supply Chain Optimization and Coordination under Quality Uncertainty with Non-linear Price Sensitive Demand

The classical objective of logistics is to be able to have the right products in the right quantity, at the right place, at the right moment at minimal cost. Efforts to produce an efficient supply chain are centered on managing logistical flow and inventory. In overcoming many of the new challenges of the comprehensive enterprise, the coordination of members along the supply chain is vital. Without coordination a supply chain system cannot be optimal as a whole since each party will only try to enhance his own profits. That is why to ensure the optimal system and to satisfy customer demands in today's competitive markets, significant information needs to be shared along the supply chain. Moreover, a high level of coordination between the supplier and retailer's decision making is also required. The concept of Joint Economic Lot Sizing (JELS) is introduced to filter traditional methods for independent inventory control and to find a more profitable joint production and inventory policy.

Based on the previous works by Sinha and Sarmah (2007), and Sarmah *et al* (2006) and we propose a new supply chain coordination model with non-linear price sensitive demand under quality uncertainty in a two-stage supply chain. In this section, we examine the following issues in this area:

- Formulating supply chain coordination models with non-linear price sensitive demand under quality uncertainty, which maximize the total profit of the supply chain,
- Developing supply chain coordination strategies which determines the optimal ranges of the retail price, and the external procurement price under quality uncertainty and non-linear price sensitive demand.

1.3 Research Contributions

The supply chain coordination and optimization models in this dissertation address the need to incorporate quality uncertainty into the strategic planning process. In particular, we contribute to the literature on supply chain coordination and optimization model as follows:

- We develop a supply chain coordination model to determine the optimal ratio of emergency procurement from an external supplier in case of stockouts due to quality uncertainty. We examined all possible scenarios for supply chain optimization and coordination in a two-stage supply chain through non-coordinated approach, suppler-driven, retailer-driven, and jointly coordination. This model can also be extended to model supplier selection problem or dual sourcing according to the performances of the external suppliers. We present a heuristic algorithm using nonlinear mixed integer programming for this model.

- We extend the first model by relaxing constraints and assumptions under a new scenario. We present a joint manufacturer-retailer production-inventory-marketing model for a defective product by a uniform distribution. The contribution of the research to the joint economic lot sizing literature is to incorporate the pricing policy as well as the imperfect quality into the previous joint manufacturer-retailer models. Our review of the literature showed that joint economic lot size models have frequently been studied in the past, and that the production of defective items and pricing decision have also been studied in this stream of research. It also became apparent, however, that imperfect production, planned shortages and pricing have not yet been studied in combination in the context of a JELS model, and that the interdependencies between these decision problems are therefore not yet well understood. This study establishes a link between the literature on shipment, ordering, pricing policies, imperfect quality and the joint economic lot-sizing literature. The second article makes a contribution to close this research gap by developing a joint economic lot size model that analyzes these problems simultaneously.

- We develop a supply chain coordination model and contract design framework that considers cost-profit structure, information asymmetry, and quality uncertainty issues in supply chains. We sought to provide implementable contractual arrangements to coordinate the channel with the consideration of supply uncertainty. We first develop a general framework that incorporates supply uncertainty. Based on the general framework, we further develop supply contracts under conditions of supply uncertainty and deterministic demand with an infinite planning horizon.

1.4 Outline of the Dissertation

After providing a survey of literature related with supply chain coordination under quality uncertainty, we have divided the dissertation into three detailed parts.

In the next chapter 2, we review and synthesize the extant literature in the supply chain coordination and competition, which help demonstrate the importance of our research and how our work will fit in with current academic interest and recent trends in supply chain practice. Chapter 3 examines a two-stage supply chain coordination model under quality uncertainty under shortage. A stochastic supply chain optimization model under quality uncertainty is addressed in Chapter 4. In Chapter 5, we study supply chain contracts under quality uncertainty with information asymmetry considerations. The conclusion and the future directions of the dissertation are summarized in Chapter 6.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

A supply chain or supply network in a real business world is extremely complex and involves numerous entities in a network, how to coordinate a decentralized supply chain has long been a key issue in supply chain management. With the development of information technology, information sharing mechanism could restructure the supply chain by coordinating decision-making and integrating supply chain activities through supply chain contracts. There have been various studies on business strategies and mathematical models on supply chain coordination through contracts and competition among supply chain members, and there are still growing interests of research in both.

However, only a limited number of research papers have analyzed this intra-chain dynamics of supply chain coordination and competition under quality uncertainty, which is one of the important motivations of the dissertation. Therefore, we must carry out our investigation from the ground level. Fortunately, substantial work has been done on supply coordination, integration, and competition in inventory theory, and we will review that relevant literature in the next section. Literature related to (1) inventory models with imperfect quality items, (2) supply/demand uncertainty in supply chains, and (3) supply chain coordination under quality uncertainty, and (4) supply chain contract design for quality improvement were reviewed and summarized in this chapter. The main focus of the literature was on the supply chain optimization and coordination, revenue management, and decision making in outsourcing.

In production planning, when there is a dynamic demand in any production period, this demand must be satisfied by one or more of the following strategies: (1) production; (2) inventory; (3) back logging; (4) outsourcing; and (5) sale loss. Note that there are limits, respectively, on production, inventory, backlogging, outsourcing, and sale loss levels. Furthermore, five kinds of costs must be taken into account: production cost (including setup cost), holding cost, backlogging cost, outsourcing cost, and sale loss cost. There are two kinds of capacity limits: (1) production capacity and (2) inventory capacity.

With the objective of minimizing the total cost aggregated from the five kinds of costs over the definite time horizon, in literature, the following four families of models are proposed, corresponding to the five strategies mentioned before.

- **Models without backlogging:** Each demand must be entirely delivered by production and/or inventory;
- **Models with backlogging:** Each demand must be satisfied by production and/or inventory from previous periods and/or from subsequent periods;
- **Lost sale models:** There are two kinds of lost sale models, stockout models and conservation models. In stockout models, the demand does not have to be entirely met in all periods. Unmet demands mean revenue lost or penalty cost;

- **Outsourcing models:** Each demand must be satisfied by production and/or inventory from previous periods and/or outsourcing.

In order to discuss interactions between quality and inventory, it is first necessary to understand each component separately. The use of quality techniques in manufacturing is not new; the American Society for Quality Control (ASQC) was already established in 1946 (Montgomery, 1991). There has been extensive research in the area of quality as a separate entity. (See Kolesar (1993) and Ebrahampour (1993) for thorough reviews on quality management).

The interactions of quality and inventory are not independent and flow in both directions. One way to gain improvement in the area of lot sizing is to address quality improvements first. Decreasing lot size can also lead to increased quality. Another theme in the quality and inventory relationship is that of systems such as Just-in-Time, Japanese manufacturing, and World Class Manufacturing. In addition, themes such as productivity, learning, equipment, maintenance, and others are linked to or by quality and inventory in the current research.

Many of the relationships between quality and inventory are modeled with optimization methods. Yano and Lee (1995) reviewed some of these works, but did not necessarily relate random yields to quality. Many of the optimization models in our work challenge or provide alternatives to the classical economic order quantity (EOQ) models when quality-related challenges exist for the production process.

We view the taxonomy in relation to the violation of some model assumptions, which include: Constant and continuous demand; no imposition of constraints;

instantaneous replacement; maintenance or inspection; time constant costs; shortages; and imperfect quality. All of the optimization models we review here assume that some level of defectives will occur.

2.2 Deterministic two-stage supply chain coordination and optimization under quality uncertainty

The issue of coordination in supply chain management (SCM) has received considerable attention from academic researchers and practitioners. Traditionally, both suppliers and retailers in the supply chain system make decisions in search of their individual benefits. However, many researchers (e.g. Parlar, et al, 1997; Qin, et al, 2007; Sarmah, et al, 2006; Weng, et al, 1997, etc.) have pointed out that coordination between both parties is important in order to gain competitive advantages through cost reduction. The importance of coordination is further increased because suppliers and retailers frequently implement the just-in-time (JIT) concept in their own systems.

A recent study pointed out that coordination is crucial to successful JIT implementation for both parties (Huang, 2004). A key technique in successful SCM is JIT application to multiple deliveries. Chung and Wee (2007) showed that increases in quality, productivity, and efficiency can be achieved through JIT delivery agreements. A recent study showed that if a long-term relationship has been established, both parties in the supply chain system can achieve further improved benefits through cooperation and information sharing (Chang, et al, 2006). Rau and OuYang (2008) presented a new integrated production-inventory policy that showed that the performance of integrated consideration is better than the performance of any independent decision from either the retailer or the supplier.

Goyal (1976) was among the first researchers focusing on the joint economic lot size (JELS) problem in the supply chain system, in which an integrated inventory model was developed assuming the supplier's production rate was infinite. Banerjee (1986) generalized Goyal's model so that the supplier produced to the retailer's order on a lot-for-lot shipment policy. Later, Goyal (1988) relaxed the lot-for-lot shipment assumption and proposed a more general JELS model that provided a lower-joint total relevant cost, in which he suggested that the supplier's economic production quantity (EPQ) should be an integer multiple of the retailer's purchase quantity. Landeros and Lyth (1989) generalized these models by incorporating the fixed shipment cost associated with each delivery to the retailer.

Recently, Goyal (1995) and Hill (1997) proposed different shipment policies and suggested that each shipment size should be determined by the first shipment size and rate of production/demand. As shown by Viswanathan (1988), neither a policy with equal-sized sub-batches nor a policy with unequal-sized sub-batches dominated the other. Ertogral *et al*. (2007) further analyzed the supplier-retailer lot-sizing problem under equal size shipment policy, in which they incorporated transportation costs explicitly into the model and developed optimal solution procedures for solving the integrated models.

More recently, Ben-Daya *et al*. (2008) presented a comprehensive and up-to-date review of the joint economic lot sizing problem and also provided some extensions of this important problem. To simplify analysis, many researchers discuss the supply chain system with a single-supplier and single-retailer. A globally optimal batching and shipment policy for a two-echelon supply chain with single-supplier and single-retailer was established by Hill (1999), in which he pointed out that the successive shipment size of the first *m* shipments using a fixed factor. Hoque and Goyal (2006) suggested an optimal procedure for a single-supplier and single-retailer production-inventory problem with equal-sized and unequal-sized shipments, in which a transportation equipment capacity constraint was included. Further, Huang (2004) developed an optimal policy for a single-supplier and single-retailer integrated production-inventory problem with process unreliability consideration. More recently, Chen and Kang (2010) developed integrated supplier-retailer cooperative inventory models with the permissible delay in payments to determine the optimal replenishment time interval and replenishment frequency.

Inventory models with imperfect quality items

In practice it quite often occurs that inventory management is affected by imperfect product quality. Porteus (1986) integrated the effect of imperfect items into the basic EOQ model, in which he used the simple model to illustrate the relationship between quality and lot size. Rosenblatt and Lee (1986) assumed that defective items could be reworked instantly at a cost and they found that the presence of defective products motivated smaller lot sizes. Later, Schwaller (1988) assumed that defective items were present in incoming lots and the inspection costs should be incurred in finding and removing such items. An EOQ-based model with demand-dependent unit production cost and imperfect production processes was proposed by Gerchak (1992), in which he formulated the inventory decision problem as a geometric program that was solved to obtain optimal solutions. Salameh and Jaber (2000) also developed an EOQ-based model for items received with imperfect quality, in which they assumed that the defective quantities could be sold as a single batch by the end of 100% screening process. They found that the economic lot size increased as the average percentage of flawed quality items increased. Goyal and Cardenas-Baeeon (2002) proposed a simple method for deter mining the EPQ for an item with imperfect quality.

Recently, Huang (2004) developed a model to determine an optimal integrated supplier-retailer inventory policy for imperfect items in JIT environment. Papachristos and Konstantaras (2006) focused on the issue of no shortages in EOQ-based models with proportional flawed quality, in which the proportion of the imperfects was assumed to be a random variable. More recently, Wee *et al*. (2007) developed an optimal inventory model for items with imperfect quality and shortage backordering in which the optimum operating inventory strategy was obtained by trading off the total revenues per unit time. Furthermore, Maddah and Jaber (2008) developed an EOQ-based model with unreliable supply, characterized by a random fraction of imperfect quality items and a screening process. They rectified a flaw developed by Salameh and Jaber (2000).

Recent operations management literature began to focus on developing integrated models that can simultaneously optimize the relevant inventory (operations) and pricing (marketing) decisions (Sajadieh, et al, 2009). A literature reviews on pricing and ordering policies for manufacturer–retailer supply chains was made by Khouja (1999). In the meantime, Petruzzi and Dada (1999) also made a review with extensions on pricing and the news supplier problem. Mantrala and Raman (1999) further investigated the effect of the retailer’s optimal ordering quantity decisions under demand uncertainty. Lau and Lau (2002) developed a joint pricing–inventory model and they found that different demand functions could lead to very different results in a multi-echelon system. Later, Viswanathan and Wang (2003) developed a simple supplier-retailer supply chain model in which the retailer faces a price-sensitive deterministic demand.

Ray *et al*. (2005) further introduced an integrated marketing inventory model for two pricing policies in which they considered price as a decision variable using mark-up pricing. More recently, Bakal *et al*. (2008) presented two inventory models with price-sensitive demand and they investigated two different pricing strategies. Pan *et al*. (2002) further constructed a two-period model to discuss pricing and ordering problems for a dominant retailer under a two-echelon supply chain.

A detailed survey of the recent inventory models with imperfect items are provided by Khan and Guiffrida (2011). Roy et al. (2011) developed an EOQ model for imperfect items where a portion of demand were partially backlogged. Combining the effect of product deterioration, imperfect quality, permissible delay and inflation with the EOQ/EPQ model, Jaggi et al. (2011) investigated an inventory model when demand is a function of selling price. Yu et al. (2012) extended Salameh and Jaber (2000) when a portion of the defectives can be utilized as perfect quality and the utilization of the acceptable defective part will affect the consumption of the remaining perfect quality items in the stock. In another model, Jaber et al. (2013) investigated Economic Order Quantity (EOQ) model for imperfect quality items under the push-and-pull effect of purchase and repair option, when the option when defectives are repaired at some cost or it is replaced by good items at some higher cost. They presented two mathematical models; one for each case and discussed optimal policies for each case.

More recently, Liu et al. (2013) studied effect of substitution when two loss averse retailers are competing for substitutable product under stochastic demand rate and deterministic substitution rate. They have developed game theoretic model obtained unique optimal policy for Nash equilibrium under certain conditions. In addition, Salameh et al. (2014) have solved joint economic lot size model with substitution and observed that substitution is highly beneficial in saving cost.

Supply-driven chain vs. Demand-driven chain

Supply chain management has actively stimulated much academic interests on both supply and demand chains. However, most of these studies in the literature focused on demand-driven supply chain. Supply-driven chain's production is different from traditional demand-driven production because its supplies must guide the full production flow toward the markets and respond actively to customer demand.

Sethi & Sethi (2001) defined this demand-driven supply chain as marketing-driven supply chain and Ayers (2006) described it as forecast-driven supply chain. These chains exist in personal computers, automobile and electronics production areas where customer demand propagates through supply chain and manufactures attempt to make best use of its resource to meet the demand while subject to production capacity limitation.

Based on the product and market demand characteristics, Fisher (1997) classified these chains into physical efficient and market responsive. The former produces basic functional products with stable demand where emphasis is on efficiency while the latter produces innovative products with fluctuating demand where the emphasis is on marketing responsiveness.

A review of some of models and solution approaches on supply chain and production planning was given by Mula et al. (2006). There is, however, another category of supply chain existing in diverse areas such as crude oil, fruit, agriculture, flower, water resource, energy production, mail and packaging processing etc. is dramatically different from a demand-driven chain. Bullow & Shapiro (2003) studied the supply chain of Alaskan and Canadian oil production, and Hameri & Palsson (2003) studied the supply-driven chain in the fishing industry. Wang et al. (2004) discussed a product-driven chain whose operation relied more on product capacity rather than demand.

Paulsen & Hensel (2007) introduced a supply-driven chain in water and energy production and discussed its different characteristics. Schultmann et al. (2006) built a supply planning model driven by reverse logistics for remanufacturing system, which can be taken as a kind of supply-driven chain driven by reverse supply. Hull (2005) reviewed supply-driven chain characteristics and provided a summary of these applications. Due to either economic characteristic, product perishability and the nature of being a co-product, or administration considerations, these chains are activated by supply, rather than customer demand, exhibiting different characteristics, and requiring different supply coordination and production planning mechanisms from demand driven chains.

Inventory models with emergency procurement option

As for the emergency procurement option in supply chain, in literatures, Khouja (1996) solves a newsboy problem with an emergency supply option. Barnes-Schuster et al. (2002) illustrate how options provide flexibility to a retailer to respond to market changes in the second period using a two-period model with correlated demand. Babich (2006) presents valuation of inventory-reorder options in a competitive environment with imperfect production system and studies the value of the deferment option. Xu and Nozick (2009) study the use of option contracts for global supply chain design. Xu (2010) studies the situation that the manufacturer may purchase option contracts from the supplier before the demand is realized, or order after the demand is realized, which is subject to random pricing and uncertain availability. Xia, et al. (2010) study two contract mechanisms to share risks in a decentralized supply chain: the option contract and the firm order contract. Compared with the sourcing modes in the existing literatures, the single sourcing with emergency option mode can combine the cost advantage of single sourcing mode and the risk dispersion advantage of buying emergency option, and is of greater application value.

2.3 Stochastic Two-Stage Supply Chain Coordination and Optimization Model under Quality Uncertainty

Today in dynamic market conditions, the supply chain coordination is becoming a key factor. In traditional supply chain management, the production, inventory, and shipment policies of supply chain members are managed separately. Therefore, the optimal lot size for one member may not result in an optimal policy for the others. In literature, the integrated manufacturer-retailer model has been addressed, where the joint total profit for both the retailer and the manufacturer is maximized.

The integration between supply chain members has long been debated as reviewed in the previous section. Goyal (1976), initiated the concept of a joint optimization problem of supplier and retailer, on the assumption that the supplier has an infinite production rate. Banerjee (1986), extended the joint economic lot size (JELS) model in which the manufacturer was obliged to order under the lot-for-lot policy. Goyal (1988), relaxed the assumption of lot-for-lot, and assumed that the production lot is shipped in a number of equal-size shipments. Goyal (1995), proposed a model where by the shipment size is raised by a factor equal to the ratio of the production rate to the demand rate.

In supply chain coordination field, over recent years, researchers have investigated multi-supplier and retailer. Recently, Glock and Kim (2015) investigated a single supplier–multi-retailer supply chain and considered the case where the supplier merged with one of its retailers. Sajadieh and Thorstenson (2014) studied a supply chain with a single retailer and either one or two supplier(s)/supplier(s). In addition, some researchers investigated multiple suppliers. Sajadieh et al. (2013) studied an integrated production–inventory model for a three stage supply chain involving multiple suppliers, multiple manufacturers and multiple retailers.

In contrast, perfect-quality products are avoided in some studies; hence, the process may deteriorate and produce defective products. Porteus (1986), Lee and Rosenblatt (1986), probed the effect of defective products on the basic Economic Order Quantity (EOQ). Numerous researchers have expanded miscellaneous imperfect quality inventory models for this critical problem involving an imperfect production process (e.g., Schwaller 1988; Zhang and Gerchak 1990; Cheng 1991; Ben-Daya and Hariga 2000; Salameh and Jaber 2000; Cardenas-Barron 2009; J.T Hsu and L.F. Hsu (2013)).

Yang and Wee (2000) investigated a joint inventory model for supplier-retailer under an imperfect production process. Another study in this area was published by Goyal et al. (2003), who introduced a simple approach to find an optimal integrated supplier–retailer inventory policy for a defective product. Hardik and Kamlesh (2014) investigated a single-supplier-single-retailer production inventory model involving defective items in both an individual and joint management system with service level constraint. Hsu and Hsu (2012) probed an integrated inventory model for supplier-retailer under the conditions of defective products, where the supplier inspects the products. Recently, Hsu and Hsu (2012) designed a model to frame an integrated supplier retailer inventory policy for defective products, where the retailer inspects the products.

Relaxation of the basic EOQ and EPQ models' assumption that stockouts are not permitted led to the development of models for the two basic cases for stockouts – backorders and lost sales. The work of Salameh and Jaber (2000) was the first model that provided an economic order quantity for a retailer who receives imperfect lots. They extended the traditional EOQ model by accounting for imperfect quality items with deterministic demand and instantaneous replenishment. Goyal and Cardenas-Barron (2002) presented a simpler EOQ/EPQ model for imperfect items and an easier approach to implement lot size calculation with defective rate to the model of Salameh and Jaber (2000). Konstantaras et al. (2007) extended the model in Salameh and Jaber (2000) along two dimensions. First, they assumed that the acceptable items are entered into work-in-process inventory in batches and not on unit-by-unit basis. Second, items that were defect free after completing rework were used to meet the demand. Chan et al. (2003) integrated lower pricing, rework and reject situations into a single economic production quantity (EPQ) model. It was assumed that rework items can be kept in stock at a cost.

Another issue in the lot sizing area that has attracted the attention of numerous researchers is the integration of production and pricing. One of the first models of this kind was formulated by Kunreuther and Richard (1971), who incorporated pricing into the traditional EOQ model considering a linear price. Reyniers (2001) later developed a model of single-manufacturer, single-retailer distribution channel, in which the retailer faces a price sensitive deterministic demand, on the assumption that the manufacturer has a finite production rate. A multitude of researchers have developed a joint inventory model for manufacturer-retailer, where market demand is a function of price (e.g., Viswanathan and Wang 2003; Ray et al. 2005; Bakal et al. 2008, Wang et al 2015). Sajadieh and Jokar (2009) proposed the supplier–retailer supply chain lot sizing models where market demand is a linear function of price, assuming that the production lot is shipped in a number of equal-size shipments. Kim et al. (2011) probed an integrated inventory model for manufacturer-retailer under the conditions of price dependent demand. The retailer places orders based on the EOQ model, and the manufacturer produces the ordered quantity on a lot-for-lot basis. Readers are referred to Sajadieh and Jokar (2008) and Glock (2012), and Ben-Daya et al. (2008), for reviews of the JELS models.

In this research, the four aforementioned literature branches are integrated in a model where the shipment, ordering, pricing policies, imperfect quality and backordering are optimized all together. In real world cases, the manufacturers usually accept the return products and sell them in the second market. That is our motivation to do this research. Incorporating these two features into the model increases the complexity. The study investigates an approach to adopt an optimal joint manufacturer-retailer inventory policy for a product with imperfect quality. In this model, market demand is a linear function of price. Shortages are allowed and assumed to be completely backordered. The authors have analysed how the coordination between two supply chain members is affected by the number of defective products with a uniform distribution while the end-customer demand is price sensitive in the first market. The models for the two-level supply chain were extracted from the non-joint and the joint policies.

2.4 Supply Chain Contract Design for Quality Improvement

Supply chain members coordinate each other by using contracts for better management of business relationship and risk management. Tsay et al. (1999) provide a good taxonomy based on contract clauses. In their work, supply contracts are classified into eight categories: specification of decision rights, pricing, minimum purchase commitments, quantity flexibility, buyback or returns policies, allocation rules, lead time, and quality. Because several novel works on supply contracts, such as price protection, revenue-sharing, etc., have appeared in the last few years, the various extensions of supply chain contracts have been proposed by researchers.

Contractual agreements between suppliers and retailers in relation to inventory management are also heavily studied with emphasis on the cost of the (decentralized) equilibrium solution as compared to the centralized optimal; see Lariviere and Porteus (2001) for wholesale price contracts, Pasternack (1985) for buy-back contracts, Tsay (1999) for quantity-flexibility contracts, Taylor (2002) for sales-rebate contracts, Bernstein and Federgruen (2005) for price-discount contracts, etc. Lariviere (1998) and Cachon (2003) surveyed related results. Our study differs from this huge body of literature in that these studies relate to inventory management decisions and represent production capacity in aggregate units, whereas we address product quality issues and the optimal ratio of outsourcing which are one of the essential decisions in an outsourcing setting.

In supply contract design, when a retailer places an order and a supplier deliver them, the issues of who controls what decisions and how entities will be compensated are critical. Due to the importance of supply contracts, the field has developed in many directions. We narrow our search to the articles which explicitly offer the analysis of the relationship between the suppliers and retailers in supply chain management area.

In the literature review, we also focus on the one-supplier-one-retailer structure, rather than including multiple-retailer and multiple-supplier structures. Since the work on supply chain contract design based on the one-supplier-one-retailer structure is ample and more in depth, which provides an insightful understanding of intra-chain dynamics under exciting contractual arrangements. The research on multiple-retailer and multiple-supplier structures, on the other hand, is relatively scarce and rarely offers optimal policies.

In buyback contract, the retailer is allowed to return the unsold inventory to some fixed amount at agreed upon prices. The manufacturers accept the returns from the retailers when the production costs are sufficiently low and demand uncertainty is not too great (Padmanabhan and Png, 1997).

Giannoccaro and Pontrandolfo (2004) and Cachon and Lariviere (2002, 2005) study revenue-sharing contracts in a supply chain with revenues determined by each retailer's purchase quantity and/or price. They demonstrate that revenue-sharing coordinates a supply chain with a single retailer. Also, they find that a number of other supply chain contracts (e.g., returns policy, quantity discount, quantity-flexibility, rebate) do not effectively coordinate all of the supply chains that they consider. However, they acknowledge several limitations of revenue-sharing contracts. Revenue sharing does not coordinate competing retailers when each retailer's revenue depends on its order quantity and the vector of the retail price.

Even though traditional inventory theory generally assumes that the retailer can order any quantity from the supplier at any time, in the quantity flexibility contracts, the supplier and the retailer accepts some of the inventory and stock out cost burden. The supplier allows the retailer to change the quantity ordered after observing actual demand. The retailer commits to a minimum purchase and the supplier guarantees a maximum coverage (Tsay, 1999). Lee et al. (1997) described these contracts as a response to certain supply chain inefficiencies. The coordination achieved by the contracts provides incentives to all supply chain members and improves the service level.

There are a number of extensions to buyback contracts and quantity flexibility contracts are presented in the literature like two period supply contract model for decentralized assembly system (Zou et al., 2008), flexible returns policies in three-level SC (Ding and Chen, 2008) to fully coordinate SC members, option based flexibility contract (Bassok and Anupindi, 2002), and time-inflexible contract (Li and Kouvelis, 1999).

As for information asymmetry issues in supply chains, Corbett and Groote (2000) derive an optimal quantity discount policy under asymmetric information about the retailer's holding costs. Corbett and Tang (1999) analyze three types of contracts from the supplier's point of view with information asymmetry considerations about the retailer's cost structure. Also, they point out that more flexible contracts allow the supplier to trade with retailers with higher costs. Ha (2001) considers designing a contract to maximize the supplier's profit in the newsboy problem when demand is stochastic and price-sensitive and the supplier has incomplete information on the marginal costs of the retailer. He shows that the supplier's profit is lower than in the complete information case while the retailer's is improved.

Finally, in the area of the supplier's quality commitment, Reyniers and Tapiero (1995) use a simple game-theoretic formulation of a supplier-producer channel to examine the impact of the contract structure on the supplier's quality and the producer's inspection practices as well as its implications for the quality of the end product. Since suppliers often have more information about the quality of the parts than the producer, Lim (2001) investigates contract design when there is incomplete information regarding the quality of the parts. He shows that when the supplier and the producer have to share damage costs, an optimal contract is one where the supplier compensates the producer by the same amount, regardless of his quality type. However, a supplier with low quality is more likely to be offered a contract with an inspection scheme, while a supplier with high quality is likely to be constrained with a warranty scheme. Finally, we seek to extend the current literature by exploring the impact of the information asymmetry on price and quality. In this dissertation, we explore it on designing contracts in a two-stage supply chain with a single-product where the product is shipped from a supplier to a retailer at a wholesale price and then sold to a price-sensitive market.

2.5 Research Gaps

Observations and Gaps in Uncertainty and Supply Chain Coordination in literature are listed as below:

- Most of the studies are restricted to two level serial supply chains. In reality, supply chain can have divergent and convergent multi-echelon structures and managers may consider other options or additional resources to handle the issues in their supply chains. The literature seems lacking to address the uncertainty concerns in such structures.

- A limitation of the existing literature is that most of the work on supply chain coordination has been connected to decisions related to ordering quantity, and inventory reviewing policies with the optimal reorder point and reorder quantity. The above mentioned models are also limited to analyze only the issues of coordination on individual pay-offs rather than making efforts towards investigating the impact of competition on the coordination of the whole supply channel.
- The literature has emphasized more on demand uncertainty, whereas, supply uncertainty can be of equal concern in the era of globalization and outsourcing. Moreover, optimization-based quantitative models can be proposed to explore the impact of supply uncertainty on supply chain performance.
- Concept of product quality risk in supply chains has not been fully investigated in literature. Although Zsidisin (2003) stated that quality risk includes the risk of producing unsafe or unreliable products that can even harm the consumer, when these defects are caused by another firm or inherited from a sub-contractor or an original equipment manufacturer (OEM). However, neither product quality risk nor its domino effect in a serial supply chain have been thoroughly studied.
- As to production quality, there are also two kinds of supply chain production models, namely perfect quality model and imperfect quality model. Most models in references above are built on the basis of perfect quality. In supply chain production practice, however, imperfect quality or defect is very common and the process may

deteriorate and produce defective or poor quality items. It can impact the production system (Radhoui et al. 2009). For example, defects can be attributed to internal production quality issues or external unqualified supply, the Chinese milk melamine scandal in 2008 (Chan, 2008) and Mattel’s toys with lead manufactured in China (Tse and Tan, 2011) are typical examples of these cases. Recently, supply chain quality management gains attentions and may form a new direction (Batson & Mcgough, 2007).

- The literature on quality uncertainty is limited by its exclusion of a coordination perspective in the supply chain. On the other hand, the coordination literature is limited by its exclusion of quality uncertainty in designing a contract of alliance for the entire supply chain. There is a scope to explore combination of supply chain contracts to deal with product quality risk in case of either overproduction or underproduction.

CHAPTER 3

INTEGRATED AND COORDINATED MODELS UNDER YIELD LOSS WITH EMERGENCY PROCUREMENT OPTION

3.1 Introduction

In today's global market, companies pay more attention to supply chain management and they realize that the performance of their businesses depends largely on collaboration, coordination, and integration across the supply chain. Increased competition on cost, quality and flexibility, profit maximization in a globalized area has compelled the researchers and the practitioners to consider the entire supply chain from material supplier through manufacturer to distributor as a single business process. So in order to maximize the profits, firms in supply chain may both compete and co-operate with each other.

Supply chain management has been increasingly discussed in academia and industry since the mid-1980s. Managing inventory in a two-stage supply chain involves minimization of inventory across each member while simultaneously meeting the customer service goals. Each stage of a supply chain thrives to improve its operations, reduce costs and increase profitability through coordination. A coordination mechanism may be necessary to motivate the members to achieve coordination. Supply chain members are dependent on each other and these members need to be coordinated by efficiently managing dependencies between each other. The concept of coordination may guide supply chain participants to work coherently to identify interdependencies between each other, to mutually define goals and to fairly share risks and rewards. Hence the consideration of joint optimization of supply chain is of interest.

The two-stage supply chain model depicts the dynamics of a retailer and a supplier: A retailer as a retailer purchases items from one main supplier and resells them at retail price for a single selling season while a supplier manufactures products and sells them to the retailer a whole sale price. Recently the cooperation between supplier and retailer for improving the performance of a supply chain has received a great deal of attention from researchers, and supply chains with multiple decision makers have begun to receive considerable interest due to the fact that independent entities in the supply chain acting in their own self-interest often make decisions that are sub-optimal. In such cases, a centralized control is supposed. In fact, a decentralized control of the supply chain is more appropriate. In a decentralized supply chain, there may be several decision makers pursuing different objectives and one party may be dominant over the other to achieve his own goal.

In the literature, the researchers and practitioners have considered the problem of coordinating a two-stage supply chain with a retailer and a supplier. Moreover, a lot of them only addressed channel coordination in supply chain paying less attention to the issues of product quality risk and supply chain coordination with emergency procurement option under shortage and stochastic demand.

The purpose of this chapter is to establish a cost-profit relationship model in a two-stage supply chain where the supplier has insufficient production capacity to the retailer because of product quality risk and the demand of retailer is independent stochastic variable. In a two-stage supply chain, first the retailer places an order at its own optimal lot size to the supplier and the supplier produces the retailer's order quantity. Because of unexpected insufficient production capacity and product quality risk, the supplier may fail to meet the market demand. A lost-sale may occur for the supplier in case of a shortage to the retailer and then the supplier is subjected to a stock-out cost for the lost sales. In this situation, the supplier has an option for emergency procurement to avoid the stock-out by coordinating with the supply chain members together.

In this chapter, we give an introductory discussion on the two types of supplier-retailer coordination model studied in this dissertation: an integrated coordination model in which the supplier and retailer can fully cooperate with each other in making decisions to maximize the total system profit, and a channel coordination model in which one party provides a certain coordination scheme to entice the other one to make decisions in a cooperative way that increases the individual profit for both parties. In addition, we also discuss a benchmark model, referred to as the individual decision model, in which there is no coordination between the supplier and retailer. For each model, we give the profit-maximizing formulation and the optimal properties of individual and system profits. We also introduce the practice in which the corresponding coordination mechanism could be meaningful. These discussion and observations are then used to support the studies on the specified supply chain coordination issues.

	Sinha *et al*.(2007)	Proposed Model
Model	1. Individual Decision Model 2. Retailer/Retailer's Perspective Coordination Model	1. Individual Decision Model 2. Manufacturer/Seller's Perspective Coordination Model 3. Retailer/Retailer's Perspective Coordination Model 4. Integrated Joint Coordination Model
Penalty Function for Shortage	1. Constant	1. Constant 2. Linear function of k
Decision variables	n, Q, k (binary, either 0 or 1)	n, Q, k (continuous, $0 \leq k^* \leq 1$)
Total profit function	$\Pi_{ch}[n, Q, k]$	$\Pi_{ch}[n, Q, k]$
Revenue Sharing Mechanism	None	Revenue sharing contract by channel performance

Table 3.1 Differences between Sinha *et al*.(2007) and the proposed model

In this research, we apply the concept of optimal outsourcing and partial backlogging into a deterministic inventory model. The penalty cost is regarded as a constant in Sinha *et al* (2007) recently. However, the warranty cost is characterized as a function of the level of either backorder or external procurement in many real situations. Table 3.1 summarizes differences between Sinha *et al* (2007) and our proposed model. Our proposed model extends the basic two stage supply chain coordination problem to consider the feature of optimal outsourcing under quality risk when a stock-out occurs. The supplier fulfils the remaining customer demand at an optimal ratio of emergency procurement from an external supplier, even though some amount of remaining customer demand becomes lost sales as we minimize the total operational costs.

This chapter is organized as follows. Section 3.2 introduces some assumptions and notations. An individual decision model of supplier and retailer are proposed in Section 3.3 and three different types of supply chain coordination models are proposed in Section 3.4.

A numerical example and applications are discussed in Section 3.4 and 3.5. Summary and concluding remarks are provided in Section 3.6.

3.2 Assumptions

We consider a simple supply chain problem with a single manufacturer/seller and a single retailer/retailer. Figure 3.1 illustrates the inventory patterns of both retailer/retailer and the supplier/supplier. The retailer has an annual demand rate of D units for the given product, and places regular orders of fixed size Q. The supplier manufactures a production lot $Q_p = nQ$ by producing items in batches of size Q and planning to have each batch delivered to the retailer in n shipments, each with a lot of Q units. The supplier fulfills the shipments of Q units immediately. Since the production process on the manufacturer's plant is not perfect, some of the Q units may be defective at the rate of r. Thus the maximum inventory level of the retailer is $(1-r)Q$. We also assume that the production capacity of the supplier is limited for some other reasons, the annual market demand D is partially satisfied, which means that the fraction of the annual demand (βD) is provided by the supplier. Once the retailer receives the lot of Q units, a 100% screening process is conducted on the retailer's side. The retailer satisfies all demand with good quality items and we assume the retailer disposes of all defective items at no costs instead of returning them to the supplier. We assume that shortages at the retailer are allowed and the supplier has an option for emergency procurement from an external supplier. The following assumptions are used in our model.

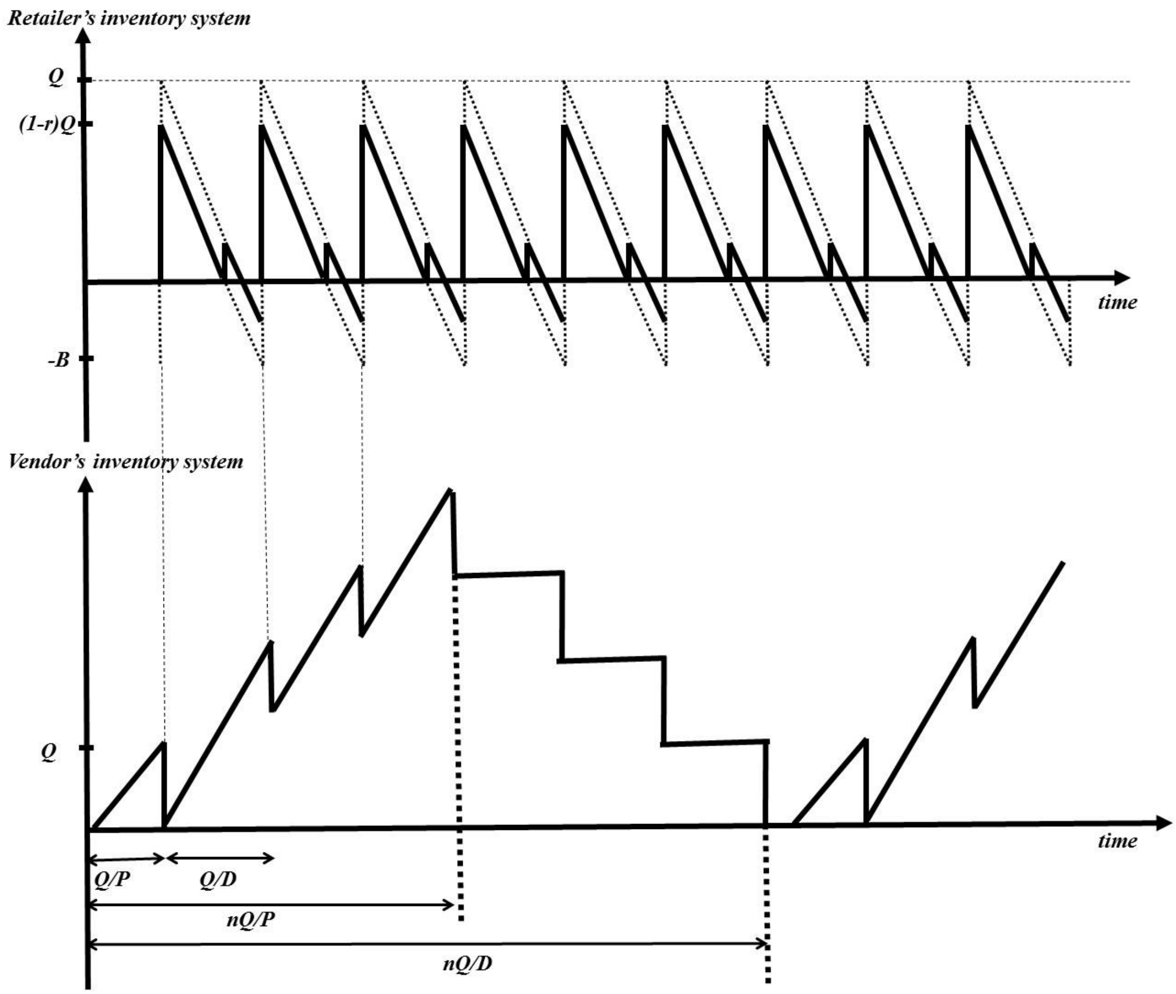


Figure 3.1 Inventory pattern of retailer and supplier

Assumptions

1. The annual demand is known, and constant
2. The defective items at the percentage of *r* exist in lot size *Q*.
3. A 100% screening process of the lot is conducted at the retailer's place and there is no inspection error. A defective item incurs a warranty cost for the supplier.

4. Shortages are allowed.
5. There is a single manufacturer/supplier and a single retailer/retailer in a supply chain.
6. The inventory holding cost per unit of the retailer (h_b) greater than that of the supplier (h_v).
7. Both the retailer and the supplier share complete information.
8. The planning horizon is infinite.
9. The replenishment is instantaneous.

3.3 Model Formulation

In this chapter we formulate two-stage supply chain coordination models when the supplier has inefficient production capacity and has an option for emergency procurement. We consider four types of two stage supply chain models.

Firstly, we formulate an individual decision model. In this independent model, manufacturing and ordering policies are independent and coordination between the supplier and the retailer will not be considered. Secondly, we consider an individual model from supplier’s point of view. This model is opposite to the retailer's point of view model. Because supplier is a decision-maker, the warehouse and retailer decide ordering policies according to the supplier's decision. For instance, the high-technology products are made by the supplier's decision regardless of the warehouse and retailer's order. Because the supplier and retailer’s inventory policies can be described by simple economic order quantity (EOQ), we can easily derive the optimal policies. Thirdly, we develop an individual model from retailer’s point of view. In this model, the retailer is a decision-maker. Therefore, the other parties follow the retailer's ordering policy. For example, department stores decide the ordering policies regardless of the other parties, because they have a power in the marketplace. Finally, we formulate an integrated joint coordination model. The supplier and the retailer fully cooperate with each other to make decisions that maximize the system profit. The assumption of full cooperation usually makes sense in the practice of supplier-managed inventory (VMI) system, where the supplier, usually a manufacturer but sometimes a distributor, is authorized to manage the inventory levels at the retailer.

3.3.1 Non-coordinated Decision Model

In this section we consider an individual decision model in a two-stage supply chain, we assume there is no coordination between a supplier and a retailer, which may represent any two upstream-downstream participants that are independently managed. In this model, the supplier and the retailer do not cooperate with each other to make decisions to maximize the system profit. Each participant makes its own decision to maximize its individual profit. In this section we consider two cases when supplier dominates supply chain decisions and when retailer has a channel power and drives market decisions.

In this situation, the supplier may face stock-outs when it can’t satisfy the market demand because of his/her insufficient production capacity or for any reason. We consider that both the retailer and the supplier have their own policies individually to maximize their net profits. The supplier annually provides only βD units, and the retailer has to modify his order so that he/she can fit the supplier insufficient production capacity. The retailer places the order at its own optimal lot size Q^* units to the supplier and the supplier produces *n* times the retailer's order quantity (Q^*) to optimize the production set-up number. It is assumed that manufacturer's inventory is multiples of retailers ordering quantity and it can be written as $Q\left(1-r\right)$ in its imperfect production process. We assume the percentage of the annual demand satisfied by the supplier, β is defined

$$\beta=\frac{(1-r)D+krD}{D}=1-r(1-k),\ \ if\ \ Supply=Demand$$

When the supplier fails to supply sufficient products to the retailer in a supply chain, it finally leads to a lost-sale, and the supplier is subject to a penalty cost per unit per year for the lost sales.

3.3.1.1 Retailer driven model

In a retailer's perspective model, we assume that the retailer has the greater channel power to initiate the replenishment decision to maximize its individual profit. The supplier needs to make decisions subject to the retailer's optimal decisions.

A general retailer driven model can be expressed as follows:

Retailer Driven Model	
Retailer's problem	Supplier's problem
Max. Retailer's Profit	*Max.* Supplier's Profit
s.t. Supplier's constraints	*s.t.* Retailer's optimal decisions
	Supplier's constraints

A retailer driven model consists of two sub-problems and can be solved in sequence. First the retailer makes decisions to maximize its individual profit in the retailer's own problem, which means that the retailer makes decisions on Q^* and n^* for the supplier and the supplier adjusts its policy according to them. The retailer's optimal decisions, in turn, become one constraint in the supplier's problem, whose objective is to maximize the supplier's profit through making decisions on manufacturing, replenishment, supply etc. Thus we can obtain the profit functions of the retailer and supplier as below

$$\begin{aligned}\Pi_b &= \text{Gross revenue} - \text{Purchasing cost} - \text{Ordering cost} - \text{Holding cost}\\ &= [\beta D + k(1-\beta)D]p_b - [\beta D + k(1-\beta)D]p_v - \frac{[\beta D + k(1-\beta)D]c_b}{Q(1-r)}\\ &\quad - \frac{Q(1-r)h_b}{2}\end{aligned} \tag{3.13}$$

From Eq. (3.1), the retailer's individual optimal lot size Q^* is obtained as follows

$$\frac{\partial \Pi_b}{\partial Q} = \frac{[\beta D + k(1-\beta)D]c_b}{(1-r)Q^2} - \frac{(1-r)h_b}{2} = 0, \qquad \therefore Q^* = \frac{1}{(1-r)}\sqrt{\frac{2[\beta D + k(1-\beta)D]c_b}{h_b}} \tag{3.14}$$

Accordingly, the retailer's individual optimal profit is given by

$$\begin{aligned}\Pi_b(Q^*) &= [\beta D + k(1-\beta)D]p_b - [\beta D + k(1-\beta)]Dp_v - \frac{[\beta D + k(1-\beta)D]c_b}{Q^*(1-r)}\\ &\quad - \frac{Q^*(1-r)h_b}{2}\\ &= [\beta D + k(1-\beta)D](p_b - p_v) - \frac{\sqrt{h_b}\cdot \beta D c_b}{\sqrt{2[\beta D + k(1-\beta)D]c_b}}\\ &\quad - \frac{\sqrt{2[\beta D + k(1-\beta)D]c_b}\cdot h_b}{2\sqrt{h_b}}\end{aligned} \tag{3.15}$$

From Eq. (3.15), corresponding to the lot size that the retailer determined, the supplier's profit function can be obtained as follows:

$\Pi_v(n^*,Q^*)$ = Gross revenue – Purchasing cost – Production Cost – Procurement Cost – Setup cost – Holding cost – Penalty Cost for Shortage

$$= \left[\beta D + k(1-\beta)D\right] p_v - \beta Dp - k(1-\beta)Dp_0 - \frac{\beta Dc_v}{nQ^*} - \frac{h_v Q^*}{2}\left\{(2-n)\frac{D}{P} + (n-1)\right\} - (1-k)(1-\beta)D(g - g_0 k) \tag{3.16}$$

From Eq. (3.17), the optimal number of delivery batches per production run, n^* of the supply chain system is expressed as follows:

$$\frac{\partial \Pi_v}{\partial n} = 0, \quad n^* = \left\lfloor \frac{1}{Q^*}\sqrt{\frac{2\beta Dc_v}{h_v}\frac{P}{P-D}} \right\rfloor, \tag{3.17}$$

where $\lfloor x \rfloor$ = the smallest integer greater than *x*.

$$Q^* = \frac{1}{(1-r)}\sqrt{\frac{2[\beta D + k(1-\beta)D]c_b}{h_b}} .$$

Thus, the total profit function of the supply chain system is given by

$$\Pi_{ch} = \left\{ \Pi_b(Q^*) + \Pi_v(n^*,Q^*) \right\}$$

$$= [\beta D + k(1-\beta)D]p_b - [\beta D + k(1-\beta)D]p_v - \frac{[\beta D + k(1-\beta)D]c_b}{Q^*(1-r)} - \frac{Q^*(1-r)h_b}{2} + \left[\beta D + k(1-\beta)D\right] p_v - \beta Dp - k(1-\beta)Dp_0 - \frac{\beta Dc_v}{n^*Q^*} - \frac{h_v Q^*}{2}\left\{(2-n^*)\frac{D}{P} + (n^*-1)\right\} - k(1-\beta)Dp_0 - (1-k)(1-\beta)D(g - g_0 k) \tag{3.18}$$

$$= [\beta D + k(1-\beta)D]p_b - \frac{[\beta D + k(1-\beta)D]c_b}{Q^*(1-r)} - \frac{Q^*(1-r)h_b}{2} - \beta Dp - k(1-\beta)Dp_0 - \frac{\beta Dc_v}{n^*Q^*} - \frac{h_v Q^*}{2}\left\{(2-n^*)\frac{D}{P} + (n^*-1)\right\} - k(1-\beta)Dp_0 - (1-k)(1-\beta)D(g - g_0 k)$$

From Eq. (3.19), by taking the first derivative of the total profit function of the supply chain system, we can obtain the solution of the optimal sourcing problem as follows

$$\frac{\partial \Pi_{ch}}{\partial k} = (1-\beta)D[p_b - p_0 - \frac{c_b}{Q^*(1-r)} - 2g_0 k + g + g_0] = 0,$$
$$\therefore k^* = \frac{1}{2g_0}[p_b - p_0 - \frac{c_b}{Q^*(1-r)} + g + g_0] \tag{3.19}$$
$$where\ \ Q^* = \frac{1}{(1-r)}\sqrt{\frac{2[\beta D + k(1-\beta)D]c_b}{h_b}}$$

3.3.1.2 Supplier driven model

In a supplier's perspective coordination model, the supplier has the greater channel power and makes decisions (e.g. supply, replenishment, manufacturing, etc.) independently to maximize its individual profit. Consequently, the retailer has to make decisions (e.g. replenishment, selling, etc.) subject to the supplier's optimal decisions. The retailer adjusts its policy according to the supplier's decisions on n^* and Q^*. The assumption of the supplier driven model usually makes sense in the situations where the supplier and retailer are two independent departments (or facilities) in the same company. For instance, the supplier may represent a warehouse owned by the logistics department and the retailer may represent a retail outlet owned by the marketing department.

A general supplier driven model can be expressed as follows:

Supplier Driven Model	
Supplier's problem	Retailer's problem
Max. Supplier's Profit	*Max.* Retailer's Profit
s.t. Supplier's constraints	*s.t.* Supplier's optimal decisions
	Retailer's constraints

A supplier's perspective model consists of two sub-problems and can be solved in sequence. First, the supplier's problem aims to make the optimal decisions (e.g. manufacturing, replenishment, supply, etc.) for the manufacturer/supplier to maximize its individual profit. The retailer's problem, in turn, aims to make the optimal decisions (e.g. replenishment and selling price, etc.) for the retailer to maximize its individual profit, subject to the retailer's optimal decisions obtained in the supplier's problem.

In this model the supplier determines this lot size Q^* by taking the first derivative of the supplier's profit function with respect to Q and finds an optimal n^* corresponding to Q^* to maximize its individual profit Π_v. The supplier's individual profit function can be expressed as follows.

Π_v = Gross revenue – Production Cost – Emergency Procurement Cost – Setup cost – Holding cost – Penalty Cost for Shortage

$$= \left[\beta D + k(1-\beta)D\right] p_v - \beta D p - k(1-\beta)Dp_0 - \frac{\beta D c_v}{nQ} - \frac{h_v Q}{2}\left\{(2-n)\frac{D}{P} + (n-1)\right\} - (1-k)(1-\beta)D(g - g_0 k) \tag{3.7}$$

From Eq. (3.8), the supplier's individual optimal lot size Q^* is obtained as follows:

$$\frac{\partial \Pi_v}{\partial Q} = \frac{\beta D c_v}{Q^2} - \frac{h_v}{2}\left\{(2-n)\frac{D}{P} + (n-1)\right\} = 0, \qquad \therefore Q^* = \sqrt{\frac{2\beta D c_v}{h_v\left\{(2-n)\frac{D}{P} + (n-1)\right\}}} \tag{3.8}$$

In a similar way, from Eq. (3.8), the supplier can derive the number of the shipments per batch production run, n^* as follows

$$\frac{\partial \Pi_v}{\partial n} = 0, \quad n^* = \left\lfloor \frac{1}{Q^*} \sqrt{\frac{2\beta D c_v}{h_v} \frac{P}{(P-D)}} \right\rfloor \tag{3.9}$$

where $\lfloor x \rfloor$ = the smallest integer greater than *x*.

$$Q^* = \sqrt{\frac{2\beta D c_v}{h_v \left\{ (2-n)\dfrac{D}{P} + (n-1) \right\}}}$$

Corresponding to the supplier's decision, the retailer accept its decisions on Q^* and n^*.

$$\begin{aligned}
\Pi_b\left(Q^*\right) &= [\ \beta D(p_b - p_v) - \frac{\beta D c_b}{Q^*(1-r)} - \frac{Q^*(1-r)h_b}{2}\ ] \qquad (3.10) \\
&= [\beta D(p_b - p_v) - \frac{\beta D c_b}{\sqrt{\dfrac{2\beta D c_v}{h_v \left\{ (2-n)\dfrac{D}{P} + (n-1) \right\}}}(1-r)} \\
&\quad - \sqrt{\frac{2\beta D c_v}{h_v \left\{ (2-n)\dfrac{D}{P} + (n-1) \right\}}} \frac{(1-r)h_b}{2}] \\
&= [\beta D(p_b - p_v) \\
&\quad - \sqrt{2\beta D}\left[\frac{c_b \sqrt{h_v \{(2-n)D + (n-1)P\}}}{2(1-r)\sqrt{c_v P}} + \sqrt{\frac{c_v P}{h_v \{(2-n)D + (n-1)P\}}} \frac{(1-r)h_b}{2} \right] \\
&\quad \textit{where } Q^* = \sqrt{\frac{2\beta D c_v}{h_v \left\{ (2-n)\dfrac{D}{P} + (n-1) \right\}}},
\end{aligned}$$

The total profit function of the supplier's perspective coordination system with lost sales is obtained as follows:

$$\Pi_{ch} = \left\{ \Pi_b(Q^*) + \Pi_v(n^*, Q^*) \right\}$$

$$= \left\{ \left[\beta D + k(1-\beta)D \right] p_b - \left[\beta D + k(1-\beta)D \right] p_v - \frac{\left[\beta D + k(1-\beta)D \right] c_b}{Q^*(1-r)} - \frac{Q^*(1-r)h_b}{2} \right\}$$

$$+\left[\beta D + k(1-\beta)D \right] p_v - \beta Dp - k(1-\beta)Dp_0 - \frac{\beta Dc_v}{n^* Q^*} - \frac{h_v Q^*}{2} \left\{ (2-n^*)\frac{D}{P} + (n^*-1) \right\} \quad (3.11)$$

$$-(1-k)(1-\beta)D(g-g_0 k)$$

$$= \left[\beta D + k(1-\beta)D \right] p_b - \beta Dp - k(1-\beta)Dp_0 - \frac{\left[\beta D + k(1-\beta)D \right] c_b}{Q^*(1-r)}$$

$$-\frac{Q^*(1-r)h_b}{2} - \frac{\beta Dc_v}{n^* Q^*} - \frac{h_v Q^*}{2} \left\{ (2-n^*)\frac{D}{P} + (n^*-1) \right\} - (1-k)(1-\beta)D(g-g_0 k)$$

$$where \;\; Q^* = \sqrt{\frac{2\beta Dc_v}{h_v \left\{ (2-n)\frac{D}{P} + (n-1) \right\}}}, \; n^* = \sqrt{\frac{1}{Q^*}\frac{2\beta Dc_v}{h_v}\frac{P}{(P-D)}}$$

$$= \left[\beta D + k(1-\beta)D \right] p_b - \beta Dp - k(1-\beta)Dp_0 - \frac{\left[\beta D + k(1-\beta)D \right] c_b}{Q^*(1-r)}$$

$$-\frac{Q^*(1-r)h_b}{2} - \frac{\beta Dc_v}{\sqrt{\frac{1}{Q^*}\frac{2\beta Dc_v}{h_v}\frac{P}{(P-D)}} \cdot Q^*}$$

$$-\frac{h_v Q^*}{2} \left\{ (2 - \sqrt{\frac{1}{Q^*}\frac{2\beta Dc_v}{h_v}\frac{P}{(P-D)}})\frac{D}{P} + (\sqrt{\frac{1}{Q^*}\frac{2\beta Dc_v}{h_v}\frac{P}{(P-D)}} - 1) \right\}$$

$$-(1-k)(1-\beta)D(g-g_0 k)$$

From Eq. (3.12), by taking the first derivative of the total profit function of the supply chain system, we can obtain the solution of the optimization problem as follows

$$
\begin{aligned}
&\frac{\partial \Pi_{ch}}{\partial k} = (1-\beta)D[p_b - p_0 - \frac{c_b}{Q^*(1-r)} - 2g_0 k + g + g_0] = 0, \\
&\therefore k^* = \frac{1}{2g_0}[p_b - p_0 - \frac{c_b}{Q^*(1-r)} + g + g_0] \\
&\quad where\ \ Q^* = \sqrt{\frac{2\beta D c_v}{h_v\left\{(2-n)\frac{D}{P} + (n-1)\right\}}}
\end{aligned}
\tag{3.12}
$$

3.3.2 Joint Coordination model

When shortage occurs, the administrative cost increases and retailer has to loose sales to their customers. In this situation, the retailer often abandons suppliers who can’t deliver the product and turn to other suppliers and sometimes other brands. Any shortage usually leads to a lost sale even interrupt the supply chain channel as a whole. In order to attract retailers and keep the supply chain going normally, both the supplier and retailer must take decisions jointly and the supplier decides to go for outsourcing to recover lost sales completely or partially. So we suppose that *k* is the fraction of the demand shortfall that may be recovered by outsourcing or external procurement, we can easily obtain the profit functions of the retailer and supplier for each model.

In an integrated joint coordination model the manufacturer/supplier and retailer/retailer fully cooperate with each other to make decisions that maximize the system profit. The assumption of full cooperation usually makes sense in the practice of supplier-managed inventory (VMI) system, where the supplier, usually a manufacturer but sometimes a distributor, is authorized to manage the inventory levels at the retailer. The manufacturer /supplier can use this information to plan production, schedule deliveries, and manage inventory levels at the retailer. As a consequence, system cost will likely be reduced while capacity utilization will be increased. A general joint coordination model can be expressed as follows.

Joint Coordination Model
Max. Total System Profit of both supplier and retailer.
s.t. Retailer's constraints
Supplier's constraints

First, the total profit function of the supply chain system can be obtained by

$$\Pi_{ch} = \left\{ \Pi_b(Q) + \Pi_v(n,Q) \right\}$$

$$\begin{aligned} &= [\beta D + kD(1-\beta)]p_b - [\beta D + kD(1-\beta)]p_v - \frac{[\beta D + kD(1-\beta)]c_b}{Q(1-r)} \\ &\quad - \frac{Q(1-r)h_b}{2} + \left[\beta D + kD(1-\beta)\right]p_v - \beta Dp - kD(1-\beta)p_0 \\ &\quad - \frac{\beta D c_v}{nQ} - \frac{h_v Q}{2}\left\{(2-n)\frac{D}{P} + (n-1)\right\} - (1-k)D(1-\beta)(g - g_0 k) \end{aligned} \tag{3.20}$$

$$\begin{aligned} &= [\beta D + kD(1-\beta)]p_b - \beta Dp - \frac{[\beta D + k(1-\beta)D]c_b}{Q(1-r)} - \frac{Q(1-r)h_b}{2} \\ &\quad - k(1-\beta)Dp_0 - \frac{\beta D c_v}{nQ} - \frac{h_v Q}{2}\left\{(2-n)\frac{D}{P} + (n-1)\right\} - (1-k)(1-\beta)D(g - g_0 k) \end{aligned}$$

Since both the supplier's and the retailer/retailer fully cooperate with each other to make decisions that minimize the total costs and maximize the system profit,

they can make coordinated decisions on Q^* and n^*. From Eq. (3.20), the optimal lot size Q^* of the entire supply chain system is obtained as follows:

$$\frac{\partial \Pi_{ch}}{\partial Q} = \frac{[\beta D + k_1(1-\beta)D]c_b}{Q^2(1-r)} - \frac{(1-r)h_b}{2} + \frac{\beta D c_v}{nQ^2(1-r)} - \frac{h_v}{2}\left\{(2-n)\frac{D}{P} + (n-1)\right\} = 0,$$

$$\therefore Q^* = \sqrt{\frac{2[\{\beta D + k(1-\beta)D\}c_b n + \beta D c_v(1-r)]}{n(1-r)\left[h_b(1-r) + h_v\left\{(2-n)\frac{D}{P} + (n-1)\right\}\right]}} \tag{3.21}$$

From Eq. (3.20), in a similar way the optimal number of delivery batches per production run, n^* of the supply chain system is expressed as follows

$$\frac{\partial \Pi_v}{\partial n} = 0, \quad n^* = \left\lfloor \frac{1}{Q^*}\sqrt{\frac{2\beta D c_v}{h_v}\frac{P}{P-D}} \right\rfloor,$$

where $\lfloor x \rfloor$ = the smallest integer greater

$$Q^* = \sqrt{\frac{2[\{\beta D + k(1-\beta)D\}c_b n + \beta D c_v(1-r)]}{n(1-r)\left[h_b(1-r) + h_v\left\{(2-n)\frac{D}{P} + (n-1)\right\}\right]}}$$

From Eq. (3.20), by taking the first derivative of the total profit function of the supply chain system with respect to *k*, we can obtain the solution of the optimization problem as follows:

$$\frac{\partial \Pi_{ch}}{\partial k} = (1-\beta)D[p_b - p_0 - \frac{c_b}{Q^*(1-r)} - 2g_0 k + g + g_0] = 0,$$

$$\therefore k^* = \frac{1}{2g_0}[p_b - p_0 - \frac{c_b}{Q^*(1-r)} + g + g_0] \tag{3.22}$$

$$where \;\; Q^* = \frac{1}{(1-r)}\sqrt{\frac{2[n\{\beta D + k(1-\beta)D\}c_b + \beta D c_v]}{n[h_b + h_v\left\{(2-n)\frac{D}{P} + (n-1)\right\}]}}$$

So far we have derived the net profit functions and the optimal policies of each supply chain model. For the proposed individual and coordinated models in this chapter, the results of individual optimization and coordinated decision are summarized in the Table 3.2.

	Individual Decision Model	Supplier Driven Model	Retailer Driven Model	Joint Coordination Model
Emergency Procurement Option	No	Yes	Yes	Yes
Q^*	$\frac{1}{(1-r)}\sqrt{\frac{2\beta Dc_b}{h_b}}$	$\sqrt{\frac{2\beta Dc_v}{h_v\left\{(2-n)\frac{D}{P}+(n-1)\right\}}}$	$\frac{1}{(1-r)}\sqrt{\frac{2[\beta D+k(1-\beta)D]c_b}{h_b}}$	$\sqrt{\frac{2[n\{\beta D+k(1-\beta)D\}c_b+\beta Dc_v]}{n(1-r)\left[h_b+h_v\left\{(2-n)\frac{D}{P}+(n-1)\right\}\right]}}$
n^*	$\left\lfloor\frac{1}{Q^*}\sqrt{\frac{2\beta Dc_v}{h_v}\frac{P}{P-D}}\right\rfloor$ $where\ Q^*=Q^*_{Individual}$	$\left\lfloor\frac{1}{Q^*}\sqrt{\frac{2\beta Dc_v}{h_v}\frac{P}{P-D}}\right\rfloor$ $where\ Q^*=Q^*_{Supplier's\ Perspective}$	$\left\lfloor\frac{1}{Q^*}\sqrt{\frac{2\beta Dc_v}{h_v}}\frac{P}{P-D}\right\rfloor$ $where\ Q^*=Q^*_{Retailer's\ Perspective}$	$\left\lfloor\frac{1}{Q^*}\sqrt{\frac{2\beta Dc_v}{h_v}\frac{P}{P-D}}\right\rfloor$ $where\ Q^*=Q^*_{Joint\ Coordination}$
k^*	Not Available	$\frac{1}{2g_0}[p_b-p_0-\frac{c_b}{Q^*(1-r)}+g+g_0]$ $where\ Q^*=Q^*_{Supplier's\ Perspective}$	$\frac{1}{2g_0}[p_b-p_0-\frac{c_b}{Q^*(1-r)}+g+g_0]$ $where\ Q^*=Q^*_{Retailer's\ Perspective}$	$\frac{1}{2g_0}[p_b-p_0-\frac{c_b}{Q^*(1-r)}+g+g_0]$ $where\ Q^*=Q^*_{Joint\ Coordination}$

Table 3.2 Summary of optimal policies

3.4 Solution Procedure

The ultimate objective of the proposed models in this chapter is to find the optimal ratio of emergency procurement, the optimal order quantity, and the minimum number of shipment such that the total joint profit of the supply chain system is maximized. These nonlinear optimization problems are to be solved for n^*, Q^* and k^*. To solve this non-linear optimization model, we modify the iterative algorithm proposed by Shinha and Sarmah (2007).

3.4.1 Heuristic algorithm for optimal solution

We first consider n^* to be constant and find out the values of Q^* and k^*. Then we go for selecting a wide range of possible values of n^* and compute the values of the objective function. Finally, we select the best solution in a direct search method. From Proposition 1, it is apparently clear that for fixed Q^* and k^*, the profit function is concave. Hence, the search for option solution, n^*, is reduced to find the local optimal solution. In other words, for given n, the maximum values will occur at the point which satisfies the optimal conditions simultaneously.

Algorithm

Step 1, Set $n = 1$, $Q_0 = 0$, $k_0 = 0$.

Step 2, For each $j = 0, 1, 2...$, perform the following procedures:

2-1) For individual decision model and supplier driven model,

i) calculate Q_j for the given n_j from Table 3.2

ii) for given Q_j and n_j, compute accordingly k_j from Table 3.2

2-2) For supplier driven model and joint coordination model,

i) for given n_j, compute Q_j and k_j simultaneously by running a nonlinear mixed integer model from Eq. (3.23).

Step 5, If $\Pi_J^{Max}(n_N^*, Q_N^*, k_N^*) \geq \Pi_J(n_N, Q_N, k_N)$, go to Step 6, otherwise, $\Pi_J(k^N, Q^N, n^N)$ is the optimal solution with maximum point. Repeat steps (1) – (5) with n = 2 to $n = n^*$ (where n^* = the highest integer value of n) until finding $(\Pi^*_{ch})_{max} = f(k^*, Q^*, n^*)$.

Step 5, Increase n by 1 and go to step 2.

Following the above-mentioned procedures, the maximum system profit can be derived in these three cases, where, (i) emergency supply option is available ($k^* \neq 0$), (ii) emergency procurement is not possible (k^* = 0), and complete outsourcing (k^* = 1) for a given unit external procurement price p_0. (See the Table 3.3.) We see that k^* is highly related with Q^* in retailer's perspective model and joint coordination model. In addition, in both the individual decision model and the supplier's perspective coordination model, change in k^* does not affect Q^*.

From Table 3.3., if we take the highest value of k possible for a corresponding optimal value of Q and the possible maximum of k = 1, then the maximum system profit will be obtained. Thus, it is found that for a particular value of n and Q, as long as $[p_b - p_0 - \frac{c_b}{Q^*(1-r)} + g + g_0] > 0$, system profit increases with increasing k and reaches the maximum value when the ratio of external procurement reaches the optimal value k^*. On the other hand, if $[p_b - p_0 - \frac{c_b}{Q^*(1-r)} + g + g_0] < 0$, it is better not to choose the emergency procurement option. The underlying mechanism is to manipulate lot size Q in such a way that the overall system cost is decreased and the savings can be utilized to go for outsourcing even at a higher price till a particular limiting value. The underlying mechanism is with consideration of all cost factors which includes inventory holding cost, ordering cost, transportation cost, etc. to optimize the lot size Q and the savings of the whole system can be utilized for the emergency supply option until the emergency procurement price goes up to a particular price much higher than the retail price. In the solution procedure, we focused on the optimal ratio of external procurement, k^* as well as either k^* = 0 or k^* = 1 and the proposed algorithm yields the best solution for the coordinated decision models. While Sinha *et al* (2007) focused on either k^* = 0 or k^* = 1 to make only binary decisions on emergency procurement under shortage, the proposed algorithm yields the best optimal solution for k^* with the coordinated policy through the proposed solution procedure. It is also shown numerically that a coordinated policy has a better system profit in numerical examples.

	Individual Decision Model	Supplier Driven Model	Retailer Driven Model	Joint Coordination Model
Q^* $if\ 0<k^*<1$	$\frac{1}{(1-r)}\sqrt{\frac{2\beta Dc_b}{h_b}}$	$\sqrt{\frac{2\beta Dc_v}{h_v\left\{(2-n)\frac{D}{P}+(n-1)\right\}}}$	$\frac{1}{(1-r)}\sqrt{\frac{2[\beta D+k(1-\beta)D]c_b}{h_b}}$	$\sqrt{\frac{2[n\{\beta D+k(1-\beta)D\}c_b+\beta Dc_v]}{n(1-r)\left[h_b+h_v\left\{(2-n)\frac{D}{P}+(n-1)\right\}\right]}}$
Q^* $if\ k^*=0$	No Change	No Change	$\frac{1}{(1-r)}\sqrt{\frac{2\beta Dc_b}{h_b}}$	$\sqrt{\frac{2[\beta D(nc_b+c_v)]}{n(1-r)\left[h_b+h_v\left\{(2-n)\frac{D}{P}+(n-1)\right\}\right]}}$
Q^* $if\ k^*=1$	No Change	No Change	$\frac{1}{(1-r)}\sqrt{\frac{2Dc_b}{h_b}}$	$\sqrt{\frac{2[D(nc_b+\beta c_v)]}{n(1-r)\left[h_b+h_v\left\{(2-n)\frac{D}{P}+(n-1)\right\}\right]}}$

Table 3.3 Summary of Q^* according to the range of k^*

3.4.2 Analysis of the coordinated decision model for optimal sourcing

The proposed two-stage supply chain coordination model is proposed to determine the optimal conditions for profit maximization when external procurement in case of capacity shortage may be a better option to improve the whole channel profit. We apply a non-linear optimization approach thereby to obtain the best solutions to increase the profits of both the retailer and the supplier beyond their non-coordinated policies in supply chains. Thus, we can reach the optimal solutions for profit maximization by solving the following non-linear optimization model for a given *n*.

Maximize Π_{ch}

Subject to,

(1) $k \geq 0$ (3.23)

(2) $k \leq 1$

(3) $nQ \leq D$

(4) $n \varepsilon I$ [Integer]

(5) $Q > 0$.

The objective of the non-linear mixed integer programming is to find out the best optimal conditions when emergency procurement from an external source is a better option to improve the total profit of the entire supply chain system. In addition, this coordination mechanism in supply chains helps maximize the profits of both the retailer and the supplier beyond individual decision models. Numerical examples to show the various cases of the proposed model will be presented in the next section.

3.5 Model Analysis

This section presents a theoretical analysis of the proposed models developed in the previous sections above:

3.5.1 Optimization

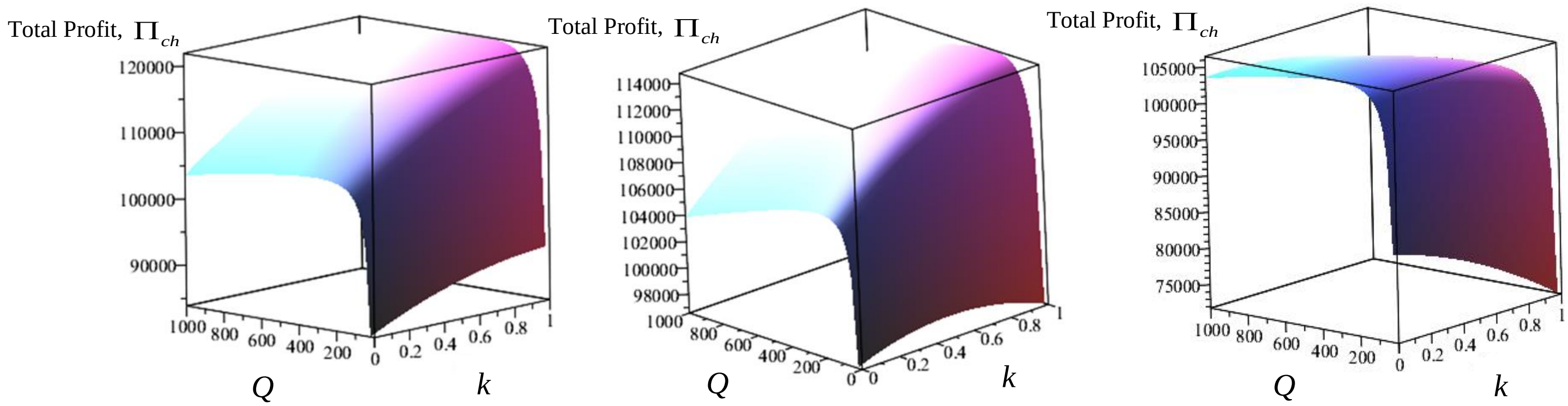
A nonlinear mixed integer optimization problem is formulated in this chapter to be solved for the optimal ratio of emergency procurement, the optimal order quantity, and the minimum number of shipment A heuristic algorithm is provided to find the optimal ratio of n^*, Q^* and k^* such that the total joint profit of the supply chain system is maximized.

Figure 3.2 shows the behaviors of the optimal solutions under different settings of the external procurement price (p_0) while n holds constant at the optimal solution. As the external procurement price (p_0) changes, the optimal ratio of external procurement (k) is determined, and accordingly the optimal solution is obtained. Obviously we see that it has the high sensitivity to the system overall benefit.

Table 3.4 presents a summary of the optimal solutions of the proposed models in this chapter. Under a normal setting of the system parameters (β = 0.8, r = 0.05, p_0 = 48) while all the other parameters hold constant, we see that the joint coordination model and the supplier driven model have the best performances for profit maximization, and the retailer driven model has the second best among the proposed models. Individual decision model without considerations of coordination has the worst performance in our case.

	Heuristic Approach vs. Simultaneous Optimization								
	Retailer’s Driven Model			Supplier’s Driven Model			Joint Coordination Model		
	n-1	n	n+1	n-1	n	n+1	n-1	n	n+1
n^*	2	2.60	3	2	2.81	3	2	2.95	3
Q^*	533.06	532.77	532.6	800	709.86	692.82	562.26	480.02	477.24
k^*	0.8084	0.8031	0.8002	0.8157	0.8135	0.8130	0.8077	0.8033	0.8032
$\prod_b$	91,875.5	92,068.7	92,968.2	94,645.3	94,651.3	94,700.3			
$\prod_v$	16,293.6	16,302.3	15,379.3	13,225.70	13,291.8	13,240.1			
$\prod_{ch}$	108,291.1	108,371.0	108,347.5	107,871.0	107,943.1	107,940.4	108291.7	108,397.8	108397.7

Table 3.4 Comparison of heuristic approach and simultaneous optimization



(i) $p_0 = 42$ (ii) $p_0 = 46$ (iii) $p_0 = 52$

Table 3.5 Total profit at the optimal k^* and Q^* according to outsourcing price, p_0 (when $p_b = 45$)

3.5.2 Profit Maximization

In this section we check the sufficient conditions for the proposed optimization models. To make profit maximization of supply chain system, theoretically the concavity of the profit function of each model is checked by the Hessian matrix.

First, for an individual decision model, it is sufficient to show $\Pi_b(Q)$ is concave for $Q > 0$. From Eq. (3.1),

$$\Pi_b(Q) = \beta D p_b - \beta D p_v - \frac{\beta D c_b}{Q(1-r)} - \frac{h_b Q(1-r)}{2}$$

$$\frac{\partial \Pi_b}{\partial Q} = \frac{\beta D c_b}{Q^2(1-r)} - \frac{h_b(1-r)}{2} = 0$$

$$\frac{\partial^2 \Pi_b}{\partial Q^2} = \frac{-2\beta D c_b}{Q^3(1-r)} < 0$$

For the profit function of the supplier in Eq. (3.11),

$$\begin{aligned}\Pi_v(n,Q,k) = {} & [\beta D + kD(1-\beta)]p_b - \beta D p - \frac{[\beta D + k(1-\beta)D]c_b}{Q(1-r)} - \frac{Q(1-r)h_b}{2} \\ & - k(1-\beta)Dp_0 - \frac{\beta D c_v}{nQ} - \frac{h_v Q}{2}\left\{(2-n)\frac{D}{P} + (n-1)\right\} \\ & - (1-k)(1-\beta)D(g - g_0 k)\end{aligned}$$

$$H(n,Q,k)=\begin{bmatrix} \dfrac{\partial^2 \Pi_{ch}}{\partial n^2} & \dfrac{\partial^2 \Pi_{ch}}{\partial n \partial Q} & \dfrac{\partial^2 \Pi_{ch}}{\partial n \partial k} \\ \dfrac{\partial^2 \Pi_{ch}}{\partial Q \partial n} & \dfrac{\partial^2 \Pi_{ch}}{\partial Q^2} & \dfrac{\partial^2 \Pi_{ch}}{\partial Q \partial k} \\ \dfrac{\partial^2 \Pi_{ch}}{\partial k \partial n} & \dfrac{\partial^2 \Pi_{ch}}{\partial k \partial Q} & \dfrac{\partial^2 \Pi_{ch}}{\partial k^2} \end{bmatrix}$$

$$=\begin{bmatrix} \dfrac{-2\beta D c_v}{n^3 Q} & -\dfrac{\beta D c_v}{n^2 Q^2}-\dfrac{h_v}{2}\left\{1-\dfrac{D}{P}\right\} & 0 \\ -\dfrac{\beta D c_v}{n^2 Q^2}-\dfrac{h_v}{2}\left\{1-\dfrac{D}{P}\right\} & \dfrac{\beta D c_v}{Q^2(1-r)} & \dfrac{\beta D c_v}{Q^2(1-r)} \\ 0 & \dfrac{-2[\beta D+k(1-\beta)D]c_b}{Q^3(1-r)}+\dfrac{(-2)\beta D c_v}{nQ^3} & -(1-\beta)D(2g_0) \end{bmatrix}=$$

$$=\begin{bmatrix} 0 & -\frac{1}{2}\, hv\left(-\frac{VectorCalculus:\text{-}D}{P}+1\right) & 0 \\ -\frac{1}{2}\, hv\left(-\frac{VectorCalculus:\text{-}D}{P}+1\right) & -\frac{2\,(b+k(1-b))\, VectorCalculus:\text{-}D\, c}{Q^3\,(1-r)} & 0 \\ 0 & 0 & -2\,(1-b(VectorCalculus:\text{-}D))\, g0 \end{bmatrix}$$

$$= -\frac{1}{2}\,\frac{hv^2\,(VectorCalculus:\text{-}D-P)^2\,(-1+b(VectorCalculus:\text{-}D))\, g0}{P^2} < 0$$

Thus the determinant of the Hessian matrix is negative, and the given function has a local maximum. It can be also proved numerically that the Hessian matrix at the stationary point is negative definite and the stationary point is a local maximum.

3.5.3 Pricing Strategy for External Procurement

Fig. 3.5 shows how much a supplier respond with strategy to handle shortage issues. These two graphs actually present how much a supplier is willing to pay for emergent procurement from an external supplier to make up for shortage on its side. We see that as the external procurement price (p_0) and the fixed penalty cost for shortage increase, the total net profit of the entire supply chain is supposed to go down.

For example, when p_0 is less than 40, the supplier need to choose the coordinated policy to maximize the total profit of the chain. But if p_0 goes beyond 49.970, the optimal ratio of k^* becomes zero, which means that the external procurement is not recommended, even though the coordinated decision making model always makes a higher profit than that under the individual policy. The same logic and procedures can be applied to penalty costs for shortage in Fig. 3.5. When the penalty cost for shortage is too high and goes beyond a certain threshold or an upper bound, then supplier will go for complete outsourcing to avoid any penalty. On the other hands, in case the penalty cost for shortage is quite low, then supplier may decide not to outsource since it is more beneficial anymore to take that shortage as goodwill-loss. Thus theoretically we determine the optimal range of the external procurement price and the fixed penalty cost with consideration of all the cost factors in the supply chain coordination model.

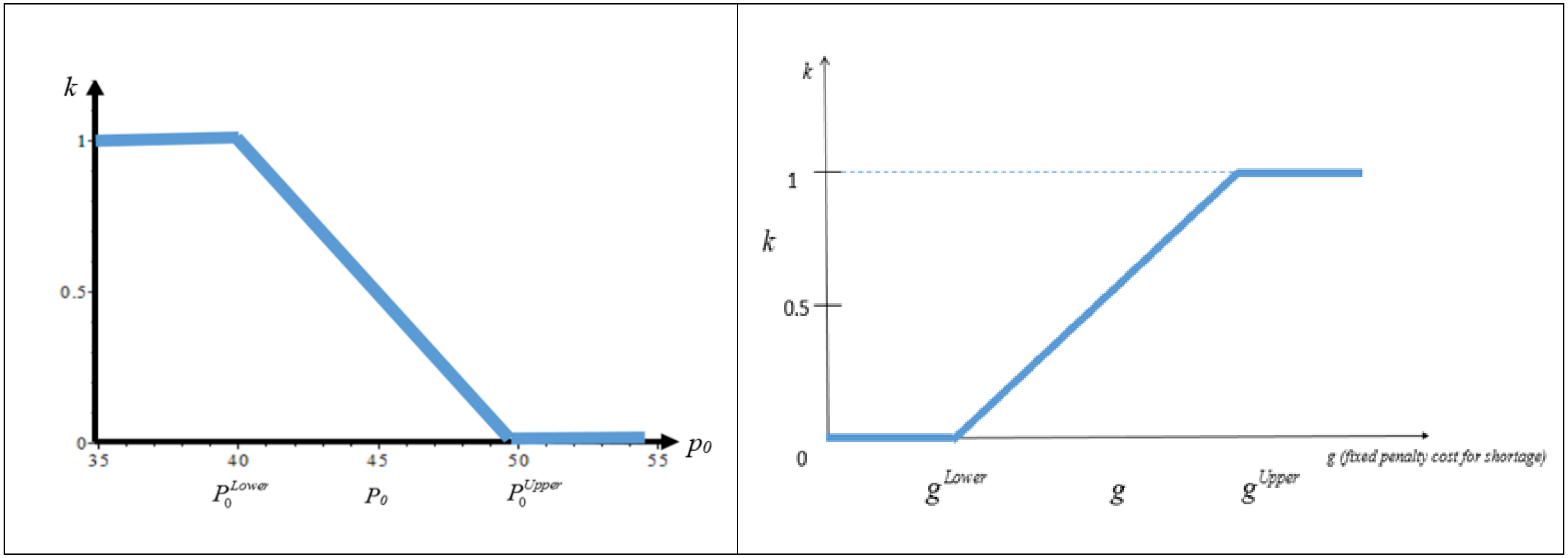


Figure 3.2 Effects on the ratio of emergency procurement k^*, as external procurement price (p_0) and the fixed penalty cost for shortage (g) changes

3.5.4 Profit Sharing and Compensation Policy

Several researchers have shown that one partner's gain may exceed the other partner's loss in the integrated model in the literature. Thus, the net benefit should be shared between the supplier and the retailer in some equitable fashion. In the literature Goyal (1976) proposed a simple compensation policy according to the sacrifice of each participant to the entire profit of the supply chain. This policy aims at sharing the benefits and the losses of the entire supply chain system according to the ratio of individual models' contributions to the profit of the supply chain. In this section, we revised Goyal's compensation policy according to their contributions to the total profit of the supply chain and then, we get the ratios for profit sharing as follows:

$$
\begin{aligned}
Z_b &= \frac{\Pi_b(Q^*)}{\Pi_b(Q^*)+\Pi_v(n^*,Q^*)} \\
Z_v &= \frac{\Pi_v(n^*,Q^*)}{\Pi_b(Q^*)+\Pi_v(n^*,Q^*)}
\end{aligned}
\tag{3.29}
$$

Note that $Z_b + Z_v = 1$, where Π_b = total profit function of the retailer, Π_v = total cost function of the supplier.

Among the most common ways used for supply chain coordination we may consider a side-payment contract. In the literature, side-payment contracts have been widely used in economics and finance fields to share the profits and costs. Robin and Carter (1995) defined side-payment as ''an additional monetary transfer between supplier (seller) and buyer that is used as an incentive for deviating from the individual optimal policy" According to this definition, we find that the side-payment in supply chains should be a monetary transfer that two channel members make so as to improve the chain wide performance; so, it is also known as transfer payment, compensation, reimbursement, etc. We find some practical examples in which business organizations in supply chains transfer side-payments for supply chain coordination. Shapiro (1998) reported a real story in which the Hollywood studios and Blockbuster (which is a video store in the United States) signed a side-payment contract to coordinate the two-echelon video supply chain. Specifically, in order to entice the Hollywood studios to reduce their wholesale prices, the video store Blockbuster agreed to transfer a part of her sale revenue to those Hollywood studios who decrease their prices. This side-payment contract is well known as ‘‘revenue-sharing" contract. We will leave this part as a future research direction.

CHAPTER 4

COORDINATING A TWO-STAGE SUPPLY CHAIN WITH IMPERFECT QUALITY ITEMS AND NONLINEAR PRICE DEPENDENT DEMAND

4.1 Introduction

Determining inventory policy in classical inventory control models is usually done independently between supplier and retailer. This yields sub-optima solution based on each point of view while in such rush competition both supplier and retailer need to collaborate in reducing total cost of the whole system. One of the weaknesses of current inventory models is the unrealistic assumption that all items produced are of good quality (Walters, 1994). Defective items, as a result of considering imperfect quality production process were initially considered by Rosenblatt and Lee (1986) and Porteus (1986). Besides imperfect quality assumption in production process, other factors such as damages and breakages during the handling process may also result in defective items. The above consideration was included in Salameh and Jaber (2000) who were the few authors who presented a model for items with imperfect quality. Later, Goyal and Cardenas-Barron (2002) then reconsidered the work done in Salameh and Jaber (2000) and presented a practical approach for determining the optimal lot size. They assumed that poor items are withdrawn from stock and no shortage was allowed. Wee (1993) developed an economic production plan for deteriorating items with partial backordering, but he assumed perfect quality.

The idea of optimizing the joint total cost in a single-supplier and a single-retailer model was first introduced by Goyal (1976). Many researchers, such as Banerjee (1986), Hill (1997), Ouyang, Wu and Ho (2004), Rad, Khoshalhan and Tarokh (2011), Rad and Khoshalhan (2011) have then extended the work of Goyal (1976). Jokar and Sajadieh (2009) have described a supplier–retailer integrated production inventory model which takes into consideration Joint Economic Lot Sizing (JELS) policy with price sensitive demand of the customer. Jokar and Sajadieh (2009) detailed a JELS model where the shipment; ordering and pricing policy are all optimized. They investigated the effectiveness of customer price sensitive linear demand. Uddin and Sano (2010) depicted a linear fraction model that maximizes the return on investment and finds the location for the facility. They also discussed an mixed integer programming (MIP) based approach to solve linear fractional problem.

Another issue in the lot sizing area that has attracted the attention of numerous researchers is the integration of production and pricing. One of the first models of this kind was formulated by Kunreuther and Richard (1971), who incorporated pricing into the traditional EOQ model considering a linear price. A multitude of researchers have developed a joint inventory model for manufacturer-retailer, where market demand is a function of price (e.g., Viswanathan and Wang 2003; Ray *et al*. 2005; Bakal *et al*. 2008, Wang *et al* 2015).

Recently, Kim, Hong, and Kim (2011) discussed joint pricing and ordering policies for price-dependent demand in a supply chain consisting of a single retailer and a single manufacturer. Some other researchers such as Ho, Ouyang and Su (2008), Chen and Kang (2010) and Chung and Liao (2011) also developed integrated inventory models that involve price-sensitive demands. The main focus of these works were on trade credit policies and they considered flexible production rates by assuming that the production rate can be varied in the fixed ratios of the demand rate.

To the best of knowledge, very few of the above-mentioned integrated production-inventory marketing models focused on investing the effects of coordination on the performance of the supply chain under quality uncertainty, especially when the demand rate has an iso-elastic function of the selling price. Therefore, the aims of this article are to study an integrated inventory model that considers operations and pricing decisions, and to investigate the effect of coordination on the system.

End customer demand is assumed to be an iso-elastic function of the selling price to account for the impact of price changes on customer demand. Furthermore, the production rate is finite and proportional to the demand rate (see for example Ho, 2011; Chang *et al*., 2009). To optimize the joint total profit, the selling price, order quantity and number of shipments will be determined in this study.

For the sake of this study, a non-linear mixed integer programming based model has been formulated by combining price sensitive demand and coordination between members of the supply chain. To control unstable consumers demand, a new exponential price sensitive demand function is introduced. This work introduces the exponential price sensitive demand function not just because it has become popular among researchers, but because the form includes an explicit term for price elasticity and is easy to manipulate mathematically. Further, it has been pointed out by many researchers, the results obtained from linear demand function may not suitable to apply directly in the case of nonlinear demand function. The goal of this work is to determine the individual and coordinated profit with the new exponential demand function.

This chapter is organized as follows. Section 4.2 introduces some assumptions and notations. An individual decision model of supplier and retailer are proposed in Section 3.3 and a joint coordination model and the solution procedure are proposed in Section 4.3. A numerical example and sensitivity analysis are followed in Section 4.4 and 4.5. Summary and concluding remarks are provided in Section 4.6.

4.2 Assumptions

We consider a simple supply chain problem with a single manufacturer/seller and a single retailer/retailer we discussed in the chapter 3. The same inventory patterns of both retailer/retailer and the supplier/supplier illustrated in Figure 3.1 is used in this chapter. In addition, the same scenarios used in the previous chapter are discussed. The mathematical models in this chapter are developed based on the following assumptions and notations:

Assumptions

1. Single manufacturer-single retailer supply chain, which is the simple and basic form of the supply chains and could be a start to present and to extend more complicated and real inventory models, is considered.

2. The demand rate is a decreasing function of the selling price $D(p_b) = a(p_b)^{-C}$ where the slope $a > 0$ and the constant elasticity $C > 0$.
3. Shortage is allowed.
4. The inventory is continuously reviewed.
5. The retailer orders Q quantity from the supplier. The supplier manufactures a production lot $Q_p = nQ$ at one setup, and dispatches it to the retailer in n shipments with size Q, where n is a positive integer.
6. The retailer's inventory holding cost per item per unit time is h_b; the supplier's inventory holding cost per item per unit time is h_v, and $h_b > h_v$.
7. The time horizon is infinite.

4.3 Model Formulation

Consider a supply chain for an imperfect product comprising of a single supplier as a manufacturer and retailer in a supply chain when the product is single. The retailer has an annual demand rate of $D(p_b) = a(p_b)^{-C}$ units for the given product and the first market demand is a non-linear function of price. The retailer orders a lot of size Q and the manufacturer produces the product at the production rate P in order to deliver the finished products with imperfect quality to the retailer.

4.3.1 Non-coordinated Decision Model

In this section we consider an individual decision model in a two-stage supply chain, we assume there is no coordination between a supplier and a retailer, which may represent any two upstream-downstream participants that are independently managed. In this model, the supplier and the retailer do not cooperate with each other to make decisions to maximize the system profit. Each participant makes its own decision to maximize its individual profit. We consider two cases when supplier dominates supply chain decisions and when retailer has a channel power and drives market decisions.

4.3.1.1 Retailer driven model

In a retailer's perspective model with assumption of a price dependent market demand, we assume that the retailer has the greater channel power to initiate the replenishment decision to maximize its individual profit. The supplier needs to make decisions subject to the retailer's optimal decisions. Since the market demand is a function of the retail price, and we assume the market demand is quite price-sensitive, the retailer as market leader makes better profit rather than the market follower, supplier in general.

A retailer driven model consists of two sub-problems and can be solved in sequence. First the retailer makes decisions to maximize its individual profit in the retailer's own problem, which means that the retailer makes decisions on p_r^*, Q^* and n^* for the supplier and the supplier adjusts its policy according to them. The retailer's optimal decisions, in turn, become one constraint in the supplier's problem, whose objective is to maximize the supplier's profit through making decisions on manufacturing, replenishment, supply etc. Thus we can obtain the profit functions of the retailer and supplier as below

$$\Pi_b = \text{Gross revenue} - \text{Purchasing cost} - \text{Ordering cost} - \text{Holding cost}$$

$$= \frac{[\beta+k(1-\beta)]a(p_b)^{-C}p_b - [\beta+k(1-\beta)]a(p_b)^{-C}p_v}{} \quad (4.1)$$

$$-\frac{[\beta+k(1-\beta)]a(p_b)^{-C}c_b}{Q(1-r)} - \frac{Q(1-r)h_b}{2}$$

From Eq. (4.1), the retailer's individual optimal lot size Q^* is obtained as follows

$$\frac{\partial \Pi_b}{\partial Q} = \frac{[\beta+k(1-\beta)]a(p_b)^{-C}c_b}{(1-r)Q^2} - \frac{(1-r)h_b}{2} = 0, \quad (4.2)$$

$$\therefore Q^* = \frac{1}{(1-r)}\sqrt{\frac{2[\beta+k(1-\beta)]a(p_b)^{-C}c_b}{h_b}}$$

Accordingly, by plugging the optimal order quantity, Q^* in Eq. (4.13), the retailer's individual optimal profit is given by

$$\begin{aligned}\Pi_b(Q^*) &= [\beta+k(1-\beta)]a(p_b)^{-C}p_b - [\beta+k(1-\beta)]a(p_b)^{-C}p_v \\ &\quad - \frac{[\beta+k(1-\beta)]a(p_b)^{-C}c_b}{Q^*(1-r)} - \frac{Q^*(1-r)h_b}{2} \\ &= [\beta+k(1-\beta)]a(p_b)^{-C}(p_b - p_v) - \frac{\sqrt{h_b}\cdot\beta a(p_b)^{-C}c_b}{\sqrt{2[\beta+k(1-\beta)]a(p_b)^{-C}c_b}} \\ &\quad - \frac{\sqrt{2[\beta+k(1-\beta)]a(p_b)^{-C}c_b}\cdot h_b}{2\sqrt{h_b}}\end{aligned} \quad (4.3)$$

By taking the first order derivative of Eq. (4.15) with respect to p_b, we have

$$\begin{aligned}\frac{\partial \Pi_b}{\partial p_b} &= [\beta+k(1-\beta)]a(p_b)^{-C} + [\beta+k(1-\beta)]a(-C)(p_b)^{-C-1}(p_b - p_v) \\ &\quad + \frac{[\beta+k(1-\beta)]a(C)(p_b)^{-C-1}c_b h_b}{\sqrt{2[\beta+k(1-\beta)]a(p_b)^{-C}c_b h_b}} = 0\end{aligned} \quad (4.4)$$

$$p_b^* = \exp\left[p_b \cdot C - \ln\left(\frac{2a \cdot \{C^2 p_v^2 - 2C^2 p_v^2 e^{p_b} + C^2 (e^{p_b})^2 + 2Cp_v e^{p_b} - 2C(e^{p_b})^2 + (e^{p_b})^2\}}{c_b \cdot h_b \cdot C^2}\right)\right]$$

$$\text{where } k = 1, b = 1, [\beta + k(1-\beta)] = 1 \tag{4.5}$$

From Eq. (4.3), corresponding to the lot size that the retailer determined, the supplier's profit function can be obtained as follows:

$\Pi_v(n^*, Q^*)$ = Gross revenue – Purchasing cost – Production Cost – Procurement Cost – Setup cost – Holding cost – Penalty Cost for Shortage

$$= \left[\beta + k(1-\beta)\right] a(p_b)^{-C} p_v - \beta a(p_b)^{-C} p - k(1-\beta) a(p_b)^{-C} p_0 - \frac{\beta a(p_b)^{-C} c_v}{nQ^*} - \frac{h_v Q}{2}\left\{(2-n)\frac{a(p_b)^{-C}}{P} + (n-1)\right\} - (1-k)(1-\beta) a(p_b)^{-C}(g - g_0 k) \tag{4.6}$$

From Eq. (4.17), the optimal number of delivery batches per production run, n^* of the supply chain system is expressed as follows:

$$\frac{\partial \Pi_v}{\partial n} = 0, \quad n^* = \left\lfloor \frac{1}{Q^*} \sqrt{\frac{2\beta a(p_b)^{-C} c_v}{h_v} \frac{P}{P - a(p_b)^{-C}}} \right\rfloor, \tag{4.7}$$

where $\lfloor x \rfloor$ = the smallest integer greater than *x*.

$$Q^* = \frac{1}{(1-r)} \sqrt{\frac{2[\beta + k(1-\beta)] a(p_b)^{-C} c_b}{h_b}}\,.$$

Thus, the total profit function of the supply chain system is given by

$$\Pi_{ch} = \left\{ \Pi_b(Q^*) + \Pi_v(n^*, Q^*) \right\}$$

$$
\begin{aligned}
&= [\beta + k(1-\beta)]a(p_b)^{-C} p_b - [\beta + k(1-\beta)]a(p_b)^{-C} p_v - \frac{[\beta D + k(1-\beta)D]c_b}{Q^*(1-r)} \\
&\quad - \frac{Q(1-r)h_b}{2} + \left[\beta + k(1-\beta)\right]a(p_b)^{-C} p_v - \beta a(p_b)^{-C} p - k(1-\beta)a(p_b)^{-C} p_0 \\
&\quad - \frac{\beta a(p_b)^{-C} c_v}{nQ} - \frac{h_v Q}{2}\left\{(2-n)\frac{a(p_b)^{-C}}{P} + (n-1)\right\} - k(1-\beta)a(p_b)^{-C} p_0 \\
&\quad -(1-k)(1-\beta)a(p_b)^{-C}(g - g_0 k)
\end{aligned}
\tag{4.8}
$$

$$
\begin{aligned}
&= [\beta + k(1-\beta)]a(p_b)^{-C} p_b - \frac{[\beta + k(1-\beta)]a(p_b)^{-C} c_b}{Q(1-r)} - \frac{Q(1-r)h_b}{2} \\
&\quad - \beta a(p_b)^{-C} p - k(1-\beta)a(p_b)^{-C} p_0 - \frac{\beta a(p_b)^{-C} c_v}{nQ} \\
&\quad - \frac{h_v Q}{2}\left\{(2-n)\frac{a(p_b)^{-C}}{P} + (n-1)\right\} - k(1-\beta)a(p_b)^{-C} p_0 \\
&\quad -(1-k)(1-\beta)a(p_b)^{-C}(g - g_0 k)
\end{aligned}
$$

From Eq. (4.19), by taking the first derivative of the total profit function of the supply chain system, we can obtain the solution of the optimal sourcing problem as follows

$$
\begin{aligned}
&\frac{\partial \Pi_{ch}}{\partial k} = (1-\beta)a(p_b)^{-C}[p_b - p_0 - \frac{c_b}{Q^*(1-r)} - 2g_0 k + g + g_0] = 0, \\
&\therefore k^* = \frac{1}{2g_0}[p_b - p_0 - \frac{c_b}{Q^*(1-r)} + g + g_0] \\
&\qquad where \;\; Q^* = \frac{1}{(1-r)}\sqrt{\frac{2[\beta + k(1-\beta)]a(p_b)^{-C} c_b}{h_b}}
\end{aligned}
\tag{4.9}
$$

4.3.1.2 Supplier driven model

In a supplier's perspective coordination model, the supplier has the greater channel power and makes decisions (e.g. supply, replenishment, manufacturing, etc.) independently to maximize its individual profit. Consequently, the retailer has to make decisions (e.g.

replenishment, selling, etc.) subject to the supplier's optimal decisions. The retailer adjusts its policy according to the supplier's decisions on n^* and Q^*. But the supplier cannot determine the retail price, p_b^* even though we assume the supplier has a dominant channel power in a supply chain. The supplier needs to accept the retail price (p_b^*) information from the retailer's side. The assumption of the supplier driven model usually makes sense in the situations where the supplier and retailer are two independent departments (or facilities) in the same company. For instance, the supplier may represent a warehouse owned by the logistics department and the retailer may represent a retail outlet owned by the marketing department.

A supplier's perspective model consists of two sub-problems and can be solved in sequence. First, the supplier's problem aims to make the optimal decisions (e.g. manufacturing, replenishment, supply, etc.) for the manufacturer/supplier to maximize its individual profit. The retailer's problem, in turn, aims to make the optimal decisions (e.g. replenishment and selling price, etc.) for the retailer to maximize its individual profit, subject to the retailer's optimal decisions obtained in the supplier's problem.

In this model the supplier determines this lot size Q^* by taking the first derivative of the supplier's profit function with respect to Q and finds an optimal n^* corresponding to Q^* to maximize its individual profit Π_v. The supplier's individual profit function can be expressed as follows.

Π_v = Gross revenue – Production Cost – Emergency Procurement Cost – Setup cost – Holding cost – Penalty Cost for Shortage

$$= \left[\beta + k(1-\beta)\right] a(p_b)^{-C} p_v - \beta D p - k(1-\beta) a(p_b)^{-C} p_0 - \frac{\beta a(p_b)^{-C} c_v}{nQ} \qquad (4.10)$$

$$- \frac{h_v Q}{2}\left\{(2-n)\frac{a(p_b)^{-C}}{P} + (n-1)\right\} - (1-k)(1-\beta) a(p_b)^{-C}(g - g_0 k)$$

From Eq. (3.8), the supplier's individual optimal lot size Q^* is obtained as follows:

$$\frac{\partial \Pi_v}{\partial Q} = \frac{\beta a(p_b)^{-C} c_v}{Q^2} - \frac{h_v}{2}\left\{(2-n)\frac{a(p_b)^{-C}}{P} + (n-1)\right\} = 0, \qquad (4.11)$$

$$\therefore Q^* = \sqrt{\frac{2\beta a(p_b)^{-C} c_v}{h_v\left\{(2-n)\frac{a(p_b)^{-C}}{P} + (n-1)\right\}}}$$

In a similar way, from Eq. (3.8), the supplier can derive the number of the shipments per batch production run, n^* as follows

$$\frac{\partial \Pi_v}{\partial n} = 0, \quad n^* = \left\lfloor \frac{1}{Q^*}\sqrt{\frac{2\beta a(p_b)^{-C} c_v}{h_v}\frac{P}{(P - a(p_b)^{-C})}} \right\rfloor \qquad (4.12)$$

where $\lfloor x \rfloor$ = the smallest integer greater than x.

$$Q^* = \sqrt{\frac{2\beta a(p_b)^{-C} c_v}{h_v\left\{(2-n)\frac{a(p_b)^{-C}}{P} + (n-1)\right\}}}$$

Corresponding to the supplier's decision, the retailer adjusts its decisions on Q^*. By taking the first order derivative of Eq. (4.15) with respect to p_b, we have

$$\frac{\partial \Pi_b}{\partial p_b} = [a(p_b)^{-C} + (p_b - p_v) a(-C)(p_b)^{-C-1}$$

$$-\left[\frac{\sqrt{ac_v}\sqrt{ac_b h_b\{(2-n)\rho + (n-1)\}}}{(1-r)\sqrt{2c_v}} + \frac{h_b(1-r)\sqrt{2ac_v}}{2\sqrt{h_b\{(2-n)\rho + (n-1)\}}}\right](-C-0.5)(p_b)^{-C-1.5}] \qquad (4.13)$$

$p_b^* = \exp\left[f(p_b) \right]$. *See the Appedix B(a).*

$$where\ k=1,\ \beta=1, [\beta+k(1-\beta)]=1, \quad \rho=\frac{D}{P}, \tag{4.14}$$

$$L=\frac{\sqrt{a\cdot h_v\left\{(2-n)\rho+(n-1)\right\}}}{(1-r)\sqrt{2}}+\frac{(1-r)h_b\sqrt{2a\cdot c_v}}{2\sqrt{h_v\left\{(2-n)\rho+(n-1)\right\}}}$$

From Eq. (4.10), by plugging Eq. (4.11), we obtain

$$\begin{aligned}
\Pi_b(Q^*) &= [\beta+k(1-\beta)]a(p_b)^{-C}p_b-[\beta+k(1-\beta)]a(p_b)^{-C}p_v \\
&\quad -\frac{[\beta+k(1-\beta)]a(p_b)^{-C}c_b}{Q^*(1-r)}-\frac{Q^*(1-r)h_b}{2} \\
&=[\beta+k(1-\beta)]a(p_b)^{-C}(p_b-p_v) \\
&\quad -\frac{[\beta+k(1-\beta)]a(p_b)^{-C}c_b}{\sqrt{\dfrac{2\beta a(p_b)^{-C}c_v}{h_v\left\{(2-n)\dfrac{a(p_b)^{-C}}{P}+(n-1)\right\}}}\cdot(1-r)} \\
&\quad -\frac{(1-r)h_b}{2}\sqrt{\frac{2\beta a(p_b)^{-C}c_v}{h_v\left\{(2-n)\dfrac{a(p_b)^{-C}}{P}+(n-1)\right\}}}
\end{aligned} \tag{4.15}$$

The total profit function of the supplier's perspective coordination system with lost sales is obtained as follows:

$$\Pi_{ch}=\left\{\ \Pi_b(p_b,Q)+\ \Pi_v(n,Q)\ \right\}$$

$$\begin{aligned}
&=\left[\beta+k(1-\beta)\right]a(p_b)^{-C}p_b-\left[\beta+k(1-\beta)\right]a(p_b)^{-C}p_v-\frac{\left[\beta+k(1-\beta)\right]a(p_b)^{-C}c_b}{Q(1-r)} \\
&\quad -\frac{Q(1-r)h_b}{2}+\left[\beta+k(1-\beta)\right]a(p_b)^{-C}p_v-\beta a(p_b)^{-C}p-k(1-\beta)a(p_b)^{-C}p_0 \\
&\quad -\frac{\beta a(p_b)^{-C}c_v}{nQ}-\frac{h_vQ}{2}\left\{(2-n)\frac{a(p_b)^{-C}}{P}+(n-1)\right\}-(1-k)(1-\beta)a(p_b)^{-C}(g-g_0k)
\end{aligned} \tag{4.16}$$

$$
\begin{aligned}
&= \left[\beta + k(1-\beta)\right]a(p_b)^{-C} p_b - \beta a(p_b)^{-C} p - k(1-\beta)a(p_b)^{-C} p_0 \\
&- \frac{\left[\beta + k(1-\beta)\right]a(p_b)^{-C} c_b}{Q1-r)} - \frac{Q(1-r)h_b}{2} - \frac{\beta a(p_b)^{-C} c_v}{nQ} \\
&- \frac{h_v Q}{2}\left\{(2-n)\frac{a(p_b)^{-C}}{P} + (n-1)\right\} - (1-k)(1-\beta)a(p_b)^{-C}(g - g_0 k)
\end{aligned}
$$

$$
where \;\; Q^* = \sqrt{\frac{2\beta a(p_b)^{-C} c_v}{h_v\left\{(2-n)\dfrac{a(p_b)^{-C}}{P} + (n-1)\right\}}}, \;\; n^* = \sqrt{\frac{1}{Q^*}\frac{2\beta a(p_b)^{-C} c_v}{h_v}\frac{P}{(P - a(p_b)^{-C})}}
$$

$$
= \left[\beta + k(1-\beta)\right]a(p_b)^{-C} p_b - \beta a(p_b)^{-C} p - k(1-\beta)a(p_b)^{-C} p_0
$$

$$
- \frac{\left[\beta + k(1-\beta)\right]a(p_b)^{-C} c_b}{Q^*(1-r)} - \frac{Q(1-r)h_b}{2} - \frac{\beta a(p_b)^{-C} c_v}{\sqrt{\dfrac{1}{Q^*}\dfrac{2\beta a(p_b)^{-C} c_v}{h_v}\dfrac{P}{(P-D)}} \cdot Q^*}
$$

$$
- \frac{h_v Q^*}{2}\left\{(2 - \sqrt{\frac{1}{Q^*}\frac{2\beta a(p_b)^{-C} c_v}{h_v}\frac{P}{(P - a(p_b)^{-C})}})\frac{a(p_b)^{-C}}{P} + \right.
$$

$$
\left.(\sqrt{\frac{1}{Q^*}\frac{2\beta a(p_b)^{-C} c_v}{h_v}\frac{P}{(P - a(p_b)^{-C})}} - 1)\right\} - (1-k)(1-\beta)a(p_b)^{-C}(g - g_0 k)
$$

From Eq. (3.12), by taking the first derivative of the total profit function of the supply chain system, we can obtain the solution of the optimization problem as follows

$$
\begin{aligned}
&\frac{\partial \Pi_{ch}}{\partial k} = (1-\beta)a(p_b)^{-C}[p_b - p_0 - \frac{c_b}{Q^*(1-r)} - 2g_0 k + g + g_0] = 0, \\
&\therefore k^* = \frac{1}{2g_0}[p_b - p_0 - \frac{c_b}{Q^*(1-r)} + g + g_0] \qquad (4.17) \\
&\qquad where \;\; Q^* = \sqrt{\frac{2\beta a(p_b)^{-C} c_v}{h_v\left\{(2-n)\dfrac{a(p_b)^{-C}}{P} + (n-1)\right\}}}
\end{aligned}
$$

4.3.2 Joint Coordination model

If the retailer chooses its selling price and ordering quantity (p_b^*, Q^*), and the supplier determines its number of shipment *n*, then the total system profit under independent optimization, $\Pi_{ch}(p_b^*, Q^*, n^*)$ is equal to the sum of the retailer's and the supplier's profits, i.e., $\Pi_{ch}(p_b^*, Q^*, n^*) = \Pi_b(p_b^*, Q^*) + \Pi_v(n^*)$. Consider the situation where the supplier and the retailer decide to coordinate and share information with each other to determine the best policy together for the integrated supply chain system. In case of stock-outs in a supply chain, as we introduced in the previous chapter, by determining the optimal fraction (k^*) of the demand shortfall that may be recovered by outsourcing or external procurement, we can easily obtain the profit functions of the retailer and supplier for each model.

Therefore, the total profit function of the supply chain system can be obtained by

$$\Pi_{ch}(p_b^*, Q^*, n^*, k^*) = \left\{ \Pi_b(p_b^*, Q^*) + \Pi_v(n^*) \right\}$$

$$\begin{aligned} = & [\beta + k(1-\beta)]a(p_b)^{-C} p_b - [\beta + k(1-\beta)]a(p_b)^{-C} p_v \\ & - \frac{[\beta + k(1-\beta)]a(p_b)^{-C} c_b}{Q(1-r)} - \frac{Q(1-r)h_b}{2} \\ & + \left[\beta + k(1-\beta)\right] a(p_b)^{-C} p_v - \beta a(p_b)^{-C} p - ka(p_b)^{-C}(1-\beta)p_0 \\ & - \frac{\beta a(p_b)^{-C} c_v}{nQ} - \frac{h_v Q}{2}\left\{(2-n)\frac{a(p_b)^{-C}}{P} + (n-1)\right\} \\ & -(1-k)a(p_b)^{-C}(1-\beta)(g - g_0 k) \end{aligned} \tag{4.18}$$

$$
\begin{aligned}
= \; & [\beta + k(1-\beta)]a(p_b)^{-C} p_b - \beta a(p_b)^{-C} p \\
& -\frac{[\beta + k(1-\beta)]a(p_b)^{-C} c_b}{Q(1-r)} - \frac{Q(1-r)h_b}{2} - k(1-\beta)a(p_b)^{-C} p_0 \\
& -\frac{\beta a(p_b)^{-C} c_v}{nQ} - \frac{h_v Q}{2}\left\{(2-n)\frac{a(p_b)^{-C}}{P} + (n-1)\right\} \\
& -(1-k)(1-\beta)a(p_b)^{-C}(g - g_0 k)
\end{aligned}
$$

Since both the supplier's and the retailer/retailer fully cooperate with each other to make decisions that minimize the total costs and maximize the system profit,

they can make coordinated decisions on Q^* and n^*. From Eq. (4.20), the optimal lot size Q^* of the entire supply chain system is obtained as follows:

$$
\begin{aligned}
\frac{\partial \Pi_{ch}}{\partial Q} &= \frac{[\beta + k_1(1-\beta)]a(p_b)^{-C} c_b}{Q^2(1-r)} - \frac{(1-r)h_b}{2} + \frac{\beta a(p_b)^{-C} c_v}{nQ^2(1-r)} \\
&\quad - \frac{h_v}{2}\left\{(2-n)\frac{a(p_b)^{-C}}{P} + (n-1)\right\} = 0, \qquad (4.19) \\
\therefore Q^* &= \sqrt{\frac{2[\{\beta + k(1-\beta)\}a(p_b)^{-C} c_b n + \beta a(p_b)^{-C} c_v (1-r)]}{n(1-r)\left[h_b(1-r) + h_v\left\{(2-n)\frac{a(p_b)^{-C}}{P} + (n-1)\right\}\right]}}
\end{aligned}
$$

From Eq. (4.20), in a similar way the optimal number of delivery batches per production run, n^* of the supply chain system is expressed as follows

$$
\frac{\partial \Pi_v}{\partial n} = 0, \quad n^* = \left\lfloor \frac{1}{Q^*}\sqrt{\frac{2\beta a(p_b)^{-C} c_v}{h_v}\frac{P}{P - a(p_b)^{-C}}} \right\rfloor,
$$

where $\lfloor x \rfloor$ = the smallest integer greater

$$
Q^* = \sqrt{\frac{2[\{\beta + k(1-\beta)\}a(p_b)^{-C} c_b n + \beta a(p_b)^{-C} c_v (1-r)]}{n(1-r)\left[h_b(1-r) + h_v\left\{(2-n)\frac{a(p_b)^{-C}}{P} + (n-1)\right\}\right]}}
$$

By taking the first order derivative of Eq. (4.15) with respect to p_b, we have

$$\frac{\partial \Pi_{ch}}{\partial p_b} = [[\beta + k(1-\beta)]a(p_b)^{-C} + [\beta + k(1-\beta)](p_b - p)a(-C)(p_b)^{-C-1}$$

$$- \frac{a(-C)(p_b)^{-C-1}(\frac{c_v}{n}+c_b)[\beta + k(1-\beta)][h_b\{(2-n)\rho + (n-1)\}]}{\sqrt{[\beta + k(1-\beta)]2a(p_b)^{-C-1.5}(\frac{c_v}{n}+c_b)[h_b\{(2-n)\rho + (n-1)\}]}} \qquad (4.20)$$

$$where\ k=1,\ \beta=1, [\beta + k(1-\beta)] = 1, \quad \rho = \frac{D}{P},$$

Then we obtain

$$p_b^* = \exp\ [p_b \cdot C - \ln(\frac{X(p_b)}{Y(p_b)}]$$

$$\begin{aligned} where\ X(p_b) = a[(2C^2 n(p_v)^2(e^{p_b})^2 - 4C^2 n(p_v)^2(e^{p_b})^3 + 2C^2 n(e^{p_b})^4 \\ + C^2 c_b h_v(n)^2 - 2C^2 c_b h_v n + C^2 c_v h_v n + 4Cnp_v(e^{p_b})^2 \\ - 4Cn(e^{p_b})^3 - 2C^2 c_v h_v + 2n(e^{p_b})^2] \\ Y(p_b) = h_v C^2(c_b h_b n + c_b n^2 - c_b n + c_v h_b + c_v n - c_v) \end{aligned} \qquad (4.21)$$

$$where\ k=1,\ \beta=1, [\beta + k(1-\beta)] = 1, \quad \rho = \frac{D}{P},$$

From Eq. (3.20), by taking the first derivative of the total profit function of the supply chain system with respect to *k*, we can obtain the solution of the optimization problem as follows:

$$\frac{\partial \Pi_{ch}}{\partial k} = (1-\beta)a(p_b)^{-C}[p_b - p_0 - \frac{c_b}{Q^*(1-r)} - 2g_0 k + g + g_0] = 0,$$

$$\therefore k^* = \frac{1}{2g_0}[p_b - p_0 - \frac{c_b}{Q^*(1-r)} + g + g_0] \qquad (4.22)$$

$$where \quad Q^* = \sqrt{\frac{2[\{\beta + k(1-\beta)\}a(p_b)^{-C} c_b n + \beta a(p_b)^{-C} c_v(1-r)]}{n(1-r)\left[h_b(1-r) + h_v\left\{(2-n)\frac{a(p_b)^{-C}}{P} + (n-1)\right\}\right]}}$$

So far we have derived the net profit functions and the optimal policies of each supply chain model. For the proposed individual and coordinated models in this chapter, the results of individual optimization and coordinated decision are summarized in the Table 4.2.

	Retailer Driven Model
$p_b{}^*$	$\exp\left[p_b \cdot C - \ln\left(\frac{2a \cdot \{C^2 p_v^2 - 2C^2 p_v^2 e^{p_b} + C^2 (e^{p_b})^2 + 2Cp_v e^{p_b} - 2C(e^{p_b})^2 + (e^{p_b})^2\}}{c_b \cdot h_b \cdot C^2}\right) \right]$ $where\ k = 1, b = 1, [\beta + k(1-\beta)] = 1$
Q^*	$\frac{1}{(1-r)} \sqrt{\frac{2[\beta + k(1-\beta)] a (p_b)^{-C} c_b}{h_b}}$
n^*	$\left\lfloor \frac{1}{Q^*} \sqrt{\frac{2\beta a (p_b)^{-C} c_v}{h_v}} \frac{P}{P - a(p_b)^{-C}} \right\rfloor$ $where\ Q^* = Q^*_{Retailer's\ Perspective}$
k^*	$\frac{1}{2g_0}[p_b - p_0 - \frac{c_b}{Q^*(1-r)} + g + g_0]$ $where\ Q^* = Q^*_{Retailer's\ Perspective}$

Table 4.1 Summary of optimal policies (I)

	Supplier Driven Model
$p_b{}^*$	See the Appendix B-1.
Q^*	$\sqrt{\dfrac{2\beta a(p_b)^{-C}c_v}{h_v\left\{(2-n)\dfrac{a(p_b)^{-C}}{P}+(n-1)\right\}}}$
n^*	$\left\lfloor \dfrac{1}{Q^*}\sqrt{\dfrac{2\beta Dc_v}{h_v}\dfrac{P}{P-D}} \right\rfloor$ $where\ Q^* = Q^*_{Supplier's\ Perspective}$
k^*	$\dfrac{1}{2g_0}[p_b - p_0 - \dfrac{c_b}{Q^*(1-r)} + g + g_0]$ $where\ Q^* = Q^*_{Supplier's\ Perspective}$

Table 4.2 Summary of optimal policies (I)

	Joint Coordination Model
$p_b{}^*$	$p_b^* = \exp\,[p_b \cdot C - \ln(\frac{X(p_b)}{Y(p_b)})]$ $where\ X(p_b) = a[(2C^2 n(p_v)^2 (e^{p_b})^2 - 4C^2 n(p_v)^2 (e^{p_b})^3 + 2C^2 n(e^{p_b})^4$ $+ C^2 c_b h_v (n)^2 - 2C^2 c_b h_v n + C^2 c_v h_v n + 4Cnp_v (e^{p_b})^2$ $- 4Cn(e^{p_b})^3 - 2C^2 c_v h_v + 2n(e^{p_b})^2]$ $Y(p_b) = h_v C^2 (c_b h_b n + c_b n^2 - c_b n + c_v h_b + c_v n - c_v)$ $where\ k = 1,\ \beta = 1, [\beta + k(1-\beta)] = 1, \quad \rho = \frac{D}{P},$
Q^*	$\sqrt{\dfrac{2[n\{\beta + k(1-\beta)\} a(p_b)^{-C} c_b + \beta a(p_b)^{-C} c_v]}{n(1-r)\left[h_b + h_v\left\{(2-n)\dfrac{a(p_b)^{-C}}{P} + (n-1)\right\}\right]}}$
n^*	$\left\lfloor \frac{1}{Q^*}\sqrt{\frac{2\beta a(p_b)^{-C} c_v}{h_v}\frac{P}{P - a(p_b)^{-C}}} \right\rfloor$ $where\ Q^* = Q^*_{Joint\ Coordination}$
k^*	$\frac{1}{2g_0}[p_b - p_0 - \frac{c_b}{Q^*(1-r)} + g + g_0]$ $where\ Q^* = Q^*_{Joint\ Coordination}$

Table 4.3 Summary of optimal policies (II)

4.4 Solution Procedure

The ultimate objective of the proposed models in this chapter is to find the optimal ratio of emergency procurement, the optimal order quantity, and the minimum number of shipment such that the total joint profit of the supply chain system is maximized. These nonlinear optimization problems are to be solved for p_b^*, n^*, Q^* and k^*. To solve this non-linear optimization model, we apply the following iterative heuristic algorithm which is used in some articles such as Ray, Gerchak and Jewkes (2005), Sajadieh and Jokar (2009), and Chen and Kang (2010) to find the optimal solution (p_r^*, Q^*, n^*, k^*). To solve this non-linear optimization model, we modify the iterative algorithm used in the chapter 3.

Step 0. Let $n = 0$ and set $\Pi_{ch}\left(p_b^{(n)},\ Q^{(n)},\ n,\ k^{(n)}\right) = 0$.

Step 1. Set $n = 1$.

Step 2. Determine $p_b^{(n)}$ by solving the first derivative function of each model with respect to p_b.

Step 3. Compute the value of $Q^{(n)}$

Step 3. Compute the value of $k^{(n)}$

Step 4. Calculate $\Pi_{ch}(p_b^{(n)}, Q^{(n)}, n, k^{(n)})$ using Eq. (4.20).

Step 5. If $\Pi_{ch}(p_b^{(n)}, Q^{(n)}, n, k^{(n)}) \geq \Pi_{ch}(p_b^{(n-1)}, Q^{(n-1)}, n-1, k^{(n-1)})$, then go to step 6.

Otherwise, the optimal solution is $(p_b^*, Q^*, n^*, k^*) = (p_b^{(n-1)}, Q^{(n-1)}, n-1, k^{(n-1)})$.

Step 6. Let $n = n + 1$, then go to step 2.

We first assume that n is a continuous variable. As Π_{ch} is convex in *n*, the following equation for n can be obtained by solving the first derivative function of Π_{ch}. For a given value of *n*, therefore the optimal value for the selling price p_b for a fixed value of *n* can be obtained by taking the first-order partial derivative of Π_{ch} with respect to p_b and setting it equal to zero (this is the necessary condition for optimality), and solving for p_b numerically. For example, the *fsolve* procedure of MATLAB or *solve* function in MAPLE could be used to solve this equation, as was done in this paper.

Following the above-mentioned procedures, the maximum system profit can be derived in these three cases, where, (i) emergency supply option is available ($k^* \neq 0$), (ii) emergency procurement is not possible ($k^* = 0$), and complete outsourcing ($k^* = 1$) for a given unit external procurement price p_0. (See the Table 4.3.) We see that k^* is highly related with Q^* in retailer's perspective coordination model and integrated joint coordination model. In addition, in both the individual decision model and the supplier's perspective coordination model, change in k^* does not affect Q^*.

From Table 4.3., if we take the highest value of k possible for a corresponding optimal value of *Q* and the possible maximum of $k = 1$, then the maximum system profit will be obtained. Thus, it is found that for a particular value of *n* and *Q*, as long as $[p_b - p_0 - \frac{c_b}{Q^*(1-r)} + g + g_0] > 0$, system profit increases with increasing k and reaches the maximum value when the ratio of external procurement reaches the optimal value k^*.On the other hand, if $[p_b - p_0 - \frac{c_b}{Q^*(1-r)} + g + g_0] < 0$, it is better not to choose the emergency procurement option. The underlying mechanism is to manipulate lot size Q in such a way that the overall system cost is decreased and the savings can be utilized to go for outsourcing even at a higher price till a particular limiting value. The underlying mechanism is with consideration of all cost factors which includes inventory holding cost, ordering cost, transportation cost, etc. to optimize the lot size Q and the savings of the whole system can be utilized for the emergency supply option until the emergency procurement price goes up to a particular price much higher than the retail price. In the solution procedure, we focused on the optimal ratio of external procurement, k^* as well as either k^* = 0 or k^* = 1 and the proposed algorithm yields the best solution for the coordinated decision models. While Sinha et al (2007) focused on either k^* = 0 or k^* = 1 to make only binary decisions on emergency procurement under shortage, the proposed algorithm yields the best optimal solution for k^* with the coordinated policy through the proposed solution procedure. It is also shown numerically that a coordinated policy has a better system profit in numerical examples.

4.5 Model Analysis

This section presents a theoretical analysis of the proposed models developed in the previous sections above:

4.5.1 Optimization

A nonlinear mixed integer optimization problem is formulated in this chapter to be solved for the optimal ratio of emergency procurement, the optimal order quantity, and the minimum number of shipment A heuristic algorithm is provided to find the optimal ratio of n^*, p_b^*, Q^* and k^* such that the total joint profit of the supply chain system is maximized.

Figure 3.2 shows the behaviors of the optimal solutions under different settings of the external procurement price (p_0) while n holds constant at the optimal solution. As the external procurement price (p_0) changes, the optimal ratio of external procurement (k) is determined, and accordingly the optimal solution is obtained. Obviously we see that it has the high sensitivity to the system overall benefit.

Table 3.4 presents a summary of the optimal solutions of the proposed models in this chapter. Under a normal setting of the system parameters (β = 0.8, r = 0.05, p_0 = 48) while all the other parameters hold constant, we see that the joint coordination model and the supplier driven model have the best performances for profit maximization, and the retailer driven model has the second best among the proposed models. Individual decision model without considerations of coordination has the worst performance in our case.

	Retailer's Driven Model			Supplier's Driven Model			Joint Coordination Model		
	n-1	n*	n+1	n-1	n*	n+1	n-1	n*	n+1
n	4	4.85	5	8	8.06	9	66	66.63	67
p_b	63.2964	63.2964	63.2964	63.0033	63.0033	63.0033	54.347	54.3444	54.347
Q	498.39	511.33	498.39	845.78	455.37	692.82	186.32	187.16	185.02
k	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	0.4299	1.0000	0.4206
$\prod_b$		77,225.2			282,751.6				
$\prod_v$		212,090.7			7,055.0				
$\prod_{ch}$	272,480.5	289,315.9	272,505.8	288,770.6	289,806.6	107,940.4	295787.8	304,259.6	295645.9

Table 4.4 Comparison of heuristic approach and simultaneous optimization

4.5.2 Profit Maximization

In this section we check the sufficient conditions for the proposed optimization models. To make profit maximization of supply chain system, theoretically the concavity of the profit function of each model is checked by the Hessian matrix.

First, for an individual decision model, it is sufficient to show $\Pi_b(Q)$ is concave for $Q > 0$. From Eq. (4.5),

$$\Pi_b(Q) = \beta a(p_b)^{-C} p_b - \beta a(p_b)^{-C} p_v - \frac{\beta a(p_b)^{-C} c_b}{Q(1-r)} - \frac{h_b Q(1-r)}{2}$$

$$\frac{\partial \Pi_b}{\partial Q} = \frac{\beta a(p_b)^{-C} c_b}{Q^2(1-r)} - \frac{h_b(1-r)}{2} = 0$$

$$\frac{\partial^2 \Pi_b}{\partial Q^2} = \frac{-2\beta a(p_b)^{-C} c_b}{Q^3(1-r)} < 0$$

A sufficient condition for a local maximum in the joint coordination model is obtained as follows:

$$H(n, p_b, Q, k) = \begin{bmatrix} \frac{\partial^2 \Pi_{ch}}{\partial n^2} & \frac{\partial^2 \Pi_{ch}}{\partial n \partial p_b} & \frac{\partial^2 \Pi_{ch}}{\partial n \partial Q} & \frac{\partial^2 \Pi_{ch}}{\partial n \partial k} \\ \frac{\partial^2 \Pi_{ch}}{\partial p_b \partial n} & \frac{\partial^2 \Pi_{ch}}{\partial {p_b}^2} & \frac{\partial^2 \Pi_{ch}}{\partial p_b \partial Q} & \frac{\partial^2 \Pi_{ch}}{\partial p_b \partial k} \\ \frac{\partial^2 \Pi_{ch}}{\partial Q \partial n} & \frac{\partial^2 \Pi_{ch}}{\partial Q \partial p_b} & \frac{\partial^2 \Pi_{ch}}{\partial Q^2} & \frac{\partial^2 \Pi_{ch}}{\partial Q \partial k} \\ \frac{\partial^2 \Pi_{ch}}{\partial k \partial n} & \frac{\partial^2 \Pi_{ch}}{\partial k \partial p_b} & \frac{\partial^2 \Pi_{ch}}{\partial k \partial Q} & \frac{\partial^2 \Pi_{ch}}{\partial k^2} \end{bmatrix} < 0$$

When we plug Q^* in the total profit function, $\Pi_{ch}(n, p_b, Q, k)$, we obtain the full Hessian matrix using Maple software (See the appendix A.) We find that the determinant of the Hessian matrix is negative, and the given function has a local maximum. It can be also proved numerically that the Hessian matrix at the stationary point is negative definite and the stationary point is a local maximum.

Appendix

B.1. Sufficient condition for a local maximum in the joint coordination model.

The Hessian matrix of the profit function of the model can be written as follows:

$$H(n,p_b,Q,k)=\begin{bmatrix} \frac{\partial^2\Pi_{ch}}{\partial n^2} & \frac{\partial^2\Pi_{ch}}{\partial n\partial p_b} & \frac{\partial^2\Pi_{ch}}{\partial n\partial Q} & \frac{\partial^2\Pi_{ch}}{\partial n\partial k} \\ \frac{\partial^2\Pi_{ch}}{\partial p_b\partial n} & \frac{\partial^2\Pi_{ch}}{\partial {p_b}^2} & \frac{\partial^2\Pi_{ch}}{\partial p_b\partial Q} & \frac{\partial^2\Pi_{ch}}{\partial p_b\partial k} \\ \frac{\partial^2\Pi_{ch}}{\partial Q\partial n} & \frac{\partial^2\Pi_{ch}}{\partial Q\partial p_b} & \frac{\partial^2\Pi_{ch}}{\partial Q^2} & \frac{\partial^2\Pi_{ch}}{\partial Q\partial k} \\ \frac{\partial^2\Pi_{ch}}{\partial k\partial n} & \frac{\partial^2\Pi_{ch}}{\partial k\partial p_b} & \frac{\partial^2\Pi_{ch}}{\partial k\partial Q} & \frac{\partial^2\Pi_{ch}}{\partial k^2} \end{bmatrix}=$$

$$\{\{-\frac{2ab(cv)p^{-C}}{n^3Q},-\frac{abCdp^{-1-C}}{n^2Q}-\frac{aC\mathrm{hv}p^{-1-C}Q}{2P},-\frac{1}{2}\mathrm{hv}(1-\frac{ap^{-C}}{P})-\frac{abdp^{-C}}{n^2Q^2},0\},$$

$$\Big\{-\frac{abCdp^{-1-C}}{n^2Q}-\frac{aC\mathrm{hv}p^{-1-C}Q}{2P},a(1-b)(-1-C)C(1-k)(g-\mathrm{g0}k)p^{-2-C}$$

$$-a(1-C)C(b+(1-b)k)p^{-1-C}+a(1-b)(-1-C)Ckp^{-2-C}\mathrm{p0}$$

$$+ab(-1-C)Cp^{-2-C}q+\frac{ab(-1-C)Cdp^{-2-C}}{nQ}$$

$$+\frac{a(-1-C)C\mathrm{hv}(2-n)p^{-2-C}Q}{2P}$$

$$+\frac{ac(-1-C)C(b+(1-b)k)p^{-2-C}}{Q(1-r)},\frac{aC\mathrm{hv}(2-n)p^{-1-C}}{2P}-\frac{abCdp^{-1-C}}{nQ^2}$$

$$-\frac{acC(b+(1-b)k)p^{-1-C}}{Q^2(1-r)},-a(1-b)C\mathrm{g0}(1-k)p^{-1-C}$$

$$-a(1-b)C(g-\mathrm{g0}k)p^{-1-C}+a(1-b)(1-C)p^{-C}$$

$$+a(1-b)Cp^{-1-C}\mathrm{p0}+\frac{a(1-b)cCp^{-1-C}}{Q(1-r)}\Big\},$$

$$\left\{-\frac{1}{2}\mathrm{hv}\left(1-\frac{ap^{-C}}{P}\right)-\frac{abdp^{-C}}{n^2Q^2},\frac{aC\mathrm{hv}(2-n)p^{-1-C}}{2P}-\frac{abCdp^{-1-C}}{nQ^2}\right.$$

$$-\frac{acC(b+(1-b)k)p^{-1-C}}{Q^2(1-r)},-\frac{2abdp^{-C}}{nQ^3}$$

$$\left.-\frac{2ac(b+(1-b)k)p^{-C}}{Q^3(1-r)},\frac{a(1-b)cp^{-C}}{Q^2(1-r)}\right\},$$

$$\{0,-a(1-b)C\mathrm{g0}(1-k)p^{-1-C}-a(1-b)C(g-\mathrm{g0}k)p^{-1-C}+a(1-b)(1-C)p^{-C}$$

$$+a(1-b)Cp^{-1-C}\mathrm{p0}+\frac{a(1-b)cCp^{-1-C}}{Q(1-r)},\frac{a(1-b)cp^{-C}}{Q^2(1-r)},-2a(1$$

$$-b)\mathrm{g0}p^{-C}\}\}$$

We can find the determinant of the Hessian matrix is negative and the profit function of the joint coordination above has a local maximum. It can be also proved numerically with the system parameters. We see the Hessian matrix at the stationary point is negative definite.

$$H(n,p_b,Q,k)=\begin{bmatrix}\frac{\partial^2\Pi_{ch}}{\partial n^2} & \frac{\partial^2\Pi_{ch}}{\partial n\partial p_b} & \frac{\partial^2\Pi_{ch}}{\partial n\partial Q} & \frac{\partial^2\Pi_{ch}}{\partial n\partial Q}\\ \frac{\partial^2\Pi_{ch}}{\partial p_b\partial n} & \frac{\partial^2\Pi_{ch}}{\partial p_b{}^2} & \frac{\partial^2\Pi_{ch}}{\partial p_b\partial Q} & \frac{\partial^2\Pi_{ch}}{\partial p_b\partial k}\\ \frac{\partial^2\Pi_{ch}}{\partial Q\partial n} & \frac{\partial^2\Pi_{ch}}{\partial Q\partial p_b} & \frac{\partial^2\Pi_{ch}}{\partial Q^2} & \frac{\partial^2\Pi_{ch}}{\partial Q\partial k}\\ \frac{\partial^2\Pi_{ch}}{\partial k\partial n} & \frac{\partial^2\Pi_{ch}}{\partial k\partial p_b} & \frac{\partial^2\Pi_{ch}}{\partial k\partial Q} & \frac{\partial^2\Pi_{ch}}{\partial k^2}\end{bmatrix}= \qquad =<0$$

CHAPTER 5

POST-OPTIMAL ANALYSIS

5.1 Post-Optimality Analysis

In this chapter, we conduct post-optimal analyses for the optimal solutions we obtained in the previous chapters. Post-optimal analysis so called sensitivity analysis is a technique used to determine how different values of an independent variable will impact a particular dependent variable under a given set of assumptions. This technique is used within specific boundaries that will depend on one or more input variables, such as the effect that changes in interest rates will have on a bond's price. Sensitivity analysis is a way to predict the outcome of a decision if a situation turns out to be different compared to the key prediction(s). Sensitivity analysis is very useful when attempting to determine the impact the actual outcome of a particular variable will have if it differs from what was previously assumed. By creating a given set of scenarios, the analyst can determine how changes in one variable(s) will impact the target variable.

In the chapter 4, an integrated production-inventory-marketing model for a two-stage supply chain is presented. It is assumed the demand rate is an iso-elastic function of the selling price. Then, the total cost functions are developed, and the optimal values of the selling price, order quantity and number of shipments are obtained under independent and joint optimizations. A numerical example and the sensitivity analysis are done, and the main following findings are attained.

Referring to the existing literature such as Sajadieh and Jokar (2009) and Chen and Kang (2010), we discuss an example with the following data: c_b = \$200/order, c_v = \$1200/setup, p = 2.5\$/unit, p_w =\$5/unit, β =0.8, h_b = \$0.5/unit/year, h_v = 0.25/unit/year, a=300,000 and b=1.245. Therefore, D(p)=$100,000,000(p_r)^{-2.35}$. The percentage improvement (PI) i.e., $PI = \frac{\Pi_{\text{joint}} - \Pi_{ind}}{\Pi_{ind}} \times 100$ is calculated to shed light on the benefits of joint optimization where Π_{joint} represent the total system profit under joint and Π_{ind} does independent optimization respectively. The total improvement should then be shared in some equitable manner and some kind of profit-sharing mechanism such as a side payment from the supplier to the retailer, or a price discount scheme needs to be employed in order to encourage cooperation and entice the retailer to change his/her lot size (see for example Ouyang, Wu & Ho, 2004; Goyal, 1976; Sajadieh and Jokar, 2009).

In order to emphasize the role of coordination in the total profit, a selection of randomly generated problem instances are solved and summarized in Table 5.1. In a second step, some of the model parameters are varied and their impact on the optimal solution and the total profit are studied.

5.2 Numerical Example and Sensitivity Analysis of Deterministic Demand Model

In this section, we present a numerical example and sensitivity analysis for both individual and coordinated models developed in the previous sections. To illustrate the behavior of our model, we adopt the same model input parameters used by the Goyal and Gopalakrishnan (1996), and Sinha and Sarmah (2007). Assuming a supplier provides 10,000 units annually to a retailer in a supply chain, the other corresponding data after tidying up are shown in Table. 3.4.

D	p_b	p_v	p	p_0	c_b	c_v
10,000	45	35	30	48	80	200
P	h_b	h_v	β	g	g_0	r
15,000 or 8000	6	5	0.8	5	3	0.05

Table 5.1 Model Input Parameters

To investigate the effects of changes in the system parameters on the optimal solution and the total system profit, a sensitivity analysis is conducted and the results for critical parameters are summarized in the following:

5.2.1 Sensitivity Analysis for the index of the fraction of the market demand satisfied by supplier (β)

Table 5.2 shows how sensitively the optimal solutions will change according to the change in the fraction of the demand satisfied by supplier (β) in the model. We assume that the initial supply by the supplier is equal to the market demand and we find the following relationship between k and β, $\beta = 1 - r(1-k)$. Basically we see as β increases from 0.95 to 1.0, the total profit of the system accordingly goes up. We also see there are no differences between the performance of the supplier driven model and that of the joint coordination model in the near range of the optimal solutions (when β is between 0.95 and 1.00). In addition to that, when retailer drives the channel decisions coordination can provide bigger performance improvements (0.44~0.46%) at the highest level of β (0.95< β<1.0).

5.2.2 Sensitivity Analysis the defective rate (*r*)

Table 5.3 shows illustrates that as the defective rate, *r*, increases, the total profit function, decreases. As the defect rate *r* goes up, we see the PI(%) slightly increases. The coordinated supply chain always prefers to reduce the mean rate of defectives to increase its total profit through coordination. We also see there are no differences between the performance of the supplier driven model and that of the joint coordination model in the near range of the optimal solutions. In addition to that, when supplier and retailer pursue independent optimization in a supply chain, coordination can provide big improvements in the all rages of the defective rate.

5.2.3 Sensitivity Analysis for the external procurement price (p_0)

Table 3.9 illustrates how a supplier makes decisions on pricing issues to make up for shortage. This table se two graphs actually present how much a supplier is willing to pay for emergent procurement from an external supplier to make up for shortage on its side. We see that as the external procurement price (p_0) goes up, k and the total profit move down. For example, when p_0 is below a certain threshold, the supplier will choose the coordinated policy to maximize the total profit of the chain. But if p_0 goes beyond a upper bound, then the optimal ratio of k^* becomes zero, which means that the external procurement is not recommended, even though the coordinated decision making model always makes a higher profit than that under the individual policy.

β	Supplier Driven Model					
	n	*Q*	*k*	$\prod_b$	$\prod_v$	$\prod_{ch}$
0.9500	2.85	529.81	0.0000	92,491.8	41,530.1	134,021.9
0.9625	2.83	535.88	0.2500	94,644.5	42,219.8	136,864.3
0.9750	2.83	540.17	0.5000	96,190.3	43,168.6	139,358.9
0.9875	2.83	542.73	0.7500	97,111.6	44,534.6	141,646.2
1.0000	2.85	543.58	1.0000	97,426.7	46,439.9	143,866.6

β	Retailer Driven Model						Joint Coordination Model				$PI_{Sup.Joint}$ (%)	$PI_{Ret.Joint}$ (%)
	n	*Q*	*k*	$\prod_b$	$\prod_v$	$\prod_{ch}$	*n*	*Q*	*k*	$\prod_{ch}$		
0.9500	2.97	757.07	0.0000	91,785.64	41,647.6	133,433.2	3.23	466.04	0.0000	134,050.2	0.02	0.46
0.9625	2.96	762.85	0.2500	93,940.53	42,337.7	136,278.2	3.22	471.38	0.2500	136,892.9	0.02	0.45
0.9750	2.96	768.05	0.5000	95,478.34	43,292.9	138,771.2	3.21	475.15	0.5000	139,387.7	0.02	0.44
0.9875	2.96	772.67	0.7500	96,398.93	44,653.6	141,052.5	3.22	477.40	0.7500	141,675.2	0.02	0.44
1.0000	2.97	776.74	1.0000	96,702.14	46,560.5	143,262.6	3.23	478.15	1.0000	143,895.7	0.02	0.44

Table 5.2 Sensitivity Analysis for the index of the fraction of the market demand satisfied by supplier (β)

r	Supplier Driven Model					
	n	Q	k	$\prod_b$	$\prod_v$	$\prod_{ch}$
0.01	3.09	765.94	1.0000	134,476.3	8,737.9	143,214.2
0.03	3.03	771.30	1.0000	134,459.8	8,778.8	143,238.6
0.05	2.97	776.74	1.0000	134,442.4	8,820.2	143,262.6
0.10	2.83	790.69	1.0000	134,407.4	8,913.1	143,320.5
0.15	2.70	805.16	1.0000	134,378.8	8,995.9	143,374.7
0.20	2.56	820.18	1.0000	134,328.8	9,095.4	143,424.2

r	Retailer Driven Model						Joint Coordination Model				$PI_{Sup.Joint}$ (%)	$PI_{Ret.Joint}$ (%)
	n	Q	k	$\prod_b$	$\prod_v$	$\prod_{ch}$	n	Q	k	$\prod_{ch}$		
0.01	2.97	521.61	1.0000	96,898.98	46,985.9	143,884.9	3.36	465.16	1.0000	143,911.5	0.49	0.02
0.03	2.91	532.37	1.0000	96,900.94	46,975.1	143,876.0	3.30	471.56	1.0000	143,903.8	0.46	0.02
0.05	2.85	543.58	1.0000	96,901.61	46,965.0	143,866.6	3.23	478.15	1.0000	143,895.7	0.44	0.02
0.10	2.70	573.78	1.0000	96,897.08	46,944.4	143,841.5	3.08	495.47	1.0000	143,873.1	0.39	0.02
0.15	2.55	607.53	1.0000	96,882.43	46,931.0	143,813.4	2.94	514.14	1.0000	143,847.1	0.33	0.02
0.20	2.40	645.50	1.0000	96,855.75	46,926.0	143,781.7	2.79	534.35	1.0000	143,817.0	0.27	0.02

Table 5.3 Sensitivity Analysis for the defective rate (r)

p_0	Supplier Driven Model					
	n	Q	k	$\prod_b$	$\prod_v$	$\prod_{ch}$
35	3	692.82	1.0000	149,771.1	-16,040.3	133,730.8
40	3	692.82	1.0000	139,771.1	-16,040.3	123,730.8
45	3	692.82	1.0000	129,771.1	-16,040.3	113,730.8
47	3	692.82	0.9797	125,329.4	-15,596.2	109,733.2
48	3	692.82	0.8130	120,076.5	-12,136.1	107,940.4
49	3	692.82	0.6464	115,492.2	-9,011.3	106,480.9
50	3	692.82	0.4797	111,572.8	-6,218.0	105,354.8
52	3	692.82	0.1464	105,735.4	-1,632.9	104,102.5
53	3	692.82	0.0000	104,014.2	-40.3	103,973.9
55	3	692.82	0.0000	104,014.2	-40.3	103,973.9
60	3	692.82	0.0000	104,014.2	-40.3	103,973.9

p_0	Retailer Driven Model						Joint Coordination Model				$PI_{Sup.Joint}$ (%)	$PI_{Ret.Joint}$ (%)
	n	Q	k	$\prod_b$	$\prod_v$	$\prod_{ch}$	n	Q	k	$\prod_{ch}$		
35	3	543.57	1.0000	96,901.61	37,206.9	134,108.5	3	482.98	1.0000	134,165.8	0.33	0.04
40	3	543.57	1.0000	96,901.61	27,206.9	124,108.5	3	482.98	1.0000	124,165.8	0.35	0.05
45	3	543.57	1.0000	96,901.61	17,206.9	114,108.5	3	482.98	1.0000	114,165.8	0.38	0.05
47	3	541.79	0.9672	96,255.79	13,859.2	110,115.0	3	482.11	0.9702	110,171.1	0.40	0.05
48	3	532.6	0.8002	92,968.15	15379.35	108,347.5	3	477.24	0.8032	108,397.7	0.42	0.05
49	3	523.26	0.6333	89,683.39	17230.51	106,913.9	3	472.32	0.6362	106,958.2	0.45	0.04
50	3	513.75	0.4663	86,397.64	19,416.6	105,814.2	3	467.34	0.4692	105,852.8	0.47	0.04
52	3	494.17	0.1325	79,833.19	24,783.2	104,616.4	3	457.23	0.1352	104,643.9	0.52	0.03
53	3	486.18	0.0000	77,228.72	27,282.4	104,511.1	3	453.07	0.0000	104,534.4	0.54	0.02
55	3	486.18	0.0000	77,228.72	27,282.4	104,511.1	3	453.07	0.0000	104,534.4	0.54	0.02
60	3	486.18	0.0000	77,228.72	27,282.4	104,511.1	3	453.07	0.0000	104,534.4	0.54	0.02

Table 5.4 Sensitivity Analysis for the external procurement price (p_0)

5.3 Numerical Example and Sensitivity Analysis of Price Dependent Demand Model

In this section, we present a numerical example and sensitivity analysis for both individual and coordinated models with price dependent demand.

5.3.1 Sensitivity analysis for the price elasticity, *C*

As can be seen in Table 5.1, the percentage improvement, *PI,* increases by b. It means that for more price sensitive demands, joint optimization shows more improvements, and it is more beneficial. This result is similar to which Sajadieh and Jokar (2009) deduced for the integrated inventory model the linear price sensitive demand. Therefore, regardless of type of the demand functions, more price sensitive demands lead to more benefits through coordination. Thus we may conclude that allowing shortages and coordinating the system become more and more important for the supply chain as the market demand becomes more price-sensitive. Such a situation could occur, for example, in a high technology market where a new competitor enters the market and partially erodes the competitive advantage of an existing company. In such a case, since the technological difference between the products offered in the market becomes smaller, customers will focus more on the price of the product. In such a situation, coordinating the supply chain and allowing shortages can improve the position of the companies in the market.

Another outcome can be inferred from Table 5.1 is that when the supply chain's members optimize their inventory systems independently, the optimal selling price is higher than its values under joint optimization. In addition, as the sensitivity of demand to price increases, the difference between the selling price in independent and joint systems increases, too. Consequently, cooperation leads to the higher demand, and so the total profit increases especially for more price sensitive demands.

One more result we obtain from Table 5.2 is that as the sensitivity of demand in the selling price increases, the optimal price is reduced, which is a well-known result from the economics literature. The opposite effect is also clear: A decrease in the selling price induces an increase in demand, and this increases the optimal order and shortage quantities.

5.3.2 Sensitivity analysis for the defective rate *r*

Table 5.6 illustrates that as the defective rate, *r*, increases, the expected joint total profit, Π_{ch}, and the improvement in the expected total profit (PI) (%), decrease. To evaluate the defect rate effect on n^*, Q^*, and Π_{ch}, we examined different values of *r* ($0.01 \le r \le 0.20$). Table 5.6 shows the behaviors of the optimal solutions versus different *r*. From the results, we can see that when *r* increases, the values of *Q* increases; while *n* holds constant. Furthermore, as *r* increases, buyer's reduction in cost increases; while vendor's increment in profit decreases. Thus, when the defective rate increases, the supplier needs to deliver greater lot size per shipment to satisfy the buyer demand. As the defect rate increases, the supplier's benefit increases simultaneously. This result indicates the greater the number of defects, the greater the importance of coordination for the supplier and retailer. Obviously, the defect rate has low sensitivity to the system's overall benefit. In addition, the effects of the defective rate on the optimal values of the decision variables could be different depending on the parameters of the problem. The coordinated supply chain always makes better performances at its lower defective rate to increase its total profit.

5.3.3 Sensitivity analysis for the external procurement price (p_0)

Table 5.7 illustrates how a supplier makes decisions on pricing issues to make up for shortage. This table se two graphs actually present how much a supplier is willing to pay for emergent procurement from an external supplier to make up for shortage on its side. We see that as the external procurement price (p_0) goes up, k and the total profit move down.

For example, when p_0 is below a certain threshold, the supplier will choose the coordinated policy to maximize the total profit of the chain. But if p_0 goes beyond a upper bound, then the optimal ratio of k^* becomes zero, which means that the external procurement is not recommended, even though the coordinated decision making model always makes a higher profit than that under the individual policy.

5.3.4 Sensitivity analysis for the ratio of the supplier's setup cost to retailer's ordering cost (c_v/c_b)

As can be discerned from Table.5.8, an increase in the ratio of the supplier's setup cost to retailer's ordering cost (c_v/c_b) increases the number of shipments and the supplier's production quantity. It is a reasonable result because under fixed value of ordering cost, c_b, higher defective rate, r requires much higher setup cost, c_v. In such a situation, it is expected from the supplier to increase its production quantity in each setup. Therefore, the number of shipments, n, and the supplier's production quantity, Q, increase accordingly. Furthermore, percentage improvement PI, decreases by r. In the table, we conclude that the coordination of the supply chain is less attractive when the supplier's setup cost is considerably lower than the retailer's ordering cost. In addition, we figure out the effect of the proportion of supplier to buyer ordering cost on PI. As illustrated, the improvement percentage increases by the ratio of c_v/c_b. In other words, it will be more beneficial for supply chains to cooperate with each other, as their ordering and setup costs are far from each other. However, the improvement in PI is negatively affected by retailer's ordering cost decreases.

C	Retailer Driven Model							C	Supplier Driven Model						
	n	p_b	Q	k	$\prod_b$	$\prod_v$	$\prod_{ch}$		n	p_b	Q	k	$\prod_b$	$\prod_v$	$\prod_{ch}$
2.00	26.19	70.21	774.13	1.0000	96,705.92	760,588.8	857,294.7	2.00	4.54	70.00	4,485.32	1.0000	848,907.2	-27,421.4	821,485.8
2.35	2.71	61.27	431.80	1.0000	96,819.15	95,570.2	192,389.3	2.35	3.52	60.93	522.62	1.0000	182,469.7	10,002.9	192,472.6
2.50	2.08	58.75	334.17	1.0000	96,527.62	8,272.5	104,800.1	2.50	2.31	58.34	498.79	1.0000	93,603.9	11,185.4	104,789.3
2.75	1.79	55.61	216.60	1.0000	95,494.85	-57,328.1	38,166.8	2.75	1.89	55.00	379.28	0.8106	22,110.5	16,042.0	38,152.5
3.00	1.70	53.41	139.27	1.0000	93,556.51	-79,789.8	13,766.7	3.00	1.80	52.53	260.24	0.8092	-2,888.6	16,644.2	13,755.5

C	Joint Coordination Model					$PI_{Ret.Joint}$ (%)	$PI_{Sup.Joint}$ (%)
	n	p_b	Q	k	$\prod_{ch}$		
2.00	4.52	60.32	6,075.41	1.0000	867,281.4	1.16	5.57
2.35	5.66	52.68	345.34	1.0000	198,789.1	3.33	3.28
2.50	2.53	50.67	379.81	1.0000	108,488.3	3.52	3.53
2.75	1.38	48.28	364.25	1.0000	39,827.1	4.35	4.39
3.00	1.00	46.89	302.55	1.0000	14,536.0	5.59	5.67

Table 5.5 Sensitivity Analysis for the price elasticity (C)

r	Supplier Driven Model						
	n	p_b	Q	k	$\prod_b$	$\prod_v$	$\prod_{ch}$
0.01	3.66	60.9291	511.59	1.0000	182,487.4	9,965.3	192,452.7
0.03	3.59	60.9291	517.01	1.0000	182,478.6	9,984.2	192,462.8
0.05	3.52	60.9292	522.62	1.0000	182,469.7	10,002.9	192,472.6
0.08	3.41	60.9293	531.40	1.0000	182,451.4	10,035.2	192,486.6
0.10	3.34	60.9293	537.52	1.0000	182,441.9	10,053.6	192495.5
0.15	3.16	60.9295	553.84	1.0000	182,414.9	10,101.0	192515.9
0.20	2.98	60.9296	571.83	1.0000	182,381.3	10,152.0	192533.3

r	Retailer Driven Model							Joint Coordination Model					$PI_{Ret.Joint}$ (%)	$PI_{Sup.Joint}$ (%)
	n	p_b	Q	k	$\prod_b$	$\prod_v$	$\prod_{ch}$	n	p_b	Q	k	$\prod_{ch}$		
0.01	2.82	61.26541	414.35	1.0000	96,786.76	95,613.9	192,400.7	Locally Infeasible					N/A	N/A
0.03	2.76	61.26541	422.89	1.0000	96,803.45	95,591.6	192,395.1	5.76	52.6832	340.14	1.0000	198,807.2	3.33	3.30
0.05	2.71	61.26541	431.80	1.0000	96,819.15	95,570.2	192,389.3	5.66	52.6844	345.34	1.0000	198,789.1	3.33	3.29
0.08	2.62	61.26541	445.88	1.0000	96,840.61	95,539.5	192,380.1	5.52	52.6863	353.47	1.0000	198,760.7	3.32	3.27
0.10	2.56	61.26541	455.78	1.0000	96,853.41	95,520.2	192,373.6	5.42	52.6876	359.11	1.0000	198,740.8	3.31	3.25
0.15	2.42	61.26541	482.60	1.0000	96,879.66	95,476.3	192,356.0	5.17	52.6911	374.11	1.0000	198,687.5	3.29	3.22
0.20	2.28	61.26541	512.76	1.0000	96,896.34	95,440.0	192,336.3	4.93	52.6949	390.52	1.0000	198,628.4	3.27	3.18

Table 5.6 Sensitivity Analysis for the index of the defective rate (r)

p_o	Supplier Driven Model						
	n	p_b	Q	k	$\prod_b$	$\prod_v$	$\prod_{ch}$
15.00	3.51	60.92919	521.30	0.8427	179,524.5	13,333.3	192,857.8
20.00	3.51	60.92919	521.65	0.8817	180,128.8	12,538.4	192,667.2
25.00	3.51	60.92919	522.07	0.9311	181,027.2	11,503.4	192,530.6
30.00	3.52	60.92919	522.59	0.9962	182,386.4	10,086.4	192,472.8
40.00	3.52	60.92919	522.62	1.0000	182,469.7	10,002.9	192,472.6
48.00	3.52	60.92919	522.62	1.0000	182,469.7	10,002.9	192,472.6
55.00	3.52	60.92919	522.62	1.0000	182,469.7	10,002.9	192,472.6
60.00	3.52	60.92919	522.62	1.0000	182,469.7	10,002.9	192,472.6

p_o	Retailer Driven Model							Joint Coordination Model					$PI_{Sup.Joint}$ (%)	$PI_{Ret.Joint}$ (%)
	n	p_b	Q	k	$\prod_b$	$\prod_v$	$\prod_{ch}$	n	p_b	Q	k	$\prod_{ch}$		
15.00	2.70	61.26562	431.54	0.8445	93,769.21	98,994.1	192,763.3	5.65	52.6849	344.79	0.8129	199,428.3	3.41	3.46
20.00	2.70	61.26552	431.65	0.8834	94,531.78	98,045.4	192,577.2	5.65	52.6848	345.07	0.8564	199,116.8	3.35	3.40
25.00	2.70	61.26545	431.75	0.9326	95,498.07	96,946.3	192,444.4	5.65	52.6846	345.29	0.9148	198,887.0	3.30	3.35
30.00	2.71	61.26541	431.80	0.9974	96,768.48	95,620.9	192,389.4	5.66	52.6844	345.34	0.9982	198,789.1	3.28	3.33
40.00	2.71	61.26541	431.80	1.0000	96,819.15	95,570.2	192,389.3	5.66	52.6844	345.34	1.0000	198,789.1	3.28	3.33
48.00	2.71	61.26541	431.80	1.0000	96,819.15	95,570.2	192,389.3	5.66	52.6844	345.34	1.0000	198,789.1	3.28	3.33
55.00	2.71	61.26541	431.80	1.0000	96,819.15	95,570.2	192,389.3	5.66	52.6844	222.17	1.0000	198,789.1	3.28	3.33
60.00	2.71	61.26541	431.80	1.0000	96,819.15	95,570.2	192,389.3	5.66	52.6844	222.17	1.0000	198,789.1	3.28	3.33

Table 5.7 Sensitivity Analysis for the external procurement price (p_0)

c_v/c_b	Supplier Driven Model						
	n	p_b	Q	k	$\prod_b$	$\prod_v$	$\prod_{ch}$
5.00	4.39	60.9286	657.06	1.0000	183,021.0	8,054.2	191,075.2
10.00	5.01	60.9282	866.47	1.0000	183,635.4	5,291.2	188,926.6
20.00	5.39	60.9282	1,178.90	1.0000	184,312.4	1,423.3	185,735.7
30.00	3.54	60.9283	1,803.97	1.0000	182,517.6	332.6	182,850.2
40.00	2.57	60.9285	2,477.75	1.0000	180,497.0	-755.3	179,741.7
50.00	1.99	60.9286	3,200.65	1.0000	178,386.8	-1,959.7	176,427.1

c_v/c_b	Retailer Driven Model							Joint Coordination Model					$PI_{Sup.Joint}$ (%)	$PI_{Ret.Joint}$ (%)
	n	p_b	Q	k	$\prod_b$	$\prod_v$	$\prod_{ch}$	n	p_b	Q	k	$\prod_{ch}$		
5.00	3.83	61.26541	431.80	1.0000	96,819.15	94,676.4	191,495.5	7.73	52.71658	331.70	1.0000	198,124.7	3.69	3.46
10.00	5.41	61.26541	431.80	1.0000	96,819.15	93,412.3	190,231.4	10.65	52.75914	318.80	1.0000	197,160.3	4.36	3.64
20.00	7.66	61.26541	431.80	1.0000	96,819.15	91,624.6	188,443.7	14.82	52.81398	306.50	1.0000	195,767.8	5.40	3.89
30.00	9.38	61.26541	431.80	1.0000	96,819.15	90,252.8	187,071.9	18.08	52.8524	299.36	1.0000	194,684.9	6.47	4.07
40.00	10.84	61.26541	431.80	1.0000	96,819.15	89,096.4	185,915.5	20.87	52.88265	294.19	1.0000	193,764.8	7.80	4.22
50.00	12.11	61.26541	431.80	1.0000	96,819.15	88,077.6	184,896.7	10.65	52.75914	318.80	1.0000	197,160.3	11.75	6.63

Table 5.8. Sensitivity analysis for the ratio of supplier's setup cost to retailer's ordering cost c_v/c_b,

CHAPTER 6

CONCLUSION AND FUTURE DIRECTIONS

6.1 Summary and Conclusion

This research developed several analytical models for typical supply chain situations to help inventory decision-makers who need mathematical models to grasp the big picture of supply chain inventory problems before making executive decisions. Additionally, we derived closed form solutions for each model and found several managerial insights from our models through sensitivity analysis of numerical examples.

In Chapter 3, we present two forms of cost-profit model under individual decision model and coordinated policy in a two-stage supply chain when a supplier faces capacity shortage and has an option for emergency procurement to meet the market demand. We propose a supply chain coordination model that under the coordinated policy with outsourcing, the retailer and the supplier can determine the optimal ratio of outsourcing to an external supplier with consideration of all the cost factors, the quality levels of both supplier and external supplier, and external procurement price. We derive the optimal conditions when the supplier may go for an emergency supply to maximize the total channel profit for a specific outsourcing price in both deterministic and stochastic environments.

The results of our analysis show that the profit of the whole supply chain system under the coordinated policy is much larger than that under the individual decision model. Our numerical example also show that under the coordinated decision making policy, the entire supply chain benefits by outsourcing for a certain range of the outsource price and the acceptable level of the product quality. Our investigations are highlighted below:

- formulation of a two-stage supply chain coordination model under quality uncertainty and shortage, which maximize the total profit of the supply chain,
- determination of the optimal ratio of external procurement under shortage with considerations of product quality risk in a supply chain coordination model.

In Chapter 4, we present an integrated production-inventory-marketing model for a two-stage supply chain is presented. It is assumed the demand rate is an iso-elastic function of the selling price. Then, the total cost functions are developed, and the optimal values of the selling price, order quantity and number of shipments are obtained under independent and joint optimizations. A numerical example and the sensitivity analysis are done, and the main following findings are attained.

The optimal selling price under independent optimization is higher than its value under joint optimization, and so coordination increases the demand- and profit of the supply chain. Furthermore, supply chain’s members can get more profits from coordination in a competitive market in which sensitivity of the demand to price is high. Another finding is that increasing the unit purchasing price, which is paid by the retailer to the supplier leads to increase in the percentage improvement. Finally, coordination of the supply chain is less attractive when the supplier's setup cost is considerably higher than the retailer's ordering cost. Future research can be done for multi-suppliers and multi-retailers supply chains. In addition, the model can be developed for imperfect products and also deteriorating items. Some future research topics may be of interest here. One is to apply multi-supplier policy when considering bounded selling price. An investigation into the sensitivity of different inventory policies for a coordinated supply chain, and an analysis of the lead-time effects and batches of different sizes are two other subjects in the works.

Finally, in Chapter 5 we sought to provide implementable contractual arrangements to coordinate the channel with the consideration of supply uncertainty. We first develop a general framework that incorporates supply uncertainty. Based on the general framework, we further develop supply contracts under conditions of supply uncertainty and deterministic demand with an infinite planning horizon.

The findings reported clearly show that ignoring incentive conflicts and supply information issues can lead to undesirable behavior. We proposed a model for how lot size, quality level, and transactions should be structured to help reduce supply chain inefficiency due to individual incentives and private information. We examined the impact of both supply and demand uncertainty on channel performance and proposed a consignment contract to help coordinate the channel. The problems investigated in this chapter are summarized below:

- a general framework of supply chain contract design under supply uncertainty,
- the design of optimal cost-sharing contracts under supply uncertainty and continuous deterministic demand,
- an exploration of the value of supply uncertainty information.

6.2 Managerial Insights

In this section, we will discuss the potential managerial implications of our findings, and explicitly address the management decisions that may be affected by using the insights for the industrial practice from our studies.

We believe that our models and the insights that we obtained from the three research projects are helpful for applications and implementations in real-life. In this dissertation, the emphasis has been on understanding the implications of supply chain coordination and competition on supply chain operations planning. More specifically, we focused on operational decision making in a supply chain with limited inventory capacity and allowed stockout under price and quality competition. We provided insights from literature survey, analytical models, and sensitivity analysis to better understand the performance consequences of the supply chains and to find effective ways of improving it. In practice, many other issues also play a role such as the negotiation power between the external supplier and the supplier. However, we believe that the results and insights that we obtained in the various research studies of this dissertation can contribute to solving the broader real-life problems related to the planning and control of outsourced supply chains.

Strategic outsourcing decisions in the literature have been mainly motivated by the transaction cost theory, resource based view theory, and the focus on core competences.

Based on our research, in which we have shown some operational implications of outsourcing under quality uncertainty, we believe that one should also consider these issues when taking the strategic outsourcing decision. Consideration of the operational implications of outsourcing when taking the strategic outsourcing decision will lead to a different and better estimate of the transaction costs and probably to a different strategic outsourcing decision.

Our research also contributes to management practitioners by providing some managerial implications of supply chain competition and coordination with emergency supply option under shortage. Even though the insufficient production capacity of a supplier may result in lost sales, the supplier can make an optimal decision from the standpoint of a supply chain optimization, rather than a marketing perspective. As the supplier coordinates with other participants in a supply chain and procures the items from external sources, the total net profit of the entire supply chain may be improved by external procurement. The demand of the retailer follows a stochastic distribution and is assumed to be a normal distribution in the numerical example. However, in practice, the demand of the retailer in the supply chain system may abide by an irregular movement. So, we shall consider that the complex relationship between cost and profit under that demand and order cost might follow other distributions in the future.

For the supply chain coordination models under quality uncertainty in Chapter 3, we distinguish our work from theirs and contribute to this literature on two main dimensions. First, we deliver the optimal ratio of external procurement for capacity shortage in a two-stage supply chain in a deterministic environment. Second, we explicitly dealt with uncertain supply conditions with imperfect quality and its dynamic interplay with outsourcing decisions. In other words, we specifically investigate how changes in the quality of product may affect capacity and outsourcing decisions.

This research also gave decision-makers insights into how to implement the situation of demand uncertainty and shortage into a mathematical model in a two-stage supply chain and showed them what differences these proposed analytical models make as opposed to the traditional models. Even though each analytical model is simple but each provided an effective overall view of the supply chain system by abstracting the features of a supply chain system as a set of parameterized functions. We implemented time-sensitive shortages into an inventory model under emergency replenishment.

This research has roots in applied probability, optimization, inventory theory, game theory, and economics. We develop optimization models aimed at minimizing entity/system costs or maximizing entity/system profits for the purpose of supply chain coordination and optimal contract design. Our focus is to formulate more realistic demand functions including price and quality factors. From the methodology perspective, our optimization models are all stochastic modeling problems that require unconstrained/constrained dynamic or nonlinear optimization techniques, depending on the factors considered.

6.3 Future Directions

This dissertation investigates supply chain coordination models under quality uncertainty and supply chain competition models through contracts. To the best of our knowledge, there is no previous work on supply chain coordination and competition models with quality uncertainty considerations. Our work seeks to fill this gap.

First, the supply chain we consider in this work consists of a single retailer and a single supplier. A direct extension of this study is to look into a network of suppliers and understand the design of external quality cost sharing contracts for product failure such as recalls with multiple suppliers.

Second, the mechanisms for coordination need to be studied in detail. The coordination mechanisms can further be of different sub-types. To coordinate the whole supply chain, the aggregation of the impact of all coordination mechanisms on the performance of supply chain is required. Various combinations may be explored to achieve much higher business goals with the help of simulation.

Third, supply chain contracts have proved to coordinate single period supply chains. Research is required to explore the utility of contracts in multi-period cases. In multi-period models, the supply chain members are more exposed to the uncertainty as they are dealing with supply chain members frequently under uncertainty issues. How various coordination mechanisms can be allied in multi-period problems as well as how we can evaluate a coordination mechanism in such case would be potentially good research questions.

Fourth, quality incentive, reward, or compensation programs have long been employed for the purpose of quality control in numerous industries. We may design a quality-compensation contract as an incentive scheme for supply chain coordination in the future. For example, electronic appliances, automobile manufacturers compensate their retailers or dealers for the quality failure of their products using a warranty program (Smith, 1997; Balachandran and Radhakrishnan, 2005). Prior studies on quality compensation advocate that the supplier and resellers can achieve higher efficiency by sharing quality failure costs in the entire supply chain (Reyniersand Tapiero, 1995; Baiman et al., 2000; Baiman et al., 2001; Balachandran and Radhakrishnan, 2005). We show that a manufacturer not only raises its efficiency with quality compensation granted to the retailer, but also fully coordinates the supply chain by carefully choosing the amount of the compensation and designing quality-compensation structure for supply chain coordination.

Finally, very few studies quantify risk or uncertainty in supply chains. The Bullwhip effect has extensively been discussed on the demand side in the literature. Actually, there can be many variations seen in supply chain like supply uncertainty, delay in delivery having cascading effect as we go downwards in the supply chain or network, which is similar to the order variation in Bullwhip effect. We think how a supply chain can help in mitigating such uncertainties is one of the important research issues in the future.

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APPENDIX

A. Sufficient conditions for a local maximum in the objective functions in Ch. 3 Deterministic model and Ch. 4 Price dependent demand model.

For the deterministic demand model in chapter 3, it is sufficient to show that the objective function $\Pi_{ch}(n,Q,k)$ is concave for *n*, *Q*, *k* >0. The Hessian matrix is given as follows:

H (*n*, *Q*, *k*) =

$$\{\{-\frac{2bdD}{n^3Q},-\frac{1}{2}\mathrm{hv}(1-\frac{D}{P})-\frac{bdD}{n^2Q^2},0\},$$

$$\left\{-\frac{1}{2}\mathrm{hv}\left(1-\frac{D}{P}\right)-\frac{bdD}{n^2Q^2},-\frac{2bdD}{nQ^3}-\frac{2cD(b+(1-b)k)}{Q^3(1-r)},\frac{(1-b)cD}{Q^2(1-r)}\right\},$$

$$\{0,\frac{(1-b)cD}{Q^2(1-r)},-2(1-b)D\mathrm{g}0\}\}$$

We see $H_{11} < 0$, and *Det* (H) with the system parameters used in the examples, we obtain the determinant of the Hessian matrix numerically as follows :

$$\mathrm{Det}[\{\{-\frac{320.D}{n^3Q},-\frac{5}{6}-\frac{160.D}{n^2Q^2},0\},$$

$$\left\{-\frac{5}{6}-\frac{160.D}{n^2Q^2},-\frac{1684210.52(0.8+0.8k)}{Q^3}-\frac{320.D}{nQ^3},\frac{673684.21}{Q^2}\right\},$$

$$\{0,\frac{673684.21}{Q^2},-1.99D\}\}]$$

$$\frac{1}{n^4Q^5}D\big(-153599.97D^2Q + 533.33Dn^2Q^3 + 1.38n^4Q^5 + n(1.45\times 10^{14} + D(-8.62\times 10^8 - 8.62\times 10^8 k)Q)\big) < 0$$

Since the all the members of the principal diagonal of the Hessian matrix are negative or zero, we conclude that the objective function is a concave function and has a local maximum.

In the same way we did above, for the price dependent demand model in chapter 4, it is sufficient to show that the objective function $\Pi_{ch}(n, p_b, Q, k)$ is concave for $n, p_b, Q, k > 0$ n, Q, k >0. The Hessian matrix is given as follows:

$$H\left(n,p_b,Q,k\right) =$$

$$\{\{-\frac{2abdp^{-C}}{n^3Q},-\frac{abCdp^{-1-C}}{n^2Q}-\frac{aC\mathrm{hv}p^{-1-C}Q}{2P},-\frac{1}{2}\mathrm{hv}(1-\frac{ap^{-C}}{P})-\frac{abdp^{-C}}{n^2Q^2},0\},$$

$$\left\{-\frac{abCdp^{-1-C}}{n^2Q}-\frac{aC\mathrm{hv}p^{-1-C}Q}{2P},a(1-b)(-1-C)C(1-k)(g-\mathrm{g0}k)p^{-2-C}-a(1-C)C(b+(1-b)k)p^{-1-C}\right.$$

$$+a(1-b)(-1-C)Ckp^{-2-C}\mathrm{p0}+ab(-1-C)Cp^{-2-C}q+\frac{ab(-1-C)Cdp^{-2-C}}{nQ}+\frac{a(-1-C)C\mathrm{hv}(2-n)p^{-2-C}Q}{2P}$$

$$+\frac{ac(-1-C)C(b+(1-b)k)p^{-2-C}}{Q(1-r)},\frac{aC\mathrm{hv}(2-n)p^{-1-C}}{2P}-\frac{abCdp^{-1-C}}{nQ^2}$$

$$-\frac{acC(b+(1-b)k)p^{-1-C}}{Q^2(1-r)},-a(1-b)C\mathrm{g0}(1-k)p^{-1-C}-a(1-b)C(g-\mathrm{g0}k)p^{-1-C}+a(1-b)(1-C)p^{-C}$$

$$\left.+a(1-b)Cp^{-1-C}\mathrm{p0}+\frac{a(1-b)cCp^{-1-C}}{Q(1-r)}\right\},$$

$$\left\{-\frac{1}{2}\mathrm{hv}\left(1-\frac{ap^{-C}}{P}\right)-\frac{abdp^{-C}}{n^2Q^2},\frac{aC\mathrm{hv}(2-n)p^{-1-C}}{2P}-\frac{abCdp^{-1-C}}{nQ^2}-\frac{acC(b+(1-b)k)p^{-1-C}}{Q^2(1-r)},-\frac{2abdp^{-C}}{nQ^3}\right.$$

$$\left.-\frac{2ac(b+(1-b)k)p^{-C}}{Q^3(1-r)},\frac{a(1-b)cp^{-C}}{Q^2(1-r)}\right\},$$

We find $H_{11} < 0$, and *Det* (H) with the system parameters used in the examples, we obtain the determinant of the Hessian matrix numerically as follows :

$$Det\{\{-\frac{40000000000b}{n^3p^{2.35}Q}, -\frac{5}{2}(1-\frac{100000000}{p^{2.35}P}) - \frac{20000000000b}{n^2p^{2.35}Q^2}, -\frac{4.7\times10^{10}b}{n^2p^{3.35}Q} - \frac{5.875\times10^8Q}{p^{3.35}P}, 0\},$$

$$\left\{-\frac{5}{2}\left(1-\frac{100000000}{p^{2.35}P}\right) - \frac{20000000000b}{n^2p^{2.35}Q^2}, -\frac{1.684210526315789\times10^{10}}{p^{2.35}Q^3} - \frac{40000000000b}{np^{2.35}Q^3}, \frac{5.875\times10^8(2-n)}{p^{3.35}P}\right.$$

$$\left. -\frac{1.978947368421052\times10^{10}}{p^{3.35}Q^2} - \frac{4.7\times10^{10}b}{np^{3.35}Q^2}, 0\right\},$$

$$\left\{-\frac{4.7\times10^{10}b}{n^2p^{3.35}Q} - \frac{5.875\times10^8Q}{p^{3.35}P}, \frac{5.875\times10^8(2-n)}{p^{3.35}P} - \frac{1.978947368421052\times10^{10}}{p^{3.35}Q^2} - \frac{4.7\times10^{10}b}{np^{3.35}Q^2}, \frac{3.1725\times10^8}{p^{3.35}}\right.$$

$$\left. -\frac{7.8725\times10^8q}{p^{4.35}} - \frac{6.629473684210526\times10^{10}}{p^{4.35}Q} - \frac{1.5745\times10^{11}b}{np^{4.35}Q} - \frac{1.968125\times10^9(2-n)Q}{p^{4.35}P}, 0\right\},$$

$$\{0,0,0,0\}\}$$

Finally, we find *Det* (H) = 0 running mathematica. We conclude that the Hessian matrix of this stationary point is negative definite and the stationary point is a local maximum.

B. Optimal solution, p_b^* of the supplier driven model

$$p_b^* =$$

$$\left\{p = \left(\frac{0.1666666667\left(\left(108.\,L\,C + 54.\,L + 6.\,\sqrt{-\frac{1.\,\left(48.\,C^3 q^3 A^2 - 324.\,C^3 L^2 + 243.\,C L^2 + 81.\,L^2\right)}{C-1.}}\right) A^2 (C-1.)^2\right)^{1/3}}{(C-1.)\,A} + \frac{2.\,C\,q\,A}{\left(\left(108.\,L\,C + 54.\,L + 6.\,\sqrt{-\frac{1.\,\left(48.\,C^3 q^3 A^2 - 324.\,C^3 L^2 + 243.\,C L^2 + 81.\,L^2\right)}{C-1.}}\right) A^2 (C-1.)^2\right)^{1/3}}\right)^2\right\}, \left\{p = \left(\right.\right.$$

$$- \frac{0.08333333333\left(\left(108.\,L\,C + 54.\,L + 6.\,\sqrt{-\frac{1.\,\left(48.\,C^3 q^3 A^2 - 324.\,C^3 L^2 + 243.\,C L^2 + 81.\,L^2\right)}{C-1.}}\right) A^2 (C-1.)^2\right)^{1/3}}{(C-1.)\,A} - \frac{1.\,C\,q\,A}{\left(\left(108.\,L\,C + 54.\,L + 6.\,\sqrt{-\frac{1.\,\left(48.\,C^3 q^3 A^2 - 324.\,C^3 L^2 + 243.\,C L^2 + 81.\,L^2\right)}{C-1.}}\right) A^2 (C-1.)^2\right)^{1/3}}$$

$$\left.\left. + 0.8660254038\,I\left(\frac{0.1666666667\left(\left(108.\,L\,C + 54.\,L + 6.\,\sqrt{-\frac{1.\,\left(48.\,C^3 q^3 A^2 - 324.\,C^3 L^2 + 243.\,C L^2 + 81.\,L^2\right)}{C-1.}}\right) A^2 (C-1.)^2\right)^{1/3}}{(C-1.)\,A} - \frac{2.\,C\,q\,A}{\left(\left(108.\,L\,C + 54.\,L + 6.\,\sqrt{-\frac{1.\,\left(48.\,C^3 q^3 A^2 - 324.\,C^3 L^2 + 243.\,C L^2 + 81.\,L^2\right)}{C-1.}}\right) A^2 (C-1.)^2\right)^{1/3}}\right)\right)^2\right\}, \left\{p\right.$$

$$= \left(- \frac{0.08333333333\left(\left(108.\,L\,C + 54.\,L + 6.\,\sqrt{-\frac{1.\,\left(48.\,C^3 q^3 A^2 - 324.\,C^3 L^2 + 243.\,C L^2 + 81.\,L^2\right)}{C-1.}}\right) A^2 (C-1.)^2\right)^{1/3}}{(C-1.)\,A} - \frac{1.\,C\,q\,A}{\left(\left(108.\,L\,C + 54.\,L + 6.\,\sqrt{-\frac{1.\,\left(48.\,C^3 q^3 A^2 - 324.\,C^3 L^2 + 243.\,C L^2 + 81.\,L^2\right)}{C-1.}}\right) A^2 (C-1.)^2\right)^{1/3}}\right.$$

$$\left.\left. - 0.8660254038\,I\left(\frac{0.1666666667\left(\left(108.\,L\,C + 54.\,L + 6.\,\sqrt{-\frac{1.\,\left(48.\,C^3 q^3 A^2 - 324.\,C^3 L^2 + 243.\,C L^2 + 81.\,L^2\right)}{C-1.}}\right) A^2 (C-1.)^2\right)^{1/3}}{(C-1.)\,A} - \frac{2.\,C\,q\,A}{\left(\left(108.\,L\,C + 54.\,L + 6.\,\sqrt{-\frac{1.\,\left(48.\,C^3 q^3 A^2 - 324.\,C^3 L^2 + 243.\,C L^2 + 81.\,L^2\right)}{C-1.}}\right) A^2 (C-1.)^2\right)^{1/3}}\right)\right)^2\right\}, \{p = 0.\}$$

C. Mathematical Programming Codes (Maple/Matlab/LINGO)

CH 3. LINGO CODES for Nonlinear Optimization

```
!Model 0 - General Model (OLD);
!Max = (0.8*10000*45)+(0.2*10000*K*45)-
((0.8*10000+0.2*10000*K)*80)/(Q*(1-0.05))-(Q*6*(1-0.05))/2-
0.8*10000*30-(0.8*10000*200)/(N*Q)-((Q*5)/2)*((2-N)*(10000/15000)+(N-
1))-(1-0.8)*10000*K*48-(1-0.8)*10000*(1-K)*(5-3*K);

!General Model with parameters v2 (BEST ORIGINAL);
Max = (b*10000*45)+((1-b)*10000*K*45)-((b*10000+(1-
b)*10000*K)*80)/(Q*(1-r))-(Q*6*(1-r))/2-b*10000*30-
(b*10000*200)/(N*Q)-((Q*5)/2)*((2-N)*(10000/15000)+(N-1))-(1-
b)*10000*K*U-(1-b)*10000*(1-K)*(5-3*K);

!b=beta;
b = 1-r*(1-K);
r = 0.05;
!N=3;
U = 48;
D = 10000;



!QR= Retailer Driven Model;
!Q = (1/(1-r))*@SQRT((2*80*10000*(b+K*(1-b))/6));
!Q = (1/(1-r))*@SQRT((2*80*D*(b+K*(1-b))/6));

!QS= Supplier Driven Model;
!Q =(@SQRT((2*b*10000*200)/(5*((2-N)*(10000/15000)+(N-1)))));
!Q =(@SQRT((2*b*D*200)/(5*((2-N)*(D/15000)+(N-1)))));

!QJ= Joint Coordination Model;
!Q = (@SQRT((2*(N*80*10000*(b+K*(1-b))+b*10000*200))/((1-r)*N*((1-
0.05)*(6+5*((2-N)*(10000/15000)+(N-1)))))));
Q = (@SQRT((2*(N*80*D*(b+K*(1-b))+b*D*200*(1-r)))/((1-r)*N*((6*(1-
0.05)+5*((2-N)*(D/15000)+(N-1)))))));

K >= 0;
K <= 1;
Q > 0;
N*Q <= 10000;
!N = 3;
N >= 1;
!K = 0;
!K = 1;
```

CH 4. LINGO CODES for Nonlinear Optimization

CHAPTER 4 CODES

```
!Model 0 - General Model (OLD);
!Max = (0.8*10000*45)+(0.2*10000*K*45)-
((0.8*10000+0.2*10000*K)*80)/(Q*(1-0.05))-(Q*6*(1-0.05))/2-
0.8*10000*30-(0.8*10000*200)/(N*Q)-((Q*5)/2)*((2-N)*(10000/15000)+(N-
1))-(1-0.8)*10000*K*48-(1-0.8)*10000*(1-K)*(5-3*K);


!General Model with parameters v2 (BEST ORIGINAL);
!Max = (b*10000*45)+((1-b)*10000*K*45)-((b*10000+(1-
b)*10000*K)*80)/(Q*(1-r))-(Q*6*(1-r))/2-b*10000*30-
(b*10000*200)/(N*Q)-((Q*5)/2)*((2-N)*(10000/15000)+(N-1))-(1-
b)*10000*K*U-(1-b)*10000*(1-K)*(5-3*K);


!chapter 4. price dependent model;
Max = (b*D*p)+((1-b)*D*K*p)-((b*D+(1-b)*D*K)*80)/(Q*(1-r))-(Q*6*(1-
r))/2-b*D*30-(b*D*200)/(N*Q)-((Q*5)/2)*((2-N)*(D/10000)+(N-1))
-(1-b)*D*K*U-(1-b)*D*(1-K)*(5-3*K);
!b=beta;
!b = 0.8;
b=1-r*(1-K);
r = 0.05;
!!!!!!!!!!!!!!!!;
!Retailers OPT conditions;
!N = 5;
!p = 63.2964;
!!!!!!!!!!!!!!!!!!;
!!!!!!!!!!!!!!!!;
!Suppliers OPT conditions;
!N = 8;
!p = 63.0033;
!!!!!!!!!!!!!!!!!!;
!!!!!!!!!!!!!!!!;
!Joint Coordination OPT conditions;
!N = 45;
!p = 54.3473;
!!!!!!!!!!!!!!!!!!;
U = 48;
!U = 50;
D = a*(p)^(-c);
! Indvidual/Suppliers/Retailers/ Model;
a = 100000000;
!p = 49.5913;
!p = 53.29;
c = 2.35;
```

```
!c = 1.60;  !K = 0
!c = 1.55;  !K = 0

!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!;
! retailer's p;
!p = ;
!(b+K*(1-b))*a*(p)^(-c)-(b+K*(1-b))*a*(c)*((p)^(-c-1))*(p-35)-(b+K*(1-
b))*(a*(-c)*(p)^(-c-1)*(80)*(6))/(@sqrt((b+K*(1-b))*2*a*((p)^(-
c))*(80)*(6)))=0;

! Supplier's p;
(b+K*(1-b))*a*((p)^(-c))-(b+K*(1-b))*a*(c)*((p)^(-c-1))*(p-
35)+(c+0.5)*((p)^(-c-1.5))*(b+K*(1-b))*(@sqrt(a*5)*80*(((5)*((2-
N)*(w)+(N-1)))+6))/(@sqrt(2*200)*(1-r))+(c+0.5)*((p)^(-c-1.5))*(6*(1-
r)*@sqrt(2*a*200))/(2*@sqrt((((5)*((2-N)*(w)+(N-1)))+6)))=0;
!p = ;

! Joint Model's p
!p = ;
!(b+K*(1-b))*a*((p)^(-c))-(b+K*(1-b))*a*(c)*((p)^(-c-1))*(p-30)-
(b+K*(1-b))*(a*(-c)*(p)^(-c-1)*((200/N)+80)*(((5)*((2-N)*(w)+(N-
1)))+6))/(@sqrt((b+K*(1-b))*2*a*((p)^(-c))*((200/N)+80)*((5)*((2-
N)*(w)+(N-1))+6)))=0;

!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!;


!Joint Coordination Model;
!a = 2000000;
!p = 69.31;
!c = 1.25;

!retail price;
!w = D/P;
w = 1;
!Demand = a*exp(-C);
!a - scale factor;
!b - price elasticity;
K >= 0;
K <= 1;
Q > 0;
!N*Q <= a*((p)^(-c));
!N*Q <= 10000;
!N = 3;
!N = 4;
!N = 5;
!N = 6;
!N = 7;
!N = 8;
!N = 9;
!N = 10;

N >= 1;
!K = 0;
!K = 1;

!Demand=a*(pb)^(-c);
```

```
!retail price pb1 (Ind, Retailer, Supplier are same);
!retail price pb2 (joint Coordination Model);

!QR= Retailer Driven Model;
!Q = (1/(1-r))*@SQRT((2*80*10000*(b+K*(1-b))/6));
!Q = (1/(1-r))*@SQRT((2*80*D*(b+K*(1-b))/6));

!QS= Supplier Driven Model;
!Q =(@SQRT((2*b*10000*200)/(5*((2-N)*(10000/15000)+(N-1)))));
Q =(@SQRT((2*b*D*200)/(5*((2-N)*(D/15000)+(N-1)))));

!QJ= Joint Coordination Model;
!Q = (@SQRT((2*(N*80*10000*(b+K*(1-b))+b*10000*200))/((1-r)*N*((1-
0.05)*(6+5*((2-N)*(10000/15000)+(N-1)))))));
!Q = (@SQRT((2*(N*80*D*(b+K*(1-b))+b*D*200*(1-r)))/((1-r)*N*((6*(1-
0.05)+5*((2-N)*(D/15000)+(N-1)))))));


N*Q <= a*((p)^(-c));
```

VITA

Changhyun Kim was born in Taegu, South Korea. After completing her work at Deokwon High School in 1991, he went onto Korea University in Seoul, South Korea where he studied statistics and business administration and received her Bachelor of Sciences in 1998. Between 1998 and 2000 he studied industrial engineering at the University of Pohang Science and Technology in Pohang, South Korea. He received a Master of Sciences in industrial engineering there. For the next five years he pursued a professional career in Six Sigma and ERP consulting in Seoul, South Korea, then he moved to Tempe, Arizona. He received the Master of Sciences in industrial engineering from Arizona State University in 2008, and Doctor of Philosophy in business administration with concentration on decision sciences from Drexel University in 2016.