SUPPLY CHAIN OPTIMIZATION

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Preface

The title of this edited book, *Supply Chain Optimization*, aims to capture a segment of recent research activity in supply chain management. This research area focuses on applying optimization techniques to supply chain management problems. While the general area of supply chain management research is broader than this scope, our intent is to compile a set of research papers that capture the use of state-of-the-art optimization methods within the field. Several researchers who initially expressed interest in contributing to this effort also expressed concerns that their work might not contain a sufficient degree of optimization. Others were uncertain as to whether the problems they proposed covered a broad enough scope in order to be considered as supply chain research. Our position has been that research that rigorously models elements of supply chain operations with a goal of improving supply chain performance (or the performance of some segment thereof) would fit under the umbrella of *supply chain optimization.* We therefore sought high-quality works from leading researchers in the field that fit within this general scope. We are quite pleased with the result, which has brought together a diverse blend of research topics and novel modeling and solution approaches for difficult classes of supply chain operations, planning, and design problems.

The book begins by taking an in-depth look at the role of information in supply chains. "Information Centric Optimization of Inventories in Capacitated Supply Chains: Three Illustrative Examples," by S. Gavirneni, considers how firms can best take advantage of the vast amounts of data available to them as a result of advanced information technologies. The author considers how capacity, inventory, information, and pricing influence supply chain performance, and provides strategies for leveraging information to enhance performance.

The second chapter, "An Analysis of Advance Booking Discount Programs between Competing Retailers," by K.F. McCardle, K. Rajaram, and C.S. Tang, considers a new mechanism for eliciting information from customers. The authors employ a strategy of providing discounts to customers who reserve a product in advance of a primary selling season. This information can be used by a supplier to reduce the uncertainty faced in the selling season, and the authors explore conditions under which equilibrium behavior among two retailers results in applying such a strategy.

In Chapter 3, A.M. Newman, C.A. Yano, and P.M. Kaminsky study a class of combined transportation and inventory planning problems faced by third-party logistics providers, who are becoming increasingly prevalent players in supply chains. This chapter, "Third Party Logistics Planning with Routing and Inventory Costs," considers route selection for full-truckload carriers contracted by manufacturers for repeated deliveries. The logistics provider faces a tradeoff between providing better service to customers through more frequent deliveries versus achieving the most cost-effective delivery pattern from a transportation cost perspective.

E. Bish addresses capacity investment and pricing decisions under demand uncertainty in Chapter 4, "Optimal Investment Strategies for Flexible Resources, Considering Pricing." While a number of past works have considered the problem of investing in flexible resources under uncertainty, this work explores how a firm's ability to set prices influences the value of resource flexibility. This work provides interesting insights on how pricing power can alter flexible resource capacity investment under different product demand correlation scenarios.

In "Multi-Channel Supply Chain Design in B2C Electronic Commerce" (Chapter 5), W.K. Chiang and D. Chhajed provide an interesting look at the challenges manufacturers face in simultaneously selling via traditional retail and direct on-line sales channels. Under a variety of scenarios and using a game-theoretic modeling approach, they provide insights on channel design strategy for both centralized and decentralized supply chains, when consumers have different preferences for direct and retail channels.

While a vast amount of literature applies game-theoretic modeling approaches to supply chain problems, J.J. Bartholdi III and E. Kemahlıoğlu-Ziya provide an innovative new model for sharing gains from cooperation in Chapter 6 ("Using Shapley Value to Allocate Savings in a Supply Chain"). They consider original equipment manufacturers (OEMs) with varying degrees of power who can influence whether a contract supplier may pool upstream inventories of common goods for multiple OEMs. By using the concept of Shapley value to create a mechanism for sharing the gains by allowing inventory pooling, the authors show that this method induces supply chain coordination and leads to a stable solution, although the resulting solution may still be perceived as "unfair" by some participants.

M.S. Pangburn and E. Stavrulaki consider an economic model of combined pricing, location, and capacity setting decisions in Chapter 7, "Service Facility Location and Design with Pricing and Waiting-Time Considerations." This model accounts for contexts where customers are sensitive to both transportation time and service waiting time that results from congestion effects. Customers will choose a facility if the associated utility (which accounts for distance and waiting-time costs) exceeds some reservation value. The authors address the implications of non-homogeneous customers, as well as equilibrium competitive behavior with two facilities.

Chapter 8 considers a recently emerging focus in supply chain design, where the robustness of the design under uncertainty is critical. In "A Conceptual Framework for Robust Supply Chain Design under Demand Uncertainty," Y. Mo and T.P. Harrison propose a modeling approach for addressing demand uncertainty in the design phase. The authors propose different robustness measures that incorporate various elements of risk and discuss different solution strategies, including the use of stochastic programming and sampling-based methods.

Staying with the supply chain design focus, Chapter 9, "The Design of Production-Distribution Networks: A Mathematical Programming Approach," by A. Martel, considers a wide range of decision factors in design. This chapter highlights important strategic factors, such as performance measures, planning horizon length and the associated uncertainty, process and product structure modeling, network flow modeling, modeling price, demand, and customer service, and facility layout options. The cost model accounts for various financial factors, such as tariffs, taxes, exchange rates, and transfer payments, in addition to transportation, inventory, and location costs. The result is a comprehensive large-scale nonlinear integer math programming model. The author discusses solution methods employed to develop a decision support system for supply chain design decisions.

Chapter 10, "Modeling & Solving Stochastic Programming Problems in Supply Chain Management Using *Xpress-SP*," by A. Dormer, A. Vazacopoulos, N. Verma, and H. Tipi, provides a further look at how to deal with uncertainty in supply chains. The authors identify various sources of risk in supply chains and how these affect performance. This chapter provides a nice discussion of stochastic programming problems in general, and in how to use the *Xpress-SP* package to model and solve these problems. Two illustrative examples of supply chain planning problems under uncertainty serve to illustrate the effective use of this tool for solving such problems.

Chapter 11 considers an operations-level planning problem facing logistics managers in container terminal operations. In "Dispatching Automated Guided Vehicles in a Container Terminal," Y.-L. Cheng, H.-C. Sen, K. Natarajan, C.-P. Teo, and K.-C. Tan study the problem of dispatching automated vehicles in a port terminal. Their model accounts for congestion effects in transportation using a deadlock prediction and avoidance scheme. They provide greedy and network flow–based heuristic solution approaches, and use a simulation model to validate the performance improvements as a result of the modeling and solution approaches they propose.

In the final chapter ("Hybrid MIP-CP techniques to solve a Multi-Machine Assignment and Scheduling Problem in Xpress-CP"), A. Vazacopoulos and N. Verma discuss hybrid constraint programming and mixed integer programming approaches for difficult multi-machine scheduling problems. While this model is motivated by the problem of scheduling jobs on different machines on a shop floor, it might also apply to the assignment of work to different facilities in a supply chain. The authors discuss the pros and cons of both constraint programming and mixed integer programming approaches, and consider hybrid approaches that combine the strengths of both of these methods. The authors illustrate the use of the *Xpress-CP* software package as a tool for implementing this hybrid approach, and compare the results obtained to prior results from the literature based on a common set of test problems.

This collection represents a set of stand-alone works that captures recent research trends in the application of optimization methods to supply chain operations, planning, and design problems. We are extremely grateful to the authors for their outstanding contributions and for their patience, which have led to a final product that far exceeded our expectations. All chapters were rigorously reviewed, and we would like to thank the anonymous reviewers for their quality reviews and responsiveness. We would also like to thank several graduate students in the ISE Department at the University of Florida for their help; in particular, we thank Ismail Serdar Bakal, Altannar Chinchuluun, and Yasemin Merzifonluoğlu for their contributions to this effort.

JOSEPH GEUNES AND PANOS PARDALOS

Chapter 1

INFORMATION CENTRIC OPTIMIZATION OF INVENTORIES IN CAPACITATED SUPPLY CHAINS: THREE ILLUSTRATIVE EXAMPLES

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Abstract Recent enhancements in information technology have played a major role in the timely availability and accuracy of information across the supply chain. It is now cheaper to gather, store, and analyze vast amounts of data and this has presented managers with new opportunities for improving the efficiency of their supply chains. In addition, the latest developments in supply chain management have led everyone to believe that cooperation between members of a supply chain can lead to larger profits. While some gains have been realized from these developments, most organizations have failed to take the most advantage of them. To overcome this, there is a need to redesign a firm's supply chain with regards to its structure and modus operandi. This chapter illustrates this need for information-centric design and management of capacitated supply chains using three examples based on three different supply chain configurations.

1. Introduction

A supply chain is a group of organizations (including product design, procurement, manufacturing, and distribution) that are working together to profitably provide the right product or service to the right customer at the right time. Supply Chain Management (SCM) is the study of strategies and methodologies that enable these organizations to meet their objectives effectively. In the past few decades, people have realized that cooperation with other organizations in the supply chain can lead to significantly higher profits. As a result, industrial supplier-customer relations have undergone radical changes resulting in a certain level of co-operation, mainly in the area of information sharing, that was lacking before. The degree of co-operation varies significantly from one supply chain to another. The information sharing could range from generic (e.g. type of inventory control policy being used, type of production scheduling rules being used) to specific (e.g. day-to-day inventory levels, exact production schedules). There is a need for new models addressing these recent developments in information sharing because traditional models were developed under demand and informational assumptions that no longer universally hold in the manufacturing sector. In addition there have been reports, from industrial sources, of differing reactions to Electronic Data Interchange (EDI) benefits - while some were very happy with improved information, others were disappointed at the benefits (see Armistead and Mapes (1993) and Takac (1992)). The popular press is full of stories about companies disillusioned with their Enterprise Resource Planning (ERP) systems. It is estimated that 70% of all ERP implementations do not recoup their investments and are branded as failures (see *InfoWorld*, October 2001). While there could be many reasons for this high failure rate, the fact that companies are not adept at using the information provided by these ERP systems is a major factor. Since the availability and accuracy of information are the key contributions of such enterprise-wide systems, the organizations must position themselves to benefit from it.

While information will always be beneficial, it is important to know when it is most beneficial and when it is only marginally useful. In the latter case, some other characteristics of the system, such as end-item demand variance or supplier capacity may have to be improved before expecting significant benefits from information sharing. With regard to the benefits of information sharing and its dependence on the various supply chain characteristics (such as capacity, variance, service level, etc.), it is necessary to answer the following questions: (1) In the presence of Information Sharing, what is the optimal control policy?; (2) What is the benefit (in dollars) of Information flow?; and (3) How can the supply chain be changed in order to maximize this benefit? In an attempt to answer these questions, we (in Gavirneni, Kapuscinksi, and Tayur (1999)) studied a simple, yet representative, supply chain consisting of one supplier and one retailer using an (s, S) policy. In spite of its simple setup, this two stage supply chain provided valuable insights into managing more complex systems efficiently. The (s, S) policy dictates that the retailer will only order when her inventory level falls below s, and at that time she will order up-to S. Under this setting, we considered three situations: (1) a traditional model where there is no information, except from past data, to the supplier prior to a demand from the retailer; (2) the supplier has the information of the (s, S) policy used by the retailer as well as the end-item demand distribution; and (3) the supplier has full information about the state of the retailer. The availability of new retailer information about inventory policy (in situation 2) and inventory levels (in situation 3) presents new opportunities for the supplier. After formulating the appropriate decision problems at the supplier, we showed that order up-to policies continue to be optimal for models with information flow for the finite horizon, the infinite horizon discounted and the infinite horizon average cost cases. We developed efficient solution procedures for these three models and performed a detailed computational study to understand the relationships between capacity, inventory, and information at the supplier level and explain how they are affected by customer $(S - s)$ values and end-item demand distribution. In addition, we tabulated the benefits (averaging around 14% and ranging from 1% to 35%) of information sharing for this supply chain and made the following observations about their behavior: (1) Since information presents the supplier with more options, it is always beneficial; (2) More information generally results in larger savings; (3) The benefit of information flow is higher at higher capacities; (4) If the variance of the demand seen by the customer is small (high), we can expect the benefit of information flow to increase (decrease) with increase in penalty cost; (5) Information is most beneficial at moderate values of variance; and (6) Information is less beneficial at extreme values of $(S - s)$. These insights can lead to better management of projects that involve information sharing between members of a supply chain.

This study (Gavirneni, Kapuscinksi, and Tayur (1999)) was one of the first papers to be published on this topic and a number of articles have been published on this topic since then. Chen (1998) studied the benefits of information flow in a multi-echelon serial inventory system by computing the difference between the costs of using echelon reorder points and installation reorder points. He observed that information sharing reduced costs by as much as 9%, but averaged only 1.75%. Cachon and Fisher (2000) and Aviv and Federgruen (1998) studied the benefits of information flow in one warehouse multi-retailer systems. Both these studies observed that the benefits of information sharing under these settings were quite small, averaging around 2% in the case of Aviv and Federgruen and about 2.2% in the case of Cachon and Fisher. Gavirneni and Tayur (1999) studied the benefits of information in a setting where the retailer is using a target-reverting policy for placing orders. A target-reverting policy is one in which the retailer attempts to quickly get back to a previously published schedule in the event that the predetermined schedule was not adhered to. In that situation, the benefits ranged from 6% to 28% and averaged around 11%. In Gavirneni (2001), I studied the benefits of information sharing in a one warehouse, multi-retailer setting and observed that savings could be as large as 27.5%, but averaged around 5%. While providing valuable insights into management of supply chains in the presence of information sharing, all these articles have failed to adequately answer an important question: *How should the supply chain structure and operating policies be changed in order to obtain the maximum benefit from these information flows?* The aforementioned studies incorporated information into the existing setup and none considered changing the structure and/or the operating procedures in order to make better use of the information. I believe that such a change must be considered if one wants to take full advantage of the information. There is a need for analysis of these supply chains centered on the inherent information flows. Such an information-centric design and management of capacitated supply chains will address the following issues:

1 How does one incorporate information flows into the decision making process?

2 How does one determine which information is useful and worth gathering? How much money can be invested in collecting the information?

3 How should the supply chain structure and operating policies be changed in order to make the best use of the information flows?

Supply chains come in many shapes and sizes. In addition, the operational characteristics (such as lead times, cost structures, yields, supplier capabilities) vary significantly from one to another. Supply chains in the retail industry tend to start at one place (distribution center or manufacturer) and diverge into many customer facing locations. Supply chains in the automotive or heavy equipment industry tend to involve a lot of assembly activities. As a result those supply chains have many suppliers shipping material into a central location. The pharmaceutical supply chains tend to have many stages, cross international boundaries, long leadtimes and also face many regulatory restrictions. Supply chains in the semi-conductor industry often involve complex, delicate manufacturing processes with significant yield losses and highly uncertain demands. Current knowledge in managing material, financial, and information flows in these supply chain leads us to believe that each of these supply chains should be treated individually. Rarely can observations on the benefits of information flows from one supply chain be extended to other supply chains. As a result, when studying the impacts of information, it is necessary to undertake research initiatives that encompass a wide variety of supply chain structures and operational characteristics.

I will demonstrate the benefits of information centric design and management of supply chains using three examples of different supply chain configurations. These examples were chosen to capture the presence of (i) significant setup or ordering costs; (ii) price fluctuations; and (iii) inventory allocation issues. These three characteristics of supply chains were identified by Lee, Padmanabhan, and Whang (1997) as the main reasons for information distortion. In section 2, I study a two stage supply chain with one supplier and one retailer facing end-customer demands. Due to the presence of a significant ordering cost, the retailer is using an (s, S) policy to manage inventories. Section 3 describes a two stage supply chain with a single supplier and a single retailer (facing i.i.d. end-customer demands) in which the supplier is charging the same price in every period. A single supplier, multi-retailer system is modeled and analyzed in section 4. For these three different supply chain configurations, I will propose, analyze, and compute the benefits of appropriate information centric policies that will significantly improve their performance. Section 5 contains ideas for future research and some closing remarks.

The models I study are discrete time periodic review non-stationary capacitated inventory control problems. The capacitated stationary inventory control problems were analyzed by Federgruen and Zipkin (1986a); Federgruen and Zipkin (1986b) and solution procedures for it were presented by Tayur (1993) and Glasserman and Tayur (1994); Glasserman and Tayur (1995). The capacitated non-stationary inventory control problem was the focus of articles by Kapuscinski and Tayur (1998), Gavirneni, Kapuscinksi, and Tayur (1999), and Scheller-Wolf and Tayur (1997). These three articles use Infinitesimal Perturbation Analysis (IPA) to solve these problems. I will use this approach as well and details on this method can be found in Glasserman (1991).

2. A two-stage supply chain with a retailer using (s, S) Policy

Consider a supply chain containing one capacitated supplier and a retailer facing i.i.d. demands for a single product. The supplier has finite production capacity, C. The end-customer demand distribution has cumulative distribution function (cdf) $\Psi(\cdot)$ and probability distribution function (pdf) $\psi(\cdot)$. The holding and penalty costs at the retailer are h_r and p_r respectively. They are h_s and p_s at the supplier. The costs and the demand distributions are known to both parties. There is a fixed ordering cost K between the retailer and the supplier. There are no lead times either at the retailer or at the supplier. The unsatisfied demands at the retailer are backlogged and the unsatisfied demands at the supplier are sent to the retailer using an expediting (e.g. overtime) strategy and p_s represents the cost of expediting. Thus, if needed, the retailer can order and receive an infinite quantity of the product in a period. All these assumptions are common in inventory control literature and in spite of its simple setup, this two stage supply chain can provide valuable insights into managing more complex systems efficiently. Cachon and Zipkin (1999), Gavirneni, Kapuscinksi, and Tayur (1999), and Gavirneni and Tayur (1999) have used settings similar to this one to understand the effect of cooperation on inventories in supply chains.

The sequence of events in this supply chain is as follows. (1) The supplier decides on her inventory level restricted by her production capacity. (2) The end-customer demands at the retailer are observed and the holding or penalty costs are incurred at the retailer. (3) The retailer places an order with the supplier, if necessary, to reach the desired inventory level. (4) The supplier satisfies (the product will be available at the retailer at the start of the next period) the retailer demands to the best of her abilities. (5) If there is inventory left at the supplier, she incurs holding costs and on the other hand if there is some unsatisfied demand, it is supplied by expediting and the costs of expediting are incurred.

For this supply chain I study two modes of operation at the retailer. In both models I assume that the retailer provides the supplier with information on the demands she is seeing in every period. In model 1, the retailer uses an (s, S) policy. That is, when her inventory falls below s, she orders up-to S; we know from Scarf (1962) that the (s, S) policy is optimal for the retailer in this case. Thus the retailer will not order every period, but provides information, to the supplier, on the end-customer demands she is experiencing. As these cumulative end-customer demands approach $S - s$, the supplier is able to predict more accurately whether she will receive an order from the retailer. She also will be able to better predict more accurately the size of demand if it would occur. Because of this predictability, her holding and penalty costs will decrease when compared to the situation in which the retailer did not provide this information. When the retailer is willing to provide this information I wish to ask the following questions: (1) is this the best way to manage this supply chain? and (2) are there ways to use the information to make the supply chain more efficient? For example, when the cumulative end-customer demand at the retailer is close to $S - s$, the supplier expects a demand and stocks inventory to meet it. If by chance, the next end-customer demand is very low and does not drop the retailer inventory below s, then the demand at the supplier is not realized and the supplier ends up incurring holding cost. There are ways to remove this uncertainty in timing of retailer demands and I formulate them in Model 2.

In model 2, the supplier and the retailer keep track of the cumulative end-customer demands since the previous retailer order. If at the end of a period, this cumulative demand is greater than a pre-specified value (denoted by δ), then the retailer must order after she has seen the next end-customer demand. In this case, the supplier knows for sure that there will be a demand in that period and can be better prepared to meet it. The supplier does not know the exact size of the order, but she knows the distribution from which it will be realized. For this model I will show that retailer uses an order up-to policy when she orders. I will also formulate the resulting non-stationary inventory control problem at the supplier and establish that her optimal policy is also order up-to, though the order up-to levels differ from one period to the next. In addition, I will choose (by exhaustive search) the δ value as the one with the lowest total cost. By using this policy I am removing some uncertainty at the supplier and this results in lower costs for her. But since an (s, S) policy is optimal for the retailer, moving to the operating policy in Model 2 is certain to increase her costs. In this paper, I want to study the relationship between these two opposing forces in the supply chain. I will show, via a detailed computational study, that if the δ value is chosen properly, the savings at the supplier are greater than the increase in costs at the retailer. Thus the total costs in the supply chain are reduced, making the supply chain more efficient.

2.1 The Models

In this section I analyze the two models described above. For each case I determine optimal policies for both the retailer and the supplier. I also present solution procedures for determining the optimal parameters.

2.1.1 Model 1 - The Traditional Model. Here the retailer is using the (s, S) policy that is optimal for her. The corresponding s and S values can be determined using an efficient solution procedure developed by Zheng and Federgruen (1991). In this setting the retailer does not order in every period, but informs the supplier about the end-customer demands. The non-stationary inventory control problem seen by the supplier was formulated and the relevant structural properties and solution procedures were described in detail in Gavirneni, Kapuscinksi, and Tayur (1999).

2.1.2 Model 2 - The Information Centric Model.

In this model I will consider a different operating policy at the retailer in the hope that the new operating policy will make better use of the information flow and thus improve the efficiency of the supply chain. Both the retailer and the supplier monitor the cumulative end-customer demand since the retailer last ordered. When this cumulative demand is greater than a predetermined value, δ, then the retailer must place an order after the next end-customer demand. Thus, the supplier knows a period ahead when demand is going to occur, but is not sure of the size of the order. She has a probability distribution from which this demand will be realized. Let us first look at the optimal retailer behavior under this strategy.

Retailer Behavior

To analyze the behavior of the retailer, it is necessary to pay close attention to the sequence of events. Let us assume that the problem is at the beginning of the first period in an n-period problem. Assume that the total end-customer demand since her last order is i and that she has y units of inventory on hand. Let $J_n(i, y)$ be the total cost of this n-period problem. If i is greater than δ, then she can place an order with the supplier at the end of this period after she has seen another end-customer demand. If i is less than δ, then she cannot place an order with the supplier and her next period will start with inventory $y - \xi$ and in state $i + \xi$ where ξ is the end-customer demand in this period. Thus:

$$J_n(i, y) = E_\xi[(y-\xi)^+ h_r + (y-\xi)^- p_r + V_{n-1}(i, \xi, (y-\xi))]$$

I use a^+ to represent $\max(0, a)$ and a^- to represent $\max(0, -a)$. In addition, E_a represents expectation with respect to the random variable a. $V_{n-1}(i, \xi, (y-\xi))$ is the optimal cost of an $n-1$ period problem when the total end-customer demand until the previous period is i, the end-customer demand in this period is ξ and the inventory before the retailer orders, if she can, is $y - \xi$. This cost can be computed as follows:

$$\begin{aligned} V_{n-1}(i, \xi, (y-\xi)) &= J_{n-1}(i+\xi, y-\xi) \text{ If } i < \delta \\ &= \min_{x \geq (y-\xi)} J_{n-1}(0, x) \text{ Else} \end{aligned}$$

Starting with the initial condition $V_0(\cdot, \cdot, \cdot) = 0$, and using arguments (as detailed in Bertsekas (1988)) based on induction and convexity it can be shown that it is optimal for the retailer to order, when she is allowed to, up-to some fixed level y_*. This optimal order up-to level can be determined using IPA. When the retailer orders, she will be incurring a fixed ordering cost, but that cost does not figure in this optimization with a fixed δ. It will however, play a key role in determining the optimal δ value. Let y_*^δ be the optimal order up-to level corresponding to δ.

Property 1. If $\delta_1 < \delta_2$, then $y_*^{\delta_1} \leq y_*^{\delta_2}$.

Proof:. Let l_1 (l_2) be the number of periods it takes the cumulative end-customer demand to jump over δ_1 (δ_2). Clearly l_1 and l_2 are random and in addition $l_1 \leq_{st} l_2$. Let $G_1(\cdot)$ ($G_2(\cdot)$) be the distribution of end-customer demand over l_1+1 (l_2+1) periods. Since $G_1(\cdot) \leq_{st} G_2(\cdot)$, and $y^{\delta_1} = G_1^{-1}(\frac{p_r}{p_r+h_r})$ and $y^{\delta_2} = G_2^{-1}(\frac{p_r}{p_r+h_r})$, it follows that $y^{\delta_1} \leq y^{\delta_2}$. □

Once the optimal retailer behavior has been determined, I can analyze the inventory control problem at the supplier.

Supplier Behavior

The supplier faces a non-stationary inventory control problem which is defined below. In every period she is in one of many possible states. Her state is determined by the cumulative end-customer demand since the retailer last ordered. For all values of i less than δ, in state i she sees no demand in that period. On the other hand for i greater than δ, she sees a demand from the distribution with cdf $\Phi_i(\cdot)$ and pdf $\phi_i(\cdot)$. I know that these distributions are related to the end-customer demand distribution as follows:

$$\Phi_i(i+t) = \Psi(t)$$

Again by formulating the appropriate stochastic dynamic programming and using arguments of convexity and induction (see Bertsekas (1988)), I can show that the optimal policy at the supplier is a modified order up-to policy and these order up-to levels can be computed using IPA.

Thus for a given δ value, I know how to solve the problem in model 2. To find the optimal δ value that results in the lowest supply chain cost, I perform an exhaustive search over the possible set of values. I used this approach to perform a detailed study comparing the total supply chain costs of these two models. The results from this study are presented in the next section.

2.2 Computational Results

There are two principle objectives for this computational study: (1) Exhibit that using the strategy in the information centric model 2 does in fact result in a reduction in the total supply chain cost; and (2) Study how the reduction in cost is affected by various supply chain parameters such as capacity, fixed cost, holding and penalty costs, and demand variance. These sensitivity results should provide some insights into when the retailer should consider moving away from the locally optimal policy in order to realize a reduction in the total supply chain costs by enabling better use of information flows at the supplier.

The experimental setup for the study is as follows. The holding cost at the supplier is 1 while the penalty cost is allowed to take values 5, 8, and 11. The retailer was also setup similarly. The end-customer demand is assumed to have a mean of 20 and was sampled from distributions Exponential(20), Erlang(2,10), Erlang(4,5), Erlang(8,2.5), and Erlang(16,1.25). Thus the standard deviations of the end-customer demand were 20, 14.2, 10, 7.1, and 5 respectively. The production capacity at the supplier was allowed to take values 25, 45, and 65. Thus the capacity was always greater than the mean demand. For all these cases I computed the costs of models 1 and 2. Although in the previous section, I proposed an exhaustive search over all the possible values of δ, for ease of analysis I considered δ values from a smaller subset. When the setup cost was greater than or equal to 10, I used δ values ranging from 0 to 80 in multiples of 10. When the setup cost was lower than 10, I considered δ values from 0 to 10 in increments of 1. Using a more exhaustive search can only result in an improved performance for model 2. The difference between the costs of these two models can be attributed to better usage of the information flows. For each case, I computed the percentage reduction as follows:

$$\%\text{ reduction} = \frac{\text{traditional model cost} - \text{information centric model cost}}{\text{traditional model cost}} \times 100.$$

My observations from this computational study are detailed below. First I study the cost per period, then the optimal δ levels followed by the percentage reduction.

2.2.1 Cost per Period. For both the models I observed that the cost per period increased with increase in demand variance, increased with increase in penalty cost, and decreased with increase in capacity. This behavior of the costs has been well documented in inventory control literature and thus I will not elaborate here. I also observed that in all but one of the 1215 cases, the cost of model 2 was lower than the cost of model 1. Thus I can conclude that, in general, model 2 makes better use of the information flows in this supply chain.

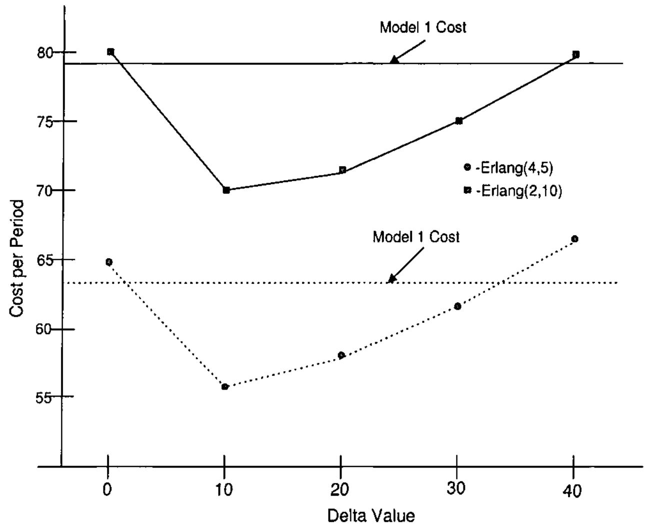

Figure 1.1. Cost per period as a function of δ value

2.2.2 Optimal δ Values. To determine the cost of model 2, I evaluated it under various values of δ and chose the δ value that resulted in the lowest cost. Figure 1.1 contains the plot of the cost per period as a function of δ for the Erlang(2,10) and Erlang(4,5) demand distributions. The retailer and supplier penalty costs were 5, the fixed ordering cost was 30, and the supplier capacity was 45. Notice that in both the cases, the optimal δ value was 10 and it was very easy to identify them. The situation was similar for all the other problem instances. The figure also contains the costs associated with model 1 for both the cases. It is worth noting that model 2 is more effective only when the δ values are chosen carefully. If they are selected arbitrarily, the performance of the supply chain could worsen. In addition I observed that the optimal δ values were (1) higher at higher capacities, (2) higher at higher fixed ordering costs, (3) lower at higher demand variances, and (4) lower at higher retailer or supplier penalty costs.

2.2.3 Percentage Reduction. In this section I will take a detailed look at the percentage reduction in cost realized by using model 2 in place of model 1. The percentage was positive in all but one (with setup cost 110, standard deviation of demand 20, capacity 25, supplier penalty cost 5, and retailer penalty cost 11) of the 1215 cases, and ranged from -0.44% to 33.7%, and averaged around 10.4%. This reduction is of significant size when compared to the savings, due to information shar-

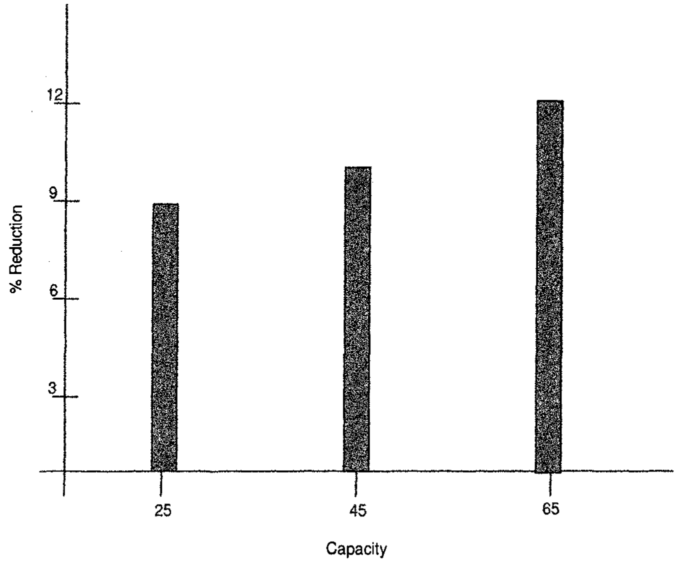

Figure 1.2. Percentage reduction as a function of capacity

ing, reported by Chen (1998), Cachon and Fisher (2000), and Aviv and Federgruen (1998). Thus in many cases, it would be better for both the supplier and the retailer to use the strategy in model 2. Clearly the retailer costs in model 2 will be higher than in model 1. But if the supplier was willing to share some of her savings, both the parties would be better off and the supply chain could be more efficient. However, if the setup cost or demand variance are extremely large, this strategy may not be effective. Let us take a closer look at how the supplier capacity, the penalty costs, and the demand variance affected the relative performance of model 2.

The Effect of Capacity

Figure 1.2 contains the average percentage reduction as a function of the supplier capacity. Model 2 was more effective at higher values of supplier capacity. The main reason for this behavior is the flexibility that additional capacity provides the supplier. If the supplier is not able to (due to tight capacity) react to the more effective information flows in model 2, there would be no reduction in cost. Thus when the supplier has higher capacity, she is able to use the information flows efficiently and reduce her costs more significantly. Thus, the strategy in model 2 makes the supply chain more efficient at larger supplier capacities.

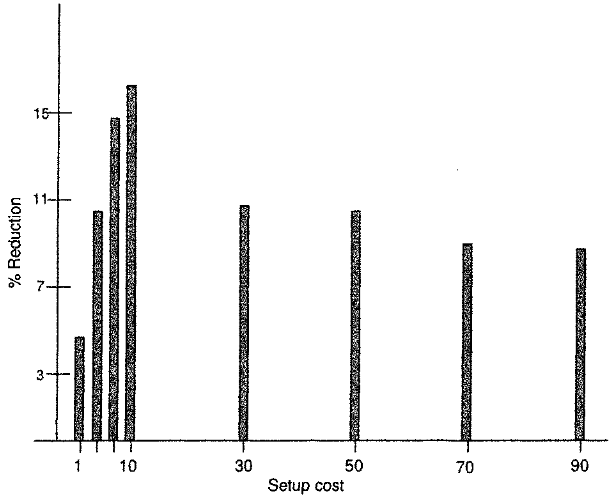

Figure 1.3. Percentage reduction as a function of setup cost

The Effect of Fixed Ordering Cost

The average relative performance of model 2 as a function of the fixed ordering cost is given in figure 1.3. The fixed cost K figures prominently in determining the optimal parameters for the two models. In model 1, the s and S are chosen in an optimal (at the retailer) fashion and for model 2, the fixed cost plays a role in determining the optimal δ value. I observed that, not surprisingly, at higher fixed costs, the optimal δ values were higher. The fact that savings in cost are lower at higher fixed costs can be explained as follows. At higher fixed ordering cost, the retailer orders (less frequently) larger amounts, and the presence of finite capacity requires the supplier to start producing well ahead of time. This reduces her ability to react to unexpected changes at the retailer and the effectiveness of model 2 is reduced. On the other hand, when the fixed costs are low, both models require that the retailer orders very frequently, thus reducing the difference in their performance. Thus, this strategy is most effective at moderate values of the fixed cost.

The Effect of Supplier and Retailer Penalty Costs

Figures 1.4 and 1.5 illustrate how the savings of model 2 are affected by the penalty costs at the supplier and the retailer respectively. Notice that model 2 performs better at higher supplier penalty costs and at lower retailer penalty costs. I observed this behavior consistently among all the distributions. The main reason for this behavior is the way the costs at the retailer and the supplier change under model 2. Recall that

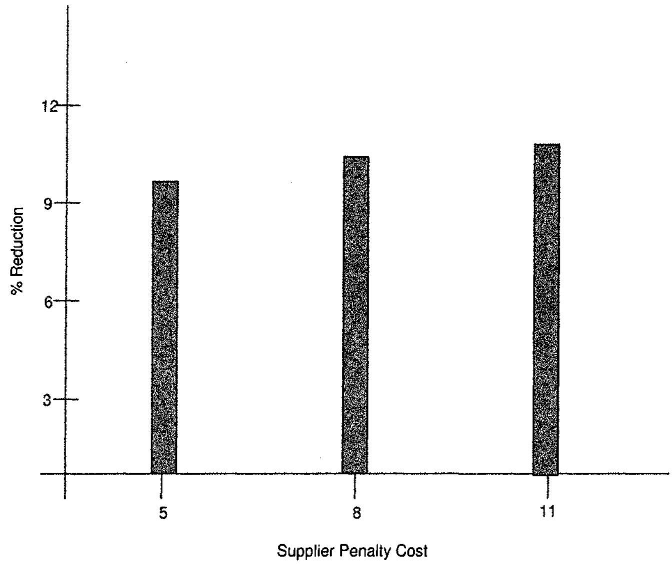

Figure 1.4. Percentage reduction as a function of supplier penalty cost

under model 2, the retailer is using a sub-optimal policy and her costs are increased while the costs at the supplier are decreased due to reduction in demand uncertainty. When her penalty costs are higher, the supplier realizes larger savings and the savings in model 2 are higher. On the other hand, when the penalty costs at the retailer are higher, her costs under model 2 increase more dramatically resulting in less effectiveness. Thus when the supplier penalty costs are high and the retailer penalty costs are low, the strategy in model 2 is more effective.

The Effect of Demand Variance

Figure 1.6 plots the average performance of model 2 as a function of the standard deviation of the end-customer demand. Notice that as the demand variance decreases the average performance of model 2 increases. Recall that while model 2 has no uncertainty about the timing of retailer demands, the quantity demanded is still uncertain. Thus when the end-customer demand has a high variance, the resulting uncertainty at the supplier is large even for model 2. Thus its performance is better at lower demand variances.

2.3 Conclusions

From the study of these two models, I conclude that using the information centric strategy defined in model 2, the information flows in

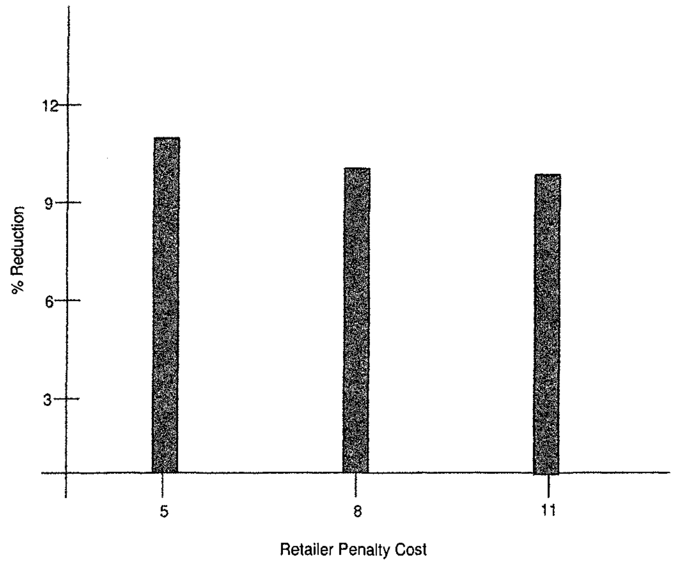

Figure 1.5. Percentage reduction as a function of retailer penalty cost

this two-stage supply chain can be better utilized resulting in an improvement (by as much as 34%) in the supply chain performance. This improvement is more dramatic when one or more of the following conditions hold: (1) the supplier capacity is high, (2) the fixed ordering cost is low, (3) the supplier penalty cost is high, (4) the retailer penalty cost is low, and (5) the demand variance is low.

3. Price Fluctuations and Supply Chain Performance

In this section, I consider the supply chain consisting of one supplier, one retailer, and one product. Existing research advocates that, in a decentralized setting, it is efficient that the retailer and the supplier use stationary order up-to policies. I show that in the presence of information sharing, the supply chain performance can be improved by the supplier offering fluctuating prices which in turn make the retailer and the supplier move away from stationary policies.

In the supply chain studied in this section, there is a single supplier with finite production capacity, C, supplying a single product to a newsvendor type retailer who is in turn facing independent and identically distributed demands (with cdf $\Psi(\cdot)$ and pdf $\psi(\cdot)$) from end-customers. The holding and penalty costs are respectively h_r and p_r at the retailer and h_s and p_s at the supplier. The costs and the demand

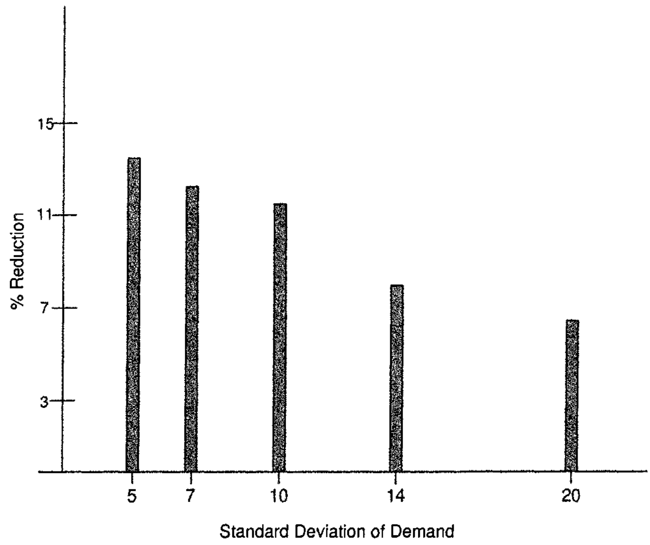

Figure 1.6. Percentage reduction as a function of standard deviation

distributions are known to both parties. There are no fixed ordering costs or lead times either at the retailer or the supplier. The unsatisfied demands at the retailer are backlogged and the unsatisfied demands at the supplier are sent to the retailer using an expediting strategy and p_s represents the cost of expediting. Thus, if needed, the retailer can order and receive an infinite quantity of the product in a period. All these assumptions are common in inventory control literature and most of them, except the one on ordering costs, can be relaxed without significantly changing the general behavior of the system. Cachon and Zipkin (1999) studied a setting similar to this one. They used game theoretic models to study the impact on inventory levels of competition and cooperation between the retailer and the supplier.

I study this supply chain under a periodic setting and the sequence of events in every period is as follows: (1) The supplier decides (restricted by her capacity) how much to produce. The product is available immediately; (2) The retailer faces the end-customer demand and satisfies it to the best of her abilities. Unsatisfied demands are backlogged; (3) The retailer decides how much to order from the supplier; (4) The supplier satisfies the retailer's demand to the best of her abilities. Unsatisfied demands are supplied through the expedited source. The product is available to the retailer at the beginning of the next period; (5) The holding and penalty costs at both the retailer and the supplier are computed and the problem goes to the next period. I measure the performance of this supply chain using the total holding and penalty costs at both the retailer and the supplier. Since the purchase costs between the retailer and the supplier are internal to the supply chain, they are not explicitly included in the total supply chain cost. The objective here is to study the effect of price fluctuations (at the supplier) and information sharing (between the retailer and the supplier) on the performance of this supply chain.

I study the interaction between these two strategies in this supply chain by formulating and analyzing the retailer and supplier behavior in two different models. In Model 1 (the everyday low price (EDLP) Model), the supplier charges the retailer the same price (c dollars per unit) in every period. In this setting, it is optimal for the retailer to use a stationary order up-to policy with the order up-to level z in every period. Thus the end-customer demands at the retailer are transmitted to the supplier without any change and the supplier sees i.i.d. demands in every period. In every period, the supplier is completely aware of the inventory level at the retailer and there is no need for the retailer to provide additional information. In Model 2 (the HI-LO pricing Model), the supplier alternates the selling price between c' and $c' - \epsilon$ from one period to the next. This leads to the retailer using an ordering pattern that repeats every two periods. In every cycle of two periods, the first period has an order up-to level z' while the second period has the order up-to level $z' + \Delta_\epsilon$. Under this retailer inventory policy, the demands seen by the supplier are no longer i.i.d. I characterize the information (retailer inventory policy parameters in setting 1 and retailer inventory levels in setting 2) available to the supplier and formulate the resulting non-stationary inventory control problem she faces. Though the variance of demands seen by the supplier is increased, the benefits realized from the associated information flow will result in lower costs at her location. In addition, I will show that this reduction in costs at the supplier far outweighs the increase in the retailer's costs. Thus, if the supplier is willing to share some of the benefit she realizes with the retailer, the retailer may be willing to provide the inventory information and the whole supply chain will be more efficient.

While the ways in which the prices at the supplier can be made to fluctuate are numerous, I restrict my attention to fluctuations that repeat every two periods. This is very similar to the *HI-LO* pricing popular among many suppliers. As will be seen later in the section on the computational results, I further assume that these fluctuations are symmetric around the price offered in the constant pricing scheme. Under these assumptions, to determine the optimal fluctuating pricing scheme, one needs only to search over the possible values of the ϵ value. I develop an efficient procedure to determine the optimal supplier and retailer behavior for a given value of ϵ and use that to search over the set of the possible ϵ values to determine the optimal fluctuating pricing scheme.

Designing efficient supply contracts has recently been a favorite topic of many in the supply chain management research community. Anupindi and Bassok (1999), Cachon (1999), and Lariviere (1999) are excellent sources of information on this topic. It is not surprising that pricing plays an important role in designing good supply contracts. Pasternack (1985) and Lee, et al. (2000) showed that price protection (a method for compensating the retailer for excess inventory at her location) is a strategy that the supplier can use to achieve channel coordination. Chen, Federgruen, and Zheng (2001) have shown that in order to achieve channel coordination in a supply chain with non-identical retailers, a discounting scheme based on three quantities (namely annual sales volume, order quantity, and order frequency) is necessary. Munson and Rosenblatt (2001) explored the benefits of using quantity discounts in a three level supply chain and showed that savings can be significant. However few researchers have specifically looked at price fluctuations and the role they play in improving supply chain performance. Iyer and Ye (2000) studied price fluctuations at the retailer and their effect on grocery supply chains. They observed that if the supplier obtains information about the price fluctuations at the retailer, in some cases she can use that information to improve her performance. In this paper, I focus on the effect of price fluctuations at the supplier and their impact on the performance of the whole supply chain.

3.1 Two Models

In this section I study two inventory control problems which differ in the way the supplier prices the product for the retailer. I establish the corresponding optimal policies for the retailer and the supplier and develop efficient solution procedures for computing the optimal parameters.

3.1.1 Model 1 - EDLP Model. In this model the supplier charges the retailer c dollars per unit in every period. Under this setting, it is optimal for the retailer to use a stationary order up-to policy with the order up-to level z. Based on the assumption of expediting at the supplier, z is the newsvendor solution for the retailer. Thus

$$z = \Psi^{-1}\left(\frac{p_r}{h_r + p_r}\right)$$

Under this retailer ordering policy the demands seen by the supplier are i.i.d. with cumulative distribution function $\Phi(\cdot)$ and density function $\phi(\cdot)$. In addition, the distribution $\Phi(\cdot)$ is exactly equal to the distribution $\Psi(\cdot)$. Based on Federgruen and Zipkin (1986a); Federgruen and Zipkin (1986b) a modified order up-to policy is optimal for the supplier. The optimal order up-to level, y, while not available in closed form, can be computed using IPA. Details on IPA validation and implementation can be found in Glasserman and Tayur (1994); Glasserman and Tayur (1995).

When the retailer uses a stationary order up-to policy, it presents a stable environment for the supplier. Since the retailer starts at her optimal order up-to level in every period and the end-customer demand is transmitted unaltered to the supplier, the supplier is fully aware of the inventory position at the retailer. There is no additional information that can be exchanged between the two.

3.1.2 Model 2 - HILO Pricing Model. In this section, I model the case in which the supplier charges the retailer fluctuating prices from one period to the next. Specifically, I will assume that the supplier alternates the selling price between c' and $c' - \epsilon$ from one period to the next. Under this setting I will study the optimal retailer and supplier behavior.

3.1.3 Retailer Behavior: Model 2.

Property 2. When the unit selling price at the supplier alternates between c' and $c' - \epsilon$, the retailer optimal order up-to level alternates between z' and $z' + \Delta_\epsilon$.

Proof. This policy with cyclic order up-to levels follows from Karlin (1960) and Zipkin (1989) as a special case of cycle length equal to 2. □

When the retailer uses this ordering policy, the demands seen by the supplier are no longer i.i.d. In the next section I formulate the corresponding non-stationary inventory control model at the supplier and determine her optimal policy.

3.1.4 Supplier Behavior: Model 2. For this model, I will analyze the supplier behavior for two specific settings. In setting 1, the supplier is only aware of the retailer inventory policy parameters (namely z' and $z' + \Delta_\epsilon$) and in setting 2, in addition to knowing the retailer policy parameters, the supplier obtains information about the day-to-day inventory levels at the retailer.

3.1.5 Setting 1: Information on Retailer Policy Parameters. Since the retailer ordering policy follows a two period pattern, the demands at the supplier also will exhibit a cyclic pattern with a cycle time of two periods. In the first period, the demand, d, at the supplier is either zero (if ξ_1 is less than Δ_ϵ) or $\xi_1 - \Delta_\epsilon$ (if ξ_1 is greater than Δ_ϵ) where ξ_1 is the end-customer demand seen at the retailer. Let us call the state the supplier is in as state 1. In the next period, she is in one of two possible states. I will say that she is in state 2 if the demand from the retailer was zero in the previous period. On the other hand, if the retailer order in the previous period was non-zero, then I will say that the supplier is in state 3. In state 2, the demand seen by supplier is $\xi_1 + \xi_2$ where both ξ_1 and ξ_2 are end-customer demands from the distribution $\Psi(\cdot)$ and ξ_1 is less than Δ_ϵ. In state 3, the supplier sees demand $\xi_2 + \Delta_\epsilon$. For ease of presentation, I will say that $\Phi_i(\cdot)$ ($\phi_i(\cdot)$) is the cdf (pdf) of the distribution of demand seen by the supplier in state i. Clearly $\Phi_1(\cdot) \leq_{st} \Phi_2(\cdot) \leq_{st} \Phi_3(\cdot)$. From states 2 and 3, the supplier transitions into state 1 in the next period. The transition probability from state 1 to 2 is $\Psi(\Delta_\epsilon)$ and the transition probability from state 1 to 3 is $1 - \Psi(\Delta_\epsilon)$.

I first present some structural properties for this problem and also discuss ways for computing the optimal solutions.

Structural Properties: Setting 1

Property 3. For finite horizon and infinite horizon (discounted and average cost) a modified order up-to policy is optimal.

Proof. Let $L_i(y)$ be the one-period cost in state i with inventory level y. It can be computed as follows:

$$L_i(y) = h\int_0^y (y-t)\phi_i(t)dt + p_s\int_y^\infty (t-y)\phi_i(t)dt$$

Let $V_n^i(x)$ be the optimal cost of an n-period problem starting in state i with inventory level (before production) x. $V_n^i(x) = \min_{y\in[x,x+C]} J_n^i(y)$ where

$$\begin{aligned} J_n^1(y) &= L_1(y) + \Psi(\Delta)V_{n-1}^2(y) + \int_\Delta^\infty V_{n-1}^3(y-t+\Delta)^+\psi(t)dt \\ J_n^2(y) &= L_2(y) + \int_0^\infty V_{n-1}^1(y-t)^+\phi_2(t)dt \end{aligned}$$