2005

Effect of lead-time variations on the operations of supply chain networks.

Niloofar Mahmoudi

University of Windsor

EFFECT OF LEAD-TIME VARIATIONS ON THE OPERATIONS OF SUPPLY CHAIN NETWORKS

by

Niloofar Mahmoudi

A Thesis
Submitted to the Faculty of Graduate Studies and Research
Through the Department of Industrial and Manufacturing Systems Engineering
In Partial Fulfillment of the Requirement for the Degree of Master of Applied Science at the University of Windsor

Windsor, Ontario, Canada
2005

ABSTRACT

"Supply Chain Management" is a philosophy that deals with the coordination and integration of the interactions between the members of a supply chain. Information system plays a key role in a successful integrated supply chain. In fact, it is impossible to achieve an effective supply chain without a suitable information system to control the factors that influence the performance of supply chain.

This thesis focuses on analyzing the value of information sharing on supply chain network. A multi-stage, multi-period, multi-product, inventory-planning model with seasonal demand is used to study the impact of information sharing and lead-time variations on the operational costs of supply chain network. .

A mixed-integer programming model is used to integrate the production and distribution planning processes throughout the supply chain. The model determines the finished goods production levels, inventory and workforce levels, assignment of the transportation modes and the number of transportation consignments in order to minimize the total costs incurred in the system. It also analyzes different inventory review policies and information systems to measure the trade-offs between the value of information sharing and overall system costs.

Three inventory review policies with different cycle lengths and costs are defined in the model in accordance with three possible degrees of automation that can affect the timeliness of inventory data and the accuracy of demand forecasting system based on Winters' method. Some empirical results are used in order to model the causal relationship between the timeliness factor of information systems and the demand

forecast error. The results of the model confirm that using updated demand information may cause a considerable reduction in the forecast errors which has an order-of-magnitude effect on overall cost reduction throughout the supply chain.

Paremetric analysis is performed to study the impact of lead-time variations on the operational costs of the supply chain network which leads to the conclusion that lead-time variations have a significant effect on the inventory and safety stock levels, and as a result on the overall system cost in a supply chain network.

ACKNOWLEDGEMENT

I would like to express my gratitude to my supervisor Dr. R.S Lashkari for his encouragement and supervision throughout my study.

I would also like to thank the members of my committee Dr. M. Ahmadi, Dr. W. Abdul-Kader and Dr. D. Ting for their useful comments that helped me improve the final copy of this thesis.

My sincere thank to Mr. Ram Barakat and Ms. Jacquie Mummery for their most valuable technical and administrative assistance.

I also like to thank my friends at University of Windsor, Leila, shahram and Afsaneh for their constant help and support.

Also, special thanks to Shervin for his support, comments and suggestions that helped me a lot through development of this thesis. I am grateful to have him by my side.

Last but not least, I would like to take this opportunity to express my profound gratitude to my beloved parents, Homa and saeed, my sisters Mandana and Negin and my brother-in- law Borzoo for their moral support and encouragement during my study. In appreciation, I dedicate this thesis to them.

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ADINS	Agent-based Dynamic Information Network for Supply Chain Management
CR	Continuous Improvement
C.F.	Cubic Feet
DSS	Decentralized Safety Stock
DC	Distribution Center
ECR	Efficient Customer Response
EAI	Enterprise Application Integration
EDI	Electronic Data Interchange
IT	Information Technology
MLT	Manufacturing Lead-Time
PSS	Pooled Safety Stock
POS	Point Of Sale
QR	Quick Response
SCM	Supply Chain Management
S.F.	Square Feet
TQM	Total Quality Management
TLT	Transportation Lead-Time
VMI	Vendor Managed Inventory

CHAPTER 1: INTRODUCTION

Traditionally, firms viewed themselves as having customers and suppliers. They did not consider the potential for either their suppliers or customers to become a partner. This philosophy in many industries led to the creation of an adversarial relation between the firms and their suppliers and customers .

Beginning in 1960s and 1970s firms began to view themselves, their suppliers and customers as closely linked functions whose common goal was to serve their customers (In reference, this internal integration was often referred to as "material management"). Adopting the "material management" structure, firms integrated their purchasing, operations and distribution functions to improve customer service and performance while lowering their operation costs (Figure 1.1). However, they were still constrained by other functions that were not integrated, or by their customers' or suppliers' unresponsiveness which prevented them from reacting quickly to market changes. Losing the market share and increased customer dissatisfaction are the results of unresponsiveness.

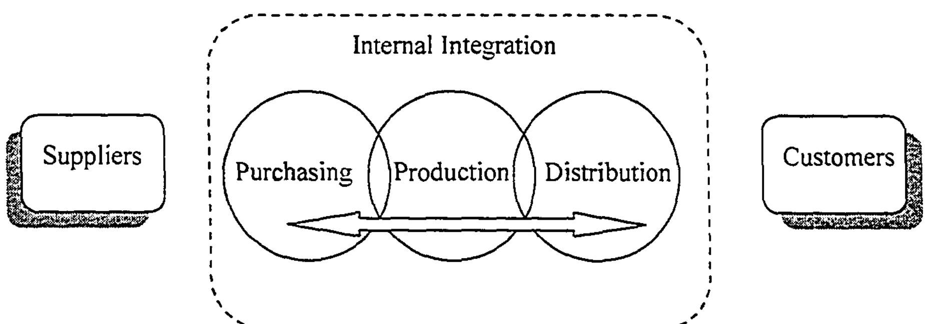

Figure1.1.Internal integration in supply chain

In the 1980s and 1990s, many firms continued to integrate their material management functions. As it became clear that leading companies in this integration could increase their profits, more firms began to adopt supply chain management practices (Fredendall and Hill, 2001).

Today, one of the biggest challenges is the need to respond to ever increasing changes in demand. In order to meet these challenges, the firms need to focus their effort upon achieving greater agility and integrity in their supply chains such that they can respond in shorter timeframe both in terms of volume and variety change. In other words, they should quickly adjust output to match market demand and increase their responsiveness. This gives the supply chain a different perception and can be used as a tool to gain competitive advantage.

1.1. The concept of supply chain management:

A supply chain is a network of facilities and distribution options that performs the function of procurement of materials, transformation of these materials into intermediate and finished products and the distribution of these products to customers (Ganeshan and Harrison, 1995).

Supply chain consists of suppliers, manufacturing facilities, warehouses, distribution centers and retail outlets as well as the raw materials, work-in-process and finished products and information that flow between facilities.

There is the constant flow of materials moving down the supply chain (raw materials, semi-finished or finished products) and the information flow which move up in the supply chain (e.g., demand and inventory information) as shown in Figure1.2.

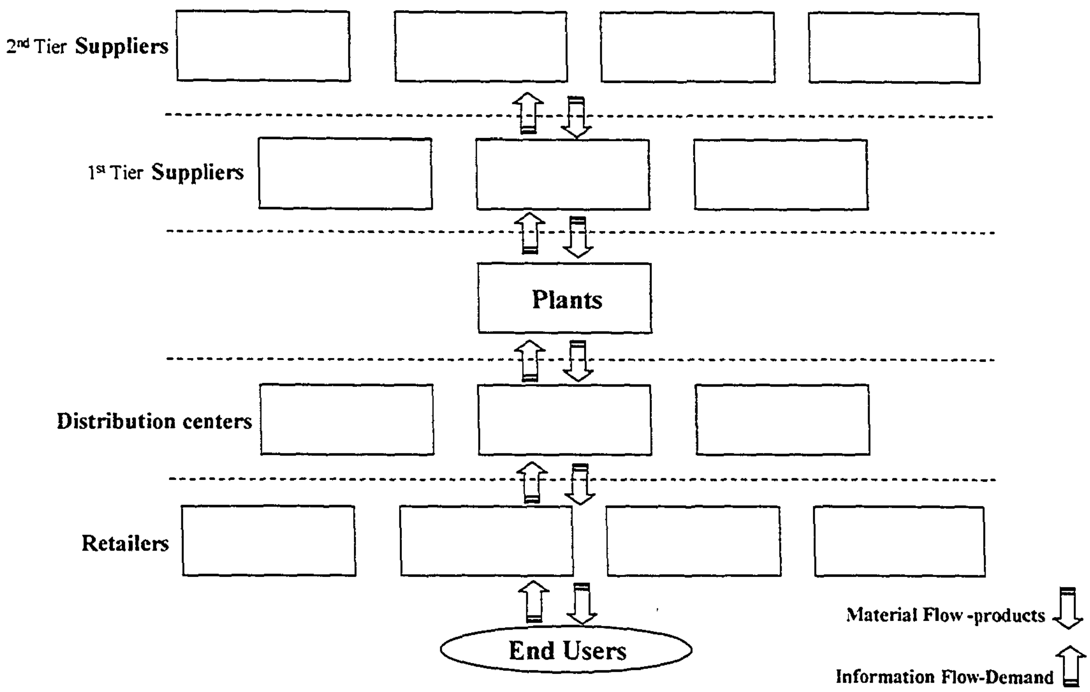

Figure 1.2. Supply chain flows

First-tier suppliers are the first level suppliers that directly supply the manufacturing facility. The sub-tiers (2^{nd} tier,3^{rd} tier,...) are the suppliers of the suppliers for the manufacturing facilities(i.e., 2^{nd} tire suppliers are the suppliers for the 1-tire suppliers,etc.) which are mostly smaller companies as shown in Figure1.3.

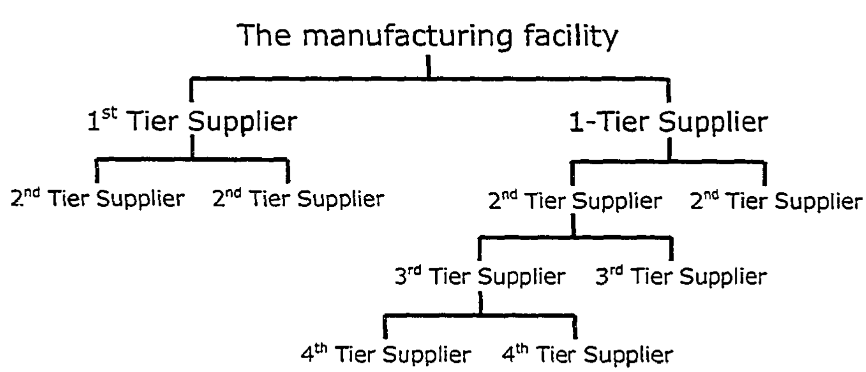

Figure1.3. Different levels of suppliers in a supply chain network

Supply chain management (SCM) is a set of approaches that efficiently integrate suppliers, manufacturer, distribution centers and retailers so that the product is produced and distributed at the right quantities to the right locations and at the right time in order to minimize system-wide costs while satisfying service level requirements (Simchi-Levy, et al.,2004).

Companies realized that by transferring costs either upstream or downstream, they are actually not increasing their competitiveness, since all costs ultimately make their way to the consumers. Thus, the emphasis in the supply chain management is on the co-operation of all the members with the common goal to increase the overall sales and profitability, rather than competing for a bigger share of a fixed profit.

1.2. Integrated supply chain management:

Supply chain management refers to the integrated planning of all the activities through the supply chain network. The evolution of this integration is described in three phases:

1) *Functional integration* of purchasing, manufacturing, transportation and warehousing activities (1960-1970).
2) *Internal integration* of these activities, where managing all the supply chain activities of a facility is integrated and defined as the responsibility of a single management (1980s).
3) *External integration (1990s):* This refers to management of supply chain functions, whereby they are unified through cooperation and coordination between upstream and downstream entities of the chain in order to maximize the

benefit of the total system. External integration is also called the integration of the location, production, inventory and distribution decisions of supply chain over strategic, tactical and operational planning horizons. Strategic planning is related to the decisions made over a longer time horizon which are closely linked to the corporate strategy, and guide the supply chain policy from a design prospective. Tactical planning involves decisions that are made over a medium term planning horizon which are typically performed on a monthly or weekly basis. Operational decisions are short term and focus on activities on a day to day basis. The effort of operational decisions is to effectively and efficiently manage the product flow in the "strategically" planned supply chain (Ganeshan and Hill, 1995; Ganeshan, et al., 1999).

1.3. Value of information sharing in a supply chain:

Information serves as the connection between the supply chain's various stages, allowing them to coordinate and bring about the benefits of maximizing the total supply chain profitably.

Having accurate information on inventory levels, demands, orders, production and delivery status throughout the supply chain provides a tremendous opportunity to improve the way a supply chain is designed and managed. In a typical supply chain information is used to:

- Reduce total Cost
- Increase system responsiveness
- Reduce system uncertainty

- Reduce lead-time
- Ease the coordination of manufacturing and distribution systems and strategies
- Reach better customer service by offering tools for locating desired items.
- Help suppliers and manufacturer make better forecasts

In order to describe and measure information, we introduce fundamental characteristics of information that supports enterprise planning and operations. These characteristics are (Talluri, 2000; Feltham, 2003):

i) ***Relevance:*** The information produced must be relevant to the decision making process otherwise it doesn't warrant the cost of producing it and does not reduce uncertainty. Relevance is being suggested as an important criterion for information. As stated in Feltham (2003), "to have information used for the purpose, in which it has no relevance is likely to be worse than having no information at all".

ii) ***Availability:*** Availability is defined as the ease of access to the existing information. Information in a supply chain must be consistently available since availability is necessary to gain responsiveness, improve decision-making and reduce uncertainty in the supply chain.

iii) ***Accuracy:*** Accuracy of the information is defined as the degree to which it matches the actual status of the system. Demand forecasts are a good example of the significance of information accuracy. Accurate information is important to reduce uncertainty in a supply chain.

iv) ***Timeliness:*** Timeliness of the information is defined as the delay between the moment an activity happens and the time its information is registered in the system. It shows how much of the actual information is registered in the system at the moment. Demand information is a good example of this characteristic. In many cases information regarding the last period's demand will be updated with a time lag of minutes, hours or even days. Real-time updates are timelier and more costly due to the additional record-keeping efforts.

v) ***Periodicity:*** Periodicity is defined as the information retrieval frequency from the system. Reports are generated on a periodic basis (e.g., daily or weekly) on the retrieved information, to assist managing and control of the supply chain.

Each one of these characteristics has the potential to reduce uncertainty, increase responsiveness and efficiency of the system if employed properly.

Two major types of information sharing are defined in a supply chain:

i) Traditional information sharing: In traditional sharing, the upstream member of the supply chain is unaware of the downstream member's demand or order policy and only observes their orders. For example, the supplier receives no information other than the orders from the retailer (Figure 1.4) (Gavirneni, et al., 1999).

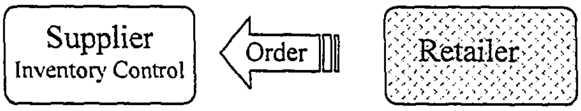

Figure1.4. Traditional information sharing in a two-level supply chain

*ii) **Full information sharing:*** In this approach, upstream member of the supply chain has immediate access to downstream member's inventory data, demand distribution they are faced with, their order policy and its parameters and immediate information about their demand. For example the supplier has all the information about the retailer's review policy, its parameters and also the order it is facing as shown in Figure 1.5 (Gavirneni, et al., 1999).

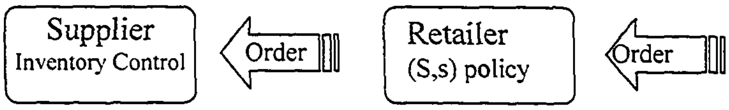

Figure1.5. Full information sharing in a two-level supply chain

Sharing demand information has also been viewed as a major strategy to counter the so called "bullwhip effect" which causes demand distortion. The "bullwhip effect" is essentially the phenomenon of demand variability amplification along a supply chain, from the retailers, distributors, manufacturers, and their suppliers. Inaccurate demand forecasts, low capacity utilization, excessive inventory and poor customer service are the results of bullwhip effect (Lee, et al., 1997).

By sharing demand information and letting the upstream member have visibility of the point-of-sale data the harmful effects of demand distortion can be reduced significantly. Demand information sharing by a downstream operator with upstream members is the cornerstone of initiatives such as quick response (QR), efficient customer response (ECR), vendor managed inventory (VMI) and continuous improvement (CR) (Lee, et al., 2000).

Information sharing also contributes to the reduction of lead-times and shipment frequency by increasing certainty and reducing the time and cost to process orders. The value of information sharing is significantly influenced by the demand pattern, the forecasting model used and the capacity tightness.

Information system in this research refers to both hardware and software. Hardware includes the physical tools, and software includes the rules and algorithms used to work with the hardware. We also define information as that which reduces uncertainty (Glazer, 1993). The value of information will be measured by the ability to reduce uncertainty in the supply chain.

1.4. Scope of the study:

Based on the discussion outlined above, it is proposed to develop an integrated model for a supply chain management system with information as a decision variable with associated costs and timeliness factors. This model would be used to measure the value of sharing demand information and also the impact of lead-time variations (as one of the key parameters of the supply chain network) on the operational costs of the supply chain network.

The proposed model is based on the model developed by Dominguez (2002), which has been modified and extended as appropriate. The modeling of the supply chain has been done in the context of the business operations of a major household appliance manufacturer located in Mexico.

The company is a manufacturer of plastic and stamped components, transmissions for washers, electric motors and compressors, as well as finished appliances. It operates 7 plants and 8 distribution centers in Mexico and produces and distributes over 200 products in the domestic and export markets. The company has approximately 8,000 employees and its total annual sales were estimated at around 700 million dollars (US) in 2001(Dominguez, 2002).

The major characteristics of the supply chain, as stated in Dominguez (2002), are:

i) Seasonal demand patterns

ii) Long lead-times

iii) Separate inventory management systems for manufacturing facilities and distribution centers.

In order to develop a general model of the supply chain management system in the appliance industry, the following changes /modifications are introduced in the model by Dominguez (2002):

1) The role of information sharing in the operation of the supply chain has been enhanced to improve the demand forecasting method. Then the relationship between the timeliness factor of the shared information and the demand forecast error values has been investigated.

2) The prevailing view in the literature on supply chain systems is that a decentralized safety stock policy is preferable in order to increase customer satisfaction and service level. In keeping with this view, a decentralized safety stock policy has been adopted as the only available option at each manufacturing facility.

3) The matter of accounting for labor hours, which was originally based on the Mexican labor laws, has been changed to reflect the labor standards in North America.

These modifications will be discussed with more details in Chapter 3.

CHAPTER 2: LITERATURE REVIEW

Logistics management, focusing on different functions such as purchasing and transportation, has evolved over the last two decades into a broader management philosophy known as Supply Chain Management (SCM). As supply chain management has become a major sub-topic of production and operation management, the literature has grown accordingly. In this Chapter we present a review of the supply chain management literature, focusing on information sharing and lead-time studies in supply chain.

2.1. Supply chain management evolution:

Supply chain management concepts have been originally developed in the works of Hanssmann (1959) and Clark and Scarf (1960) on multi-echelon inventory systems.

Several trends in logistics management have emerged subsequently. Each of these broadened while improving the focus of the earliest literature. The *cost-cost* tradeoffs notion was introduced to present that the lowest total cost might not be achieved by pursuing the lowest cost of each logistics process constituent. Hence, the concept of logistics integration was introduced by Bowersox (1969).

Many companies recognized the fact that in optimizing logistics costs, all relevant sub-tiers inside and outside of the firm must be included with their physical and information flows. It became a challenge for logistics managers to integrate logistical performance across all operating entities of a supply chain. Meanwhile, researchers such as Houlihan (1985, 1988), Lee and Billington (1993), Cooper and Ellram (1993), and

Thomas and Griffin (1996) started to introduce and implement the supply chain management concepts.

Huang, et al., (2002) developed and implemented a model to assist organizations in the selection of the supply chain. They classified manufacturing supply chains into three types; lean, agile and hybrid, then presented the characteristics of these supply chains and proposed that to achieve an optimal performance the selection of an appropriate supply chain should be driven by the characteristics of each organization's product.

Singh (2003) studied the emerging technologies supporting supply chain management. He outlined important developments in supply chain management and supply chain infrastructure including technologies in optimization and modeling systems, which have had a remarkable imprint on supply chain decision making and discussed the developments in communication devices and software, optimization, constraint programming and artificial intelligence and their role in supply chain decision making.

Gupta and Costas (2003) studied demand uncertainty in a multi-site supply chain. They used a stochastic programming based approach to model the planning process as it reacts to demand realizations over time. In theirs model the manufacturing decisions were made before demand realization while the logistics decisions were postponed to optimize in the face of uncertainty. In addition, the trade-off between customer satisfaction level and production costs was also captured in the model. The proposed model provided an effective tool for evaluating and actively managing the exposure of enterprises assets (such as inventory levels and profit margins) to market uncertainties.

Bandyopadhyay and Sprague (2003) focused on the implementation of total quality management in the automotive industry supply chain. They described how a TQM (Total

Quality Management) approach can be implemented throughout the supply chain, from product design to supplier certification, to achieve supply chain quality management in manufacturing industry.

Ioannou, et al (2004) have addressed the problem of inventory positioning, in a multi product supply chain with normally distributed demand, from a design perspective .The objective was to minimize the inventory-holding cost with a pre-specified order fill rate. They formulated a comprehensive model and proposed an analytical approach for determining the supply chain node in which inventory should be held, in order to minimize the inventory-holding cost under service level constraints.

2.2. Information sharing in supply chain:

Bourland, et al. (1996), Chen (1998), Aviv (1998) and Gavirneni, et al. (1999), showed how sharing demand and inventory information can improve the supplier's order quantity decisions in models with known and stationary retailer demands. Gavirneni, et al. (1999) measured the benefit of sharing the parameters of the retailer's ordering policy with the supplier. Lee, et al. (2000) and Raghunathan (2001) used shared information to improve the supplier's order quantity decisions in a serial system with a known non-stationary demand Process. Thonemann (2002) analyzed the impact of sharing advanced demand information on the supply chain performance.

The reported benefits of information sharing vary considerably. Lee, et al. (1997) found that sharing information reduces the supplier's demand variance, which should benefit the supply chain, but they did not quantitatively measure this benefit. Chen (1998) showed that by sharing demand and inventory information, supply chain costs were lowered up to 9%. Aviv (1998) reported cost reduction up to 5%. Gavirneni et al. (1999) reported that sharing the retailer's demand data reduces the supplier's cost up to 35% .In Lee, et al. (2000) research information sharing in supply chain resulted in cost reduction of about 23% while Cachon and Fisher (2000) result showed that sharing information can reduce total cost up to 12% (variations in the reduced costs are mostly because of the fact that these results are from studies on different supply chain networks with different characteristics, using different aspects of information sharing in the supply chain).

Feldmann and Muller (2003) focused on the problem of deliberately falsified data, reported in the supply chain. They studied different reasons for deficits in release and transmission of information, reviewed the various incentive schemes and presented one to establish a tendency towards providing true and reliable information in the supply chain.

Croson and Donohue (2003) examined the impact of sharing point of sale (POS) data on the ordering decision in a multi-echelon supply chain from a behavioral prospective. They focused on how exposure to POS data may help reduce the "bullwhip effect".Using a simulation experiment; they found that sharing POS information can reduce the order oscillation of upstream members.

Kemppainen and Vepsalainen (2003) focused on the development of supply chains and networks in industrial companies, the expected growth in use of supporting IT systems, extent of information sharing and the scope of coordination efforts. Their studies which are based on empirical data from 25 Finish industrial supply chains, showed that among all the information systems, order handling and inventory management systems are the ones which are actively used and implemented by most of the companies while supply chain planning systems are implemented by only a few (Figure 2.1).

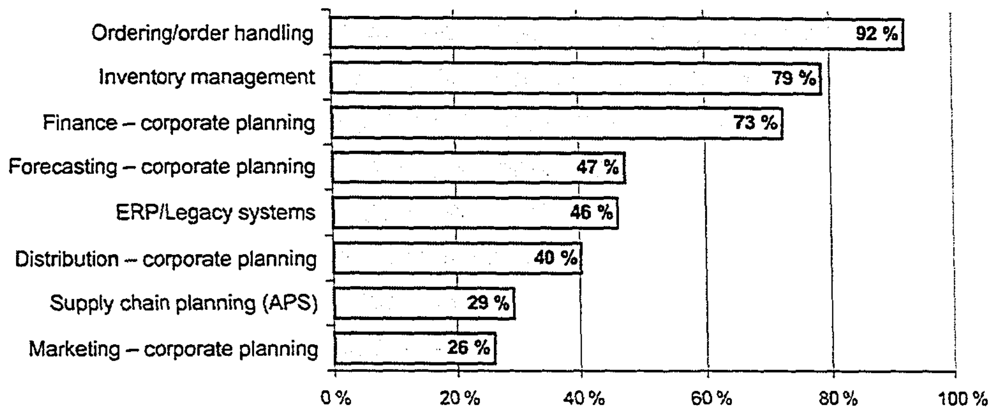

Figure 2.1. The average use of information systems within a company, (Kemppainen et al. 2003)

Their studies also indicated that the order-spec information such as lead-times and order status are shared more than planning information, i.e., production and sales, in a supply chain(Figure 2.2).

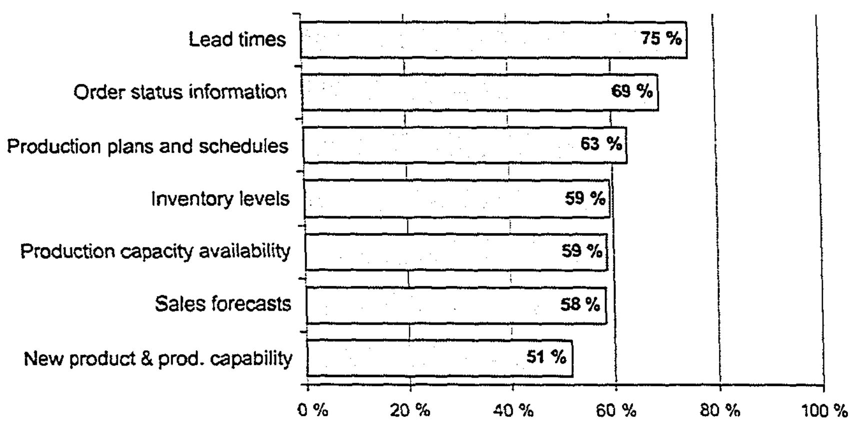

Figure 2.2. The average information sharing within a supply chain (Kemppainen, et al. ,2003)

Kalchschmidt, et al. (2003) studied integrated inventory management in a multi-echelon spare part supply chain with variable and lumpy demand pattern. They started with a situation of extremely variable demand where no information was provided along the supply chain and inventory control at the various echelons of the chain was completely decentralized .They then showed that fine comprehension of the sources of demand variability, a probabilistic forecast and inventory management leads to performance improvement in the supply chain .In addition they showed that a proper collection of information regarding the purchasing plans of a few large customers (i.e. that usually contribute significantly to the total variance of demand) can improve the performance of the supply chain substantially.

Eng (2004) investigated the extent to which e-business tools of the e-marketplace are used by channel members in the retail sector for supply chain management. Their study was based on a survey involving food service companies, retailers, and wholesalers in the UK. It showed that the e-marketplace supply chain applications enable the majority of companies to automate transaction based activities and procurement-related processes rather than strategic supply chain activities. The results also indicated that full participation in e-marketplaces requires companies to integrate their internal and external supply chain activities and share strategic information.

Themistocleous, et al. (2004) investigated the integration of supply chain management systems through enterprise application integration (EAI) technologies. They introduced an evaluation framework for assessing integration technologies that were used to unify inter-organizational and intra-organizational information systems. They defined and classified the permutations of available information systems according to their characteristics and integration requirements. These classifications of system types were then adopted as part of the evaluation framework and empirically tested within a case study.

Williamson, et al. (2004) analyzed the development and role of inter-organizational information systems within supply chain management and their impact on the effectiveness of the supply chain. They categorized their studies into communication improvements, supplier relations and customer service improvements of a supply chain and described and studied the impact of an inter-organizational information system and internet in each category.

Machuca and Barajas (2004) used a web-based supply chain simulator to demonstrate the potential benefits of using Electronic Data Interchange (EDI) in supply chain management. The simulation experiment measured the impact of EDI on mean inventory costs, orders placed, cumulative cost, amplification and net excess stock in the supply chain. The results showed that the comprehensive use of EDI provides substantial cost savings as well as notable improvements in supply chain management

Gunasekaran and Ngai (2004) reviewed and classified the literature on information systems in supply chain integration and management using suitable criteria like strategic decisions, potential areas of IT applications in SCM (Supply Chain Management) and the level of interaction between various constituents in developing an effective supply chain. They critically developed a framework for the development and implementation of IT in SCM. Based on their reviews they made following suggestions:

- The strategic information systems should include the strategic objectives of SCM.
- Information systems architecture must be specially designed for supply chain management which could be different from that of traditional organizations.

- Successful strategic information systems require major changes in how a business operates both internally and with external partner.

Ahn and Lee (2004) proposed an agent -based approach to improve the global efficiency of a supply chain by enabling participating companies to form a reasonably efficient supply chain dynamically and also to minimize the bullwhip effects in a supply chain via information sharing among co-operative agents. for this purpose they presented an agent-based dynamic information network for supply chain management (ADINS) and discussed its associated pros and cons.

Simchi-Levi and Yao (2004) studied the impact of information sharing on the forecasting accuracy in a multi-stage distribution system with stationary demand. They considered a simple supply chain with a single manufacturer, single distribution center and multiple retailers with and without order information sharing .Their study showed that sharing order information improves the manufacturer's forecast accuracy relative to no information sharing.

2.3. Lead-time studies in supply chain:

So and Zheng (2003) studied the impact of supplier's lead-time and demand forecast updating on retailer's order quantity variability .They used a two-level(supplier , retailer) supply chain model to study how the supplier's variable lead-times and the correlation of the external demands can amplify the variability of the order quantities of the downstream member in the supply chain. Based on analytical and numerical results, they made the following conclusions:

- Supplier's variable lead time can greatly increase the order quantity variability of the retailer.
- Demand correlation can also increase the order quantity variability of the retailer.
- The amplification of order quantity variability is especially pronounced when the demand correlation is high, the variability of the demand process is large, and the capacity utilization at the supplier is high.

Cakanyildirim and Luo (2003) studied lead-time options in a two-level (manufacturer and retailer) supply chain where the retailer used the (*R; Q*) inventory policy and numerically illustrated the benefits of lead-time options in improving supply chain performance. They established the optimal lead-time policy and provided an approximation for the critical levels associated with the lead-time policy. Their studies showed that *R* is much more sensitive to lead- time than *Q*.

Li, et al. (2004) studied the information transformation in a single-item, multi-stage (with one member at each stage) supply chain. They studied the impact of lead-time on the bullwhip effect and the so called "lead-time paradox". Their results showed that information transformation decreases at the higher stages of the supply chain due to long lead-times at a lower stage of supply chain.

Treville, et al. (2004) investigated the role of lead-time reduction in improving the demand chain performance. They suggested that manufacturing facilities with short lead-times should concentrate on demand information sharing, and manufacturing facilities with long lead-times on integrating their planning and forecasting activities with their customers. They also proposed that improvement of lead-times should be prioritized by demand information sharing.

Talluri, et al. (2004) presented a model for managing supply chain safety stocks in a large company with variable demand and lead-time. Their results emphasized the importance of the accuracy of the forecasting models and lead-times, which both have a great impact on safety stock level. They also suggested using centralized inventory for slow moving items and decentralize inventory policy for fast moving items.

Chopra, et al. (2004) studied two major areas that managers look into to reduce inventories in a supply chain without hurting the service level; reduction of the replenishment lead-time from suppliers and the variability of this lead-time. They proposed the existence of a service-level threshold greater than 50%, below which reorder points increase with a decrease in lead-time variability. They concluded that, for a firm operating just below this threshold, reducing lead-times decreases reorder points, whereas reducing lead-time variability increases reorder points. Also for firms operating at these service levels, decreasing lead-time is the right tool if they want to cut inventories, not reducing lead- time variability.

Hosoda and Disney (2004) investigated a three-stage supply chain model with stationary demand, using combination of statistical model, control theory and simulation. Their analysis revealed that the level of supply chain has no impact upon bullwhip effect; rather bullwhip effect is determined by the accumulated lead-time from the customer. They also found that the conditional variance of forecast error over the lead-time is identical to the variance of inventory.

Zhang (2004) studied the impact of forecasting method on the bullwhip effect for a replenishment system in which a first-order autoregressive process describes the customer demand and an order-up-to inventory policy characterizes the replenishment decision. His results showed that forecasting methods play an important role in determining the impact of lead-time and demand autocorrelation on the bullwhip effect.

Considering the literature, with respect to the studies on the value of information and the lead-time variations in supply chain, to our knowledge no studies have considered the impact of timeliness factor of shared information on the demand forecasts and the demand forecast errors in a supply chain network with seasonal demand pattern.

In this thesis we will use the potential advantage of information sharing to update our demand forecasts. Furthermore, we propose a method to calculate demand forecast errors in accordance with the timeliness of the shared information. We will also study the impact of lead-time variation on the operational costs and safety stock levels in an integrated multi-product, multi-stage, multi-period supply chain management system, with shared information.

CHAPTER 3: MATHEMATICAL MODEL

The model developed in this thesis is built upon an existing mixed integer-programming model: the capacitated, multi-location, production-distribution model by Dominguez (2002), which was defined for a large appliance company located in Mexico. For the purpose of our research, some modifications and changes are made in the following components of the model:

1) Forecasting method
2) Safety stock policy
3) Demand forecast error calculation
4) Overtime labor hour calculation

These modifications are described in details in the following sections.

3.1. Forecasting method:

There is often a time lag between the occurrence of an event, and awareness of the event. This lead-time is the main reason for planning and forecasting (Markridakis, 1998).

Forecasting is an integral part of the decision making activities of management. The need for forecasting is increasing as management attempts to decrease its dependence on chance and become more scientific in dealing with its environments. Since each area of an organization is related to all others, a good or bad forecast can affect the entire organization. Scheduling, acquiring resources and determining resource requirements are some of the areas in which forecasting plays an important role.

Forecasting situations vary widely in their time horizons, factors determining actual outcomes, type of data patterns and many other aspects. In order to deal with such diverse applications, several forecasting techniques have been developed that would be employed according to the available information about the actual status. Winters' method is a quantitative forecasting technique mostly used to forecast time series for which trend and seasonality components are known.

In Winters' method at the end of period t, the forecast for period $t + \tau$ is calculated as follows (Nahmias, 2001):

$$F_{t+\tau} = \begin{cases} (S_t + \tau . G_t).\, C_{t+\tau-N} & \tau \leq N \\ (S_t + \tau . G_t).\, C_{t+\tau-2N} & N < \tau \leq 2N \\ (S_t + \tau . G_t).\, C_{t+\tau-3N} & 2N < \tau \leq 3N \end{cases}$$

where:

$F_{t+\tau}$: the forecast for period $t + \tau$

N: the number of periods in the length of the seasonal pattern

S_t : the estimate of the base level

$$S_t = \alpha(D_t / C_{t-N}) + (1-\alpha)(S_{t-1} + G_{t-1})$$

D_t : the demand for period t

C_t : the estimate of a seasonal multiplicative factor for month t

$$C_t = \gamma(D_t / S_t) + (1-\gamma)C_{t-N}$$

Gt: the per-period trend

$$G_t = \beta(S_t - S_{t-1}) + (1-\beta)G_{t-1}$$

α, γ, β: the smoothing constants in the range of $0< \alpha, \gamma, \beta<1$

In order to calculate the initial estimates of the base (S_0) and the trend (G_0), the average demand in each of the last two seasons must be calculated (V_1 and V_2) then the initial values are calculated as follows:

$$G_0 = \frac{V_2 - V_1}{N}$$

$$S_0 = V_2 + G_0 \frac{N-1}{2}$$

In forecasting, the word "accuracy" refers to "the goodness of fit" which in turn refers to how well the forecasting model is able to reproduce the actual data. To the customer of forecast it is the accuracy of the future forecasts that is most important. Accuracy of the forecast is calculated for various purposes. One primary use is to gauge the accuracy of the forecasting system. Another is to track the flow of errors in order to monitor and control the system seeking the best forecasting model and parameter combination. An extremely important use is to apply a measure of the errors in setting the appropriate level of safety stock for each item. This is needed to provide an acceptable level of customer service (Makridakis, 1998).

The demand forecast error is the difference between the forecasts and the demand, and it is a highly useful observation in controlling he forecasts. Calculating the standard deviation of the demand forecast error, σ, is one of the most common methods of measuring the accuracy of the demand forecast .In this research we calculate the demand forecast error σ by:

$$\sigma = \frac{\sqrt{\sum_{t=1}^{T} (FD_t - AD_t)^2}}{(N-1)}$$

where:

σ : is the demand forecast error standard deviation for the product

FD_t: is the forecasted demand for the product in period t

AD_t: is the actual demand for the product in period t

N: is the total number of periods.

3.1.1. Proposed demand forecast technique:

In the model developed by Dominguez (2002), the distribution centers' demands were forecasted using Winters' method at the beginning of the planning horizon based on historical demand data.

In today's competitive business environment, companies need to respond quickly to changes in customer demands. Thus, timely and accurate estimates of the demand are essential if the company wants to adjust the outputs rapidly to match market demand .

In this regard, with an approach to the value of information sharing, a modified version of Winters' method is proposed to calculate a more accurate demand forecasts. The proposed method combines Winters' method with the concept of rolling horizon to update the demand forecasts.

In Winters' method the forecasts can be updated, when new information about the demands is received using the following steps:

1) Recalculating S_t (the estimate of the base level), G_t (the trend) and C_t (the estimate of a seasonal multiplicative factor) for period t (the period for which we received new information).

2) Updating the demand forecasts $F_{t+\tau}$ for the next periods.

Rolling horizon refers to the situation in which only the first-period decision of an N-period problem is implemented. The full N-period problem is rerun each period to determine a new forecast period's decision. This means that at the time of next decision a new forecast of demand is appended to the former forecasts, and the old forecast might be revised to reflect the new information.

The proposed method uses the last period's actual demand information to update the rest of the demand forecasts, at the beginning of each period using the Winters' forecast update method as shown in Figure 3.1.

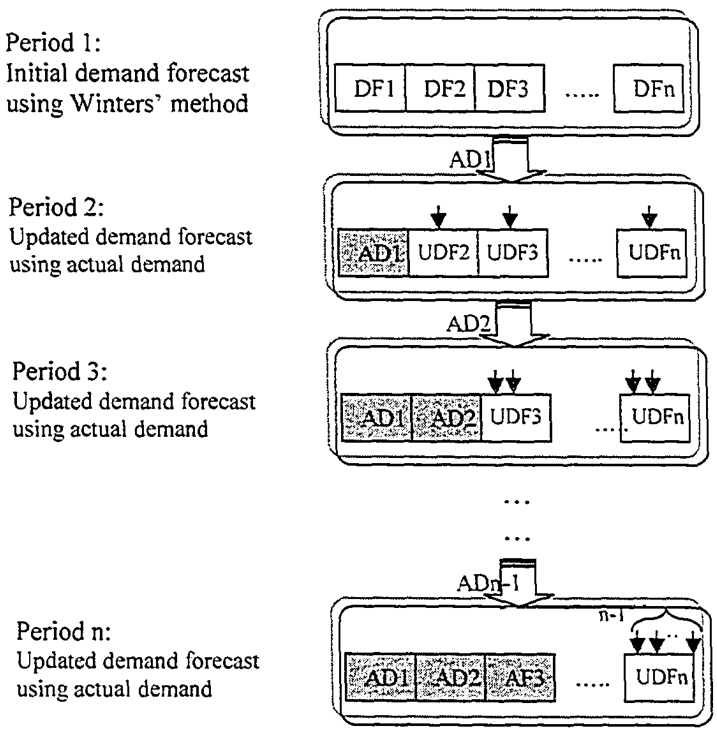

Figure 3.1. Demand forecast update method. DF_i is the demand forecast for period i. AD_i is the actual demand for period i. UDF_i is the updated demand forecast for period i. ↓ means updated demand.

Consider a twelve period system with twelve demand forecasts. At the end of period one, the actual demand for period 1 is available (it's accuracy being dependent on how timely the information system is), and is used to update the demand forecast for periods 2, 3,...,12. At the end of period 2, it's actual demand would be used to update demand forecast for periods 3, 4,..., 12. At the end of period 3, it 's actual demand would be used to update demand forecast for the periods 4,5,...,12, and so on .

Updating the demand forecast using the proposed method results in a more realistic realization of the demand, and a significantly smaller demand forecast error values. Table 3.1 shows the demand forecast values for the traditional methods (without updating) and the proposed method (with updating) for 3 sample products.

	σ_{pnk} *(Units of Product)*	
Product ID #	Traditional method	Proposed method
P1N1K4	6.51	5.5
P6N1K1	358.33	292.12
P5N3K1	757.44	461.73

Table 3.1. Examples for comparing the forecast errors using the traditional and proposed methods. ($P_p N_n K_k$, represents product family *n*, produced at manufacturing facility *p*, kept at distribution center *k*)

3.2. Safety stock policy:

Dominguez (2002) introduced two safety stock policies:

- ***Centralized policy***, in which the safety stock is pooled at each manufacturing facility and the related costs are the premium information and transportation cost, and the cost of holding inventory.
- ***Decentralized policy***, where safety stock is kept at each distribution center and the related costs are the transportation cost and the inventory holding cost.

According to the desired level of customer service during lead-time and the trade-offs between the two strategies, the model would choose the optimal safety stock policy for each product at each manufacturing facility.

In the proposed model the decentralized safety stock policy is the only option available for each manufacturing facility according to the fact that nowadays with the new market trends that makes customer satisfaction the main objective of each service activity, those inventory policies that keep inventories closer to the customers are most preferred, to increase the customer satisfaction and service level. As a result the safety stock related costs in our model include the transportation and the holding cost (for more information please refer to Section 3.5.2.8).

3.3. Demand forecast error calculation:

Demand forecast error calculation will be discussed in details in Section 3.5.3.19.

3.4. Overtime labor hour calculation:

The model of Dominguez (2002) computes the overtime hours according to the Mexican labor laws. In this method, workers are committed to complete a certain number of contractual hours over the planning horizon (not necessarily uniformly distributed over the periods). At the end of the planning horizon, based on the difference between the workers' total working time and their contractual working time over the planning horizon, their overtime/undertime working hours will be calculated:

$$O_p = \sum_{t=1}^{T} (f_{pt}^{+} - f_{pt}^{-}) \qquad (\forall\ p=1 \ldots P)$$

where,

O_p is the total overtime scheduled at the end of planning horizon at manufacturing facility p.

f^+_{pt} is the additional labor hours at manufacturing facility p in period t

f^-_{pt} is the reduced labor hours at manufacturing facility p in period t

There is also an additional cost to be paid for any extra labor hours at each manufacturing facility in any period (R_p).

For the purpose of generalization, we change this to the standard overtime evaluation method which calculates the worker's overtime hours at the end of each period (for more information please refer to Section 3.5.2.4).

3.5. Mathematical model formulation:

The supply chain under consideration consists of the following components: There is a set of manufacturing facilities P with the indices $p=1,\ldots, P$, each producing a set of product families N with indices $n=1,\ldots,N$. Product families are sold in a set of distribution centers K with indices $k=1,\ldots,K$. The planning horizon is uniformly divided into T time periods with indices $t=1,\ldots,T$. There is also a set of transportation modes J with indices $j=1,\ldots,J$ to move the finished goods from the manufacturing facilities to distribution centers. We assume a set of inventory review policies i with indices $i = 1,\ldots,I$ which differ in their cycle lengths. We also consider a set of information systems M with indices $m = 1,\ldots,M$ that represent the different options that can be used to collect inventory information at various levels of accuracy (timeliness factor) at manufacturing facilities.

In the formulation of the model the following assumptions are considered (Dominguez, 2002):

- We have constraints on labor-hours not on machine hours.
- Time value of money over the planning horizon is not considered except for the purchase and operating costs of information systems that are expressed as uniform equivalent annual costs.
- No sub-contracting is allowed because of the policy of the company.
- Overhead costs are considered to be constant.
- Items in the same product family have similar characteristics in terms of size and the number of labor hours employed to produce them.
- Manufacturing setup costs are negligible due to the flexible manufacturing system that operates in the company.
- Service level to clients remains constant and is set as a strategic planning parameter.
- Manufacturing facilities and distribution centers are two points of data entry. This is important to know because two different business entities must match their information of what has been produced versus what has been received. This is due to the fact that the company's manufacturing operations are separated from its distribution activities.

3.5.1. Notation:

i. Index Sets:

p = Index for manufacturing facilities, $p \in \{1 \ldots P\}$

n = Index for product family produced at manufacturing facility p, $n \in \{1 \ldots N\}$

j = Index for transportation mode, $j \in \{1 \ldots J\}$

k = Index for distribution center, $k \in \{1 \ldots K\}$

t = Index for time period, $t \in \{1 \ldots T\}$

m = Index for Information system $m \in \{1 \ldots M\}$

i = Index for periodic-review policy, $i \in \{1 \ldots I\}$

ii. Decision Variables:

TU_{pjkt}	Number of mode j transportation units used to ship products from manufacturing facility p to distribution center k in period t.
X_{pnt}	Number of units of product family n produced at manufacturing facility p in period t.
Y_{pnjkt}	Units of product family n shipped from manufacturing facility p in mode j to distribution center k in period t.
I_{pnt}	Inventory of product family n in manufacturing facility p at the end of period t.
I_{pnkt}	Inventory of product family n produced at manufacturing facility p in distribution center k at the end of period t.
IT_{pnjkt}	In-transit inventory of product family n in mode j from manufacturing facility p to distribution center k at the end of period t.
O_{pt}	Total overtime scheduled at manufacturing facility p *in period* t.
W_{pt}	Total regular labor-hours available for manufacturing facility p in period t.
W_{pt}^{+}	Increase in labor hours at manufacturing facility p from period (t-1) to t (Hiring).
W_{pt}^{-}	Decrease in labor hours at manufacturing facility p from period (t-1) to t (Lay-off).
β_{pi}	1 If cycle length in periodic-review policy i is in effect and 0 otherwise.
δ_{pm}	1 If information system m is used at manufacturing facility p and 0 otherwise.
r_{pnmt}	Linearization auxiliary variable which equals $\gamma_{pmnt}X_{pnt}$ if δ_{pm} equals 1 and 0 otherwise.
Ln_{pmi}	Linearization auxiliary variable which equals 1 if δ_{pm} and $\hat{L}'_{pmi}$ equal 1 and 0 otherwise.
DS_{pnk}	Decentralized safety stock of product n produced at manufacturing facility p in DC k

iii. Parameters:

L_p	Cost of a regular labor-hour at manufacturing facility *p*.
$L_p^{'}$	Cost of a labor-hour on overtime at manufacturing facility *p*.
C_p	Cost to increase the labor-hour level by one labor-hour at manufacturing facility *p* (includes the organizational cost of hiring and training cost).
$C_p^{'}$	Cost to decrease the labor-hour level by one labor-hour at manufacturing facility *p* (includes the organizational cost of reducing labor–hours and compensation cost).
CM_{pn}	Cost of raw materials required to produce one item of product family *n* at manufacturing facility *p*.
h_{pn}	Inventory carrying cost for a unit of product family *n* produced at manufacturing facility *p* held from one period to the next in the same facility (includes capital cost, space cost, insurance cost, and obsolescence).
h_{pnk}	Inventory carrying cost for a unit of product family *n* produced at manufacturing facility *p* held from one period to the next in distribution center *k*.
TC_{pjk}	Transportation cost of one shipment from manufacturing facility *p* to distribution center *k* using transportation mode *j*.
Th_{pn}	In-transit inventory carrying cost for an item of product family *n* produced at manufacturing facility *p* held from period *t-1* to *t* (includes capital and insurance costs).
Θ_p	Maximum overtime allowed at manufacturing facility *p* (the ratio of overtime labor hour capacity to regular time labor-hour ,$\Theta_p < 1$).
a_{pn}	Number of labor-hours required to produce one unit of product family *n* produced at manufacturing facility *p*.
D_{pnkt}	Expected demand for product family *n*, produced at manufacturing facility *p*, at distribution center *k* in period *t*.
IC_p	Inventory capacity of manufacturing facility *p* in terms of available floor area.
IC'_{kt}	Inventory capacity of distribution center *k* in period *t* in terms of available floor area.
S_{pn}	Floor area required per item of product family *n* produced at manufacturing facility *p*.
V_{pn}	Volume (cubic space) of an item of product family *n* produced at manufacturing facility *p*.
LT_{pjk}	Lead-time of transportation mode *j* from manufacturing facility *p* to distribution center *k*.
FTL_j	Capacity of a mode *j* full transportation consignment in terms of Volume (cubic space)
PC_{pt}	Labor hour upper limit for manufacturing facility *p* in period *t*.
TLT_{pk}	Average Lead-time from manufacturing facility *p* to distribution center *k*.
λ	Strategic inventory factor which ensures availability of inventory at the beginning of each period.
MLT_{pn}	Average Lead-time to produce a family *n* item at manufacturing facility *p*.

iii. Parameters-continued:

PI_{pnk}	Demand forecast error equation slope(as a function of the information system timeliness factor) for product family *n* in manufacturing facility *p* sold in distribution center *k*.
PII_{pnk}	Demand forecast error equation intercept (as a function of the information system timeliness factor) for product family *n* in manufacturing facility *p* sold in distribution center *k*.
z_α	Value of the standard normal variable in which the Standard Normal Cumulative probability is α (Normal deviate). This variable is used to represent service level.
CP_{pi}	Fixed cost of the information system (information gathering, communications required and planning costs) using periodic-review policy i at manufacturing facility *p*.
γ_{pm}	Timeliness of inventory information factor at the production-distribution link for manufacturing facility *p* using information system *m*.
CI_{pm}	Cost of timeliness using information system *m* at manufacturing facility *p*
TP_{pi}	Cycle length for periodic-review policy *i* at manufacturing facility *p*
DSS_{pnk}	Decentralized safety stock for product family n produced at manufacturing facility p at distribution center k.

3.5.2. Objective Function:

The objective function of the model minimizes the total costs consisting of the following components:

1. Production cost: $\sum_{p=1}^{P} L_p \sum_{t=1}^{T} W_{pt}$

where L_p is the known cost per regular labor hour at manufacturing facility *p* and W_{pt} is the total regular labor hours available at manufacturing facility *p* in period *t*.

2. Cost of increasing labor: $\sum_{p=1}^{P} C_p \sum_{t=1}^{T} W_{pt}^{+}$

where C_p is the cost of increasing labor hours at manufacturing facility *p* (including organizational cost of hiring and training new personnel), and W_{pt}^{+} is the increase in labor hours at manufacturing facility *p* from period *t-1* to *t* (i.e., hiring).

3. Cost of decreasing labor: $\sum_{p=1}^{P} C_p^{'} \sum_{t=1}^{T} W_{pt}^{-}$

where $C_p^{'}$ is the cost of decreasing labor hours at manufacturing facility p (including organizational cost of laying-off workers, such as compensations and paper work), and W_{pt}^{-} is the decrease in labor hours at manufacturing facility p from period $t-1$ to t (i.e., layoff) .

4. Total overtime cost: $\sum_{p=1}^{P} L_p^{'} \sum_{t=1}^{T} O_{pt}$

where $L_p^{'}$ is the cost of one labor hour on overtime at manufacturing facility p, and O_{pt} is the scheduled overtime at manufacturing facility p at the end of period t.

5. Total transportation cost: $\sum_{p=1}^{P} \sum_{j=1}^{J} \sum_{k=1}^{K} TC_{pjk} \sum_{t=1}^{T} TU_{pjkt}$

where TC_{pjk} is the cost of transporting one consignment from manufacturing facility p to distribution center k, using transportation mode j, and TU_{pjkt} is the number of mode j transportation units used to ship products from manufacturing facility p to distribution center k in period t.

6. Cost of carrying inventory at manufacturing facilities: $\sum_{p=1}^{P} \sum_{n=1}^{N} h_{pn} \sum_{t=1}^{T} I_{pnt}$

where h_{pn} is the inventory carrying cost of product family n produced at manufacturing facility p held from one period to the next; it includes capital, space, insurance and obsolescence costs. These components usually depend on the company's financial policy. I_{pnt} is the inventory of product family n at manufacturing facility p at the end of period t.

7. Cost of carrying in-transit inventory: $\sum_{p=1}^{P}\sum_{n=1}^{N} Th_{pn} \sum_{j=1}^{J} \sum_{k=1}^{K} \sum_{t=1}^{T} IT_{pnjkt}$

where Th_{pn} is the in-transit inventory cost for a unit of product family n, produced at manufacturing facility p held from one period to the next; it includes the capital cost of the items held in-transit. IT_{pnjkt} is the in-transit inventory of product family n on transportation mode j from manufacturing facility p to distribution center k at the end of period t.

8. Cost of carrying inventory at distribution centers: $\sum_{p=1}^{P}\sum_{n=1}^{N} \sum_{k=1}^{K} h_{pnk} \sum_{t=1}^{T} I_{pnkt}$

where I_{pnkt} is the inventory of product family n produced at manufacturing facility p in distribution center k at the end of period t, and h_{pnk} is the corresponding inventory carrying cost .

9. Cost of inventory review policy: $\sum_{p=1}^{P}\sum_{i=1}^{I} CP_{pi} \ \beta_{pi}$

where CP_{pi} is the fixed cost of using the inventory periodic-review policy i at manufacturing facility p. The binary variable β_{pi} is one if the inventory review policy i is selected at manufacturing facility p and zero otherwise. The inventory review policy refers to the review and ordering discipline used in inventory control (i.e., how frequently should orders be placed).

10. Cost of Information system: $\sum_{p=1}^{P}\sum_{m=1}^{M} CI_{pm}\ \delta_{pm}$

where CI_{pm} is the cost of using information system m at manufacturing facility p. The binary variable δ_{pm} is one if information system m is used at manufacturing facility p and zero otherwise.

11. Cost of raw materials: $\sum_{p=1}^{P}\sum_{n=1}^{N}\sum_{t=1}^{T} CM_{pn}X_{pnt}$

where CM_{pn} is the cost of raw material required for producing one item of product family n at manufacturing facility p and X_{pnt} is the production level of product family n at manufacturing facility p in period t.

3.5.3. Constraints:

The model is subject to the following constraints:

12. Workforce level adjustment: $W_{pt} = W_{p(t-1)} + W_{pt}^{+} - W_{pt}^{-}$ $(\forall\ p=1 \ldots P;\ t=1 \ldots T)$

At the beginning of each period, the available workforce level (labor hours) is equal to the previous period's workforce level plus/minus the increased/decreased labor hours in the same period.

13. Workforce level adjustment: $\sum_{n=1}^{N} a_{pn}X_{pnt} = W_{pt} + O_{pt}$ $(\forall\ p=1 \ldots P;\ n=1 \ldots N,\ t=1 \ldots T)$

Total required labor hours in anytime period are equal to the allowable regular labor hours plus the overtime labor hours.

14. Maximum Overtime allowed: $O_{pt} \leq \theta_p W_{pt}$ ($\forall$ *p=1...P; t=1...T*)

Overtime labor hours in any time period cannot exceed a fixed percentage of the contractual hours.

15. Labor capacity Upper bound: $W_{pt} \leq PC_{pt}$ ($\forall$ *p=1...P; t=1...T*)

In any period, the total workforce level can not exceed a given upper limit that is the maximum available labor hours per time period in each manufacturing facility.

16. Shipment balance at manufacturing facility p :

$$16.1.\sum_{j=1}^{J}\sum_{k=1}^{K} Y_{pnjkt} \leq I_{pn(t-1)} + X_{pnt}\sum_{m=1}^{M}\gamma_{pm}\delta_{pm} \qquad (\forall p=1...P,\ n=1...N,\ t=1...T)$$

$$16.2.\sum_{m=1}^{M}\delta_{pm} = 1, \qquad (\forall p=1...P)$$

The amount of product family *n* produced at manufacturing facility *p* that is shipped to the distribution center *k* in period *t* cannot exceed last period's inventory level plus that part of period *t*'s production which has been registered in the database so far (depending on the timeliness factor of the selected information system).

Constraint set *16.2* ensures that each manufacturing facility selects only one information retrieval system .

16.3. Linearization:

Constraint 16.1 is nonlinear because of X_{pnt} and δ_{pm}. In order to reduce the mathematical complexity, we reformulate the function using a linearization technique used by Bennett (1998), by introducing an auxiliary variable r_{pnmt} representing the number of units of product family n produced in period t at manufacturing facility p for which information is available in the information system m and thus are available for shipment to the distribution centers. The nonlinear constraint is then replaced by an equivalent set of linear constraints:

$$16.3.1. \sum_{j=1}^{J}\sum_{K=1}^{K} Y_{pnjkt} \leq I_{pn(t-1)} + \sum_{m=1}^{M} r_{pnmt} \qquad (\forall p=1...P,\ n=1...N,\ t=1...T)$$

$$16.3.2. \sum_{n=1}^{N}\sum_{t=1}^{T} r_{pnmt} \leq M\delta_{pm} \qquad (\forall\ p=1...P;\ m=1..M)$$

$$16.3.3. \gamma_{pm} X_{pnt} \geq r_{pnmt} \qquad (\forall p=1...P, n=1...N, m=1..M, t=1...T)$$

where M represents a large positive number.

The linearized constraints do not effect the optimal solution since constraints (16.3.2 and 16.3.2) force $r_{pnmt}=0$ when $\delta_{pm}=0$, and $r_{pnmt}=\gamma_{pm}X_{pnt}$ if $\delta_{pm}=1$.

17. Manufacturing facility warehouse capacity:

$$\sum_{n=1}^{N} S_{pn} I_{pnt} \leq IC_p \quad (\forall p=1...P, t=1...T)$$

Space required by the net inventory at manufacturing facility p in any time period should not exceed the available storage space.

18. Inventory review policy:

$$\sum_{i=1}^{I} \beta_{pi} = 1, \qquad (\forall p=1...P)$$

The binary variable β_{pi} ensures that no more than one inventory review policy is selected at each manufacturing facility.

19. Safety stocks

Safety stocks are usually either centralized (pooled at the manufacturing facility) or decentralized (kept at the distribution centers), depending on the desired level of customer service, the cost of stock out, the inventory holding cost and the transportation cost in the two options.

As explained earlier, in line with the increasing emphasis on customer satisfaction, those inventory policies that keep inventories closer to customer centers are the most preferred. Therefore, a decentralized safety stock policy is chosen in the modeling of the supply chain.

19.1. Decentralized safety stock (at distribution centers):

In any time period, the inventory at a distribution center *k* should be at least equal to a pre-specified percentage (λ) of the next period's demand plus the safety stock. A value of λ=0.5 is considered as a strategic policy in this case. This factor may vary or may not apply for different firms.

$$I_{pnkt} \geq \lambda D_{pnk(t+1)} + \left(z_{\alpha} \sigma_{pnk} \sqrt{MLT_{pn} + TLT_{pk} + \sum_{i=1}^{I} \beta_{pi} TP_{pi}} \right)$$

$(\forall p=1...P,\ n=1...N,\ k=1...K,\ t=1...T)$

$$DSS_{pnk} = z_{\alpha} \sigma_{pnk} \sqrt{MLT_{pn} + TLT_{pk} + \sum_{i=1}^{I} \beta_{pi} TP_{pi}} \qquad (\forall p=1...P,\ n=1...N,\ k=1..K)$$

DSS_{pnk} is the decentralized safety stock for product family *n* produced at manufacturing facility *p* and held at distribution center *k*. The formula for calculating this decision variable is based on inventory theory (Elsayed and Boucher,1994) which assumes a normal distribution of the forecast error.

To adjust the forecast error to a lead-time forecast error, σ_{pnk} is multiplied by the lead-time adjustment factor, which is the square root of the total lead-time. The total lead-time is the manufacturing lead-time for product family n at manufacturing facility p (MLT_{pn}) plus the total transportation lead-time from manufacturing facility p to distribution center k (TLT_{pk}) plus the cycle time of the inventory review policy being considered at manufacturing facility p ($\beta_{pi}TP_{pi}$), where β_{pi} is a binary variable that equals one if inventory review policy i is employed at manufacturing facility p. A major assumption underlying safety stock calculation is that all the items in a product family have similar behavior in terms of forecast error. Thus, it is possible to put them in one product family (Elsayed and Boucher, 1994).

In order to calculate the decentralized safety stock, two elements are required: z_α, and σ_{pnk}. z_α is the standard normal variate which is set by the decision-maker in order to fix the service level at $1-\alpha$. In this model we let $z_\alpha = 1.65$ ($\alpha = 0.05$) as a strategic policy. σ_{pnk} is the standard deviation of the forecast error when the forecast is calculated based on the overall demand for product family n produced at manufacturing facility p.

Information systems used as resources in this model differ in timeliness factors (accuracy) and costs. According to the modified method of updating the demand forecasts, the accuracy characteristic of the information- how much of the actual information is registered in the information at the moment- can change the standard deviation of the forecast error (the more accurate the information system, the more realistic our demand forecast will be and as a result we will have smaller values for demand forecast error). Table 3.2 shows, for 3 sample products, the change in the demand forecast error values when the timeliness factor varies and compares them with the demand forecast values calculated with the traditional method.

Product ID #	σ_{pnk} (*Units of Product)* Traditional method	Proposed method		
		γ_1	γ_2	γ_3
P1N1K4	6.51	6.23	6.11	5.7
P6N1K1	358.33	317.12	299.52	294.07
P5N3K1	757.44	593.77	502.29	469.5

Table 3.2. Examples for comparing the σ_{pnk} calculated by traditional and proposed method ($\gamma_1 < \gamma_2 < \gamma_3$).
($P_p N_n K_k$, represents product family *p*, produced at manufacturing facility *p*, kept at distribution center *k*)

In order to estimate the mathematical relation between the demand forecast error σ_{pnk} and the timeliness factor γ_{pm} of the information system *m* used in the manufacturing facility, twelve sets of demand forecasts data have been randomly generated for each product family and used as historical demand forecasts for the calculations. Figure 3.2, shows these data for a sample product.

Historical demand data for $P_1N_2K_1$ (IN UNITS):

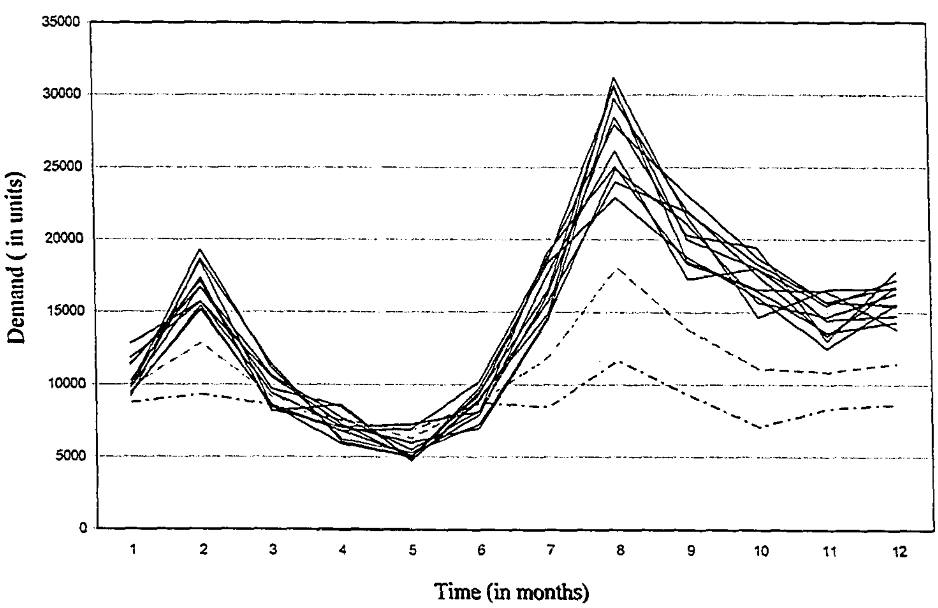

Figure 3.2. Generated demand forecasts for $P_1N_2K_1$.
($P_p N_n K_k$, product family *p*, produced at manufacturing facility *p*, kept at distribution center *k*)

Using these data, the demand forecast errors have been calculated for each product family under different possible scenarios (all timeliness factor options in each manufacturing facility for each set of historical demand forecasts). Assuming a linear relationship these results have been used to perform a linear regression analysis as shown in Figure 3.3, using the following model:

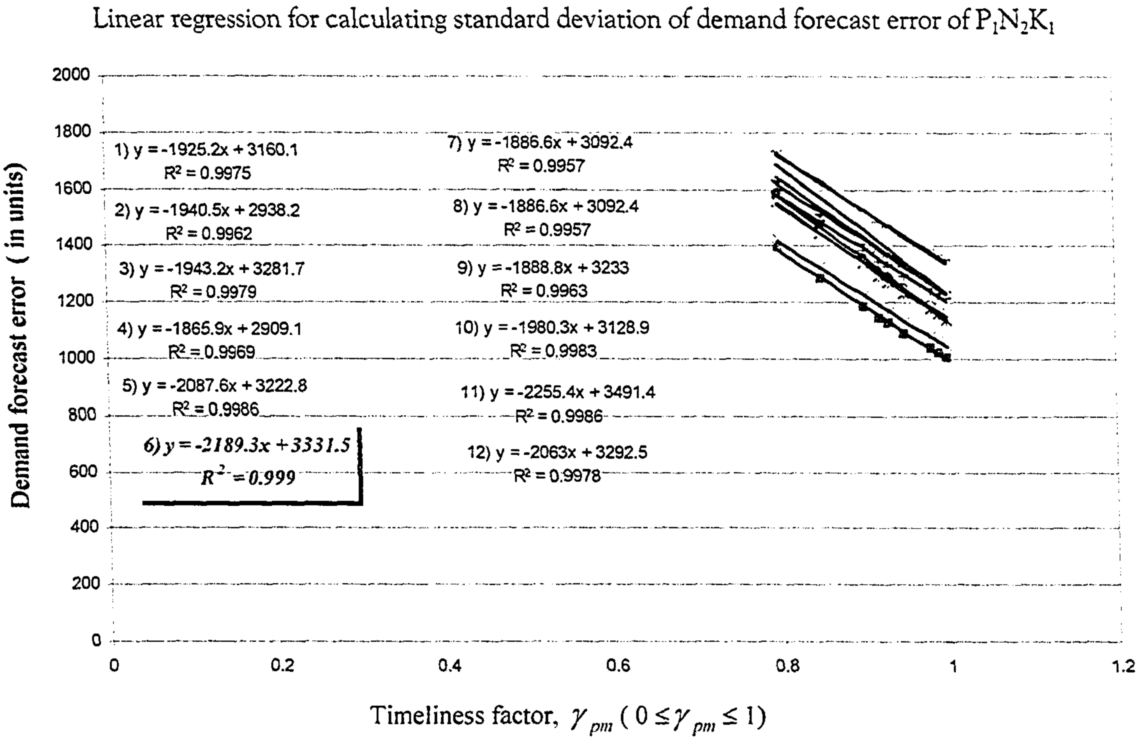

Figure3.3. Linear regression for calculating the demand forecast error for $P_1N_2K_1$.
($P_pN_nK_k$: Represents product family *p*. produced at manufacturing facility *p*. kept at distribution center *k*)

19.1.1. $\sigma_{pnk} = PI_{pnk} - PII_{pnk} \cdot \gamma_{pm}$ *(∀p=1...P ,n=1...N, k=1..K)*

where:

PI_{pnk} is the regression intercept

PII_{pnk} is the regression slope

These parameters (PII_{pnk} and PI_{pnk}) have been calculated for every product family at each manufacturing facility, and they are only valid for the current demand pattern.

Summing up the above, the equation to calculate the decentralized safety stock would be:

$$19.1.2.\ I_{pnkt} \geq \lambda D_{pnk(t+1)} + \left(z_{\alpha}(PI_{pnk} - PII_{pnk} \sum_{m=1}^{M} \gamma_{pm} \delta_{pm}) \sqrt{MLT_{pn} + TLT_{pk} + \sum_{i=1}^{I} \beta_{pi} TP_{pi}} \right)$$

$$(\forall p=1\ldots P,\ n=1\ldots N,\ k=1\ldots K,\ t=1\ldots T)$$

19.2. Linearization:

The safety stock expressed in equation 19.1.2 is nonlinear and may be linearized using the following procedure (Dominguez, 2002).

First we consider the lead-time adjustment factor $\sqrt{MLT_{pn} + TLT_{pk} + \sum_{i=1}^{I} \beta_{pi} TP_{pi}}$ as a set of *i* lead-time alternatives for product family *n* at manufacturing facility *p*, dropping the binary variable β_{pi} and summation over *i*:

$$19.2.1.\ \mathrm{Alt}_{pnik} = \sqrt{MLT_{pn} + TLT_{pk} + TP_{pi}} \qquad (\forall p=1..P;\ n=1\ldots N,\ i=1\ldots I,\ k=1\ldots k)$$

Equation 19.1.2 can be replaced by:

$$19.2.2.\ I_{pnkt} \geq \lambda D_{pnk(t+1)} + \left(z_{\alpha}(PI_{pnk} - PII_{pnk} \sum_{m=1}^{M} \gamma_{pm} \delta_{pm}) \sum_{i=1}^{I} Alt_{pnik} \beta_{pi} \right)$$

$$(\forall p=1\ldots P;\ n=1\ldots N,\ k=1\ldots K;\ t=1\ldots T)$$

which maybe linearized by applying the zero-one polynomial programming technique in Philips (1976) to obtain the following equations:

$$19.2.3.\ I_{pnkt} \geq \lambda D_{pnk(t+1)} + z_{\alpha}(PI_{pnk} \sum_{i=1}^{I} Alt_{pnik} \beta_{pi} - PII_{pnk} \sum_{m=1}^{M} \sum_{i=1}^{I} Alt_{pnik} \gamma_{pm} LN_{pmi})$$

$$(\forall\ p=1\ldots P,\ n=1\ldots N,\ k=1\ldots K,\ t=1\ldots T)$$

19.2.4. $\beta_{pi} + \delta_{pm} - 2LN_{pmi} \geq 0$, $(\forall\ p=1..P, m=1...M, i=1...I)$

19.2.5. $\beta_{pi} + \delta_{pm} - LN_{pmi} \leq 1$, $(\forall\ p=1..P, m=1...M, i=1...I)$

20. Distribution center warehouse capacity:

$$\sum_{p=1}^{P}\sum_{n=1}^{N} S_{pn} I_{pnkt} \leq IC'_{kt}, \qquad (\forall\ k=1...K,\ t=1...T)$$

The space required by the net inventory at each distribution center in any time period t should not exceed the available storage space.

21. Inventory balance at manufacturing facility p:

$$I_{pnt} = I_{pn(t-1)} + X_{pnt} - \sum_{j=1}^{J}\sum_{k=1}^{K} Y_{pnjkt}, \qquad (\forall p=1...P,\ n=1...N,\ t=1...T)$$

In any period, the inventory of product family n at manufacturing facility p is equal to the last period's inventory plus the production level of the product, minus the total shipments of product family n to all distribution centers in the same period.

22. In-transit inventory balance:

$$IT_{pnjkt} = IT_{pnjk(t-1)} + Y_{pnjkt} - Y_{pnjk(t-LT_{pjk})}, \qquad (\forall p=1...P,\ n=1...N, j=1...J,\ k=1...K,\ t=1...T)$$

In any time period, the in-transit inventory of product family n produced at manufacturing facility p being shipped on transportation model j to distribution center k is equal to the last period's in-transit inventory plus the shipments sent from manufacturing facility p in that period minus the received shipments at distribution center k in the same period.

23. Inventory balance at distribution center k:

$$I_{pnkt} = \sum_{j=1}^{J} Y_{pnjk(t-LT_{pjk})} + I_{pnk(t-1)} - D_{pnkt} \qquad (\forall p=1...P,\ n=1...N,\ k=1...K,\ t=1...T)$$

In any time period, the inventory of product family n produced at manufacturing facility p at distribution center k is equal to the last period's inventory plus total received shipments in that period minus the demand in the same period.

24. Number of transportation consignments of mode *j*:

$$\frac{\sum_{n=1}^{N} V_{pn} Y_{pnjkt}}{FTL_j} \leq TU_{pjkt} \qquad (\forall\ p=1...P,\ n=1...N,\ j=1...J,\ k=1...K,\ t=1...T)$$

In any time period, the number of mode j transportation consignments shipped from manufacturing facility p to distribution center k should be greater than or equal to the total volume required by the products shipped, divided by the volume capacity of the mode j transportation consignment.

25. Non negativity constraint: $X_{pnt}, W^{+}_{pt}, W^{-}_{pt}, O_{pt}, I_{pnt}, I_{pnkt}, IT_{pnjkt} \geq 0$,

$(\forall p=1...P,\ n=1...N,\ j=1...J,\ k=1...K,\ t=1...T)$

26. Integer constraint: $X_{pnt}, I_{pnt}, I_{pnkt}, IT_{pnjkt}, TU_{pjkt}, Y_{pnjkt} = Integer$,

$(\forall p=1...P,\ n=1...,\ j=1...J,\ k=1...K,\ t=1...T)$

27. Binary Constraints: $\beta_{pi}, \delta_{pi}, LN_{pmi} \in \{0,1\}$, $(\forall\ p=1...P,\ n=1...N,\ i=1...I,\ m=1...M)$

3.5.4. Complete model:

Assembling the above, the complete statement for the mixed integer program is as follows:

Minimize Total Cost:

$$\text{Min } \mathbf{Z} = \sum_{p=1}^{P} L_p \sum_{t=1}^{T} W_{pt} + \sum_{p=1}^{P} C_p \sum_{t=1}^{T} W_{pt}^{+} + \sum_{p=1}^{P} C_p^{'} \sum_{t=1}^{T} W_{pt}^{-} + \sum_{p=1}^{P} L_p^{'} \sum_{t=1}^{T} O_{pt} +$$

$$\sum_{p=1}^{P}\sum_{j=1}^{J}\sum_{k=1}^{K} TC_{pjk} \sum_{t=1}^{T} TU_{pjkt} + \sum_{p=1}^{P}\sum_{n=1}^{N} h_{pn} \sum_{t=1}^{T} I_{pnt} + \sum_{p=1}^{P}\sum_{n=1}^{N} Th_{pn} \sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{t=1}^{T} IT_{pnjkt}$$

$$+ \sum_{p=1}^{P}\sum_{n=1}^{N}\sum_{k=1}^{K} h_{pnk} \sum_{t=1}^{T} I_{pnkt} + \sum_{p=1}^{P}\sum_{i=1}^{I} CP_{pi}\ \beta_{pi} + \sum_{p=1}^{P}\sum_{m=1}^{M} CI_{pm}\ \delta_{pm} + \sum_{p=1}^{P}\sum_{n=1}^{N}\sum_{t=1}^{T} CM_{pn} X_{pnt} \qquad (1)$$

Subject to:

$$W_{pt} = W_{p(t-1)} + W_{pt}^{+} - W_{pt}^{-}, \qquad (\forall\ p=1...P) \qquad (2)$$

$$\sum_{n=1}^{N} a_{pn} X_{pnt} = W_{pt} + O_{pt}, \qquad (\forall p=1...P,\ t=1...T) \qquad (3)$$

$$O_{pt} \le \theta_p W_{pt}, \qquad (\forall p=1...P,\ t=1...T) \qquad (4)$$

$$W_{pt} \le PC_{pt}, \qquad (\forall\ p=1...P,\ t=1...T) \qquad (5)$$

$$\sum_{m=1}^{M} \delta_{pm} = 1, \qquad (\forall p=1...P) \qquad (6)$$

$$\sum_{j=1}^{J}\sum_{k=1}^{K} Y_{pnjkt} \le I_{pn(t-1)} + \sum_{m=1}^{M} r_{pnmt}, \qquad (\forall p=1...p,\ n=1...N,\ t=1...T) \qquad (7)$$

$$\sum_{n=1}^{N}\sum_{t=1}^{T} r_{pnmt} \le M\delta_{pm}, \quad (\forall\ p=1...P,\ m=1..M) \qquad (8)$$

$$r_{pnmt} \le \gamma_{pm} X_{pnt}, \qquad (\forall\ p=1...P,\ n=1...N,\ m=1..M,\ t=1...T) \tag{9}$$

$$\sum_{n=1}^{N} S_{pn} I_{pnt} \le IC_p, \qquad (\forall p=1...P,\ t=1...T) \tag{10}$$

$$\sum_{i=1}^{I(p)} \beta_{pi} = 1, \qquad (\forall p=1...P) \tag{11}$$

$$I_{pnkt} \ge \lambda D_{pnk(t+1)} + z_\alpha (PI_{pnk} \sum\nolimits_{i=1}^{I} Alt_{pnik} \beta_{pi} - PII_{pnk} \sum\nolimits_{m=1}^{M} \sum\nolimits_{i=1}^{I} Alt_{pnik} \gamma_{pm} LN_{pmi}),$$
$$(\forall\ p=1...P,\ n=1...N,\ k=1...K,\ t=1...T) \tag{12}$$

$$Alt_{pnik} = \sqrt{MLT_{pn} + TLT_{pnk} + TP_{pi}}, \quad (\forall p=1..P,\ n=1...N,\ i=1...I,\ k=1...k) \tag{13}$$

$$\beta_{pi} + \delta_{pm} \text{-} 2LN_{pmi} \ge 0, \qquad (\forall\ p=1..P;\ i=1...I) \tag{14}$$

$$\beta_{pi} + \delta_{pm} \text{-} LN_{pmi} \le 1, \qquad (\forall p=1..P,\ i=1...I) \tag{15}$$

$$\sum_{p=1}^{P} \sum_{n=1}^{N} S_{pn} I_{pnkt} \le IC'_{kt}, \qquad (\forall k=1...K;\ t=1...T) \tag{16}$$

$$I_{pnt} = I_{pn(t-1)} + X_{pnt} - \sum_{j=1}^{J} \sum_{k=1}^{K} Y_{pnjkt}, \qquad (\forall p=1...P,\ n=1...N,\ t=1...T) \tag{17}$$

$$IT_{pnjkt} = IT_{pnjk(t-1)} + Y_{pnjkt} - Y_{pnjk(t-LT_{pjk})},$$
$$(\forall p=1...P,\ n=1...N,\ j=1...J,\ k=1...K,\ t=1...T) \tag{18}$$

$$I_{pnkt} = \sum_{j=1}^{J} Y_{pnjk(t-LT_{pjk})} + I_{pnk(t-1)} - D_{pnkt}, \ (\forall p=1...P,\ n=1...N,\ k=1...K,\ t=1...T) \tag{19}$$

$$\frac{\sum_{n=1}^{N} V_{pn} Y_{pnjkt}}{FTL_j} \leq TU_{pjkt}, \quad ,(\forall p=1 \ldots P, j=1 \ldots J, k=1 \ldots K, t=1 \ldots T) \tag{20}$$

$$X_{pnt}, W_{pt}^{+}, W_{pt}^{-}, O_{p_t}, I_{pnt}, I_{pnkt}, IT_{pnjkt} \geq 0,$$

$$(\forall p=1 \ldots P, n=1 \ldots N, j=1 \ldots J, k=1 \ldots K, t=1 \ldots T) \tag{21}$$

$$X_{pnt}, I_{pnt}, I_{pnkt}, IT_{pnjkt}, TU_{pjkt}, Y_{pnjkt} = Integer,$$

$$(\forall p=1 \ldots P, n=1 \ldots N, j=1 \ldots J, k=1 \ldots K, t=1 \ldots T) \tag{22}$$

$$\beta_{pi}, RP_{pn}, DI_{pn}, \delta_{pm}, LN_{pmi} \in \{0,1\},$$

$$(\forall p=1 \ldots P, n=1 \ldots N, i=1 \ldots I, m=1 \ldots M) \tag{23}$$

CHAPTER 4: NUMERICAL EXAMPLE AND RESULTS

In this chapter, we present the results of a numerical example used to demonstrate the model application. We also investigate the impact of employing our proposed method of updating the demand forecasts on the operational costs of the supply chain network. In the sections below we present the relevant information regarding the context in which modeling is done and the numerical example considered.

4.1. Brief description of the supply chain

As stated earlier, the supply chain under consideration here is that of a major household appliance company in Mexico (Dominguez, 2002). Below we provide some information about the operation of the company.

The company comprises 7 manufacturing facilities and 8 distribution centers. Products are categorized into product families. It is assumed that all the products in the same product family have the same characteristics in terms of manufacturing operations. The company produces 27 product families as listed in Table 4.1.

The planning horizon is 12 months which has been divided into time periods of one week duration. Thus, all the demand forecasts, production levels, information system and inventory review policy selection and other allocations are performed on a weekly basis

Manufacturing Facility, p	Product Family, n	Description
1	1	Wringer washers
	2	Compact washers
	3	4 & 5 kg compact washers
	4	Q line washers
	5	Two-tub washer
2	1	Automatic washers
3	1	Freestanding 20" ranges
	2	Freestanding 30" ranges
	3	30" Value stove w/oven
	4	20" Value stove w/Oven
	5	Drop-in 20" ranges
	6	Value cooktops w/cabinet
	7	Freestanding 24" ranges
4	1	30" Hoods
5	1	Freestanding 30" ranges
	2	Freestanding 30" luxury ranges
	3	Drop-in 30" luxury ranges
	4	Cooktops
6	1	11' & 13' No frost refrigerators
	2	Water coolers
7	1	8.6' - 10.6' refrigerators
	2	8.6' -10.6' semiautomatic
	3	8.6' - 10.6' frost free
	4	7.6' refrigerators
	5	6.6' refrigerators
	6	3.7' compact refrigerators
	7	14' & 16' frost free

Table 4.1. Product families in each manufacturing facility

4.1.1. Information parameters

In this section we discuss the input parameters that are related to information. As previously stated, these can be categorized into:

i) Parameters related to the timeliness of information(Table 4.2).They are :

γ_{pm} = timeliness factor of the information system m

CI_{pm} = cost of using information system with timeliness of γ_{pm}

Plant, P	Information system ,m	γ_{pm} (Timeliness Factor)	CI_{pm} (Cost of Information system,$)
1	1	0.8	500,000
1	2	0.85	520,000
1	3	0.99	600,000
2	1	0.8	400,000
2	2	0.85	410,000
2	3	0.98	440,000
3	1	0.8	410,000
3	2	0.95	425,000
3	3	0.99	440,000
4	1	0.9	650,000
4	2	0.95	655,000
4	3	0.99	670,000
5	1	0.85	600,000
5	2	0.95	620,000
5	3	0.99	660,000
6	1	0.8	500,000
6	2	0.93	510,000
6	3	0.98	540,000
7	1	0.8	500,000
7	2	0.92	570,000
7	3	0.98	630,000

Table 4.2. Information System timeliness and the related costs

It must be noted that in this example, only three information system options (with different timeliness factors) are available at each manufacturing facility as given in Table 4.3.

Information System Identifier, m	Type
1	Manual
2	Semi-automatic
3	Automatic

Table 4.3. Information system timeliness description

Information System $m=1$, at manufacturing facility 1 has an information timeliness factor of $\gamma_{pm}=0.8$, which means that, at the end of a period 80% of items produced are registered in the database and so they are available for shipment to the distribution centers. The other 20% are physically in stock but unavailable since the information about them hasn't been registered in the system yet. The associated system with this characteristic is a manual system in which an operator counts the number of units entering the manufacturing facility's warehouse and adds this information to the database. The cost is related to the resources required for this operation in terms of time and labor used during this period.

For information system m=2 at plant 1, the information timeliness factor is 0.85. This represents a semi-automatic system in which an operator collects a set of bar-coded cards from the finished goods and slides the cards through a scanner to register the information directly into the database. The cost is related to labor, operating and purchasing expenses of the improved information system and the related hardware over the planning horizon.

Finally, information system m=3 at plant 1, is an online automated processing system. Information about the products is captured at the end of the production lines with a high technology bar code scanner, which is connected directly to the database. The cost represents the operating and purchasing expenses of this information system and the related hardware over the planning horizon.

ii) Parameters related to the periodicity of information (Table 4.4). They are:

TP_{pi}= Cycle length for periodic review policy i employed at manufacturing facility p.

CP_{pi}= Corresponding cost of this review policy.

Plant, P	Preview policy,i	TP_{pi} ,Cycle length(in months)	CP_{pi}, Cost of review policy ($)
1	1	0.125	110,000
1	2	0.25	80,000
1	3	0.5	65,000
2	1	0.125	120,000
2	2	0.25	75,000
2	3	0.5	60,000
3	1	0.125	120,000
3	2	0.25	85,000
3	3	0.5	65,000
4	1	0.125	90,000
4	2	0.25	70,000
4	3	0.5	63,000
5	1	0.125	130,000
5	2	0.25	90,000
5	3	0.5	70,000
6	1	0.125	80,000
6	2	0.25	62,000
6	3	0.5	45,000
7	1	0.125	85,000
7	2	0.25	6,000
7	3	0.5	55,000

Table 4.4. Review Policy, Cycle time and related costs

It must be mentioned that in our example there are three alternative inventory review policies i to chose from at each manufacturing facility, which differ in their cycle lengths as given in Table 4.5.

Review Policy Identifier	Type
1	Short cycle time
2	Medium cycle time
3	Long cycle time

Table 4.5. Inventory review policies description

The cost, CP_{pi}, represents the human resources and analytical systems required for each alternative and does not depend on the size of the manufacturing facility or the number of product families considered.

iii) Parameters related to the accuracy of information (Table 4.6). They are:

PII_{pnk} = Regression slope in calculating σ_{pnk}

PI_{pnk} = Regression intercept in calculating σ_{pnk}

Plant, *p*	**Product Family, *n***	**Distribution Center ,k**	**PII**	**PI**
1	5	7	90	296
1	4	2	1	15
1	4	1	1,100	2,631
1	1	4	3	8
1	3	3	223	1,145
1	2	8	2,189	3,332
1	1	7	3	36
1	1	1	80	127

Table 4.6. Information accuracy parameters for manufacturing facility 1

These parameters are calculated for each product family *n* produced at manufacturing facility *p* and used at distribution center *k*, to calculate the standard deviation of demand forecast error as a function of the timeliness factor of the information system *m* as stated in Chapter 3:

$$\sigma_{pnk} = PI_{pnk} - PII_{pnk} \cdot \gamma_{pm} \quad , \quad (\forall p=1...P, n=1...N, k=1..K)$$

where,

σ_{pnk} is the standard deviation of the demand forecast error for product family *n* produced at manufacturing facility *p* ,at distribution center *k*

γ_{pm} is the timeliness factor of the information system *m* used at manufacturing facility *p*

4.1.2. Transactional Parameters

Transactional input data are categorized based on the three main entities in the supply chain under consideration. In each case, only a sample of the data is given. However, the full data sets are provided in appendix II.

i) Plant input data: These data include the plant general information as shown in Table 4.7 for a typical product at manufacturing facility 1.

Plant,p	Cost of Reducing Labor hours,S	Cost of Increasing Labor hours, S	Cost of Labor,S	Cost of Overtime,S	Plant Capacity (S.F.)	Max Overtime, θ_p	Initial Available Labor hour
1	7.4	3	0.62	1.2	3,500	0.2	35,000

Table 4.7. General input data for manufacturing facility 1

Table 4.8 shows the maximum labor hours allowed in manufacturing facility1 at each period.

Plant, p	Period, t	Labor hour limit
1	1	35000
1	2	35000
1	3	35000
1	4	35000
1	5	35000
1	6	35000
1	7	35000
1	8	35000
1	9	35000
1	10	35000
1	11	35000
1	12	35000

Table 4.8. General input data for manufacturing facility 1

ii) Product family input data:

These data include general information about the product families as shown in Tables 4.9 and 4.10 for product family 1.

Family,n	Plant,p	Cubic Space Requires(C.F.)	Labor Hour Required	Floor Area Required(S.F.)	Inventory Cost,S	In-Transit Inventory Cost,S	Manufacturing Lead-Time (months)	Cost of Raw material,S
1	5	0.964	3	1	0.87	0.74	0.25	320
1	2	0.896	3.5	1	1.02	0.85	0.25	370
1	3	0.44	3	1	0.36	0.342	0.25	100
1	1	0.516	2	1	0.63	0.53	0.25	228
1	4	0.14	1	1	0.11	0.09	0.25	50
1	6	1.217	3	1	1.07	0.9	0.25	390
1	7	0.904	3	1	0.89	0.75	0.25	325

Table 4.9. General input data for product family 1

Family,n	Plant,p	Distribution Center,k	Initial Inventory ,Units
1	4	6	490
1	3	6	94
1	6	1	1017
1	6	7	444
1	1	4	10
1	1	7	36
1	1	1	556
1	2	3	442
1	2	6	169

Table 4.10. General input data for product family 1

iii) Distribution centers input data:

These data include general information about the distribution centers, their demands and the transportation systems between plants and distribution centers, as shown in Tables 4.11- 4.15.

Distribution Center,k	Description
1	Mexico 101
2	Mexicalli 102
3	Monterrey 105
4	Reynosa 108
5	Chihuahua 109
6	Merida 110
7	Torreon 112
8	Guadalajara 103

Table 4.11 Distribution centers

Table 4.12 shows, as an example, the demands at distribution center 1 for product family *1*, produced at manufacturing facility *1* at each period.

Plant, p	Product Family, n	Distribution Center, k	Period, t	Demand, Units
1	1	1	1	19
1	1	1	2	45
1	1	1	3	65
1	1	1	4	81
1	1	1	5	114
1	1	1	6	95
1	1	1	7	161
1	1	1	8	197
1	1	1	9	278
1	1	1	10	133
1	1	1	11	89
1	1	1	112	67

Table 4.12 Distribution center 1 demand for product family 1 produced in manufacturing facility 1

Table 4.13 shows the available transportation modes from manufacturing facilities to distribution centers.

Transportation mode, j	Description	Transportation mode capacity (C.F.)
1	48' Trailer (FAST)	102.2
2	48' Trailer (Normal)	102.2
3	Boxcar	142.33

Table 4.13 Available transportation modes

Table 4.14 shows, as an example, the transportation cost for each transportation mode from manufacturing facility 1 to each distribution centers.

Plant, P	Transportation mode, j	Distribution center, k	Transportation Cost,S
1	1	1	1492
1	1	2	2899
1	1	3	178
1	1	4	601
1	1	5	1278
1	1	6	2747
1	1	7	766
1	1	8	1246
1	2	1	995
1	2	2	1933
1	2	3	118
1	2	4	401
1	2	5	852
1	2	6	1831
1	2	7	510
1	2	8	831
1	3	1	748
1	3	2	10000
1	3	3	10000
1	3	4	10000
1	3	5	10000
1	3	6	10000
1	3	7	10000
1	3	8	930

Table 4.14 Transportation costs for manufacturing facility 1

Table 4.15 shows, as an example, the transportation lead-time between manufacturing facility 1 and each distribution centers.

Plant, p	Distribution Center, k	Transportation lead-time (months)
1	1	0.25
1	2	0.6
1	3	0.18
1	4	0.25
1	5	0.35
1	6	0.32
1	7	0.25
1	8	0.36

Table 4.15 Transportation Lead-Times for manufacturing facility 1

4.2. Solution Methodology

The supply chain network model was tested using Lingo (Lindo Systems Inc., 2004) as the solver (see Appendix III). The size of the problem and the complexity of the database made the solution of the model intractable, so it was necessary to use the relaxed version of the model by considering the general integer variables as continuous variables. As mentioned in Winston (1994), the relaxed model gives a good approximation of the integer solution.

The supply chain network model was run under four different scenarios in order to calculate the corresponding minimal cost solutions and to evaluate the cost reduction opportunities among them. The focus is mainly on the impact of employing the proposed method for updating demand forecasts on the operational costs and information system allocations of the model in an environment with or without a decentralized safety stock policy. Table 4.16 shows the four defined scenarios.

		Safety Stock Policy	
		Decentralized	Centralized/Decentralized
Employing proposed method	No	*Scenario1*	*Scenario3*
	Yes	*Scenario2*	*Scenario4*

Table 4.16. Four defined scenarios

4.2.1. Scenario1

In this scenario the proposed method is **not employed** and **decentralized** safety stock policy would be the only available option to choose. Table 4.17 is the summery of the results of the model solution under this scenario.

Number of variables	22,899
Number of constraints	12,939
Total run time	2 min and 24 sec
Optimal objective function value	$ 37,248,756

Table 4.17. Model results under scenario1

To study this scenario we need a more detailed result including the operation costs, inventory review policy and information system allocations. Table 4.18 displays the breakdown of the total costs, and Table 4.19 shows the allocations of inventory review policy and the information system.

Cost Break Down	**Costs of Scenario1 ($)**
Production	257,603
Cost of Labor(Decrease, Increase, Overtime)	1,262,747
Transportation	493,943
Inventory	
At Plant	61,773
In-Transit	65,502
At distribution center	309,630
Review Policy	633,000
Information system	3,560.000
Raw materials	30,604,560
Total Cost	**$ 37,248,756**

Table 4.18. Operation costs for scenario 1

Scenario1		
Plant, *p*	Inventory review policy, *i*	Information system, *m*
1	1	1
2	1	1
3	2	1
4	3	1
5	2	1
6	1	1
7	1	1

Table 4.19. Inventory review policy /Information systems allocations, scenario 1

4.2.2. Scenario2

In this scenario our proposed method is **employed** and **decentralized** safety stock policy would be the only available option to choose. Table 4.20 is the summery of the results of the model solution under this scenario.

Number of variables	23,868
Number of constraints	13,406
Total run time	2 min and 56 sec
Optimal objective function value	$ 31,466,756

Table 4.20. Model results under scenario2

Table 4.21 displays the breakdown of the total costs, and Table 4.22 shows the allocations of inventory review policy and the information system.

Cost Break Down	Costs of Scenario 2 ($)
Production	208,924
Cost of labor(Decrease, Increase, Overtime)	1,264,560
Transportation	400,348
Inventory	
At Plant	53,707
In-Transit	58,529
At distribution center	253,745
Review policy	613,000
Information system	3,775,000
Raw materials	24,838,940
Total Cost	**$ 31,466,756**

Table 4.21. Operation costs for scenario 2

Scenario2		
Plant ,*p*	Inventory review policy, *i*	Information system, *m*
1	1	3
2	1	2
3	3	2
4	3	1
5	2	2
6	1	1
7	1	2

Table 4.22. Inventory review policy /Information systems allocations, scenario 2

4.2.3. Scenario 3

In this scenario the proposed method is **not employed** and there is the option of choosing either **decentralized** or **centralized** safety stock policy, depending on the tradeoffs between the customer service level requirements, the inventory and transportation cost of the decentralized policy, and the premium transportation cost and the inventory cost of the centralized policy.

It is noted that in our example, the centralized safety stock policy is associated with the premium transportation costs which are almost 1.5 times the regular transportation costs. Therefore, the model tends to choose a decentralized safety stock policy in most cases unless where the company's policy forces a centralized safety stock policy, or where the inventory costs at the distribution center and the transportation costs of the product is high compared to the premium transportation costs. Table 4.23 is the summery of the results of the model solution under this scenario.

Number of variables	22,953
Number of constraints	12,966
Total run time	2 min and 43 sec
Optimal objective function value	$37,237,090

Table 4.23. Model results under scenario3

The breakdown of the total costs is shown in Table 4.24, and the allocations of the inventory review policy and the information system are given in Table 4.25.

Cost Break Down	Costs of Scenario 3 ($)
Production	257,006
Cost of labor(Decrease, Increase, Overtime)	1,262,881
Premium Transportation	65,439
Transportation	492,190
Inventory	
At Plant	62,706
In-Transit	65,354
At distribution center	301,468
Review policy	673,000
Information system	3,560,000
Raw materials	30,497,040
Total Cost	**$ 37,237,090**

Table 4.24. Operation costs for scenario 3

Scenario 3		
Plant, p	Inventory review policy, i	Information system, m
1	1	1
2	1	1
3	2	1
4	3	1
5	1	1
6	1	1
7	1	1

Table 4.25. Inventory review policy /Information systems allocations, scenario 3

4.2.4. Scenario 4:

In this scenario our proposed method is **employed** and there is the option of choosing either **decentralized** or **centralized** safety stock policy, as in scenario 3. Table 4.26 is the summery of the results of the model solution under this scenario.

Number of variables	24,346
Number of constraints	13,974
Total run time	12 min and 27sec
Optimal objective function value	$31,447,220

Table 4.26. Model results under scenario4

The breakdown of the total costs is shown in Table 4.27, and the allocations of the inventory review policy and the information system are given in Table 4.27.

Cost Break Down	**Costs of Scenario 4 ($)**
Production	208,425
Cost of labor(Decrease, Increase, Overtime)	1,264,513
Premium Transportation	63,058
Transportation	398,684
Inventory	
At Plant	57,631
In-Transit	58,099
At distribution center	245,890
Review policy	613,000
Information system	3,775,000
Raw materials	24,762,920
Total Cost	**$ 31,447,220**

Table 4.27. Operation costs for scenario 4

Scenario4		
Plant, *p*	Inventory review policy, *i*	Information system, *m*
1	1	3
2	1	2
3	3	2
4	3	1
5	2	2
6	1	1
7	1	1

Table 4.28. Inventory review policy /Information systems allocations, scenario 4

4.2.5. Scenarios 1 and 2

In this section we compare the results of scenarios 1 and 2 to study the impact of employing our proposed method on the operational costs of the supply chain network under a decentralized safety stock policy.

As states in Chapter 3, the proposed method has two parts: first updating the demand forecasts which results in more accurate demand forecasts (i.e., a smaller error standard deviation, σ_{pnk}), and second, the calculation of the forecast error standard deviation, σ_{pnk} ,as a function of the timeliness factor of the information system used; the higher the timeliness factor, the smaller the value of σ_{pnk}.

Considering the decentralized safety stock equation:

$$DSS_{pnk} = \left(z_\alpha (PI_{pnk} - PII_{pnk} \sum_{m=1}^{M} \gamma_{pm} \delta_{pm}) \sqrt{MLT_{pn} + TLT_{pk} + \sum_{i=1}^{I} \beta_{pi} TP_{pi}} \right)$$

where, $\sigma_{pnk} = PI_{pnk} - PII_{pnk} \sum_{m=1}^{M} \gamma_{pm} \delta_{pm}$ $\quad (p=1 \ldots P,\ n=1 \ldots N,\ k=1..K)$

We note that a smaller σ_{pnk} means a smaller decentralized safety stock, resulting in a decrease in production costs, raw material costs, transportation costs, inventory costs (at manufacturing facilities , in-transit, distribution centers), and a decrease in the overall system cost.

Since the objective function is to minimize the total cost, going from scenario 1 to scenario 2 we expect to see a tendency to choose information systems with higher timeliness factors, resulting in higher information system costs, and also a decrease in the demand forecast error standard deviation, decentralized safety stock level, the total inventory costs and the overall system costs. Table 4.29 compares the results of these two scenarios, indicating an overall decrease of 15.5 %, (5,781,950 $) in the total costs. Table 4.29 presents that in scenario 2 the cost of information system has increased by 6%, (215,000$) as a result of the selection of information systems with higher timeliness factors as shown in Table 4.30.

It is also noted that the cost of inventory review policy is decreased by 3%, (20,000 $) as a result of the reallocation of inventory policies with longer cycle times, as shown in Table 4.31. This can be explained by the fact that since we are using timelier information systems we can afford to have a review policy with a longer cycle times if it results in lower costs and no loss in service.

The 0.14% (1,819 $) increase in the cost of labor can be justified by the fact that with the decrease in the production rate, the optimal and cost effective policy would be to respond to the additional labor hour requirements by increase in the overtime labor hour instead of increasing labors(hiring).

As discussed earlier, the decentralized safety stock level should decrease from scenario 1 to scenario 2. Figure 4.1 shows the safety stock levels for the two scenarios, indicating a difference of 25% from scenario 1 to scenario 2.

Cost Break Down	**(1)-Scenario 1**	**(2)-Scenario 2**	**(1) - (2)**	**Percentage decrease**
Production	257,603	208,924	48,682	19%
Cost of Labor(Decrease, Increase, Overtime)	1,262,747	1,264,560	-1,819	-0.14%
Transportation	493,943	400,348	93,699	19%
Inventory				
At Plant	61,773	53,707	8,124	13%
In-Transit	65,502	58,529	6,924	11%
At distribution center	309,630	253,745	55,723	18%
Inventory review policy	633,000	613,000	20,000	3%
Information system	3,560,000	3,775,000	-215,000	-6%
Raw materials	30,604,560	24,838,940	5,765,710	19%
Total Cost ($)	**37,248,756**	**31,466,756**	**5,781,950**	**15.5%**

Table 4.29. Cost comparison between scenarios 1 and 2

Information System		
Plant, P	Scenario1	Scenario2
1	1	3
2	1	2
3	1	2
4	1	1
5	1	2
6	1	1
7	1	2

Table 4 .30.Information system in scenarios 1and 2

Inventory Review Policy		
Plant, P	Scenario 1	Scenario 2
1	1	1
2	1	1
3	2	3
4	3	3
5	2	2
6	1	1
7	1	1

Table 4.31. Inventory review policy in scenarios 1 and 2

4.2.6. Scenarios 3 and 4

By comparing the results of scenarios 3 and 4 we will study the impact of employing our proposed method on the operational costs of the supply chain network when the safety stock policy can be either centralized or decentralized. It should be pointed out that in addition to what was discussed in Chapter 3 regarding the decentralized safety stocks, we should also consider the standard deviation of demand forecast error at manufacturing facilities, σ_{pn}, which is used to calculate the pooled safety stock at the manufacturing facility. σ_{pn} will also be calculated as a function of the timeliness factor of information system.

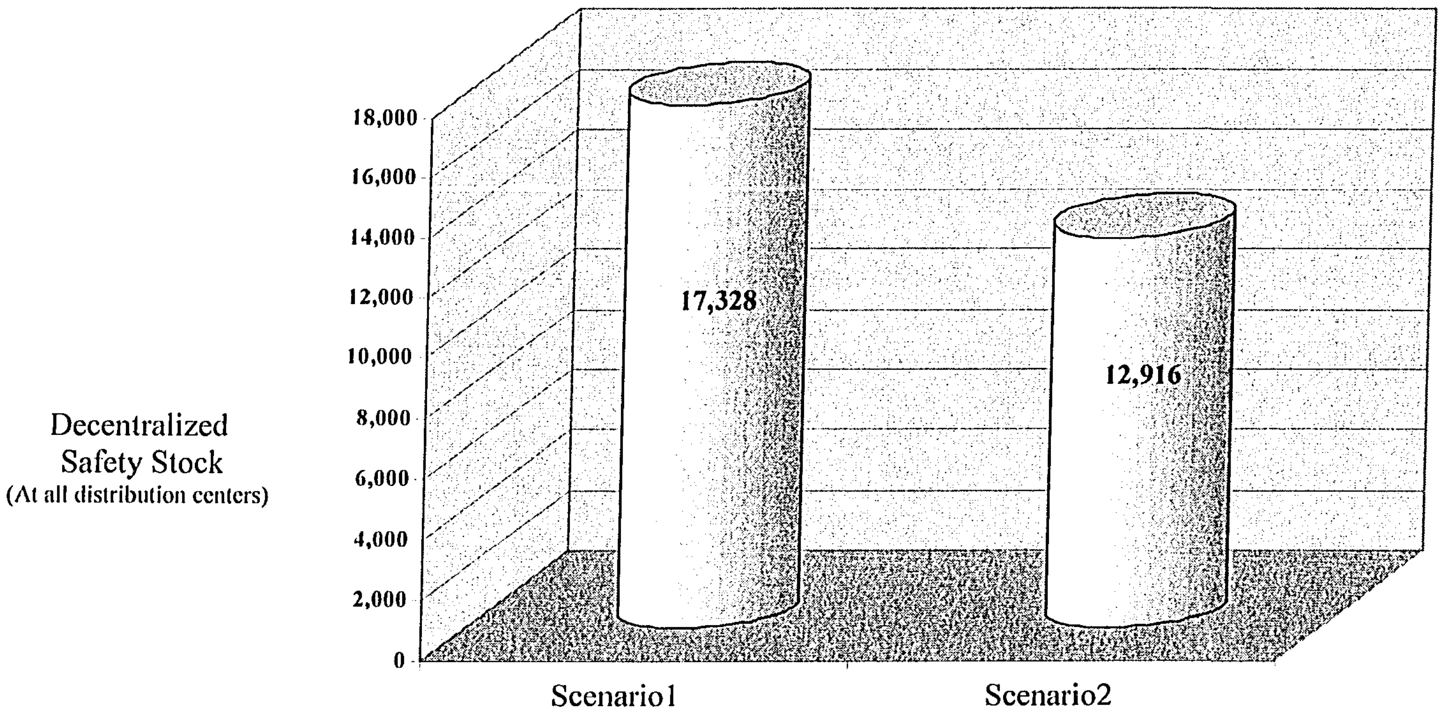

Figure 4.1.Decentralized safety stock level in scenarios 1 and 2

The only difference is that the demand used at the manufacturing facility would be the aggregate demand for the entire distribution network. In this case, the pooled safety stock, PSS_{pn}, expression is:

$$\mathrm{PSS}_{pn} = \left(z_{\alpha}(PI_{pn} - PII_{pn} \sum_{m=1}^{M} \gamma_{pm} \delta_{pm}) \sqrt{MLT_{pn} + \sum_{i=1}^{I} \beta_{pi} TP_{pi}} \right)$$

where, $\sigma_{pn} = PI_{pn} - PII_{pn} \sum_{m=1}^{M} \gamma_{pm} \delta_{pm}$ $\qquad (\forall p=1...P,\ n=1...N)$

We note that a smaller σ_{pn} means a smaller pooled safety stock at the manufacturing facility, resulting in a decrease in production costs, raw material costs, inventory costs (at manufacturing facility), and a decrease in the overall system cost.

Since the objective function is to minimize the total cost, going from scenario 3 to scenario 4 we expect to see a tendency to choose information systems with higher timeliness factors, resulting in higher information system costs, and also a decrease in the demand forecast error standard deviation, decentralized and centralized safety stocks, the total inventory costs and the overall system costs. Table 4.32 compares the results of these two scenarios, indicating an overall decrease of 15.5 %,(5,789,870 $) in the total cost.

As shown in Table 4.32 in scenario 3 the cost of the information has been increased by 6%,(215,000 $) as a result of the selection of information systems with higher timeliness factors as shown in Table 4.33.

It's also shown that the cost of inventory review policy is decreases by 9%, (60,000$) as a result of the reallocation of inventory policies with longer cycle times, as shown in Table 4.34. This is explained by the fact that since we are using timelier information systems we can afford to have longer cycle times in our review policies.

Cost Break Down	**(1)-Scenario 3**	**(2)-Scenario 4**	**(1) - (2)**	**Percentage decrease**
Production	257,006	208,425	48,581	19%
Cost of Labor(Decrease, Increase, Overtime)	1,262,881	1,264,513	-1,679	-0.13%
Premium Transportation	65,439	63,058	2,381	4%
Transportation	492,190	398,684	93,506	19%
Inventory				
At Plant	62,706	57,631	5,075	8%
In-Transit	65,354	58,099	7,255	11%
At distribution center	301,468	245,890	55,578	18%
Inventory review policy	673,000	613,000	60,000	9%
Information system	3,560,000	3,775,000	-215,000	-6%
Raw materials	30,497,040	24,762,920	5,734,120	19%
Total Cost($)	**37,237,090**	**31,447,220**	**5,789,870**	**15.5%**

Table 4.32. Cost comparison between scenarios 3 and 4

Information System		
Plant, P	Scenario 3	Scenario 4
1	1	3
2	1	2
3	1	2
4	1	1
5	1	2
6	1	1
7	1	1

Table 4.33. Information system in scenarios 3 and 4

Inventory Review Policy		
Plant, P	Scenario 3	Scenario 4
1	1	1
2	1	1
3	2	3
4	3	3
5	1	2
6	1	1
7	1	1

Table 4.34. Inventory review policy in scenarios 3 and 4

The 0.13% (1,679 $) increase in the cost of labor can be justified by the fact that with the decrease in the production rate, the optimal and cost effective policy would be to respond to the additional labor hour requirements by increase in the overtime labor hour instead of increasing labors (hiring).

The decentralized and centralized safety stock levels are expected to decrease from scenario 3 to scenario 4. Figure 4.2 shows that the decentralized safety stocks decrease by 25% and the centralized safety stocks decrease by 26% from scenario 3 to scenario 4.

There are four main parameters in a supply chain that affect the selection of a centralized or decentralized safety stock policy:

- Premium transportation costs
- Demand forecast error standard deviation , σ_{pnk} or σ_{pn}

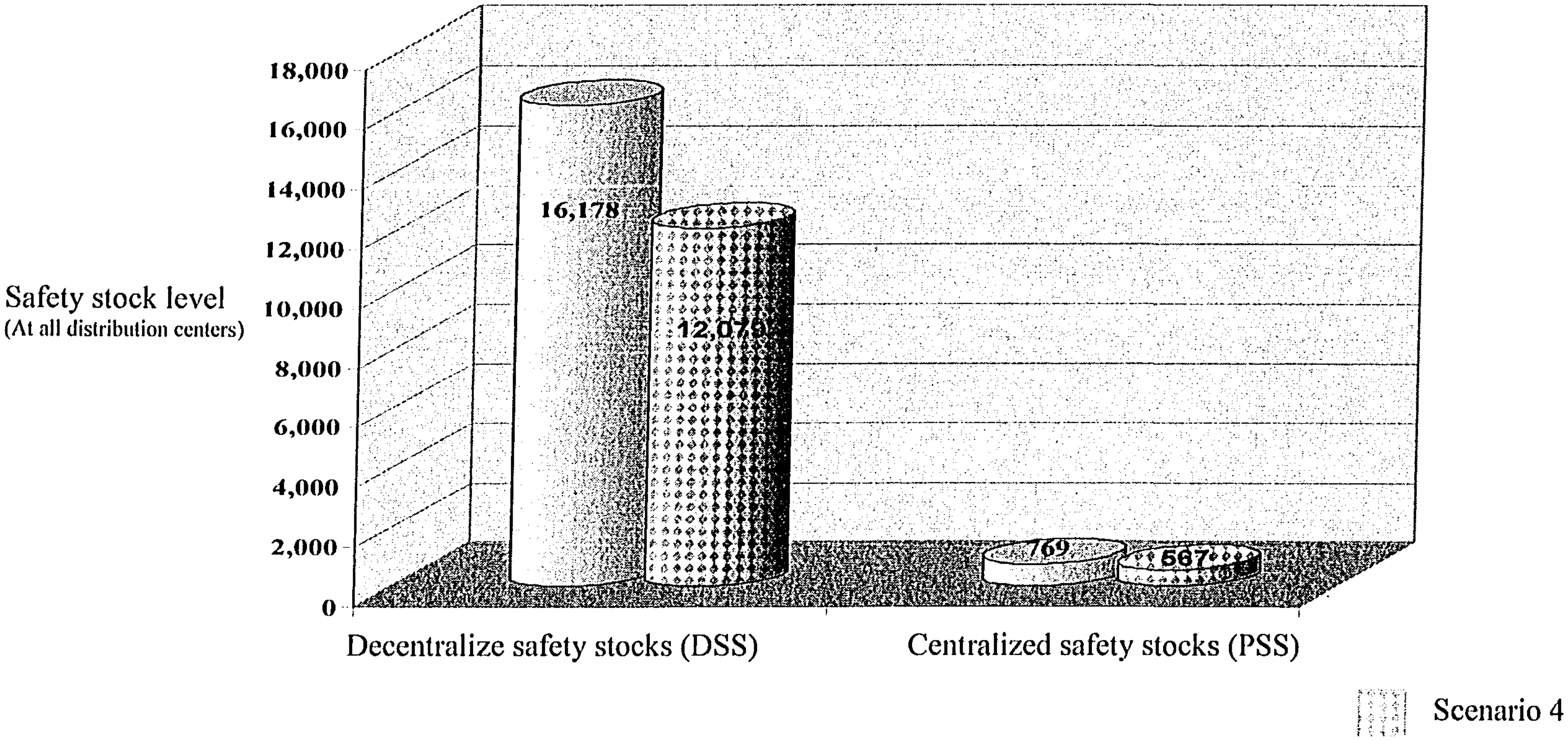

Figure 4.2. Decentralized and centralized safety stock levels in Scenarios 3 and 4

- Inventory carrying costs(at manufacturing facility, in-transit, at distribution center)
- Customer Service level

Usually, the much higher premium transportation costs and a higher customer service level favor the selection of a decentralized safety stock policy, so do the decrease in (σ_{pnk} and the inventory carrying cost, although, technically speaking, it is the interaction among these parameters that affect the choice of a safety stock policy. This can be observed when comparing scenarios 3 and 4 where the forecast error has decreased (due to improved forecasting method in scenario 4). As shown in Table 4.32 the model tends to chose decentralized safety stock policy in scenario 4.

4.2.7. Scenarios 2 and 4

As a final observation, we compare the results of scenarios 2 and 4 in which the improved forecasting method is employed; however, in scenario 4 the safety stock policy maybe centralized or decentralized. Table 4.35 displays the results, which indicate that by going from scenario 2 to 4:

- The total transportation costs increased by about 15% as a result of the premium transportation costs incurred in the system.
- The level of inventories at the manufacturing facilities increase, while the level of inventories at the distribution centers decrease. This is due to the fact that the model chooses a centralized inventory policy for some products, thus increasing the level of inventory at some manufacturing facilities, but increasing the total inventory at distribution center.

As expected, there are no changes in the information system or inventory review policy costs.

Cost Break Down	(1)-Scenario 2	(2)-Scenario 4	(1) - (2)	Percentage decrease
Production	208,924	208,425	496	0.24%
Cost of Labor(Decrease, Increase, Overtime)	1,264,560	1,264,513	-47	0.00%
Total Transportation	400,348	461,742	-61,498	-15.37%
Inventory				
At Plant	53,707	57,631	-3,982	-7.42%
In-Transit	58,529	58,099	479	0.82%
At distribution center	253,745	245,890	8,017	3.16%
Inventory review policy	613,000	613,000	0	0.00%
Information system	3,775,000	3,775,000	0	0.00%
Raw materials	24,838,940	24,762,920	76,020	0.31%
Total Cost($)	**31,466,756**	**31,447,220**	**19,590**	**0.06%**

Table 4.35. Cost comparison between scenarios 2 and 4

CHAPTER 5: LEAD-TIME ANALYSIS

In a multi-echelon supply chain network, lead-time is the amount of time a product takes to reach from one echelon to the next. As shown in Figure 5.1, all the supply chain lead-times cumulatively define the product pipeline. The length of this pipeline is one of the factors which determine the supply chain's ultimate profitability: the shorter it is, the more profitable is the supply chain.

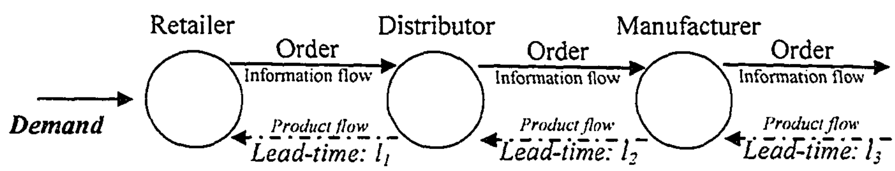

Figure 5.1. Lead-time in a 3 echelon supply chain network

Lead-time is one of the contributing factors to the "bullwhip effect" and lean manufacturing. Also, much of supply chain inventory is the result of uncertainty and variation in lead-time.

In Chapters 3 and 4 we studied the impact of demand uncertainty on the inventory levels in a supply chain network. In this Chapter we will focus on the impact of lead-time variations on a supply chain network with decentralized safety stock and shared information. For this purpose we perform a parametric analysis on the lead-time.

5.1. Parametric analysis

We can define an analysis as a test or series of tests in which purposeful changes are made to the input variables of a process or system so that we may observe and identify the reasons for changes in the output response.

In designing an analysis, selecting the variables (factors) and their levels (factor levels) are significantly important. The selected variables must be influential on the output response and also an important strategic factor of the system. The factor levels are mostly defined according to the characteristic and importance of the factor.

As mentioned previously, lead-time is one of the critical factors in a supply chain. In the following sections, we design a parametric analysis to study the impact of lead-time variation on the operational costs and the inventory level of the supply chain network.

5.1.1. The design factors

There are two types of lead-time in our supply chain network:

Manufacturing lead-time (MLT), which is the time between receipt of an order at the manufacturing facility from a distribution center, and the time the product, is ready to ship to the distribution center.

Transportation lead-time (TLT), which is the time, it takes to transport the ordered products from manufacturing facility to the distribution center.

The factor levels in our analysis are defined in two sets to investigate the behavior of the system response to different levels of the lead-time variation. In set 1, each factor will change by $\pm$ 20% relative to the current level, and in set 2, each will change by $\pm$ 50% relative to the current level. For each set of the factor levels we will perform a parametric analysis (design 1 and design 2) as shown in Figure 5.2.

Considering the 2 factors (manufacturing lead-time and transportation lead-time) each at 3 levels, there would be 9 possible combinations to investigate for each set as shown in Figure 5.2.

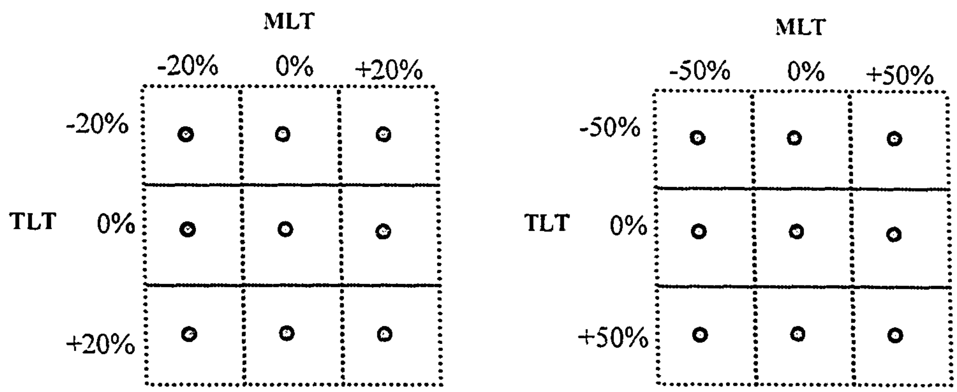

Figure 5.2. Lead-time analysis: Design1 and Design 2

5.1.2. The design analysis

Tables 5.1 and 5.2 show the results of the analysis for the two designs, respectively. We categorize the runs into 2 categories:

i) Runs with changes in MLT or TLT. In reality any increase in the lead-times increases the uncertainty in the supply chain network. In this situations, to reduce the risk of facing unsatisfied or delayed orders, distribution centers tend to keep more inventories which leads to "bullwhip" effect. Mathematically, any increase in lead-time (MLT or TLT) tends to increase the safety stock level in the supply chain network (see Chapter 3, section 3.5.4, equation 13). That explains the increase in production costs, costs of labor, transportation costs, inventory levels (in-transit, at distribution centers) and raw material costs. Also, for the same reason the inventory at manufacturing facility decreases since we are transporting more product from manufacturing facilities to distribution centers(see Chapter 3, section 3.5.4, equation 17).

As can be seen in Tables 5.1 and 5.2, it seems that the lead-time variation does not affect the selection of the inventory review policy, and therefore, the cost of inventory review policy doesn't change in any runs in design 1 or 2. The cost of information system increases as the lead-times increase, which means that to counter the uncertainty caused by longer lead-times the model tends to select timelier information systems to decrease the forecast error standard deviation and mitigate the impact of increased lead-time. On the other hand, as the lead-times decrease, the uncertainty in the system decreases, leading to the selection of less timely information system and lower costs.

Increasing the lead-times decreases the uncertainty in the supply chain network, thus reducing the production costs, costs of labor, transportation costs, inventory levels (in-transit, at distribution centers) and raw material costs. Lower inventory levels at distribution centers leads to less transportation from manufacturing facilities to distribution centers and as a result higher inventory level at manufacturing facility.

It's also shown that the impact of the manufacturing lead-time variations is more than that of the transportation lead-time on the total cost of the supply chain network. This seems reasonable because of the larger magnitude of manufacturing lead-time (MLT) compared to the transportation lead-time (TLT).

ii) *Runs with changes in MLT and TLT.* As seen in Table 5.1 and 5.2, increasing both the lead-times results in more uncertainty in the supply chain network and higher production costs, costs of labor, transportation costs, inventory levels (in-transit, at distribution centers) and raw material costs as well as lower inventories at manufacturing facilities compared to the case when any one of the lead-times increases. The reverse is true when we decrease both the lead-times.

When increasing MLT and decreasing TLT, because of the stronger impact of the manufacturing lead-time, the effect of the increasing MLT dampens the effect of decreasing TLT. As a result, production costs, costs of labor, transportation costs, inventory levels (in-transit, at distribution centers) and raw material costs increase and also the inventories at the manufacturing facilities decrease. The reverse is true when MLT decreases and TLT decreases.

As shown in Table 5.1 and 5.2 the maximum decrease in the total cost when both the lead-times decrease by 20 %(design1) is about $*241,565* or *0.77%*; when both lead-times decrease by 50% (design 2), the change is about *658,546* or 2.09%. This information helps the managers to decide how much they are willing to pay for the lead-time reduction in the system. It also demonstrates that the relation between the lead-time variations and the change in the total cost in the supply chain is not linear.

	Variations in MLT and TLT								
Costs	Run1	Run2	Run3	Run4	Run5	Run6	Run7	Run8	Run9
	+20% , 0	0 ,+20%	-20% ,+20%	0 ,-20%	-20% , 0	+20%,+20%	-20% ,-20%	+20%,-20%	0 , 0
Production	209,774	209,651	208,921	208,226	208,093	***210,542***	207,693	208,982	208,924
Labor (Decrease, Increase, Overtime)	1,264,591	1,264,580	1,264,399	1,264,394	1,264,381	1,264,604	1,264,452	1,264,570	1,264,560
Transportation	402,174	402,514	400,765	397,912	398,275	***404,482***	397,735	399,790	400,348
Inventories									
At Plant	53,337	53,370	54,337	54,286	54,324	***53,254***	57,064	53,420	53,707
In-Transit	58,603	58,606	58,538	58,506	58,511	***58,629***	58,497	58,566	58,529
At DC's	259,651	258,829	253,215	248,918	248,024	***264,598***	244,351	254,520	253,745
Inventory review policy	613,000	613,000	613,000	613,000	613,000	***613,000***	613,000	613,000	613,000
Information system	3,785,000	3,785,000	3,765,000	3,765,000	3,765,000	***3,785,000***	3,695,000	3,785,000	3,775,000
Raw materials	24,943,810	24,923,280	24,825,730	24,750,130	24,727,780	***25,034,110***	24,687,400	24,850,160	24,838,940
Total Cost	31,589,940	31,568,830	31,443,904	31,360,372	31,337,387	***31,688,220***	31,225,191	31,488,008	31,466,756
% Change, relative to run #9	0.39%	0.32%	-0.07%	-0.34%	-0.41%	**0.70%**	-0.77%	0.07%	0.00%

Table 5.1. The supply chain operation costs for design I

↑ ***Maximum*** (Run6)   ⇡ ***Minimum*** (Run7)

Costs	Variations in MLT and TLT								
	Run1	Run2	Run3	Run4	Run5	Run6	Run7	Run8	Run9
	50%,50%	50%,0	50%,-50%	0,50%	0,-50%	-50%,-50%	-50%,0	-50%, 50%	0,0
Production	***213,100***	211,138	209,148	210,788	207,366	***204,539***	207,014	208,700	208,924
Labor (Decrease, Increase, Overtime)	***1,263,903***	1,264,525	1,264,585	1,264,609	1,264,452	***1,264,352***	1,264,420	1,264,379	1,264,560
Transportation	***410,267***	405,110	399,233	405,926	395,955	***390,302***	396,954	401,254	400,348
Inventories									
At Plant	***52,105***	53,195	53,374	53,240	57,070	***57,705***	57,238	54,407	53,707
In-Transit	***58,691***	58,639	58,558	58,644	58,453	***57,914***	58,473	58,546	58,529
At DC's	***278,720***	268,189	255,659	266,206	242,304	***223,848***	239,873	251,761	253,745
Inventory review policy	***613,000***	613,000	613,000	613,000	613,000	***613,000***	613,000	613,000	613,000
Information system	***3,815,000***	3,785,000	3,785,000	3,785,000	3,695,000	***3,695,000***	3,695,000	3,765,000	3,775,000
Raw materials	***25,288,910***	25,106,810	24,878,660	25,057,670	24,654,920	***24,301,550***	24,596,470	24,789,400	24,838,940
Total Cost	***31,993,696***	31,765,606	31,517,218	31,715,083	31,188,520	***30,808,210***	31,128,441	31,406,446	31,466,756
% Change, relative to run #9	**1.67%**	0.95%	0.16%	0.79%	-0.88%	**-2.09%**	-1.08%	-0.19%	0.00%

Maximum (Run1)

Minimum (Run6)

Table 5.2. The supply chain operation costs for design 2

In Table 5.3 and 5.4 the relative impact of the variations in MLT and TLT on the total system costs. It is seen that the impact of MLT variations on the total cost of supply chain network is more than that of TLT; when MLT is increased by 50%, it leads to an increase in the total cost of 0.95%, while an increase of 50% in TLT leads to a change of 0.79% in the total cost. It is also shown that the impact of TLT variations is more on the transportation and in-transit inventory cost compared to that of the MLT variations. This information points out which lead-time reduction must have the first priority according to the strategic goal of the company.

As explained before, increasing lead-times result in higher levels of decentralized safety stock in the supply chain network and vice versa. In Figures 5.3 and 5.4 the changes in the decentralized safety stock levels are shown for each combination in our analysis. As shown, the larger changes in the decentralized safety stock levels occur when increasing both the lead-times, and the smaller changes in the level of decentralized safety stocks occur when decreasing both the lead-times. The stronger impact of MLT compared to TLT is also clearly be observed.

Also, comparing the results of the two designs, it is seen that the changes in the decentralized safety stock levels are larger as the lead-time variation level increases; the maximum decentralized safety stock level is 7% in design 1, 17% in design 2. Thus, there is a relation between the safety stock level change and the lead-time variations but it is not a linear one.

MLT		
Costs	Run1-Run9	Run5-Run 9
Production	850	-832
Labor (Decrease, Increase, Overtime)	30	-179
Transportation	1,825	-2,074
Inventories		
At Plant	-371	616
In-Transit	74	-18
At DC's	5,906	-5,721
Inventory review policy	0	0
Information system	10,000	-10,000
Raw materials	104,870	-111,160
Total Cost	123,185	102,075
% Change, relative to run #9	**0.39%**	**-0.41%**

TLT		
Costs	Run2-Run9	Run4-Run 9
Production	727	-698
Labor (Decrease, Increase, Overtime)	19	-167
Transportation	2,166	-2,437
Inventories		
At Plant	-338	578
In-Transit	77	-23
At DC's	5,084	-4,827
Inventory review policy	0	0
Information system	10,000	-10,000
Raw materials	84,340	-88,810
Total Cost	102,075	-106,384
% Change, relative to run #9	**0.32%**	**-0.34%**

Table5.3. Comparing the relative impact of MLT and TLT variations on total system costs (design1)

MLT		
Costs	Run2-Run9	Run7-Run 9
Production	2,214	-1,911
Labor (Decrease, Increase, Overtime)	-35	-141
Transportation	4,762	-3,395
Inventories		
At Plant	-513	3,530
In-Transit	110	-56
At DC's	14,444	-13,872
Inventory review policy	0	0
Information system	10,000	-80,000
Raw materials	267,870	-242,470
Total Cost	298,850	-338,315
% Change, relative to run #9	**0.95%**	**-1.08%**

TLT		
Costs	Run4-Run9	Run5-Run 9
Production	1,863	-1,558
Labor (Decrease, Increase, Overtime)	48	-109
Transportation	5,577	-4,394
Inventories		
At Plant	-468	3,362
In-Transit	115	-76
At DC's	12,461	-11,441
Inventory review policy	0	0
Information system	10,000	-80,000
Raw materials	218,730	-184,020
Total Cost	248,327	-278,236
% Change, relative to run #9	**0.79%**	**-0.88%**

Table5.4. Comparing the relative impact of MLT and TLT variations on total system costs (design2)

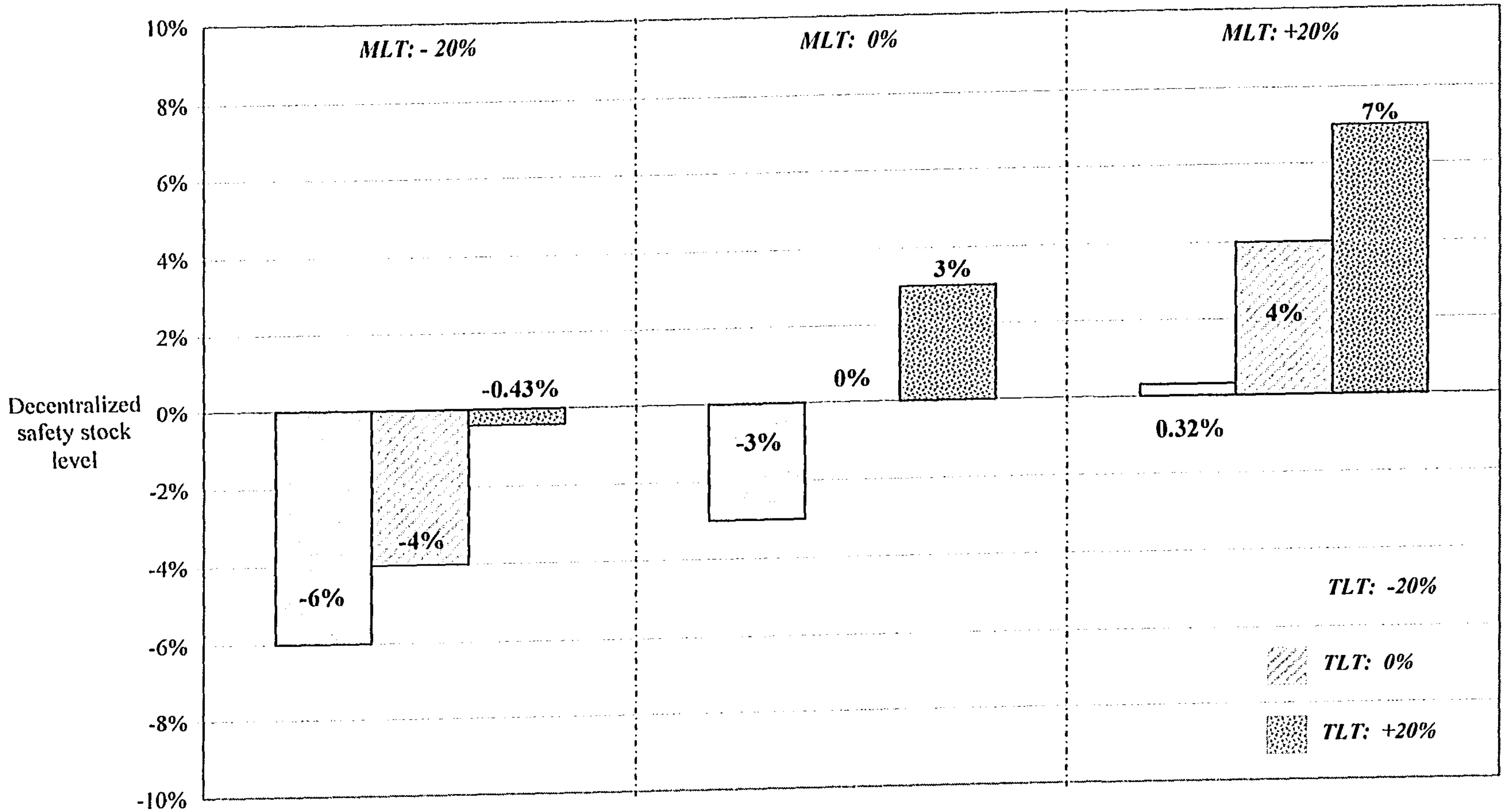

Figure 5. 3. Lead-time variations vs. decentralized safety stock variations, design 1

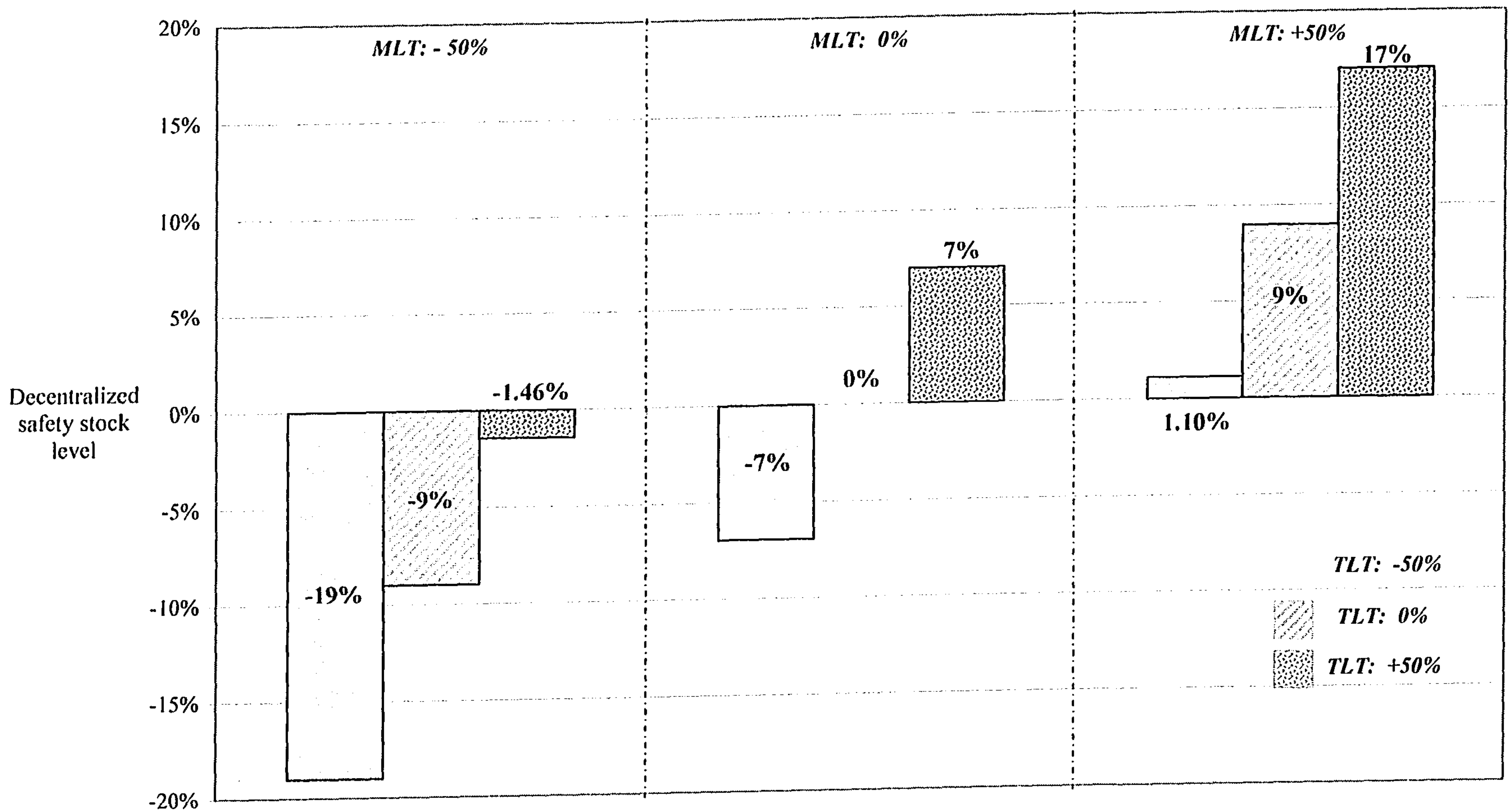

Figure 5.4. Lead-time variations vs. decentralized safety stock variations, design 2

Our findings of the study of the lead-time variation impact on the operational costs of the supply chain network may be summarized as follows:

1. Lead-time variations have a direct impact on the operational cost of a supply chain; the larger the variations the larger the changes in the costs, and vice versa. However, the relationship is not a linear one.
2. In the supply chain network under consideration, manufacturing lead-time variations seem to have a larger impact than transportation lead-time variations.
3. Lead-time variations also have a direct impact on the decentralized safety stock (DSS) level in the supply chain network. The higher the variations the higher the DSS levels in system and vice versa; however the relationship is not linear.

It must also be noted that in this model the cost of raw material is the largest component of the total cost, around 87%, and all the other costs constitute 23% of the total cost. Thus, the major changes in the total costs come from changes in the cost of raw material.

CHAPTER 6: SUMMARY AND FUTURE DIRECTIONS

In this Chapter we summarize the major contributions of this thesis. We also discuss and summarize the conclusions we made in the thesis and then present some future research directions.

6.1 Summary of the Present Work:

In this research we adapt a multi-stage, multi-period, multi-product supply chain network model with a seasonal demand pattern and a decentralized safety stock policy (Dominguez, 2002) to quantify the benefits of demand information sharing in a supply chain network.

The model determines the assignment of the finished goods production, inventory and workforce levels, transportation modes and the number of transportation consignments in order to minimize the total costs incurred in the system. It also analyzes the different inventory review policies and information systems to measure the trade-offs between the value of information sharing and the overall system costs.

Considering the value of demand information sharing in improving the efficiency of the supply chain network, we present a method for updating the demand forecasts based on the parameters of the selected information system which results in a more accurate demand forecast (i.e., a smaller demand forecast error standard deviation). It is assumed that the demand forecast errors are a function of the timeliness factor of the selected information system. We assume this function to be linear and the experimental results of the regression analysis appear to support this.

The supply chain network model was modified by incorporating the above method of demand forecasting, and was utilized in order to measure the impact of these modifications on the model by comparing the costs, inventory levels and the timeliness level of selected information system in the supply chain network. For this purpose we run the model under 4 different scenarios and compared the results.

The results shows that with the new forecasting method, spending a little more (6%) on information systems and selecting timelier information systems leads to a significant decrease (15.5%) in the total cost of the supply chain network. It must be pointed out that employing a "timelier" information system may also incur some hidden costs (i.e., training, hardware setup, etc). Furthermore, the hidden costs of a timely information system in some cases correspond to some strategic or infrastructural issues that are extremely hard to be introduced to a model that deals with operational level decisions. Due to all the reasons mentioned above, these costs are excluded from the model.

Since the demand forecast error affects the safety stock level, we also investigated the impact of employing our proposed method on decentralized and centralized safety stock levels. The results show that by using our proposed method, decentralized safety stock levels can be reduced by 25% (in scenario 2, with decentralized safety stock policy). Also, in scenarios with both centralized and decentralized safety stock policies (scenario4) there is a 25% decrease in the decentralized safety stock level, and 26% decrease in the centralized safety stock level.

We also studied the impact of lead-time variations as one of the key factors in a supply chain network by performing parametric analysis. Our analysis indicates that lead-time variations have a nonlinear impact on the operational costs of the supply chain network. It's also shown that the effect of the manufacturing lead-time (MLT) is more significant than that of the transportation lead-time (TLT) on the total costs of supply chain network. This seems reasonable because of the larger magnitude of the manufacturing lead-time (MLT) compared to the transportation lead-time (TLT). This information points out which lead-time reduction must have the first priority regarding the strategic policy of the supply chain.

The impact of lead-time variations on the safety stock levels in the supply chain network has also been studied. The results indicate that lead-time variations and safety stock levels are highly correlated, i.e., an increase in the lead-time increases the safety stock levels, and vice versa. It is also shown that the impact of manufacturing lead-time (MLT) variation on the safety stock levels is more significant than the impact of transportation lead-time (TLT).

Our analysis shows that reducing lead-time may lead to a reduction in the overall system costs in a supply chain network. Lead-time reduction could be accomplished by applying quick response manufacturing principles to existing operations or through dedicating flexible capacity to customized products. Lead-time reduction in a supply chain is a difficult and expensive process but considering the benefits and the advantages, it is feasible in most cases.

6.2. Future research directions:

There are a number of research issues which remain to be examined and several potential directions to be continued on this subject. Here are some of these directions:

1. The supply chain in this thesis includes the manufacturer and the distribution centers. The model can be enhanced to include the suppliers, retailers and customer zones. Then the impact of sharing demand information between different levels of supply chain network can be studied.

2. In this thesis we consider just 3 levels of information timeliness factors and inventory review policies. Further considerations in the information timeliness factors and inventory review policies and their related costs can be introduced in the model. i.e., breaking down the timeliness levels and inventory review policies into some more detailed echelons may lead to a better understanding of the internal causality mechanisms of the supply chain.

3. As mentioned, the safety stock policy (decentralized or centralized) is selected based on parameters like, premium transportation costs, demand forecast error, inventory carrying cost and customer service level. A sensitivity analysis can be performed to study the impact of these parameters on the selection of safety stock policy and the operation of supply chain network.

4. In lead-time sensitivity analysis we assumed the lead-times to be fixed so that this variability was not included in our study. Considering the stochastic nature of the lead-times it is proposed to perform this analysis considering the variability of the lead-times. This can be done by fitting probability distributions to different types of lead-time (MLT, TLT) and then trying to perform detailed analysis based on their stochastic behavior.

6. In this model no transshipments (shipments between distribution centers) are assumed in the supply chain network. The model can be extended by considering this type of

shipments which maybe economically feasible, especially when there is an excess inventory in one location that can be used in other locations.

7. In this study all shortages are considered as lost sales, which might not necessarily be a convenient assumption. In real life we also have unsatisfied demands that are carried on to the next periods. However, considering the size of the model, this may lead to an intractable model.

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Appendices(CD Format)

Appendix I :Database structure

Appendix II :Database file (Access format)

Appendix III :Lingo script

VITA AUCTORIOS

NAME:	Niloofar Mahmoudi
COUNTRY OF BIRTH:	Iran
YEAR OF BIRTH:	1976
EDUCATION:	Bachelor of Engineering Sharif University of Technology Tehran,Iran,1999
	Master of Applied Science in Industrial Engineering University of Windsor Windsor,ON,Canada,2005