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MODELING AN INTEGRATED SUPPLY CHAIN MANAGEMENT SYSTEM FOR AN APPLIANCE COMPANY: A VALUE OF INFORMATION APPROACH

By

Hugo Dominguez

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ABSTRACT

The present research is focused on the broad concept of "Supply Chain Management", a philosophy that has to do with the coordination and integration of complex interactions in the production-distribution chain of a business operation. This includes the flow of material and information from raw material suppliers to end-customers.

This thesis focuses on analyzing the Supply Chain from an inventory management point-of-view. Specifically, we propose a multi-stage, multi-period, multi-product, combinatorial inventory-planning model with stochastic demand. The mixed-integer programming model integrates the production and distribution planning processes of a large household appliance manufacturer located in Mexico. The proposed model determines the assignment of the finished goods production level (units), workforce level (labor hours), transportation mode, number of transportation consignments, and inventory levels (in units) as well as the allocation of information resources in order to minimize the total costs incurred in the system. Sensitivity analysis is carried out to test the robustness of the model.

All in all the major contribution of this research is the inclusion of the information resources allocation concept, which measures the trade-offs between the value of the information and the overall system costs.

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NOTATION

Index Sets

p	=	Index for manufacturing facilities, $p \in \{1 \ldots P\}$
n	=	Index for product family produced at manufacturing facility p, $n \in \{1 \ldots N(p)\}$
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 $m \in \{1 \ldots M(p)\}$
i	=	Index for periodic-review policy, $i \in \{1 \ldots I(p)\}$

Decision Variables

X_{pnt}	=	Number of units of product family n produced 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).
f_{pt}^{+}	=	Additional labor hours at manufacturing facility p in time period t (without hiring).
f_{pt}^{-}	=	Reduced labor hours at manufacturing facility p in time period t (without layoff).
O_p	=	Total overtime scheduled at the end of the planning horizon at manufacturing facility p.
TU_{pjkt}	=	Number of mode j transportation units used to ship product from manufacturing facility p to distribution center k 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.
DI_{pn}	=	1 If a decentralized inventory policy is to be followed in family n at manufacturing facility p and 0 otherwise.
RP_{pn}	=	1 If postponement is applied for product family n at manufacturing facility p and 0 otherwise.
β_{pi}	=	1 If cycle length is considered from periodic-review policy i and 0 otherwise.
PS_{pn}	=	Pooled safety stock for product family n at manufacturing facility p.
δ_{pm}	=	1 If information system m is used at manufacturing facility p and 0 otherwise.
$\hat{L}_{pni}$	=	Linearization auxiliary variable which equals 1 if β_{pi} and RP_{pn} equal 1 and 0 otherwise.
$\hat{L}'_{pni}$	=	Linearization auxiliary variable which equals 1 if β_{pi} and DI_{pn} equal 1 and 0 otherwise.
r_{pmnt}	=	Linearization auxiliary variable which equals $\gamma_{pmnt}X_{pnt}$ if δ_{pm} equals 1 and 0 otherwise.

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.
R_p	=	Additional cost incurred due to employee transportation and/or refreshment when exceeding contractual labor time 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).
PC_{pt}	=	Labor hour upper limit for manufacturing facility *p* in period *t*.
a_{pn}	=	Number of labor-hours required to produce one unit of an item of product family *n* produced at manufacturing facility *p*.
θ_p	=	Limit of allowable working time in a time period that is the ratio of overtime capacity in labor-hours to regular time labor-hour level for manufacturing facility *p* ($\Theta_p < 1$).
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 an item 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 an item of product family *n* produced at manufacturing facility *p* held from one period to the next in distribution center *k*.
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).
TC_{pjk}	=	Transportation cost of one shipment from manufacturing facility *p* to distribution center *k* using mode *j*.
λ	=	Strategic inventory factor which ensures availability of inventory at the beginning of each time period.
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*.
FTL_j	=	Capacity of a mode *j* full transportation consignment in terms of Volume (cubic space)
LT_{pjk}	=	Lead-time of transportation mode *j* from manufacturing facility *p* to distribution center *k*.
TLT_{pk}	=	Average Lead-time from manufacturing facility *p* to distribution center *k*.
MLT_{pn}	=	Average Lead-time to produce a family *n* item at manufacturing facility *p*.
D_{pnkt}	=	Expected demand for product family *n*, produced at manufacturing facility *p*, in distribution center *k* during period *t*.
σ_{pn}	=	Standard deviation of the overall distribution network forecast error for product family *n* in manufacturing facility *p*.
σ'_{pnk}	=	Standard deviation of the demand forecast error 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.
PTC_{pn}	=	Premium transportation cost when using a centralized safety stock policy for family *n* produced at manufacturing facility *p*.
CP_{pi}	=	Fixed cost of the information system (information gathering, communications required and planning costs) using periodic-review policy *i* at manufacturing facility *p*.
TP_{pi}	=	Cycle length for 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*

CHAPTER 1. INTRODUCTION

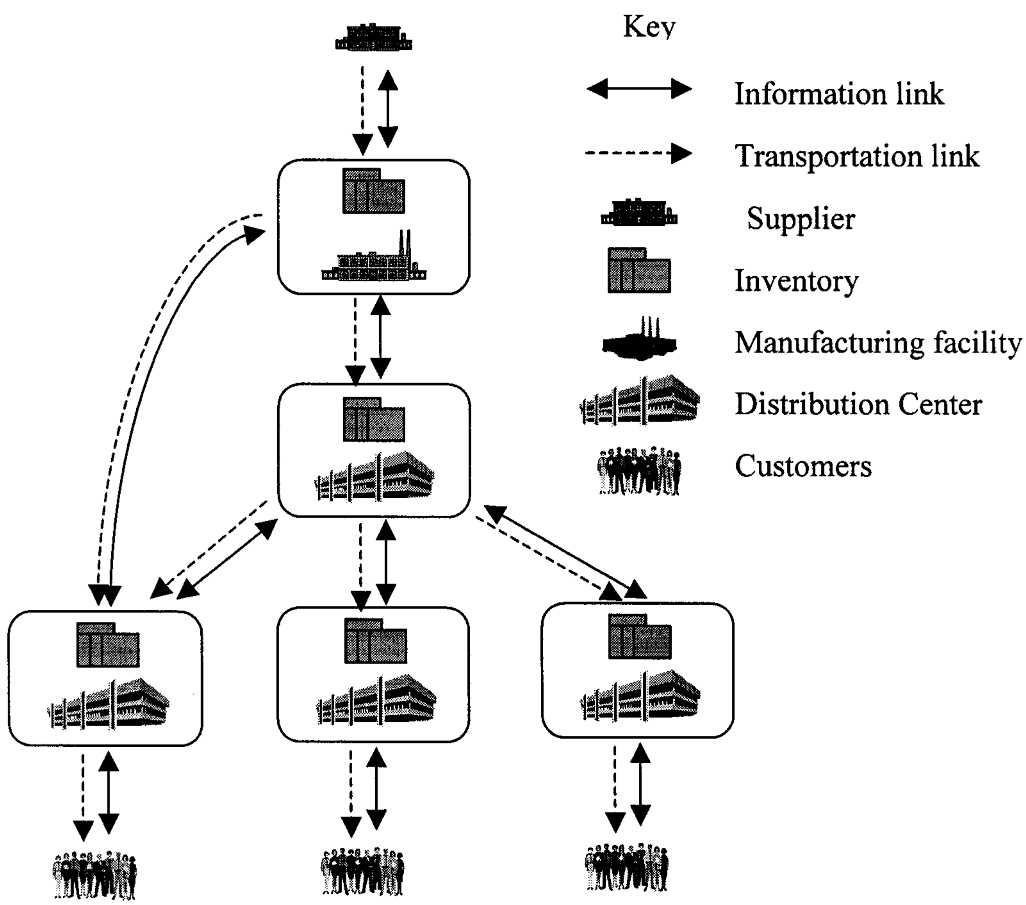
Competitive business environment and the current slowdown in the global economy have forced companies to aggressively seek cost reduction and responsiveness opportunities. In the 1980's companies discovered new techniques and manufacturing technologies that allowed them to reduce costs and increase competitiveness in different markets. Production strategies such as just-in-time, lean manufacturing, total quality management, applied operations research modeling techniques (see Johnson and Montgomery, 1974) and others became very popular means of increasing productivity within the four walls of manufacturing and large amounts of resources were invested in implementing these strategies. In recent years, these efforts have flourished to the point where product and quality have become comparable among manufacturers, and costs have been greatly reduced. Hence, many of these companies are now competing on the basis of inventory turns and speed to market. This has evoked Supply Chain Management as a means of further increasing profit and market share (Simchi-Levy et al., 2000).

1.1 The Concept of Supply Chain Management

Supply Chain Management (SCM) is a collection of procedures, information technologies, equipment and people used to coordinate the flow and storage of products and related information from point of origin to point of destination in order to minimize system-wide costs while satisfying service level requirements.

A typical Supply Chain (supply chain network or value-added chain) consists of suppliers, manufacturers, distributors, retailers and customers, which are linked together by the inventory transportation pipeline and information channels. Figure 1 presents the general structure of a supply chain network. Multiple products, several manufacturing sites, distribution centers, a forward flow of materials, a bi-directional flow of information and a wide variety of equipment and operations generally characterize supply chains.

Figure 1. An example of a Supply Chain (extracted from Lee and Billington, 1992)



SCM involves the integration of production, distribution and transportation in order to correctly position products to facilitate sales (value-adding function) at the minimum cost. Unfortunately, integration of the supply chain is not easy because each one of the mentioned functions may have different and conflicting objectives. For example, manufacturers typically would prefer to produce large batches, which in turn conflicts with the objective of both warehouses and distribution centers to reduce inventory. Thus, the emphasis is not only on minimizing costs in each functional area, but to take an overall systems approach to cost reduction. In summary, we can say that the goal of SCM is to achieve a targeted level of customer service at the lowest possible *overall* cost (Simchi-Levy et al., 2000).

For individual firms, SCM expenditures typically range from 5 to 35 percent of the sales depending on the type of business, geographical area of operation and volume/value ratio of products and materials. These costs typically account for one of the highest costs of doing business, second only to materials in manufacturing or cost of goods sold in wholesaling and retailing (Bowersox, 1996). These high expenses underscore the necessity of cost reduction within the supply chain.

1.2 Background

During the 1950's, the majority of US firms were managing their supply chains purely on a functional basis. No concept or theory of integrated SCM existed. The main reason behind this fact was that communications, computers and quantitative techniques were not widely available and manual analysis and integration of holistic information (i.e., information relating to all the functional areas in the supply chain) was intractable. In the decades that followed, computer applications and quantitative techniques focused on improving the performance of specific supply chain functions such as order processing, forecasting, inventory control and transportation. Nowadays, integrated planning has become possible due to advances in Information Technology (IT) and quantitative techniques, but most companies have much to learn about these new tools and their effective application (Shapiro, 2001).

Literature provides evidence that SCM has its roots in the evolutionary path followed through materials management and physical distribution after World War II, functional logistics (different managers for different functions) and integrated logistics (one manager for all functions).

According to Ganeshan et al. (1999), Houlihan in 1985 is credited with first coining the term "Supply Chain", in a paper which discusses the concepts underlying the new approaches to managing change in international chains, the barriers to be overcome and the lessons learned. Houlihan concludes that a holistic approach to international SCM requires the integration of a logistical approach into the strategic decisions of any company.

Masters and Pohlen (1994) have depicted the evolution of logistics into three main phases:

a) Functional management (1960-1970). Functions such as purchasing, shipping and distribution are each managed separately

b) Internal integration (1980's). The management of the supply chain functions of a single facility are unified and become the responsibility of a single manager.

c) External integration (1990's-2000's). The management of supply chain functions is unified requiring cooperation and coordination between the links of the chain. Over these years, integrated planning has been possible due to advances in IT, such as e-commerce, astonishing gains in personal computers and computing speeds, and the power and flexibility of data management software.

It is important to mention that in general these phases have followed in developed countries, but in some developing countries the aforementioned phase pattern has a time lag of several years. Such is the case of some companies in Mexico, which according to empirical evidence, are in the phase of internal integration and although the trend is to achieve external integration, it is believed that this will not be accomplished until internal integration is fully realized.

Several different disciplines have contributed to strengthen the SCM theory. These include marketing, economics, systems dynamics, operations research/management science and operations management. For a thorough review of specific contributions refer to Ganeshan et al. (1999).

1.3 Integrated Supply Chain Management

Integration in the Supply Chain, as stated by Shapiro (2001), may be viewed from 3 different perspectives:

a) Functional Integration, which refers to the synchronization and coordination of the activities such as production and distribution.

b) Spatial Integration, which refers to the coordination of activities across geographically dispersed vendors, facilities and markets.

c) Intertemporal Integration. Also called hierarchical planning, aims at achieving coherence and consistency within the overlapping decisions of the three planning levels: strategic, tactical and operational. Strategic level planning deals with decisions that have a long lasting effect on the firm. This includes decisions regarding the location, size, and optimal numbers of suppliers, plants and distributors to be used in the network. Tactical level planning involves supply planning, which includes the optimization of flow of goods through a given supply chain. The tactical level includes decisions on purchasing, production, inventory policies and transportation strategies. Tactical level planning is medium-range planning, which is typically performed on a monthly or weekly basis. Finally, operational level planning is short-range planning, which involves production or distribution scheduling at all plants on a daily or an hour-to-hour basis. It is at this level that much of the modeling and research effort has focused (Gunaseharan, 2001).

1.4 Value of Information and Modeling of the SC: Scope of the Study

In this thesis, information technology is defined as having two components: Hardware and Software. Hardware refers to the physical means of carrying out the tasks to achieve objectives or goals, whereas software is defined as a set of rules, guidelines, and algorithms necessary for using the hardware.

As discussed earlier, information technology is advancing at a phenomenal rate in terms of speed and storage capability with simultaneous dramatic reductions in cost and size, generating a wide range of applications. For example, many companies have been induced into the implementation of ERP (Enterprise Resource Planning) systems by the preconceived notion that these will help in facilitating the integration of supply chain activities with increased availability of information. However, results have been less than expected or desired because, as many managers have come to realize, ready access to transactional data does not automatically lead to integration or better decision-making. Shapiro (2001) proposes that by differentiating between the form and function of Transactional IT and Analytical IT, companies will be able to effectively apply IT in managing their supply chains.

Transactional IT is related to data about the firm's supply chain and the means of acquisition, communication and processing of these data. Transactional IT collects and structures data. Analytical IT, on the other hand, is related to the evaluation of supply chain planning problems. Data is converted into information by means of both the analytical and transactional IT, which is the basis for decision-making.

Shapiro (2001) also notes that an essential component of analytical IT are optimization models, which are the only tools capable of fully evaluating large, numerical databases to identify optimal, or demonstrably good, plans for redesigning and operating supply chains.

Glazer (1993) suggests that companies that successfully integrate their IT strategy with their business strategy focus on information itself as the real carrier of value and source of competitive advantage. These companies focus on the output of the IT, the information itself, as the carrier of value and the variable to be analyzed in any discussion of the benefits in performance resulting from IT investments.

Although a complete definition of information is somewhat problematic, in our research we will define information as that which reduces uncertainty (Glazer 1993). In the context of the present work, the value of information is measured in terms of its ability to reduce uncertainty throughout the supply chain. It has been shown that variability increases as different partners communicate through the supply chain in the process of fulfilling a customer's order. This phenomenon is known as the bullwhip effect (see Lee et al., 1997a, 1997b; Metters, 1997; Chen et al., 1999).

Common forms of information in the supply chain environment include customer and replenishment orders, sales forecasts, inventory levels and transportation requirements. For the purpose of our research, in order to be able to describe and measure information, we use 4 characteristics that are fundamental to adequately support enterprise planning and operations (Talluri, 2000). It is important to say that each one of these characteristics has implicit technological factors (i.e., hardware and software) that define the level of information generated. These characteristics are:

a) Availability. Information in the supply chain must be readily and consistently available. Availability refers to the ease with which existing information is retrieved. Rapid availability is necessary to respond to customers and improve decision-making. In this way, information can reduce uncertainty in the supply chain.

b) Accuracy. Accuracy refers to the degree with which information matches actual physical status. For example, when there is low consistency between physical and information system inventory levels, safety stocks are necessary to buffer against this uncertainty. Sales forecasts are another example of information in which accuracy is important. In this way accurate information reduces uncertainty and thus, inventories.

c) Timeliness. This characteristic refers to the delay between when an activity occurs and when the information is registered in the information system. A good example concerns the movement of inventory from work-in-process to finished goods. In many cases although a continuous flow of material takes place, information regarding inventory status in the system may be updated with a time lag of minutes, hours or even days. Real-time updates are timelier, however, costs are increased due to additional record-keeping efforts. Timely information reduces uncertainty generated by the need to make decisions without information (i.e., guessing).

d) Periodicity. Periodicity refers to the frequency with which information is retrieved from the system. Management controls produce information on a periodic basis such as daily or weekly in the form of performance reports. Inventory control systems also generate information on a periodic basis, extracting data from transactional IT.

In general, each one of the characteristics mentioned above has the potential to reduce uncertainty throughout the supply chain, which in turn has the ability to reduce inventories; however, increasing the levels of these characteristics may also result in higher costs. A good example of how information is used to reduce uncertainty, and thus inventories, is through the application of two principles that are an important strategy in SCM: Delayed differentiation (or postponement) and modularization (Ernst and Kamrad, 2000). The two concepts are closely interrelated and by their implementation firms have been able to gain competitive advantage. Postponement can be separated into time postponement and form postponement. Time postponement refers to the delay in the movement of finished products through the supply chain. The strategy is to maintain a full-line anticipatory inventory at one or a few strategic locations, waiting until forward deployment of inventory is required by customer orders and thus reducing the risk of positioning the product at the wrong locations, which in turn reduces uncertainty. This is why time postponement has also been called Risk Pooling by some authors (Simchi-Levy et al., 2000). In form postponement the delay is related to the product's final configuration. The risk associated with improper or wrong manufacturing of a product is automatically eliminated. Modularization, closely related to form postponement, implies a product design approach in which a set of standardized constituent units is used to assemble the end product.

The concept of postponement has long been discussed in the literature (Alderson, 1957), but only recently some of its practical applications in SCM have been published (see for example He et al., 1998). We argue that information has played a vital role in the potential for delayed differentiation applicability, which has been driven by increased capability to process, transmit and deliver orders with a high degree of accuracy and speed (Bowersox, 1996).

Based on the motivation outlined in the previous sections, and the basic ideas in this section, it is proposed that an integrated approach to modeling a SCM system be developed. Furthermore, it is proposed that information be considered as a decision variable with associated costs, and integrated into an optimization model in order to minimize the total costs of managing the supply chain.

The modeling of the supply chain is done in the context of a real-world business operation. The company selected is a major household appliance manufacturer located in Mexico, which for the sake of confidentiality will be called *AG, Inc.* The appliance firm started manufacturing kitchen cabinets 50 years ago and gradually has become one of the Latin-American leaders in the appliance market (refrigerators, washers and ranges). AG, Inc. is a vertically integrated manufacturer of plastic and stamped components, transmissions for washers, electric motors and compressors, in addition to finished appliances. Today, the company operates 7 plants (of which only 2 existed initially and 5 were incorporated over the past 15 years) and 8 distribution centers in Mexico. AG, Inc. produces and distributes over 200 products in the domestic and export markets. Presently, the company has approximately 8,000 employees and its total annual sales are estimated at around 700 million dollars (US).

After visiting AG, Inc. the following major characteristics of the supply chain were distinguished:

a) Demand follows seasonal patterns. Cultural and economic reasons make Mexican customers increase their purchases of appliances around two major celebrations: Mothers Day and Christmas. Plant capacities are generally surpassed during these periods but low demand periods result in excess capacity.

b) Sales increase towards the end of each fiscal month. It was observed that demand is not uniformly distributed over each month, but rather, sales are much higher during the last week of each month. This leads to the fact that, in general, during the last week of each month there is not enough plant capacity to fulfill requirements and therefore buffer inventories must be built. We assume that this is a consequence of the bullwhip effect between retailers and AG, Inc.

c) Long Lead-times. Production and distribution lead-times are generally long due to the distances between clients and manufacturing facilities.

d) Manufacturing facilities and distribution centers are considered as separate entities and use separate inventory management systems. This generates a time lag between the time a product is finished and the time the product is actually available in the distribution system for shipment.

e) Manufacturing facilities work under a flexible working time system. In this system, workers are committed to complete the total contractual hours over the planning horizon (e.g., 3 months), but these may not be uniformly distributed over the periods. For example, in one period workers may work less than the normal time (40 hrs/week); but in another period workers may be asked to work more than the normal time, depending on production requirements. At the end of the planning horizon the workers' total working time is calculated and if there is an excess of hours compared to the contractual hours then she/he is paid overtime for the additional hours. Even though this system is introduced to keep stability in the workforce level, there may be times when hiring or firing will be necessary due to economic factors.

f) Internal functional integration effort is taking place. As previously stated it is necessary to achieve internal integration before venturing into external integration of the supply chain. We believe that unless the company uses a systems approach for integrating its own Supply Chain, the effort will indeed be futile.

Given the above characteristics we decided to model the Supply Chain from an inventory management point-of-view. Specifically, we use a mathematical programming approach in the modeling of a large scale multi-echelon inventory system in order to optimize the deployment of inventory, transportation modes, production and warehouse capacities based on stochastic demand with seasonal patterns. Information, as previously stated is considered as an important decision variable. Consequently, this research is concerned with production planning, acquisition of capacity, inventory management and distribution of finished goods under the premise that information is a valuable asset that also requires optimal allocation in order to minimize system-wide costs.

CHAPTER 2. LITERATURE REVIEW

We consider three areas of studies that have attempted to link the flow of materials and/or information across different stages of the supply chain. First, we have perused general literature that treats the supply chain problem from a theoretical quantitative perspective; we assert that most of the literature in this area is only applicable as the basis of real-world large-scale supply chain problems, either because of the limitations in the size of the problems which can be handled, or because of their underlying assumptions. Subsequently, we have considered several real world large-scale applications of production-distribution models; our intention is to find effective modeling techniques that researchers have utilized and to understand the scope of existing supply chain management problems. Finally, we address papers that have utilized the concept of value of information in conjunction with inventory theory.

2.1 Theoretical Quantitative Approaches

Hanssmann (1959) is probably the earliest approach to integrated multi-product, multi-stage supply-production-distribution planning. In his paper, he uses a series of inventory stations in which all stations work together to deliver the end product to the customer. His model calculates optimal inventory levels at different warehouses in series using a method that combines dynamic programming and a maximization procedure considering a normally distributed static demand. A rather unique assumption used is the fact of considering demand as sensitive to delivery time, which in turn is affected by the inventory policy. The model does not consider production or warehouse capacities.

Clark and Scarf (1960) also introduced a single product multi-period, un-capacitated inventory system with warehouses in series that they called multi-echelon inventory system. The concept of echelon inventory is defined as the stock at a warehouse plus all stock in its succeeding warehouses. The optimal inventory policy at each warehouse is calculated by decomposing the system into several separate single-warehouse systems that are specified and solved recursively.

Zangwill (1966) presents a model that integrates production and distribution decisions in a deterministic multi-product and multi-facility environment. The author develops efficient dynamic programming algorithms in order to find the optimal production schedule and inventory levels at each facility. The model considers production lead-times but does not consider transportation times or costs. Finally, the paper presents several small-scale examples in order to show the mechanics of calculation.

Gavish and Graves (1980) extended a conventional production model by considering finished goods inventories. Their model considers stochastic demands for finished products and production lot-sizes of one in a single manufacturing, single product and single warehouse environment. The paper is distinct from others in that it takes advantage of the existing relationship between queueing systems and production-inventory systems to develop an efficient algorithm for finding an optimal inventory policy. The authors comment on their computational experience in which solution times are less than of 1/8 of a second.

Cohen and Lee (1988) develop a comprehensive framework which links decisions and performance through the production/distribution supply chain. The modeling approach is to develop a series of linked, approximate sub-models, which use tractable stochastic models, and a heuristic approximation procedure. The paper, however, does not consider production or distribution center capacities; also it does not consider the dynamic nature of demand, which limits its applicability to supply chains with highly seasonal patterns and trends. The main contribution of the paper is the notion of developing a fully integrated supply chain model.

Benjamin (1990) considers the transportation mode selection problem in a deterministic production-distribution inventory system. The problem is formulated as a single period, single part, and cost minimization non-linear program. Local optimum solutions are found using a general reduced gradient algorithm (GINO) and Bender's decomposition. The paper presents a small-scale real world problem with 4 manufacturing facilities, 3 warehouses and 2 transportation modes that is solved efficiently using Bender's decomposition. The main contribution of the model is to explicitly consider multimodal transportation costs simultaneously with total supply chain network costs.

The study of multi-echelon inventory systems has further attracted the attention of researchers and practitioners. Dynamic programming has been extensively applied even in recent years. Additional developments may be found in Federgruen and Zipkin (1984a, 1984b), De Bodt and Graves (1985), Stenger (1996), Moinzadeh and Aggarwal (1997), Ganeshan (1999) and Bhattacharjee (2000).

2.2 Large-Scale Applications

In this section, we focus on the application of large-scale mathematical programming models. Mixed integer programming (MIP) formulations are among the most widely used techniques, which address global, single-country, local or regional environments.

In their seminal work, Geoffrion and Graves (1974) present a MIP model and an algorithm based on Benders decomposition to solve the multi-commodity, single-period, production-distribution problem. This approach is successfully applied to a real problem for a major food firm with 17 commodity classes, 14 plants, 45 possible distribution sites, and 121 customer zones. Their major conclusion is the demonstration of feasibility of Benders Decomposition as a computational strategy for static multi-commodity intermediate location problems.

Brown et al. (1987) present an extension of Geoffrion and Graves (1974) in a paper that models a deterministic, multi-commodity, production-distribution system and is solved using the primal decomposition method. The mixed-integer model is the basis of a decision support system developed for Nabisco bakeries to manage complex problems involving facility selection, equipment location and utilization, and production and distribution of several hundred products. A realistic prototype problem with 44,388 variables and 19,841 constraints is presented. The model performs up to expectations but is not compared with the Bender's decomposition.

Cohen and Lee (1989) present a deterministic linear programming model for resource deployment of an international value added supply chain. The model was designed to support the evaluation of global manufacturing strategies explicitly considering suppliers, plants, distribution centers and customers. Two main problems are addressed:

a) The design problem, which deals with the location and capacity of all production and distribution sites around the world.

b) The material flow management problem, which deals with the determination of the suppliers, plant allocations, distribution center allocations, transportation policies and markets to serve.

The authors demonstrate by means of sensitivity analysis that profit rates under different network configurations are not significantly different. This shows that the creation of international supply chains is a suitable method for driving increased firm flexibility.

Lee and Billington (1993) develop a model intended to enhance material flow at Hewlett-Packard (HP), which manages inventories under decentralized control, i.e., the type of control where a supply chain has individual units that partially control inventory decisions based on local information. The model represents the supply chain of a printer and takes into consideration:

a) The uncertainties in supply, demand, and production lead-time and,

b) A capacitated production system.

In order to represent uncertainties in the system the model considers supply and demand as normally distributed; additionally the production lead-time is a function of the throughput rate and flow time in the manufacturing of the product, the occurrence and duration of production downtimes and the capacity of the manufacturing process. The stochastic element of the production lead-time is included in the downtime occurrences, which are assumed as Poisson. However, the paper does not discuss the implications in the model of trends or seasonality in demand. The main contribution of the paper is to provide the basic framework within which general supply chain inventory problems can be tackled and to show how these problems were addressed in the specific case at Hewlett Packard.

Martin et al. (1993), present a decision support system called FLAGPOL, which is based on a deterministic linear programming approach. FLAGPOL deals with 200 products, 40 demand centers and 4 manufacturing facilities in a 12-month planning horizon. The objective function of the model is a maximization of total margin over the planning horizon. This includes operating revenues and costs and also reflects changes in the value of inventory over the horizon. The model provides the optimal assignment of the customer's orders to the manufacturing facilities, optimal mode of transportation and optimal inventory level. In terms of variables, the model handles approximately 99,000 variables and 26,000 constraints. Typical execution times are three to four hours on a Sun Sparcstation. However, once a given problem is solved, additional scenarios can be completed in as little as five minutes. The design and implementation of FLAGPOL required a team of 5 people and 2 years to complete. Annual savings due to the implementation of FLAGPOL were estimated to be more than $2,000,000 at the glass company for which it was originally designed.

Robinson et al. (1993) present a deterministic mixed integer programming model of a two echelon uncapacitated facility location problem. The model is applied to DowBrands Inc. in the form of an optimization based Decision Support System. They carry out a sensitivity analysis in order to test for trade-offs between customer-service and total cost. The authors discover several cost reduction opportunities and insights in the design of the distribution network. Savings are expected to be approximately $1,400,000 per year.

In another example of optimization models applied to industry, Arntzen et al. (1995) provide a model devoted to the design of the Global Supply Chain of Digital Equipment Corporation (DEC). The strategic model recommends a production, distribution, and vendor network using a deterministic, multi-period, multi-product, large-scale mixed integer programming approach that minimizes weighted total supply chain cost and activity days subject to meeting estimated demand and restrictions on local content, offset trade, weight of products through facilities and joint capacity for multiple products, echelons and time periods. In order to solve such a large optimization problem (20,000 variables and 6,000 constraints), the authors take advantage of the special structure contained in the model and use elastic penalties in the constraints, row factorization, cascaded problem solution, and constraint-branching enumeration, which they claim greatly simplifies the model. They report on solution times of one minute, with an integrality gap tolerance of 0.001 percent. The savings, which may be ascribed to the model implementation, are approximately $300 million (US) in the logistics area. Total implementation time for the model took more than 4 years.

Chen and Wang (1997) prove that a great financial benefit can be gained by integrating production and distribution planning. They use a deterministic, single-period, profit maximization linear programming model to optimize the integrated production-distribution operations of a steel manufacturing company. Their model considers one central plant and several finishing factories in other locations that service customers directly. Suppliers are also considered as part of the model as well as Transportation costs.

A recent paper by Vidal and Goetschalckx (2000) has proposed a mixed integer-programming model to address a global logistics production-distribution scenario. This paper is a further step in the modeling of supply chains inasmuch as it considers uncertainties explicitly in the form of stochastic lead-times and supplier reliability. The authors assume that the production capacity is static over the single time period modeled.

As can be inferred by our literature survey, several researchers have written articles based on quantitative techniques for the improvement and optimization of supply chains. Mixed integer programming models are among the most widely used techniques because of their capacity to handle large and complex problems and to give good approximations of actual systems.

2.2 Value of Information in Supply Chain Management

With respect to measuring the value of information when used in the management of the supply chain, several authors have addressed this issue in the inventory management context. The common denominator within these studies is the stochastic nature of the models and the attempt at measuring the impact of different levels of information.

Qi-Ming (1996) presents a study in which the value of information is considered in a two-echelon system consisting of a raw-materials warehouse and a manufacturing facility where the demand process and the replenishment lead-times are stochastic. The basic approach is to compare the performance of inventory-production systems with different levels of information. The model combines Markov decision processes to study optimal inventory replenishment policies and a queuing model to account for the production process. The main contribution of the research is the analysis of the value of the information about production status used in inventory replenishment for the raw materials warehouse. The paper concludes that an information tie should be established in order to reduce inventory costs, and gives a notion of under what conditions, which level of information is of more value.

Gavirneni et al. (1999) incorporate the concept of information into a supplier-retailer model with known probability distributions of demand. The model attempts to measure the impact of information in three contexts:

a) No information from the retailer to the supplier except for past data
b) The supplier knows the (s,S) policy used by the retailer and the end item demand distribution.
c) The supplier knows inventories, (s,S) policy used and end item demand distribution.

The authors conclude, by experimental results, that additional information drives increased performance. However, they discover that when there is a high variance in the retailer's demand, the order quantities are very large or very small, or the supplier has low capacity, information is not that beneficial. Hence, they recommend dealing with the retailer's variance, fixed ordering costs and supplier's capacity before engaging in information sharing.

Cachon and Fisher (2000) study the value of shared information in a one supplier, N identical retailer system with stationary stochastic consumer demand and explain how shared inventory and demand information can be used to improve the supplier's allocation of inventory among retailers and supplier replenishments. In their model, capacity is unrestricted, lead-times are deterministic and demand has a known probability distribution. Two levels of information are considered and compared. In the traditional information policy the supplier observes the retailer's orders and reorder point policies are used. Full Information policy refers to when the supplier has immediate access to the retailer's inventory data. Retailers use a reorder point policy but the supplier does not. The supplier uses information to better allocate inventory among retailers and improve its order decisions. The value of shared information is measured as the difference between the total costs of a reorder point policy with full information and one with a traditional information policy. A numerical study with 768 scenarios shows that demand and inventory information sharing is not as beneficial as commonly thought. They conclude that the benefits of IT in practice are more closely related to the reduction of lead-time and batch size than in facilitating information sharing, although they recognize that this conclusion is limited to the setting considered therein, in which retailers have identical probability distributions of demand. A very important observation they make is the fact that the problem with non-identical retailers has not been addressed even in terms of traditional information.

The studies mentioned up to this point have considered information as an implicit variable and neglect the cost of obtaining the specified information, which is usually high and, sometimes, other issues (such as regulation and unionization) may be involved. In this regard, Bourland et al. (1996) present a paper in which a study of a two level system is presented. The system consists of a supplier (component plant) and a single customer (or final assembly plant). The authors examine the effect that timely demand information has on the inventories of both the supplier and the client in the context of a periodic-review policy for both factories. Specifically, they study the effect on inventories of having delayed demand information and compare it to the case where immediate demand information is available, and argue that with more accurate information the supplier could reduce inventories, or improve reliability of its deliveries to its customer, or both. In the model, a fixed cost of acquiring timely demand information is considered. The scope of the problem is posed in a theoretical framework and the applicability to real world problems is not discussed. The conclusion of the research is that the cost reduction potential of information (value) increases as the supplier's service level, supplier's holding costs and demand variability increase, and the length of the order cycle decreases.

In a similar fashion, Murray (1996) presents a decision support system that examines supply chain integration from the perspective of a mid-tier manufacturer. A queueing-based model is developed to assess the benefits of entering into more information-intensive relationships with customers. The main contribution of this model is to consider information as an implicit decision variable with the associated cost. The theoretical foundation is the basis for the development of a realistic DSS based on a simulation model, which creates demand forecasts and assigns shipments based on available and projected inventory, and a linear programming model, which calculates a smoothed production schedule. The supply chain modeled is limited to a single manufacturing site. A case study is presented to illustrate how timely and accurate information about future demands from selected customers can reduce variation in aggregate demand as perceived by the manufacturer. The system can be used to define the optimal subset of customers that should be considered for information-enriched cooperative relationships.

With respect to the value of information applied to SCM, we have observed that the majority of authors select a data set which they call information and model the impacts of different levels of information relative to those sets. Finally, after a set of simulations or sensitivity analyses they conclude to what extent the specific information set is useful in decision-making. Our approach is different in the sense that we consider a single model in which we allocate information resources depending on trade-offs between the value of the information and the overall systems costs. Therefore we believe that our research is a step forward in the modeling of production-distribution systems, namely SCM Systems.

Although several authors have considered measuring the effect of information with known probability distributions of demand, to the best of our knowledge, no author has considered the effect of demand seasonality in the context of information value.

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 et al. (2000). This model was suitably modified for the scope of our research and is intended to aid in the management of AG, Inc.'s supply chain. However, with some modifications and/or additions it could be used as a general model for different types of industry.

3.1 Model: Capacitated, Multi-location, Production-distribution Problem

The Capacitated, Multi-location, Production-Distribution model by Dominguez et al. (2000) was considerably enhanced in order to explicitly include information decision variables and to account for uncertainties in the demand parameter. Several variables were added to consider the cost and timeliness effects of information and adequate modifications in the objective function and constraints had to be considered. Specifically, three cost elements were added to the objective function:

a) Premium transportation and information cost for a centralized inventory policy. As previously stated, time postponement has been made possible due to the increased capability to process, transmit and deliver orders. We argue that in some cases, keeping inventory in a central location will lead to an increase in the transportation and information expenses if the intent is not to reduce customer service in terms of responsiveness.

b) Cost of Information for the inventory review policy. This cost is mainly related to the cost of ordering in a periodic review inventory policy, where the ordering cost is considered to be the information system usage cost (i.e., data gathering and processing, and communications costs). It attempts to measure how often information is required, given the overall conditions of the specific supply chain being studied.

c) Cost of information timeliness. In order to have timely information it is necessary to install information systems that have the required capabilities to link the supply chain and in most cases are technologically advanced (e.g., bar-coding, improved communications, integrated databases); in general, as the degree of sophistication of these systems increases, their cost of acquisition and operation also increases. The cost of timeliness is aimed towards measuring the tradeoffs associated with rapid availability of information; That is, the gathering, processing and transmission cost versus the effect that this information has on the overall supply chain performance. In our model we focus specifically on the timeliness of information about inventories at the manufacturing facility.

Several constraint sets were also added to the model in order to increase the degree of robustness. One constraint set added considers that finished inventory, which might be physically available at the manufacturing warehouse, may not be available in terms of information, which, we argue, slows down the ability to continue the flow to the next echelon; this constraint set is related to information timeliness. Furthermore, a set of constraints was added to account explicitly for uncertainty in the demand. These constraints are intended to define the most adequate amount and location of safety stock, based on the postponement strategy. In line with this approach, the shortage cost was eliminated given the fact that a level of safety stock would be present and that this ensures a constant service level with implicit shortages.

3.2 Mathematical Formulation

Assume there is a set of manufacturing facilities $\boldsymbol{P}$ with the indices $p=1,\ldots,P$, each producing a set of product families $\boldsymbol{N}$ with indices $n=1,\ldots,N(p)$. This product family is sold in a set of $\boldsymbol{K}$ distribution centers labeled with indices $k=1,\ldots,K$ during a planning horizon uniformly divided into $\boldsymbol{T}$ time periods which are labeled with indices $t=1,\ldots,T$. In order to move the finished goods between the manufacturing facilities and the distribution centers there is a set of $\boldsymbol{J}$ transportation modes with indices $j=1,\ldots,J$. Assume also the existence of a set of inventory review policies $\boldsymbol{I}$ with indices $i = 1,\ldots,I(p)$. The difference among these review policies is the cycle length. Additionally we consider a set of $\boldsymbol{M}$ information systems with indices $m = 1,\ldots,M(p)$. These information systems are different options that can be used to capture inventory information at a manufacturing facility.

In the formulation of the model the following assumptions are considered:

- Machine hours are not a constraint only labor-hours are.
- 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 quality policy of the company.
- Overhead cost is 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 appliance company at hand.
- There is a cost associated with additional labor hours required above the normal labor time (e.g., 8 hrs/shift). It includes transportation cost for the workers, additional refreshment cost etc.
- Service level to be offered to clients remains constant and is set as a strategic planning parameter; therefore, the cost of lost sales remains constant and does not need to be considered.
- Total demand requirements across the planning horizon are fixed. However, production levels may vary due to the build-up of anticipation inventories; hence, the variable costs of production (i.e., raw material costs) are considered (Albright et al., 1999; Winston, 1995; Johnson and Montgomery, 1974).
- An information system refers to the complete solution for the function being performed, which includes the software, hardware and variable human resources.
- Customers are located in the proximity of the Distribution centers or pick up their products directly at the Warehouse.

- Two transportation modes are used for the shipment of products between the manufacturing facilities and the distribution centers. These are truck and rail. Air is seldom used, except in the cases of extreme urgency.
- Supplier and retail Operations are not considered mainly because of two reasons: One being that, as discussed in Chapter 1, AG, Inc. is in the phase of internal integration and the second, to keep the model within tractable limits. The inclusion of both supplier and retailer operations into the model is left as a topic for future research.
- Cycle length for the periodic-review policy is fixed for the entire distribution network of each plant.
- The manufacturing facility is the receptor of information into the system about finished goods production. This is a critical part of the system because two different business entities have to match their information of what has been produced vs. what has been received. This is due to the fact that AG, Inc. is divided into the manufacturing company and the distribution company, and once the product goes into the distribution network it is consigned to the distribution company until it is sold. Timeliness of information is critical for the linkage between these two business entities, better known as the "production-distribution link".

Our production-distribution model determines the assignment of the finished goods production level (in units), workforce level (in labor hours), transportation mode, number of transportation consignments, and inventory levels (in units) as well as the allocation of information resources in order to minimize the total costs incurred in the system.

The total cost framework of the model considers the following elements:

Minimize: [cost of labor] + [cost of increasing labor-hours] + [cost of decreasing labor-hours]
+ [cost of additional labor-hours] +[cost of raw materials]+[cost of transportation]
+ [cost of carrying finished goods inventory at manufacturing facilities]
+ [cost of carrying in-transit inventory] + [cost of carrying inventory at distribution centers]
+ [cost of overtime] +[premium transportation and information cost]
+ [information cycle cost]+[information timeliness cost]

The cost elements are formulated as follows:

- [Cost of labor]= $\sum_{p=1}^{P} L_p \left(\sum_{t=1}^{T} W_{pt} \right)$, (1)

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

- [Cost of increasing labor-hours]= $\sum_{p=1}^{P} C_p \left(\sum_{t=1}^{T} W_{pt}^{+} \right)$, (2)

where C_p includes the organizational cost of hiring and training new personnel at plant p, and W_{pt}^{+} is equivalent to the Increase in labor hours at manufacturing facility p from one period to the next (i.e., hiring).

- [Cost of decreasing labor-hours]= $\sum_{p=1}^{P} C'_p \left(\sum_{t=1}^{T} W_{pt}^{-} \right)$, (3)

where C'_p includes costs related to laying-off personnel such as compensations and paperwork at manufacturing facility p, and W_{pt}^{-} denotes the decrease in labor hours at manufacturing facility p from one period to the next (i.e., layoff).

- [Cost of additional labor-hours]= $\sum_{p=1}^{P} R_p \left(\sum_{t=1}^{T} f_{pt}^{+} \right)$, (4) where R_p represents the cost per additional labor hour required at the manufacturing facility p. This cost is considered because even in the flexible labor scheme, additional labor may drive additional costs. The variable f_{pt}^{+} denotes the number of additional labor hours in time period t required at manufacturing facility p (without hiring).

- [Cost of raw materials]= $\sum_{p=1}^{P}\sum_{n=1}^{N(p)}\sum_{t=1}^{T} CM_{pn} X_{pnt}$, (5)

where CM_{pn} represents the cost of raw materials required for producing one item of family n at manufacturing facility p and X_{pnt} is the amount of units produced of the same item in period t.

- [Cost of transportation]= $\sum_{p=1}^{P}\sum_{j=1}^{J}\sum_{k=1}^{K} TC_{pjk}\left(\sum_{t=1}^{T} TU_{pjkt}\right)$, (6)

Where TC_{pjk} represents the cost of one transportation consignment from manufacturing facility p to distribution center k using mode j and TU_{pjkt} expresses the number of mode j transportation units used to ship product from manufacturing facility p to distribution center k in period t.

- [Cost of carrying inventory at manufacturing facilities]

$$=\sum_{p=1}^{P}\sum_{n=1}^{N(p)} h_{pn}\left(\sum_{t=1}^{T} I_{pnt}\right), \qquad (7)$$

where h_{pn} is the known 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. Components of the inventory cost will depend on each specific company's financial policy. I_{pnt} symbolizes the inventory of product family n in manufacturing facility p at the end of period t.

- [Cost of carrying in-transit inventory]= $\sum_{p=1}^{P}\sum_{n=1}^{N(p)} Th_{pn}\left(\sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{t=1}^{T} IT_{pnjkt}\right)$, (8)

where Th_{pn} is the in-transit inventory carrying cost for an item of 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 in mode j from manufacturing facility p to distribution center k at the end of period t.

- [Cost of carrying inventory at distribution centers]

$$= \sum_{p=1}^{P}\sum_{n=1}^{N(p)}\sum_{k=1}^{K} h_{pnk}\sum_{t=1}^{T} I_{pnkt}, \qquad (9)$$

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

- [Cost of over time]= $L'_p O_p$, (10)

where L'_p is the cost of a labor-hour on overtime at manufacturing facility p; this element considers the overtime incurred in the planning horizon. O_p represents the total overtime scheduled at the end of the planning horizon at manufacturing facility p.

- [Premium transportation and information cost] $=\sum_{p=1}^{P}\sum_{n=1}^{N(p)} PTC_{pn}PS_{pn}$, (11)

where PTC_{pn} is the cost of expediting the delivery of an item of family n produced at manufacturing facility p when a centralized inventory policy is being used; the cost of expediting includes premium transportation cost and information cost such as increased communication speed with all the links in the supply chain or the tracking system required to keep the delivery time to the customer within acceptable limits. PS_{pn} is the inventory of product family n, which will be pooled at the warehouse of the manufacturing facility p in case a centralized inventory policy is chosen (see below for more details).

- [Inventory review policy cost] = $\sum_{p=1}^{P}\sum_{i=1}^{I} CP_{pi}\beta_{pi}$, (12)

where CP_{pi} is the fixed cost of the information system for the planning horizon given that a periodic-review inventory policy i is being used at manufacturing facility p. The auxiliary variable β_{pi} takes the value of one if the inventory policy i is selected at manufacturing facility p and zero otherwise. The inventory policy refers to the review and ordering discipline used in controlling the inventory (i.e., how frequently should orders be placed).

- [Information timeliness cost]= $\sum_{p=1}^{P}\sum_{m=1}^{M(p)} CI_{pm}\delta_{pm}$, (13)

where CI_{pm} is the cost of information timeliness using system m at manufacturing facility p. The auxiliary variable δ_{pm} takes the value of one if the inventory information retrieval system m is used at manufacturing facility p and zero otherwise.

The model is subject to the following constraints:

- **Resource adjustment:**

  At the beginning of every time period, the available workforce level is equal to the previous period's workforce level plus increased labor hours or minus decreased labor hours in the same period.

$$W_{pt} = W_{p(t-1)} + W_{pt}^{+} - W_{pt}^{-}, \qquad (\forall p=1...P) \qquad (14)$$

- **Resource constraint**:

Total required labor-hours in any time period are equal to the available resources in that time period. The variables f_{pt}^{+} and f_{pt}^{-} are used to model the flexible working scheme that is used at AG, Inc. For companies not following this flexible working system, we would suitably modify the model according to each company's policy.

$$\sum_{n=1}^{N(p)} a_{pn} X_{pnt} = W_{pt} + f_{pt}^{+} - f_{pt}^{-}, \qquad (\forall\, p=1...P;\ t=1...T) \qquad (15)$$

- **Maximum over time in period t:**

Additional labor hours in any time period do not exceed an allowable percentage of contractual hours.

$$f_{pt}^{+} \le \theta_p W_{pt}, \qquad (\forall p=1...P;\ t=1...T) \qquad (16)$$

- **Overall overtime hours:**

Overtime is equal to the total additional labor hours minus the total reduced labor hours over the planning horizon.

$$O_p = \sum_{t=1}^{T} \left(f_{pt}^{+} - f_{pt}^{-}\right), \qquad (\forall p=1...P) \qquad (17)$$

- **Labor capacity upper bound**

In any time period the workforce level may not surpass a given upper bound. This constraint sets the limit to the equivalent plant capacity and/or maximum allowed labor hours per time period in each manufacturing facility.

$$W_{pt} \leq PC_{pt}, \qquad (\forall p=1...P;\ t=1..T) \qquad (18)$$

- **Shipment within the same period of manufacturing:**

In any given period, the amount shipped to the distribution centers may not be greater than the last period's inventory plus a pre-specified proportion of this period's production.

$$\sum_{j=1}^{J}\sum_{k=1}^{K} Y_{pnjkt} \leq I_{pn(t-1)} + X_{pnt} \sum_{m=1}^{M(p)} \gamma_{pm}\delta_{pm},$$

$$(\forall p=1...P;\ n=1...N(p);\ t=1...T) \qquad (19)$$

This constraint includes the timeliness of information factor that is used to represent how close the information signal is to the real event (see Feltham (1968)). An important assumption considered herein is that shipments to distribution centers cannot be effected if information is not available in the inventory system. Additionally, constraint set (20) ensures that only one information retrieval system is selected for each manufacturing facility:

$$\sum_{m=1}^{M(p)} \delta_{pm} = 1, \qquad (\forall p=1...P) \qquad (20)$$

As it may be observed, constraint (19) is nonlinear in X_{pnt} and δ_{pm}. In order to alleviate the mathematical complexity, we reformulate the function using a modified version of the linearization technique used by Bennett (1998),

- **Safety stocks:**

For the calculation of safety stocks, the concept of dynamic adaptive safety stocks (DASS) is introduced. In this scheme, the allocation of safety stocks is either centralized (pooled at the manufacturing facility) or decentralized (sent to the distribution centers), depending on the need for supplying a certain service level during lead-time and the tradeoffs between premium information and transportation, and holding costs when a centralized safety stock policy is chosen (i.e., $RP_{pn}=1$) versus the cost of holding and transporting products when carrying decentralized safety stocks (i.e., $DI_{pn}=1$). In this manner, our formulation separates the calculation for centralized and decentralized safety stocks by activating only those constraint sets that refer to the centralized or decentralized policy for each product family n produced at manufacturing facility p. Specifically, this is controlled by the following constraint set (22) in conjunction with the safety stock constraints shown below:

$$RP_{pn} + DI_{pn} = 1, \quad (\forall p=1 \ldots P;\ n=1 \ldots N(p)) \tag{22}$$

a) Centralized safety stocks (at manufacturing facility p):

In any given time period, the inventory level of product family n in manufacturing facility p may not be less than the pooled safety stock. PS_{pn} is the pooled safety stock for product family n at manufacturing facility p. 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. In order to calculate the pooled safety stock, two parameters are required: σ_{pn} and z_{α},. σ_{pn} 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. z_{α} is the normal distribution standard deviate z_{α} which is set by the decision-maker in order to fix the service level. It is necessary to adjust the forecast error to a lead-time forecast error. For this, we multiply σ_{pn} by the lead-time adjustment factor, which is the square root of the total lead-time. It is important to note that the units used in the forecast, from which the standard deviation of the forecast error is generated, are to be consistent with those used in the lead-times (e.g., months or weeks). In our case the total lead-time is the manufacturing lead-time for product family n (MLT_{pn}) plus the cycle time of the inventory review policy being considered for 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. It is worth noting that the delivery time from the manufacturing facility to the customer is neglected due to the quick response that is expected when a postponement policy is applied. A major assumption underlying safety stock calculation is that items within families have similar behavior in terms of forecast error; thus it is possible to cluster them by product family (Elsayed and Boucher (1994)). The auxiliary variable RP_{pn} takes the value of one if postponement is applied to product family n at manufacturing facility p. The set of constraints (24) ensure that only one inventory review policy is chosen.

$$PS_{pn} = RP_{pn}\left(z_{\alpha}\sigma_{pn}\sqrt{MLT_{pn} + \sum_{i=1}^{I(p)} \beta_{pi}TP_{pi}} \right), \quad (\forall\ p=1 \ldots P;\ n=1 \ldots N(p)) \qquad (23)$$

$$I_{pnt} \geq PS_{pn}, \qquad (\forall\ p=1...P;\ n=1...N;\ t=1...T) \qquad (24)$$

$$\sum_{i=1}^{I(p)} \beta_{pi} = 1, \qquad (\forall p=1...P) \qquad (25)$$

Constraint set (23) results in a nonlinear equation, which we linearize using the following procedure:

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

$$ALT_{pni} = \sqrt{MLT_{pn} + TP_{pi}}, \qquad (\forall p=1..P;\ n=1...N(p);\ i=1...I(p)) \qquad (26)$$

Equation (23) can now be replaced by the function:

$$PS_{pn} = RP_{pn}\left(z_{\alpha} \sigma_{pn} \sum_{i=1}^{I(p)} ALT_{pni} \beta_{pi} \right), \ (\forall p=1...P;\ n=1...N(p)) \qquad (27)$$

which may be linearized by applying the zero-one polynomial programming technique in Taha (1982) to obtain the following function:

$$PS_{pn} = z_{\alpha} \sigma_{pn} \sum_{i=1}^{I(p)} ALT_{pni} \hat{L}_{pni}, \quad (\forall\ p=1...P;\ n=1...N(p)) \qquad (28)$$

where $\hat{L}_{pni}$ is an auxiliary binary variable, which satisfies the following sets of constraints:

$$\beta_{pi} + RP_{pn} - 2\hat{L}_{pni} \geq 0, \qquad (\forall p=1..P;\ n=1...N(p);\ i=1...I(p)) \qquad (29)$$

$$\beta_{pi} + RP_{pn} - \hat{L}_{pni} \leq 1, \qquad (\forall p=1...P;\ n=1...N(p);\ i=1...I(p)) \qquad (30)$$

Constraints (29) and (30) must be added to ensure that $\hat{L}_{pni} = 1$ when β_{pi} and RP_{pn} are 1, and 0 otherwise.

b) Decentralized safety stocks (at distribution center k):

In any time period, the inventory at distribution center k should be at least equal to a pre-specified percentage (λ) of the next week's demand plus the safety stock. The factor (λ) creates additional inventory that ensures that the required product will be available at the beginning of each time period. For AG, Inc., a value of λ=0.5 is considered as a strategic policy. This factor may vary or may not apply for different firms.

$$I_{pnkt} \geq \lambda D_{pnk(t+1)} + DI_{pn}\left(z_{\alpha}\sigma'_{pnk}\sqrt{MLT_{pn} + TLT_{pk} + \sum_{i=1}^{I(p)}\beta_{pi}TP_{pi}} \right),$$

$$(\forall p=1...P;\ n=1...N(p);\ k=1...K;\ t=1...T) \qquad (31)$$

The calculation of the safety stock at the distribution centers is similar to the manufacturing facility's safety stock calculation (eq. 23); it results in a nonlinear expression, which after linearization generates the following sets of constraints:

$$I_{pnkt} \geq \lambda D_{pnk(t+1)} + z_{\alpha}\sigma'_{pnk}\sum_{i=1}^{I(p)} ALT'_{pnik}\hat{L}'_{pni},$$

$$(\forall\ p=1...P;\ n=1...N(p);\ k=1...K;\ t=1...T) \qquad (32)$$

$$\beta_{pi} + DI_{pn} - 2\hat{L}'_{pni} \geq 0, \qquad (\forall\ p=1...P;\ n=1...N(p);\ i=1...I(p)) \qquad (33)$$

$$\beta_{pi} + DI_{pn} - \hat{L}'_{pni} \leq 1, \qquad (\forall p=1...P;\ n=1...N(p);\ i=1...I(p)) \qquad (34)$$

where, $\hat{L}'_{pni} = 1$ when β_{pi} and DI_{pn} are 1, and 0 otherwise, and

$$ALT'_{pnik} = \sqrt{MLT_{pn} + TLT_{pnk} + TP_{pi}},$$

$$(\forall p=1...P;\ n=1...N(p);\ i=1...I(p);\ k=1...k) \qquad (35)$$

The following constraint set was added to assure that if a postponement strategy is chosen, a decentralized strategy is not and vice versa. It should be noted that although this constraint may be considered as redundant to constraint set (22), we argue that its inclusion in the model reduces the number of feasible alternatives at the time of calculation when using the branch and bound algorithm of integer programming.

$$\sum_{i=1}^{I(p)}\left(\hat{L}_{pni}+\hat{L}'_{pni}\right)=1, \qquad (\forall\ p=1...P;\ n=1...N(p)) \qquad (36)$$

- **Distribution center warehouse capacity:**

Space required by the net inventory in any time period t should not exceed the available storage space. This constraint is the only shared resource constraint in the model given the fact that all product families n from all manufacturing facilities p may be stored at any given distribution center k.

$$\sum_{p=1}^{P}\sum_{n=1}^{N(p)} S_{pn} I_{pnkt} \le IC'_{kt}, \qquad (\forall\ k=1...K;\ t=1...T) \qquad (37)$$

- **Inventory balance at manufacturing facility p:**

In any time period, net inventory is equal to the previous period's net inventory plus production in that period minus shipments to all distribution centers in the same period.

$$I_{pnt}=I_{pn(t-1)}+X_{pnt}-\sum_{j=1}^{J}\sum_{k=1}^{K} Y_{pnjkt}, \qquad (\forall p=1...P;\ n=1...N(p);\ t=1...T) \qquad (38)$$

- **In-transit inventory balance:**

In any time period, in-transit inventory is equal to the previous period's in-transit inventory plus shipments in that period minus received shipments at all distribution centers in the same period.

$$IT_{pnjkt} = IT_{pnjk(t-1)} + Y_{pnjkt} - Y_{pnjk(t-LT_{pjk})},$$

$$(\forall p=1\ldots P;\ n=1\ldots N(p);\ j=1\ldots J;\ k=1\ldots K;\ t=1\ldots T) \qquad (39)$$

- **Inventory balance at distribution center *k*:**

In any time period, net inventory is equal to the previous period's net inventory plus received shipments in that period minus demand in the same period.

$$I_{pnkt} = \sum_{j=1}^{J} Y_{pnjk(t-LT_{pjk})} + I_{pnk(t-1)} - D_{pnkt},$$

$$(\forall p=1\ldots P;\ n=1\ldots N(p);\ j=1\ldots J;\ k=1\ldots K;\ t=1\ldots T) \qquad (40)$$

- **Number of transportation consignments of mode *j*:**

The number of mode *j* transportation consignments in any time period shipped from manufacturing facility *p* to distribution center *k* should be at least equal to the volume required by the products to be shipped from the same manufacturing facility to the same distribution center divided by the volume capacity of the mode *j* transportation consignment.

$$\frac{\sum_{n=1}^{N(p)} V_{pn} Y_{pnjkt}}{FTL_j} \leq TU_{pjkt}, \qquad (\forall\ p=1\ldots P;\ j=1\ldots J;\ k=1\ldots K;\ t=1\ldots T) \qquad (41)$$

- **Non negativity constraint:**

$$X_{pnt}, W^+_{pt}, W^-_{pt}, f^-_{pt}, f^+_{pt}, O_p, I_{pnt}, I_{pnkt}, IT_{pnjkt} \geq 0,$$

$$(\forall p=1...P;\ n=1...N(p);\ j=1...J;\ k=1...K;\ t=1...T) \qquad (42)$$

- **Integer constraint:**

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

$$(\forall p=1...P;\ n=1...N(p);\ j=1...J;\ k=1...K;\ t=1...T) \qquad (43)$$

- **Binary Constraints:**

$$\beta_{pi}, RP_{pn}, DI_{pn}, \delta_{pi}, \hat{L}_{pni}, \hat{L}'_{pni} \in \{0,1\},$$

$$(\forall p=1...P;\ n=1...N;\ i=1...I(p)) \qquad (44)$$

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

Minimize Total Cost:

$$Z = \sum_{p=1}^{P}\left(\sum_{t=1}^{T}\left(L_p W_{pt} + C_p W^+_{pt} + C'_p W^-_{pt} + R_p f^+_{pt} + \sum_{j=1}^{J}\left(\sum_{k=1}^{K} TC_{pjk} TU_{pjkt}\right)\right.\right.$$
$$\left.\left. + \sum_{n=1}^{N(p)}\left(CM_{pn} X_{pnt} + h_{pn} I_{pnt} + \sum_{k=1}^{K}\left(\sum_{j=1}^{J} Th_{pn} IT_{pnjkt} + h_{pnk} I_{pnkt}\right)\right)\right)\right.$$
$$\left. + L'_p O_p + \sum_{n=1}^{N(p)} PTC_{pn} PS_{pn} + \sum_{i=1}^{I(p)} CP_{pi}\beta_{pi} + \sum_{m=1}^{M(p)} CI_{pm}\delta_{pm}\right) \qquad (45)$$

Subject to:

$$W_{pt} = W_{p(t-1)} + W^+_{pt} - W^-_{pt}, \qquad (\forall p=1...P) \qquad (46)$$

$$\sum_{n=1}^{N(p)} a_{pn} X_{pnt} = W_{pt} + f^+_{pt} - f^-_{pt}, \qquad (\forall p=1...P;\ t=1...T) \qquad (47)$$

$$f^+_{pt} \leq \theta_p W_{pt}, \qquad (\forall p=1...P;\ t=1...T) \qquad (48)$$

$$O_p = \sum_{t=1}^{T} \left(f_{pt}^{+} - f_{pt}^{-} \right), \quad (\forall p=1...P) \tag{49}$$

$$W_{pt} \leq PC_{pt}, \quad (\forall p=1...P;\ t=1..T) \tag{50}$$

$$\sum_{m=1}^{M(p)} \delta_{pm} = 1, \quad (\forall p=1...P) \tag{51}$$

$$\sum_{j=1}^{J} \sum_{k=1}^{K} Y_{pnjkt} \leq I_{pn(t-1)} + \sum_{m=1}^{M(p)} r_{pmnt}, \quad (\forall p=1...P;\ n=1...N(p);\ t=1...T) \tag{52}$$

$$\sum_{n=1}^{N(p)} \sum_{t=1}^{T} r_{pmnt} \leq M\delta_{pm}, \quad (\forall p=1...P;\ m=1..M(p)) \tag{53}$$

$$r_{pmnt} \leq \gamma_{pm} X_{pnt}, \quad (\forall\ p=1...P;\ m=1..M(p);\ n=1...N(p);\ t=1...T) \tag{54}$$

$$\sum_{n=1}^{N(p)} S_{pn} I_{pnt} \leq IC_p, \quad (\forall p=1...P;\ t=1...T) \tag{55}$$

$$\sum_{i=1}^{I(p)} \beta_{pi} = 1, \quad (\forall p=1...P) \tag{56}$$

$$RP_{pn} + DI_{pn} = 1, \quad (\forall p=1...P;\ n=1...N(p)) \tag{57}$$

$$I_{pnt} \geq PS_{pn}, \quad (\forall\ p=1...P;\ n=1...N;\ t=1...T) \tag{58}$$

$$PS_{pn} = z_\alpha \sigma_{pn} \sum_{i=1}^{I(p)} ALT_{pni} \hat{L}_{pni}, \quad (\forall\ p=1...P;\ n=1...N(p)) \tag{59}$$

$$ALT_{pni} = \sqrt{MLT_{pn} + TP_{pi}}, \quad (\forall p=1..P;\ n=1...N(p);\ i=1...I(p)) \tag{60}$$

$$\beta_{pi} + RP_{pn} - 2\hat{L}_{pni} \geq 0, \quad (\forall p=1..P;\ n=1...N(p);\ i=1...I(p)) \tag{61}$$

$$\beta_{pi} + RP_{pn} - \hat{L}_{pni} \leq 1; \quad (\forall p=1...P;\ n=1...N(p);\ i=1...I(p)) \tag{62}$$

$$I_{pnkt} \geq \lambda D_{pnk(t+1)} + z_\alpha \sigma'_{pnk} \sum_{i=1}^{I(p)} ALT'_{pnik} \hat{L}'_{pni}, \quad (\forall\ p=1...P;,\ n=1...N(p);\ k=1...K;\ t=1...T) \tag{63}$$

$$ALT'_{pnik} = \sqrt{MLT_{pn} + TLT_{pnk} + TP_{pi}} \text{ ,}$$

$$(\forall p=1...P;\ n=1...N(p);\ i=1...I(p);\ k=1...k) \qquad (64)$$

$$\beta_{pi} + DI_{pn} - 2\hat{L}'_{pni} \geq 0 \text{ ;} \qquad (\forall p=1...P;\ n=1...N(p);\ i=1...I(p)) \qquad (65)$$

$$\beta_{pi} + DI_{pn} - \hat{L}'_{pni} \leq 1 \text{ ;} \qquad (\forall p=1...P;\ n=1...N(p);\ i=1...I(p)) \qquad (66)$$

$$\sum_{i=1}^{I(p)} \left(\hat{L}_{pni} + \hat{L}'_{pni} \right) = 1 \text{ ,} \qquad (\forall p=1...P;\ n=1...N(p)) \qquad (67)$$

$$\sum_{p=1}^{P} \sum_{n=1}^{N(p)} S_{pn} I_{pnkt} \leq IC'_{kt} \text{ ,} \qquad (\forall k=1...K;\ t=1...T) \qquad (68)$$

$$I_{pnt} = I_{pn(t-1)} + X_{pnt} - \sum_{j=1}^{J} \sum_{k=1}^{K} Y_{pnjkt} \text{ ,} \qquad (\forall p=1...P;\ n=1...N(p);\ t=1...T) \qquad (69)$$

$$IT_{pnjkt} = IT_{pnjk(t-1)} + Y_{pnjkt} - Y_{pnjk(t-LT_{pjk})} \text{ ,}$$

$$(\forall p=1...P;\ n=1...N(p);\ j=1...J;\ k=1...K;\ t=1...T) \qquad (70)$$

$$I_{pnkt} = \sum_{j=1}^{J} Y_{pnjk(t-LT_{pjk})} + I_{pnk(t-1)} - D_{pnkt} \text{ ,}$$

$$(\forall p=1...P;\ n=1...N(p);\ j=1...J;\ k=1...K;\ t=1...T) \qquad (71)$$

$$\frac{\sum_{n=1}^{N(p)} V_{pn} Y_{pnjkt}}{FTL_j} \leq TU_{pjkt} \text{ ,} \qquad (\forall p=1...P;\ j=1...J;\ k=1...K;\ t=1...T) \qquad (72)$$

$$X_{pnt}, W^{+}_{pt}, W^{-}_{pt}, f^{-}_{pt}, f^{+}_{pt}, O_{p}, I_{pnt}, I_{pnkt}, IT_{pnjkt} \geq 0 \text{ ,}$$

$$(\forall p=1...P;\ n=1...N(p);\ j=1...J;\ k=1...K;\ t=1...T) \qquad (73)$$

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

$$(\forall p=1...P;\ n=1...N(p);\ j=1...J;\ k=1...K;\ t=1...T) \qquad (74)$$

$$\beta_{pi}, RP_{pn}, DI_{pn}, \delta_{pm}, \hat{L}_{pni}, \hat{L}'_{pni} \in \{0,1\},$$

$$(\forall p=1 \ldots P;\ n=1 \ldots N;\ i=1 \ldots I(p)) \qquad (75)$$

3.3 Discussion on Information Related Parameters.

As it was discussed in Chapter 1, the focus of our study is on the value of information, as reflected in the variables $\gamma_{pm,}$ $CI_{pm,}$ $TP_{pi,}$ $CP_{pi,}$ σ_{pn} and σ'_{pnk}. These variables are the focal point in our study of the production-distribution model and are related to the accuracy, timeliness, periodicity and technological factors of information. The accuracy characteristic of information is represented by means of the standard deviation of the forecast error ($\sigma_{np,}$ and σ'_{npk}). Technological factors for accuracy are not represented explicitly in our model, but forecasting software would be a good example. Timeliness is represented by the variable γ_{pm}, the timeliness factor, with technological factors considered in the corresponding cost CI_{pm}. Finally, TP_{pi} , the cycle length, represents periodicity, with technological factors considered in the corresponding cost CP_{pi}.

At this point it is important to note that the availability characteristic of information is assumed to be high and therefore it is not explicitly modeled.

CHAPTER 4. THE APPLIANCE COMPANY: A CASE STUDY

The main objective of the case study at this point is two-fold: One is to test the model with a realistic-sized problem in order to validate its calculations and outcomes, and the second to measure the impact of considering a systems approach to the real world, large scale problem (i.e., integrating the supply chain).

We start our analysis by presenting and explaining the company's relevant input parameters and values.

4.1 Current State of AG, Inc.

As stated previously, the company comprises 7 manufacturing facilities and 8 distribution centers. AG, Inc.'s manufacturing facilities are deployed in Table 1, product families in Table 2 and distribution centers in Table 3, respectively. General input parameters are also included and explained in detail.

The upper bound of the workforce level in hours/week, shown in Table 1, is a rough estimate of the actual data, which was not available at the time. We assume that the manufacturing facilities will generate accurate figures at the time of the implementation. The values for this parameter should be based on several factors such as the number of shifts per day and the maximum number of manufactured units per day for each plant. The storage capacity, also shown in Table 1, is an approximation of the usable warehouse areas of the plants in square feet (i.e., not considering offices, aisles or docks).

Table 1. AG, Inc. manufacturing facilities

Manufacturing Facility, p	Plant Description	Max. Labor Capacity, PC_{pt} (hrs./wk.)	Storage Space, IC_p (sq.ft)
1	Washers 1	35,000	3,500
2	Washers 2	20,000	8,000
3	Stoves 3	55,000	4,500
4	Hoods 4	7,000	400
5	Stoves 5	20,000	2,615
6	Refrigerators 6	15,000	600
7	Refrigerators 7	60,000	55,000

The grouping of similar items into product families (Table 2) was performed using the current criteria followed by the logistics area of the company. Within families, products are not significantly different in terms of manufacturing operations. Each manufacturing facility is dedicated to the production of unique types of products, which are not replicated in the remaining production facilities.

The storage space capacity for each distribution center in Table 3 is calculated in a manner similar to that of the manufacturing facility's storage capacities, except that space utilized by damaged and obsolete products was deducted from the effective capacity. For this case study we assume that the available storage space will not vary throughout the planning horizon. However, in our formulation the variable IC_{kt} includes the index of time, t, to account for variations in the available storage capacity that might occur due to changes in the inventory of damaged and obsolete products or due to increases or reductions in the effective capacity of the warehouses.

Table 2. Product families by manufacturing facility

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 3. Distribution center descriptions and storage areas.

Distribution Center, *k*	**Location**	**Storage Capacity, IC_{kt} (sq.ft)**
1	Mexico	106,215
2	Mexicalli	7,875
3	Monterrey	45,898
4	Reynosa	3,236
5	Chihuahua	7,931
6	Merida	10,013
7	Torreon	7,278
8	Guadalajara	39,713

The planning horizon was broken into weeks (i.e., time periods t represent weeks). The reason for choosing weeks was the fact that the distribution of demand within each month is not uniform and this generates the need to measure and control inventory levels at the end of each week. In order to ensue consistency with the company's policies we adopt a planning horizon of 15 weeks which AG, Inc. uses to account for monthly targets and the fact that demand forecasts lose accuracy over a longer period (see Suri, 1998). The data borrowed from AG, Inc. starts from the end of February 2000 and the planning horizon is shown in Table 4. Note that March and May have 5 weeks, and April and June have 4 weeks, respectively. The weekly distribution of demand percentages for each month shown were calculated by AG, Inc. based on averages of historical demand.

Table 4. Planning horizon

Period, *t*	Description	Demand Distribution	Total by Month
1	Week I, March '00	6%	
2	Week II, March '00	14%	
3	Week III, March '00	20%	
4	Week IV, March '00	25%	
5	Week V, March '00	35%	100%
6	Week I, April '00	13%	
7	Week II, April '00	22%	
8	Week III, April '00	27%	
9	Week IV, April '00	38%	100%
10	Week I, May '00	30%	
11	Week II, May '00	20%	
12	Week III, May '00	15%	
13	Week IV, May '00	15%	
14	Week V, May '00	20%	100%
15	Week I, June '00	13%	

As discussed in Dominguez et al. (2000), the rolling horizon environment aids in considering the uncertainties of future data. The model is run with updated data sets to obtain decision guidelines for future periods, which give the production, distribution, transportation, and sales areas estimates of relevant information for planning purposes.

As a means of illustration we now show the informational and transactional input data for plant 1 (Washers), and briefly explain the important parameters and their values. Appendix I shows the data for the remaining plants. The values of the cost parameters were converted to US dollars.

4.1.1 Information Parameters

In this section we briefly explain the input variables that have to do with information. As previously discussed in section 3.3, these variables are considered as the focal point of the production-distribution model and are related to the timeliness (γ_{pm}, CI_{pm}), periodicity (TP_{pi}, CP_{pi}) and accuracy (σ_{pn} and σ'_{pnk}) of information. The accuracy characteristic of information contained in σ_{pn} and σ'_{pnk} is left as a transactional parameter because of its direct relevance to transactional decisions. We do not explicitly consider different levels or technological factors of σ_{pn} or σ'_{pnk}, however, if these are available, trade-off analysis can be carried out in order to measure their impact.

For plant p=1, three different levels of information timeliness were considered along with their associated costs (Table 5). System $m=1$, has an information timeliness factor of γ_{pm}=.8, which means that 80% of items produced are available for shipment to the distribution centers during a production week and 20% are physically in stock but unavailable until the following week. 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 sends this information to the distribution system. The cost CI_{pm}=*$1,000* is computed over the 15-week planning horizon, and is related to the time required for this operation in terms of labor and the information system used during this period.

Table 5. Information timeliness parameters

Information System, m	Manufacturing Facility, p	Timeliness Factor, γ_{pm}	Information system cost, CI_{pm} ($/15-weeks)
1	1	0.8	$1,000
2	1	0.85	$5,000
3	1	0.99	$10,000

With information system m=2, the information timeliness factor is increased to .85. This physically represents a semiautomatic system in which an operator collects a set of bar-coded cards from the finished goods and slides these cards through a scanner that reads the information directly into the distribution system. The cost is related to labor, operating and purchasing of the improved information system over the planning horizon.

Finally, information system m=3 is a real-time representation. The input of produced items occurs at the end of the production lines with a high technology bar code scanner, which is connected directly to the distribution area of the company. The cost represents the operating and purchasing of this information system over the planning horizon.

Table 6 shows three alternative inventory review policies i for all the manufacturing facilities $(p=1,..,7)$. The basis for the selection of the cycle lengths TP_{pi} was the historical trend followed by AG, Inc., in which the company started reviewing inventories every month and finally came to a bi-weekly revision. The units used for the cycle length are in months (where one month is assumed to be 28 days).

Table 6. Periodic-review policy alternatives

Review Policy, i	Cycle Length TP_{pi} (months)	Periodic-review policy Cost, CP_{pi} (\$/15-weeks)
1	0.125	\$12,000
2	0.25	\$7,000
3	0.5	\$5,000

The objective of this approach is to give the model the possibility of choosing, within a given range, several alternatives in a piecewise manner while moving closer to a continuous review policy as the information cycle length tends to 0. This allows the model to select a review policy that makes a trade off between the cost of the policy and the total cost of the system. The cost CP_{pi} considered herein was estimated, based on factors such as human resources and analytical systems required for each alternative. Transactional system costs are considered as fixed for AG, Inc. because this type of system is not only used for planning purposes but also in the daily operation of the firm. In general, we consider CP_{pi} as a cost that does not depend on the size of the manufacturing facility or the number of families considered. This is mainly because transactional system costs are fixed.

4.1.2 Transactional Parameters

Input data for operations parameters was compiled directly from AG, Inc.'s databases and in some cases requested specially for the purpose of this research. Table 7 shows general labor data for manufacturing facility $p=1$.

Table 7. Labor data for manufacturing facility $p=1$

Layoff Cost, C'_p (\$/hour)	Hiring Cost, C_p (\$/hour)	Labor Cost, L_p (\$/hour)	Refreshment Cost, R_{pt} (\$/hour)	Overtime Cost, L'_p (\$/hour)	Overtime Factor, θ_p
\$7.4	\$3	\$0.62	\$0.2	\$1.2	0.2

The cost of layoff C'_p was calculated based on the legal requirements of the country, which include the following payments to workers:

- Payment of vacations not taken, with a minimum of 6 days per year.
- Christmas bonus, with a minimum of 6 days per year and proportional to the number of days worked throughout the year.
- 3 months of salary for indemnification.

- 20 days of salary for each year worked based on the current salary.
- Contributions to the savings fund and profit shares, proportional to the number of days worked throughout the year.

The cost of layoff per worker was estimated to be about $259 USD, which results in a $7.40 cost per hour (35 hours per worker per week). The remaining labor related costs C_p, L, R_{pt} and L'_p are based on training costs, minimal wages and other factors considered by the company. The values shown are rough estimates based on empirical knowledge of these costs at the time of compilation. θ_p, the limit of allowable over time is based on the fact that the contractual working week for AG, Inc. is 5 days, thus providing the flexibility to use Saturdays' for the flexible working system as required.

Table 8 shows the parameter values for each product family at manufacturing facility $p=1$. V_{pn} is the volume of an item for each family given in cubic meters, and is used to calculate the transportation requirements. The parameter a_{pn} gives the average number of labor hours required to produce an item of each product family. S_{pn} is the floor area required per item in square feet. The value shown is the one used by AG, Inc. to measure warehouse space utilization, but is a very rough estimate based on experience. We also envisage the need for the company to adjust the values to more realistic ones, which will result in improved management of space at the warehouses, leading to better management of the Supply Chain. A separate issue is the problem of having different measurement systems for areas and volumes. We suggest standardization as a means of avoiding confusions, but do not further address the matter.

Table 8. Input data for product families for manufacturing facility (MF) $p=1$

Product Family, n	Volume V_{pn} (cu.mts/unit)	Labor, a_{pn} (hours/unit)	Floor Area, S_{pn} (sq.ft/unit)	MF Holding Cost, h_{pn} (\$/week/unit)	In-transit Holding Cost Th_{pn} (\$/week/unit)	MF Std. Dev. of Forecast Error σ_{pn}	Manufacturing Lead-time, MLT_{pn} (months)	Premium Transportation and Information Cost, PTC_{pn} (\$/unit)	Raw Materials Cost, CM_{pn} (\$/unit)	MF Initial Inventory, $I_{pn(0)}$
1	0.516	2	1	$0.63	$0.53	307.8	0.25	$13	$228	0
2	0.516	2.5	1	$0.54	$0.45	4197.5	0.25	$11	$196	661
3	0.355	2.1	1	$0.41	$0.35	1143.3	0.25	$10	$150	297
4	0.355	2.3	1	$0.33	$0.28	1889.5	0.25	$10	$120	241
5	1.002	2.8	1	$0.54	$0.45	926.2	0.25	$17	$196	76

Inventory holding costs h_{pn} and Th_{pn}, for inventories held at the manufacturing facility, were calculated considering estimates of capital costs, insurance, space and damage and are given in terms of cost per unit per week. The calculation of the sample standard deviation of the forecast error σ_{pn} is explained together with the forecast methodology below. MLT_{pn} is the manufacturing lead-time committed by the plants. In the case of AG, Inc., this lead-time is 1 week (.25 months) and although in many cases production can be faster, plants hold no responsibility to produce before this official lead-time. For PTC_{pn} (premium transportation and information cost) we assume that the amount shipped will be proportional to the demand at each distribution center, and therefore the corresponding cost is a weighted average that corresponds to the following equation:

$$PTC_{pn} = \frac{\sum_{k=1}^{K} PTC'_{pnk}\left(\sum_{t=1}^{T} D_{pnkt}\right)}{\sum_{k=1}^{K}\sum_{t=1}^{T} D_{pnkt}}, \qquad (\forall p=1 \ldots P;\ n=1 \ldots N(p)) \qquad (76)$$

where PTC'_{pnk} is the cost to ship a unit of product family n from manufacturing facility p to distribution center k using a very efficient means of transportation and information. Additionally, it is known that for this type of service, costs are not correlated directly to distances but rather to the type of service resulting in costs that do not vary significantly from location to location, except for the farthest locations. In our case, premium transportation is a third party expedited-shipping company, which offers a comprehensive network of service centers and real-time introducing an auxiliary variable r_{pmnt} representing the number of units of product family n produced in period t at manufacturing facility p for which information is available in the transactional system and thus are available for shipment to the distribution centers. The nonlinear constraint is then replaced by an equivalent set of linear constraints:

$$\sum_{j=1}^{J}\sum_{K=1}^{K} Y_{pnjkt} \leq I_{pn(t-1)} + \sum_{m=1}^{M(p)} r_{pmnt}, \quad (\forall p=1...P;\ n=1...N(p);\ t=1...T) \tag{19a}$$

$$\sum_{n=1}^{N(p)}\sum_{t=1}^{T} r_{pmnt} \leq M\delta_{pm}, \quad (\forall p=1...P;\ m=1..M(p)) \tag{19b}$$

$$r_{pmnt} \leq \gamma_{pm} X_{pnt}, \quad (\forall\ p=1...P;\ m=1..M(p);\ n=1...N(p);\ t=1...T) \tag{19c}$$

where M represents a large positive number.

The optimal solution obtained by replacing the linearized constraints is equivalent to the original optimal solution with the nonlinear constraints. This is explained by noting that the auxiliary variable r_{pmnt} assumes the value of $\gamma_{pm}X_{pnt}$ if $\delta_{pm}=1$ and 0 otherwise; this is because constraint (19b) forces $r_{pmnt}=0$ whenever $\delta_{pm}=0$, and allows r_{pmnt} equal its optimal value ($\gamma_{pm}X_{pnt}$) from constraint (19c) if $\delta_{pm}=1$.

- **Manufacturing facility warehouse capacity:**

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

$$\sum_{n=1}^{N(p)} S_{pn} I_{pnt} \leq IC_p, \quad (\forall p=1...P;\ t=1...T) \tag{21}$$

information systems. The service provided by the shipping company is a guaranteed two-day LTL (less than truck load) freight service. CM_{pn}, the material cost, was not available, however, it was estimated based on the company's average standard cost for each product family. Finally, $I_{pn(0)}$, the initial inventory at the manufacturing facility, was extracted from AG, Inc.'s transactional database containing information at the end of February, 2000.

Table 9 includes the transportation lead-times TLT_{pk} from the manufacturing facility to the respective distribution centers given in months. These times include loading and unloading of the product and are considered as standard because they are related to the most convenient mode of transportation in terms of cost defined by the traffic department of AG, Inc. under normal conditions. The parameter TLT_{pk} is fixed and is only used for the calculation of safety stocks as discussed in Chapter 3.

Table 9. Official transportation lead-times to distribution centers

Manufacturing Facility, *p*	**Distribution Center, *k***	**Lead-time, TLT_{pk}** (months)
1	1	0.15
1	2	0.60
1	3	0.18
1	4	0.25
1	5	0.35
1	6	0.32
1	7	0.25
1	8	0.36

Three transportation modes are mainly used for the movement of products within AG, Inc.'s supply chain network. Table 10 provides the general details for each one, showing capacities for each mode in cubic meters. Modes j=1 and j=2 are the same type of transportation with the sole difference that mode $j=1$ is an expedited shipment (but not premium) used only to relieve stock outs, with a respective higher cost.

Table 10. Transportation modes

Mode, j	Capacity FTL_j (cu. mts.)	Description
1	102.20	48' Trailer (FAST)
2	102.20	48' Trailer (Normal)
3	142.33	Rail Boxcar

Table 11 gives specific details of the cost and lead-times by transportation mode (LT_{pjk}) in weeks from plant $p=1$ to the distribution centers using transportation mode j. Lead-times by transportation mode are rounded to the nearest integer values, and are used in the in-transit and distribution center inventory balancing equations to calculate the approximate weekly inventory levels. A lead-time of zero means that, in general, shipments will be shipped and received within the same week. This convention has been widely applied in material requirements planning (Orlicky, 1975) and distribution resource planning (Martin, 1983) systems. Modes that are not available for a plant-distribution center route are not listed. As it may be noted, two different lead-time units are being used in the model: months for TP_{pi}, MLT_{pn} and TLT_{pk} (used in the safety stock calculation) and weeks for LT_{pjk} (used in some of the inventory balance equations). As it was previously discussed in Chapter 3, the units used for MLT_{pn} and TLT_{pk} must be consistent with those in the demand forecast used to calculate the standard deviation of the forecast errors (σ_{pn} and σ'_{pnk}) and these will not necessarily coincide with the time units used to define the planning horizon (T) because they are not strictly related in the underlying processes used to define each one (i.e., the reason for choosing weeks as the units for t has nothing to do with the reason for forecasting demand by months). In order to make this discrepancy transparent to the user, the transactional information system can handle homogeneously defined units that are then converted to the units required by the model's variables.

Table 11. Transportation costs and lead-times by mode

Manufacturing Facility, p	Mode, j	Distribution Center, k	Transportation Cost, TC_{pkj} ($/transportation consignment)	Lead-time LT_{pjk} (weeks)
1	1	1	$1,492	0
1	1	2	$2,899	0
1	1	3	$178	0
1	1	4	$601	0
1	1	5	$1,278	0
1	1	6	$2,747	0
1	1	7	$766	0
1	1	8	$1,246	0
1	2	1	$995	1
1	2	2	$1,933	1
1	2	3	$118	0
1	2	4	$401	0
1	2	5	$852	1
1	2	6	$1,831	2
1	2	7	$510	0
1	2	8	$831	1
1	3	1	$748	2
1	3	8	$930	2

Holding costs at distribution centers, h_{pnk}, which are shown in Table 12, were calculated based on the same considerations as h_{pn} (Table 8). As may be noted, holding costs at the distribution centers are different from those at the manufacturing facilities for the same product families. There are several reasons behind this difference that are mainly related to the cost of space included in the holding costs. For example, differences in the cost of land in an industrial area as compared to the cost of land in a commercial area or differences in design and size of the warehouses, which allow the company to take advantage of economies of scale. Table 12 also shows the sample standard deviations of the forecast errors σ'_{pnk} calculated for each product family and distribution center for manufacturing facility $p=1$. In terms of the sample standard deviation of the forecast error σ_{pn} and σ'_{pnk}, and the expected demand (demand forecast) D_{pnkt}, the calculation of the values for these parameters should be performed by a robust forecasting system. Given the fact that these values were not readily available, we use Winters' method (Winters, 1960) that considers trends and seasonal patterns. This forecasting procedure is simple and has been proven in many empirical studies to work well when seasonal data is present (Nash, 2001; Chatfield, 1996). Winters' model assumes that observations are independent; albeit this might not be true for all of AG, Inc.'s data, using Winters' model when observations are dependent works reasonably well, although other methods such as Box-Jenkins exploit this dependency and generally produce superior results (Johnson and Montgomery, 1974).

Table 12. Sample standard deviations of the forecast error by product family-distribution center

Manufacturing Facility, p	Product Family, n	Distribution Center, k	Std. Dev. of Fcst Error, σ'_{pnk}	Distribution Center Holding Cost, h_{pnk} ($/week/unit)
1	1	1	95	$0.97
1	1	2	6.86	$1.20
1	1	3	217.78	$1.25
1	1	4	14.37	$1.05
1	1	5	25.39	$1.01
1	1	6	0	$0.98
1	1	7	47.82	$1.10
1	1	8	87.59	$0.97
1	2	1	1,460.54	$0.97
1	2	2	24.22	$1.20
1	2	3	3,020.03	$1.25
1	2	4	63.12	$1.05
1	2	5	190.83	$1.01
1	2	6	23.76	$0.98
1	2	7	325.33	$1.10
1	2	8	1,545.07	$0.97
1	3	1	461.05	$0.97
1	3	2	0	$1.20
1	3	3	608.45	$1.25
1	3	4	18.2	$1.05
1	3	5	20.98	$1.01
1	3	6	370.82	$0.98
1	3	7	47.7	$1.10
1	3	8	265.57	$0.97
1	4	1	1,463.04	$0.97
1	4	2	9.73	$1.20
1	4	3	924.07	$1.25
1	4	4	11.11	$1.05
1	4	5	20.46	$1.01
1	4	6	179.23	$0.98
1	4	7	51.62	$1.10
1	4	8	228.47	$0.97
1	5	1	389.54	$0.97
1	5	2	3.49	$1.20
1	5	3	843.02	$1.25
1	5	4	7.4	$1.05
1	5	5	29.33	$1.01
1	5	6	13.04	$0.98
1	5	7	115.42	$1.10
1	5	8	186.66	$0.97

It is assumed that as the accuracy of the demand forecast increases, the cost to generate the information will also increase. We suggest that the production-distribution model at hand will be of use in the evaluation of trade offs between the costs of the new forecasting systems and the expected benefits associated with their implementation.

We now show the procedure for determining σ'_{pnk} and D_{pnkt} for product family n=1, at distribution center k=1, produced at manufacturing facility p=1 in time period t. A further analysis of the outcome or a more detailed explanation of the method is not provided in this thesis, however appendix II shows the calculations for D_{pnkt} and σ'_{pnk} for all the families-distribution centers-plants and σ_{pn} for all families-plants where the large amount of information underscores the need for adequate transactional and analytical IT used to handle and process this information. The calculation of σ_{pn} follows the same methodology shown for σ'_{pnk} except that the aggregate historical demand for the entire distribution network by month is used.

Two years of historical data by month were available in AG, Inc.'s databases at the stock-keeping unit (SKU) by location level. Table 13 shows the data for the product family at hand and Figure 2 depicts the seasonal patterns of historical demand and the final forecast because of a decreasing trend.

In order to model the forecast method, a collection of 36 data points with indices $t'=1...36$ are used. These 36 data points represent a data set of 3 years. Year 1 (i.e., $t'=1...12$) and year 2 (i.e., $t'=13...24$) provide historical data to be used in forecasting year 3 ($t'=25...36$). With this is mind, let $AD_{npkt'}$, ($t'=1...24$) be the observed values of the historical demand time series during period t' for product family n produced at manufacturing facility p and sold in distribution center k.

Table 13. March 1998-February 2000 historical demand data for n=1, p=1 & k=1

	$AD_{npkt'}$											
Year	**Mar**	**Apr**	**May**	**June**	**July**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Jan**	**Feb**
98-99	1,282	1,470	1,017	763	962	1,066	1,017	1,446	1,591	784	652	931
99-00	846	1,345	785	637	656	639	854	1,420	1,075	449	249	381

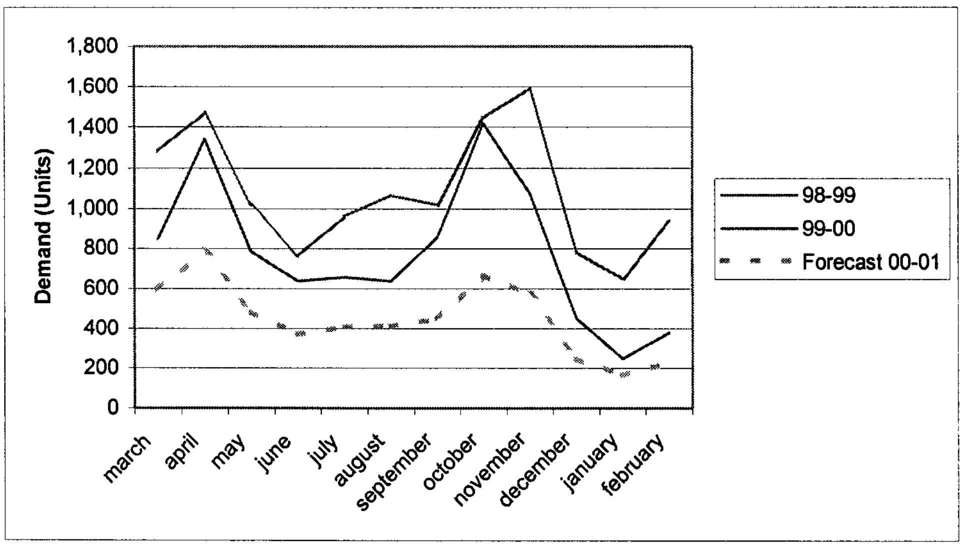


Figure 2. Demand patterns and Forecast for n=1, p=1 and k=1

The forecasting method shown uses a reformulated and slightly modified version of the procedure used by Elsayed and Boucher (1994). This small modification allows us to estimate a forecast with only one year of historical demand data instead of two years, which were not available at the time. The forecast is calculated using the set of equations below:

$$\hat{a}_{npkt'} = \alpha \frac{AD_{npkt'}}{\hat{c}_{npk(t'-12)}} + (1-\alpha)\left(\hat{a}_{npk(t'-1)} + \hat{b}_{npk(t'-1)}\right),$$

$$(\forall n=1...N(p);\ p=1...P;\ k=1,...K;\ t'=1...24) \qquad (77)$$

$$\hat{b}_{npkt'} = \varphi\left(\hat{a}_{npkt'} - \hat{a}_{npk(t'-1)}\right) + (1-\varphi)\hat{b}_{npk(t'-1)},$$

$$(\forall n=1...N(P);\ p=1...P;\ k=1...K;\ t'=1...24) \qquad (78)$$

$$\hat{c}_{npkt'} = \gamma \frac{AD_{npkt'}}{\hat{a}_{npkt'}} + (1-\gamma)\hat{c}_{npk(t'-12)},\ (\forall n=1...N(P);\ p=1...P;\ k=1...K;\ t'=1...24) \qquad (79)$$

$$fd_{npkt',T'} = \left(\hat{a}_{npkt'} + \hat{b}_{npkt'}T'\right)\hat{c}_{npkt'},\ (\forall n=1...N(P);\ p=1...P;\ k=1...K;\ t'=12...23;\ T'=1)$$

$$(\forall n=1...N(P);\ p=1...P;\ k=1...K;\ t'=24;\ T'=1...12) \qquad (80)$$

where,

$\hat{a}_{npkt'}$	=	Smoothed level component of product family n produced at manufacturing facility p in distribution center k at the end of period t'.
$\hat{b}_{npkt'}$	=	Smoothed trend component of product family n produced at manufacturing facility p in distribution center k at the end of period t'.
$\hat{c}_{npkt'}$	=	Smoothed seasonal component of product family n produced at manufacturing facility p in distribution center k at the end of period t'.
α	=	Smoothing constant for level.
φ	=	Smoothing constant for trend.
γ	=	Smoothing constant for seasonality.
$fd_{npkt',T'}$	=	Sales forecast of product family n produced at manufacturing facility p in distribution center k to be realized in the $(t'+T')$'th period based on information available through the t'th period.
T'	=	Number of periods to forecast into the future.

In the forecasting procedure, the calculated level ($\hat{a}_{npkt'}$), trend ($\hat{b}_{npkt'}$) and seasonal ($\hat{c}_{npkt'}$) components (eqs. 77-79), and the number of periods (T') are combined to derive the forecast (eq. 80). In order to start the forecasting process, the initial values for the smoothed level, trend and seasonal factors above are required and are calculated using the following equations:

$$\bar{s}_{1npk} = \frac{\sum_{t'=1}^{12} AD_{npkt'}}{12}, \qquad (\forall n=1...N(P); p=1...P; k=1...K) \qquad (81)$$

$$\bar{s}_{2npk} = \frac{\sum_{t'=13}^{24} AD_{npkt'}}{12}, \qquad (\forall n=1...N(P); p=1...P; k=1...K) \qquad (82)$$

$$\hat{b}_{npk0} = \frac{\bar{s}_{2npk} - \bar{s}_{1npk}}{12}, \qquad (\forall n=1...N(P); p=1...P; k=1...K) \qquad (83)$$

$$\hat{a}_{npk0} = \bar{s}_{2npk} - 18.5\hat{b}_{npk0}, \qquad (\forall n=1...N(P); p=1...P; k=1...K) \qquad (84)$$

$$SE_{npkt'} = \frac{AD_{npkt'}}{\bar{s}_{2npk} + \hat{b}_{npk0}(t' - 18.5)}, \qquad (\forall n=1...N(P); p=1...P; k=1...K; t'=1...24) \qquad (85)$$

$$\hat{c}_{npk(t'-12)} = \frac{\frac{SE_{npkt'} + SE_{npk(t'+12)}}{2}}{\sum_{t'=1}^{12} \frac{SE_{npkt'} + SE_{npk(t'+12)}}{2}}, \qquad (\forall n=1...N(P); p=1...P; k=1...K; t'=1...12) \qquad (86)$$

where,

$\bar{s}_{1npk}$	=	The average sales in year 1 of product family n produced at manufacturing facility p in distribution center k.
$\bar{s}_{2npk}$	=	The average sales in year 2 of product family n produced at manufacturing facility p in distribution center k.
$\hat{b}_{npk0}$	=	Average trend component for the two years (also used as initial trend) of product family n produced at manufacturing facility p in distribution center k.
$\hat{a}_{npk0}$	=	Initial level component of product family n produced at manufacturing facility p in distribution center k.
$SE_{npkt'}$	=	Initial estimates for seasonality in both years of product family n produced at manufacturing facility p in distribution center k.
$\hat{c}_{npk(t'-12)}$	=	Normalized initial seasonal components for product family n produced at manufacturing facility p in distribution center k.

Table 14 presents the final outcome of the forecasting process. It is important to emphasize that during year one, Winters' method is applied without making any forecasts; the reason being that year 1 is used only to estimate the initial values of the smoothed level, trend and seasonal variables. The smoothing constants α (level), φ (trend) and γ (seasonal) were set at 0.1, 0.1 and 0.01, respectively, following a trial and error selection process in order to minimize the sample standard deviation. These same values are applied to all of AG, Inc.'s product families, which is a valid procedure according to Holt et al. (1960).

Table 14. Final estimate of Demand for product family *n=1* produced at manufacturing facility *p=1* sold in distribution center *k=1* during time period t′=*13...36*

	$fd_{npkt'}$											
Year	**Mar**	**Apr**	**May**	**June**	**July**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Jan**	**Feb**
99-00	948	1269.1	809.11	631.13	720.48	745.31	826.02	1284.9	1172.2	529.64	367.3	515.4
00-01	595.32	787.22	485.12	368.81	407.21	410.99	447.21	667.73	576.03	250.13	167.1	229.9

The sample standard deviation is used as a metric for measuring the accuracy of the forecast. It is calculated based on the error generated when forecasting the second year of historical demand; this is done in order to minimize the effects of initializing the system during the first year. Furthermore, we assume that the error of the estimated versus actual demand for the second year is also an estimate of the forecast error for year 3, thus, the standard deviation of the error is:

$$\sigma'_{pnk} = \sqrt{\frac{\sum_{t'=13}^{24}\left(fd_{npkt'} - AD_{npkt'}\right)^2}{11}}, \quad (\forall p=1...P;\ n=1...N(P);\ k=1,...K) \qquad (87)$$

Consequently, for our example $\sigma'_{111}=95$, which is the value shown in Table 12 for $p=1$, $n=1$ and $k=1$.

The forecasting procedure ends by breaking the monthly forecast $fd_{npkt'}$ into a forecast of periods commensurable with those used in the production-distribution model (i.e., D_{pnkt}). We do this by multiplying the monthly forecast by the weekly distribution percentages of demand given in Table 4. It is important to note that for the planning horizon of 15 weeks, we need the forecast of 4 months. Table 15 shows the final demand forecast by week. With little loss, we round off the weekly forecasts to the next largest integer values.

As previously stated, the parameter σ_{pn} is to be calculated in almost the same manner as σ'_{pnk} by dropping the index k from equations 77-86. In order to save space we do not present the formulas; however, appendix II contains the calculations for all product family-plants, where the variables have been renamed by adding a $'$ (prime) to the ones shown above. In this manner $AD'_{npt'}$ is the cumulative demand, at all the warehouses, for product family n produced at manufacturing facility p at the end of month t':

$$AD'_{npt'} = \sum_{k=1}^{K} AD_{npkt'}, \quad (\forall n=1...N(P);\ p=1...P;\ t'=1...24) \qquad (88)$$

Table 15. Demand forecast by week for product family $n=1$ produced at manufacturing facility $p=1$ sold in distribution center $k=1$

Period, t	Description	Demand Distribution	Forecast by Month, $fd_{npkt'}$	Forecast by Week, D_{pnkt}
1	March I '00	6%	595.32	36
2	March II '00	14%		84
3	March III'00	20%		120
4	March IV'00	25%		149
5	March V '00	35%		209
6	April I '00	13%	787.22	103
7	April II '00	22%		174
8	April III'00	27%		213
9	April IV'00	38%		300
10	May I '00	30%	485.12	146
11	May II '00	20%		98
12	May III '00	15%		73
13	May IV '00	15%		73
14	May V '00	20%		98
15	June I '00	13%	368.81	48

4.2 Solution Methodology

The production-distribution model was tested using Lingo (Lindo Systems Inc., 2002) as the solver (see appendix III). Given the fact that the size and complexity of the database made the solution of the model intractable, it was deemed necessary to relax constraint set (74) by considering the general integer variables as continuous. As discussed in Winston (1994), the relaxed model gives a reasonable approximation of the integer solution. It is important to point out that additional simplification could be carried out by taking advantage of the special structure (primal block angular) of the model in which specialized algorithms might be applied in order to find a solution (Bradley et al., 1977). This is left as a topic for future research (for a brief introduction to the underlying theory see appendix IV).

The model was run under four different scenarios in order to calculate the corresponding minimal cost solutions and to evaluate cost reduction opportunities among them. The focus is mainly on comparing the current state of the system, which is considered as inflexible, to an ideal system in which flexibility is increased by means of integration. These four scenarios were selected considering the four possible combinations of adopting an inflexible or a flexible production system (IFPS/FPS) and an inflexible or a flexible information system (IFIS/FIS). Table 16 provides the 4 scenarios to be studied. Each scenario is defined as follows:

Scenario 1. Inflexible production system with an inflexible information system.

Scenario 2. Inflexible production system with a flexible information system.

Scenario 3. Flexible production system with an inflexible information system.

Scenario 4. Flexible production system with a flexible information system.

Table 16. Case Study Scenarios

	IFIS	**FIS**
IFPS	Scenario 1	Scenario 2
FPS	Scenario 3	Scenario 4

Physically, we define an inflexible system as an environment in which full integration between production and the rest of the logistics functions (distribution, transportation and sales) has not been achieved. This translates into low flexibility because the information used to link the functions in the supply chain lacks completeness, therefore causing the manufacturing and information systems to work under rigid general rules in order to reduce perceived uncertainty and assure compliance of plans. The representation of an inflexible system in the context of our model is discussed below. The counterpart, a flexible production or information system, is simply modeled by disregarding these inflexibility conditions.

4.2.1 Production System Inflexibility (IFPS)

Low flexibility in the production system can be modeled by adding the following constraint sets to the model. These are related specifically to our case study and therefore are not general in nature because of their dependence on the fiscal calendar and the production policies of AG, Inc:

- **Production volume for each family within the month**

The production volume for a product family should be the same in each week of the month. For example, constraint set (89) states that the production volume in period $t=1$ should be equal to the production volumes for $t=2, 3, 4$ and 5; the constraint set represents the production for each product family in March. Constraints (90) and (91) represent the April and May production volumes, respectively.

$$X_{pnt} = X_{pn1}, \quad (\forall p=1 \ldots P;\ n=1 \ldots N(P);\ t=2, 3, 4, 5) \tag{89}$$

$$X_{pnt} = X_{pn6}, \quad (\forall p=1...P;\ n=1...N(P);\ t=7,\ 8,\ 9) \tag{90}$$

$$X_{pnt} = X_{pn10}, \quad (\forall p=1...P;\ n=1...N(P);\ t=11,12,13,14) \tag{91}$$

- **Maximum product family production volume increase within the planning horizon**:

At the beginning of every month, the product family production volume may be at most 30% above the previous month's volume.

$$X_{pnt} \leq 1.3 X_{pn(t-5)}, \quad (\forall p=1...P;\ n=1...N(P);\ t=6,15) \tag{92}$$

$$X_{pnt} \leq 1.3 X_{pn(t-4)}, \quad (\forall p=1...P;\ n=1...N(P);\ t=10) \tag{93}$$

We assume that the first month's volume is consistent with the above rule due to the absence of historical data but the following constraint would be adequate for this case:

$$X_{pnt} \leq 1.3 X_{pn0}, \quad (\forall p=1...P;\ n=1...N(P);\ t=1) \tag{94}$$

where X_{pn0} is the previous month's production volume relative to the first month of the planning horizon.

4.2.2 Information System Inflexibility (IFIS)

Inflexibility in the information system was modeled by fixing the information parameters as follows:

- **Information timeliness**

From the perspective of inventory information systems used at the production-distribution link, Table 17 shows the current parameter levels associated with each manufacturing facility. The costs and levels vary depending on several factors, inherent to each manufacturing facility such as volume produced, current information system being used and capacity of the manufacturing facility's warehouses. For example, manufacturing facility $p=1$ uses an automated information system while manufacturing facility $p=2$ uses a manual system.

For the purpose of representing inflexibility in the model we fixed the auxiliary variable δ_{pm} at 1 for the current information system m with an information timeliness factor γ_{pm} used at manufacturing facility p.

Table 17. Inventory information systems

Information System, m	Manufacturing Facility, p	Timeliness Factor, γ_{pm}	Information System Cost, CI_{pm} (\$/15-weeks)
3	*1*	0.99	\$10,000
1	*2*	0.8	\$1,000
2	*3*	0.95	\$2,000
1	*4*	0.9	\$1,000
2	*5*	0.95	\$7,000
2	*6*	0.93	\$2,000
1	*7*	0.8	\$1,000

- **Inventory review policy**

Currently, AG, Inc. is reviewing inventories based on a one-week information cycle length (i.e., $TP_{pi}=.25\ \forall p=1...7\ \&\ i=2$). In order to match our model to this policy it was necessary to fix the binary auxiliary variable β_{pi} at 1 for the periodic-review policy i corresponding to the one week cycle at each manufacturing facility p *(i.e.,* $i=2$ and $p=1...7$*)*. The corresponding cost at the manufacturing facilities, $CP_{pi} = \$7{,}000$ *(* $\forall p=1...7\ \&\ i=2$*)*, makes apparent the fact that costs are not related to the size or type of manufacturing facility as discussed on page 55.

- **Risk pooling**

The consideration of no formal application of time postponement at AG, Inc. made it necessary to fix the allocation of safety stocks at the distribution centers as a means of representing inflexibility in the forecasting system. The decision variable DI_{pn} was set to 1, forcing the model to manage a decentralized safety stock policy at all warehouses for product families produced at all manufacturing facilities (i.e., $DI_{pn}=1\ \forall p=1...7\ \&\ n=1...N(p)$).

4.3 Overall Results

The current state of the system as presented above was used for all the 4 scenarios. The basic idea of our analysis was to run the model with increasing levels of flexibility and compare the relevant outcomes of each scenario. It is important to note that in order to be consistent with AG, Inc.'s inventory policy, the final period's (*t=15*) inventory levels were set to be any number greater or equal to zero. Table 18 summarizes the costs obtained from the model using the aforementioned scenarios. For example, scenario 1 represents the supply chain with inflexibility in the production system as well as in the information system at a total cost of $158,182,855.29. Conversely, scenario 4 considers a flexible production system combined with a flexible information system, at a total cost of $152,014,220.73; this combination is equivalent to the model as defined in Chapter 3. The difference between these two scenarios presents a cost reduction opportunity of $6,168,634.55 or 3.9% over the planning horizon of 15 weeks.

Figure 3 delineates the AG, Inc.'s supply chain network aggregate inventory behavior in the context of seasonal demand patterns. From the graph it is observed that scenario 4 yields the lowest level of inventory and thus the most inventory turns, especially throughout the initial part of the planning horizon, where it is assumed a lower degree of uncertainty exists. To further analyze the model's response to changes in system flexibility, we first consider scenario 2 in Table 18 which represents an inflexible production system combined with a flexible information system. The total cost is $152,359,124.64, which represents a cost reduction opportunity of $5,823,730.65 or 3.68%; moreover, from Figure 3 we may observe that the cost reduction opportunity between scenarios 1 and 2 is also amplified throughout the initial periods of the planning horizon where the difference in inventory is greater.

Table 18. Scenario cost detail

Category	Scenario 1		Scenario 2		Scenario 3		Scenario 4	
	Cost	%	Cost	%	Cost	%	Cost	%
Labor	$1,380,595.00	0.87%	$1,335,071.00	0.88%	$1,374,315.00	0.87%	$1,333,932.00	0.88%
Increasing labor	$5,917.37	0.00%	$1,074.26	0.00%	$3,448.97	0.00%	$1,590.45	0.00%
Reducing labor	$507,077.50	0.32%	$374,198.10	0.25%	$311,774.10	0.20%	$328,813.80	0.22%
Refreshment	$58,757.02	0.04%	$52,240.78	0.03%	$58,300.31	0.04%	$53,563.48	0.04%
Transportation	$1,946,924.00	1.23%	$1,836,694.00	1.21%	$1,915,496.00	1.22%	$1,774,075.00	1.17%
Manufacturing facility inventory	$219,136.80	0.14%	$252,040.70	0.17%	$167,011.00	0.11%	$266,026.70	0.18%
In-transit inventory	$200,296.60	0.13%	$192,241.20	0.13%	$199,464.00	0.13%	$202,481.20	0.13%
Distribution center inventory	$1,976,151.00	1.25%	$1,374,683.00	0.90%	$1,663,648.00	1.06%	$1,180,909.00	0.78%
Overtime	$0.00	0.00%	$0.00	0.00%	$0.00	0.00%	$0.00	0.00%
Premium transportation and information	$0.00	0.00%	$242,581.60	0.16%	$0.00	0.00%	$256,929.10	0.17%
Periodic-review policy	$49,000.00	0.03%	$84,000.00	0.06%	$49,000.00	0.03%	$84,000.00	0.06%
Timeliness	$24,000.00	0.02%	$39,500.00	0.03%	$24,000.00	0.02%	$34,500.00	0.02%
Raw materials	$151,815,000.00	95.97%	$146,574,800.00	96.20%	$151,354,200.00	96.33%	$146,497,400.00	96.37%
Total	**$158,182,855.29**	**100.00%**	**$152,359,124.64**	**100.00%**	**$157,120,657.38**	**100.00%**	**$152,014,220.73**	**100.00%**

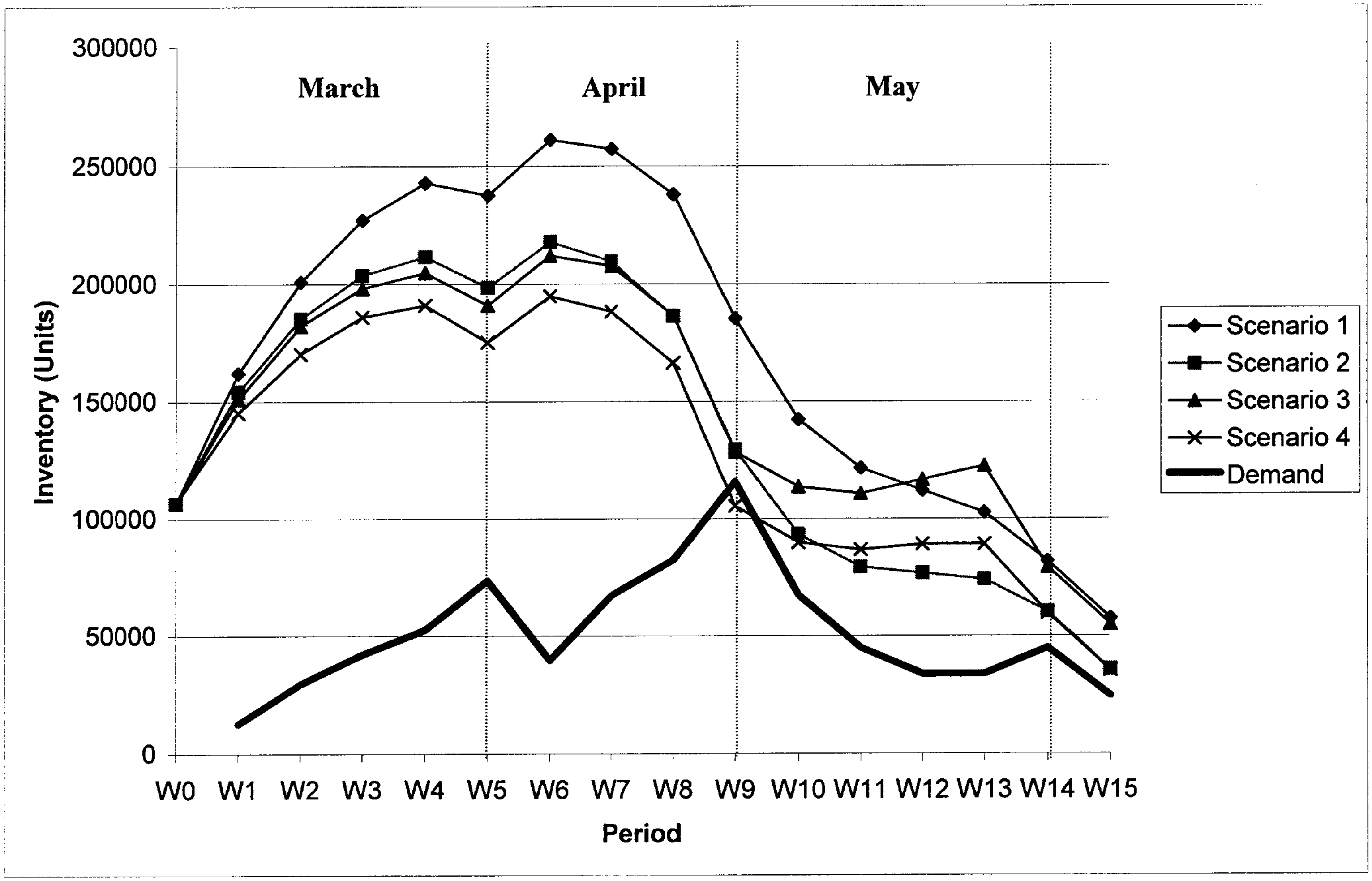


Figure 3. Total supply chain inventory for various scenarios

Second, Table 18 shows a cost difference of $5,106,436.64 or 3.25% between scenarios 3 and 4, when we change the flexibility level of the information system in a flexible production system; however, from Figure 3 it is obvious that the cost reduction opportunities are concentrated towards the end of the planning horizon, leading to the conclusion that information is of more value in a constrained production environment. Another interesting result is that flexibility changes in the production system do not have as significant an impact on the total cost as do flexibility changes in the information system; this is discerned by comparing scenarios 1 with 3, and 2 with 4, which result in cost reductions of only $1,062,197.92 or 0.67% and $344,903.90 or 0.23%, respectively. This fact provides an insight into the notion of the relative importance of information flexibility in SCM decisions; however, it is necessary to further analyze the outcome in detail to fully understand the mechanics of why information has such an impact on the supply chain. We do this by comparing and analyzing the cost elements in scenarios 3 and 4. Table 19 shows the difference between the corresponding cost elements of these scenarios. It is observed that the major reduction occurred in the raw materials cost, followed by the total inventory costs. On the other hand, a major increase occurred in the total cost of information followed by the cost of inventory at the manufacturing facility. Intuitively, we may think that the model has reduced inventories significantly by pooling stocks at the manufacturing facilities' warehouses. We further investigate this matter by analyzing some of the decision variables in each scenario.

Table 19. Difference in cost between scenarios 3 and 4

Category	Difference
Production	-$40,383.00
Increasing labor	-$1,858.51
Reducing labor	$17,039.70
Refreshment	-$4,736.83
Total Labor	**-$29,938.64**
Transportation	-$141,421.00
Manufacturing facility inventory	$99,015.70
In-transit inventory	$3,017.20
Distribution center inventory	-$482,739.00
Total inventory	**-$380,706.10**
Overtime	$0.00
Periodic-review policy	$35,000.00
Timeliness	$10,500.00
Premium transportation and information	$256,929.10
Total Information	**$302,429.10**
Raw materials	-$4,856,800.00
Total	**-$5,106,436.64**

First we focus on the selection of the information timeliness systems, which are given in Table 20. In going from scenario 3 to 4, the model changed the information systems at plants 3, 4 and 6, resulting in an information cost increase of only $10,500. This small increase in the cost of information suggests that this parameter has little impact on the overall cost reduction. We will further investigate this question when we perform sensitivity analyses in Chapter 5.

The next parameter that we delve into is the selection of the inventory review policy. For scenario 4 the model chose $TP_{pi}=.125$ ($\forall p=1...7$ & $i=1$) at a related cost of CP_{pi} = $12,000 ($\forall p=1...7$ & $i=1$); this selection results in an information cost increase of $35,000. As previously discussed, Cachon and Fisher (2000) concluded that the major benefit obtained from information is in lead-time reduction. Our results support this statement in the sense that as a result of increasing the information level, the lead-time in all the manufacturing facilities is reduced (i.e., from .25 to .125 months). Suri (1998), on the other hand, pursues a relentless reduction of lead-time in all aspects of the firm's operation. Our model demonstrates to be a complement to his lead-time reduction approach by focusing on reducing lead-times across the supply chain functions. The impact of TP_{pi} on the overall cost is further investigated when we perform sensitivity analyses.

Table 20. Inventory information system allocation

		Scenario 3			Scenario 4	
Manufacturing Facility, p	Information System, m	Timeliness Factor, $\gamma_{\mu\pi}$	Information system cost, CI_{pm}	Information System, m	Timeliness Factor, $\gamma_{\mu\pi}$	Information system cost, CI_{pm}
1	3	0.99	$10,000	3	0.99	$10,000
2	1	0.8	$1,000	1	0.8	$1,000
3	2	0.95	$2,000	3	0.99	$7,000
4	1	0.9	$1,000	3	0.99	$5,000
5	2	0.95	$7,000	2	0.95	$7,000
6	2	0.93	$2,000	3	0.98	$3,500
7	1	0.8	$1,000	1	0.8	$1,000

Finally, the third parameter to be evaluated is the model's response to the allocation of safety stocks in the distribution system. Table 21 shows the calculated safety stocks (SS) for scenarios 3 and 4 aggregated by manufacturing facility p over all product families n and distribution centers k. Here, we introduce, for analysis purposes, a new variable DS_{pnk}, the decentralized safety stock, whose value is calculated from equation 32 in Chapter 3. We may observe that the reduction in safety stocks due to the combined effect of lead-time reduction (i.e., periodic review cycle reduction) and risk-pooling application were 20,308 units or a 31% (column G). By observing columns (B) and (C) in detail, it becomes apparent that in the flexible scenario the model tends to centralize the inventory at the manufacturing facility because it chooses a centralized policy in 19 (or 70%) of the 27 families; however, we note that the number of units centralized only represents 37.4% of the total supply chain safety stock. We further investigate this matter in Chapter 5 in order to evaluate the factors affecting the risk pooling policy. Simchi-Levi et al. (2000) show that, in general, the application of the risk pooling principle reduces variability, which in turn reduces safety stocks; by quantifying this policy we demonstrate that in some cases the application of risk pooling is not possible or economically feasible from the overall system perspective.

4.4 Detailed Results

In order to demonstrate the scope of the information generated by the model, we now consider, in more detail, some of the results calculated by the model for scenario 4. Appendix V lists the complete results for this scenario in terms of the informational and transactional decision variables; the appendix gives the reader an idea about the volume of information generated by the model and underscores the necessity of using transactional information systems in order to aggregate this data in line with each user's specific requirements.

Table 21. Safety stock comparison for scenarios 3 and 4

	Scenario 3	Scenario 4					
	(A)	*(B)*	*(C)*	*(D)*	*(E)*	(F)	(G)
MF, p	$\sum_{n=1}^{N(p)}\sum_{k=1}^{K} DS_{pnk}$	$\sum_{n=1}^{N(p)} RP_{pn}$	$\sum_{n=1}^{N(p)} DI_{pn}$	$\sum_{n=1}^{N(p)} PS_{pn}$	$\sum_{n=1}^{N(p)}\sum_{k=1}^{K} DS_{pnk}$	**Total SS (D)+(E)**	**SS Difference (F)-(A)**
1	18,715	3	2	3,155	10,790	13,945	-4,770
2	4,840	1	0	1,760	0	1,760	-3,080
3	13,403	5	2	4,357	5,513	9,870	-3,532
4	3,173	0	1	0	2,858	2,858	-315
5	6,719	3	1	963	4,381	5,344	-1,375
6	3,895	1	1	271	2,873	3,144	-751
7	14,768	6	1	6,397	1,886	8,283	-6,485
Total	**65,513**	**19**	**8**	**16,903**	**28,301**	**45,204**	**-20,308**

Notes:

MF = Manufacturing facility
SS = Safety stock
(A) = Aggregate decentralized safety stock for all product families produced at manufacturing facility p under scenario 3
(B) = Number of product families produced at manufacturing facility p in which a centralized safety stock policy was chosen under scenario 4
(C) = Number of product families produced at manufacturing facility p in which a decentralized safety stock policy was chosen under scenario 4
(D) = Aggregate centralized safety stock for all product families produced at manufacturing facility p under scenario 4
(E) = Aggregate decentralized safety stock for all families produced at manufacturing facility p under scenario 4

Here we limit our presentation to a few instances of each decision variable in order to save space. Tables 22-26 provide the detail of the optimal allocation of the resources in the supply chain. For example, table 22 shows the allocation of the workforce over the planning horizon at manufacturing facility $p=1$. In this case, we start with 35,000 hours/week of labor, which are equivalent to 1000 workers at the rate of 35 hours/week. The labor hours are reduced by 1,019 hours in period $t=3$ and by a further 9,313 hours in period $t=9$. This is equivalent to 296 workers or 29.6% of the initial workforce level. It is important to note that layoffs and overtimes are kept at the minimum levels possible by using a flexible working system. For example, in period $t=1$, there is no hiring and the workers put in an additional 7,000 hours of work without being paid overtime ($f_{1,1}^{+}$=7,000); however in period $t=12$, workers are receiving their normal payment, but they put in 3,351 less hours of work ($f_{1,12}^{-}$=3,351). It is not until the end of the planning horizon that the total additional and reduced hours are compared in order to account for any overtime, $O_1 = \sum_{t=1}^{15}\left(f_{pt}^{+} - f_{pt}^{-}\right)$, which in this case equals zero. Additionally, it is noted that the amount of decreased hours (f_{pt}^{-}) at the end of the planning horizon are the same as the workforce level (W_{pt}) at that time. This is mostly because of two reasons; one is the finite number of periods used, which means that any excess capacity could be used to cover the requirements of periods beyond the planning horizon, and the second is the low peak in demand due to the seasonality of sales. It is suggested that the rolling horizon approach of the model will adjust the figures as time goes on and new periods are added.

Table 23 provides information about the inventory, centralized safety stocks and the production quantities for each product family *n* produced at manufacturing facility $p=1$ over the planning horizon. For example, considering product family $n=1$, the production level in period $t=1$ is 357 units, the centralized safety stock is 311 units, and the final inventory is 311 units, which is a function of the amount produced, the timeliness factor, the amount shipped and the safety stock constraint.

As a second example, we consider product family $n=2$ that follows a decentralized safety stock policy. In period $t=1$, the production level is 11,983 units, and the ending inventory is 119 units, which represent the number of units which could not be shipped because of the timeliness factor. This information helps the production and inventory personnel at the manufacturing facility to plan for future resource requirements that are not implicit in the model, such as the workforce level at the warehouse, the dock capacity or materials handling systems required. It is noted that at the end of period 15, the safety stocks for all of the product families are at zero. Although this is in line with AG, Inc.'s inventory policy, in some instances, such as for product families 1, 4 and 5, the ending inventory at the end of the planning horizon cannot be made zero.

Table 24 shows the number of units to be shipped and the units in-transit using various transportation modes *j* for all of the product families *n* produced at manufacturing facility $p=1$ for time periods $t=1,...,4$ only. This information is useful as a guideline so that the enhanced material flow strategy is followed in terms of the allocation of inventories throughout the supply chain in a time-phased fashion. For example, for product family $n=2$ in period $t=1$ the schedule of shipments to distribution center $k=1$ is as follows:

- 1,790 units shipped via expedited truck (transportation mode $j=1$),
- 1,860 units shipped via truck (transportation mode $j=2$),
- 2,461 units shipped via rail (transportation mode $j=3$).

The corresponding number of units in transit are 0, 1,860, and 2,461, respectively. Intuitively, one would assume that using the lowest cost transportation mode (rail) would be the reasonable alternative. However, the results here demonstrate that by considering a systems approach, the transportation mode selection may be different from the intuitive selection, which in turn leads to improved overall performance.

Table 25 shows the number of transportation consignments by various transportation modes j, corresponding to the units shipped from manufacturing facility $p=1$ to all distribution centers for periods $t=1,\ldots,15$. For example, in period $t=1$ for shipments to distribution center $k=1$, 12.23 expedited trucks (transportation mode $j=1$), 11.09 trucks (transportation mode $j=2$) and 10.90 boxcars (transportation mode $j=3$) are required. This information is of significance when negotiating transportation rates with carriers in order to take advantage of economies of scale. It is noted that our result may be rounded up to the nearest integer units without significantly affecting the decisions to be made.

Table 26 presents the inventory status and the minimum inventory levels for all product families produced at manufacturing facility $p=1$ at all distribution centers in periods $t=1,\ldots,4$. The data shows how the model is minimizing inventory levels relative to the safety stocks. For example, for product family $n=2$ at distribution center $k=1$, the inventory level is 2,512 units at the end of period $t=1$, which is equal to the minimum allowed decentralized safety stock plus a pre-specified percentage of next week's demand. In some cases, however, it may be seen that initial inventories are high and thus it is not possible to keep future inventories at the minimum. For example, for product family $n=1$ at distribution center $k=3$, the inventory level is 560 units at the end of period $t=1$, which is exceeding the minimum level of 12 by 548 units. In the following period $t=2$ the inventory of 536 units is exceeding the minimum by 518 units. In these cases, it is a normal practice to redistribute the surplus product to other locations where it is urgently needed, however this is a complicated issue that is out of the scope of our thesis.

In conclusion, tables 22-26 show the workforce, production, inventory and safety stock levels, transportation consignments and the units shipped for AG, Inc.'s distribution network under scenario 4. The information's contained in these tables are implicitly connected through the formulation of the model given the fact that each data set is closely related to other data sets following the model's objective function and constraints. For example, the labor allocations shown in table 22 are a function of the hours required because of the production requirements for all product families produced by manufacturing facility $p=1$ given in table 23; this relationship is implicit in constraint set (15) of Chapter 3.

It is emphasized that the figures given by the model are guidelines that should be used in the tactical and operational planning of the production, distribution, transportation, sales and financial areas of the company. The mechanisms by which the tactical and operational planning functions are to be linked, as well as the implementation issues, are left for future research given the implicit vastness of the topics.

Table 22. Labor resource allocation for manufacturing facility $p=1$, in hours

	Period, t															
Variable	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**Total**
Regular labor, W_{pt} (hrs/wk)	35,000	35,000	33,980	33,980	33,980	33,980	33,980	33,980	24,666	24,666	24,666	24,666	24,666	24,666	24,666	**446,542**
Layoff, W_{pt}^- (hrs/wk)	0	0	1,019	0	0	0	0	0	9,313	0	0	0	0	0	0	**10332**
Hiring, W_{pt}^+ (hrs/wk)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**
Reduced hrs, f_{pt}^- (hrs/wk)	0	0	0	0	0	0	0	0	0	0	0	3,351	14,050	22,573	24,666	**64640**
Additional hrs, f_{pt}^+ (hrs/wk)	7,000	7,000	6,796	6,796	6,796	6,796	6,796	6,796	4,933	4,933	0	0	0	0	0	**64640**

Table 23. Inventory I_{pnt}, safety stocks PS_{pn} and production X_{pnt} for product family $n=1,\ldots,5$ at manufacturing facility $p=1$ in period $t=1,\ldots,15$

		Period, *t*														
Product Family, *n*	Variable	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	I_{pnt}	311	311	311	311	311	311	311	311	311	311	311	311	311	311	258
	PS_{pn}	311	311	311	311	311	311	311	311	311	311	311	311	311	311	0
	X_{pnt}	357	71	276	232	333	449	307	328	216	160	157	198	30	32	0
2	I_{pnt}	119	75	89	72	97	79	76	87	68	52	54	43	51	0	0
	PS_{pn}	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	X_{pnt}	11,983	7,540	8,963	7,234	9,731	7,999	7,652	8,768	6,844	5,274	5,440	4,350	2,516	0	0
3	I_{pnt}	14	43	28	25	29	36	32	29	19	18	15	15	292	0	0
	PS_{pn}	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	X_{pnt}	1,419	4,390	2,876	2,575	2,904	3,668	3,203	2,924	1,984	1,859	1,584	1,552	742	0	0
4	I_{pnt}	1,909	1,909	1,909	2,155	2,126	2,136	1,909	1,909	1,909	1,909	1,909	1,909	1,909	1,909	1,315
	PS_{pn}	1,909	1,909	1,909	1,909	1,909	1,909	1,909	1,909	1,909	1,909	1,909	1,909	1,909	1,909	0
	X_{pnt}	1,998	5,428	3,810	3,394	3,594	4,618	4,059	3,573	1,566	3,733	2,071	1,980	426	366	0
5	I_{pnt}	935	935	935	935	935	935	935	935	935	935	935	935	935	935	774
	PS_{pn}	935	935	935	935	935	935	935	935	935	935	935	935	935	935	0
	X_{pnt}	1,338	463	1,075	3,217	504	554	1,773	1,370	1,531	1,285	949	795	616	424	0

Table 24. Units shipped Y_{pnjkt} and in-transit inventory IT_{pnjkt} for product families $n=1,\ldots,5$ from manufacturing facility $p=1$ to distribution center $k=1,\ldots,8$ in periods $t=1,\ldots,4$

			Transportation Mode, j															
			1 (expedited truck)					2 (truck)								3 (rail)	
			Distribution Center, k					Distribution Center, k								Distribution Center, k	
Product Family, n	Period, t	Variable	1	2	5	6	8	1	2	3	4	5	6	7	8	1	8
1	1	Y_{pnjkt}	0	0	0	0	0	0	0	0	0	0	0	0	46	0	0
		IT_{pnjkt}	0	0	0	0	0	0	0	0	0	0	0	0	46	0	0
	2	Y_{pnjkt}	0	0	0	0	0	0	0	0	0	0	0	0	72	0	0
		IT_{pnjkt}	0	0	0	0	0	0	0	0	0	0	0	0	72	0	0
	3	Y_{pnjkt}	0	0	0	0	0	0	1	0	0	0	0	3	96	93	82
		IT_{pnjkt}	0	0	0	0	0	0	1	0	0	0	0	0	96	93	82
	4	Y_{pnjkt}	0	0	0	0	0	0	2	0	0	0	0	21	0	138	70
		IT_{pnjkt}	0	0	0	0	0	0	2	0	0	0	0	0	0	232	152
2	1	Y_{pnjkt}	1,790	43	138	0	2,215	1,860	12	3,162	50	87	0	396	307	2,461	0
		IT_{pnjkt}	0	0	0	0	0	1,860	12	0	0	87	0	0	307	2,461	0
	2	Y_{pnjkt}	0	0	0	0	1,170	0	15	817	23	115	0	205	1,956	3,282	0
		IT_{pnjkt}	0	0	0	0	0	0	15	0	0	115	0	0	1,956	5,743	0
	3	Y_{pnjkt}	0	0	0	0	0	0	20	1,081	30	153	0	272	2,607	2,886	1,898
		IT_{pnjkt}	0	0	0	0	0	0	20	0	0	153	0	0	2,607	6,168	1,898
	4	Y_{pnjkt}	0	0	0	0	0	0	13	1,441	39	146	0	363	314	3,068	1,864
		IT_{pnjkt}	0	0	0	0	0	0	13	0	0	146	0	0	314	5,954	3,762
3	1	Y_{pnjkt}	688	0	0	580	217	0	0	216	0	0	0	0	0	0	0
		IT_{pnjkt}	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	2	Y_{pnjkt}	796	0	0	214	193	1,054	0	319	0	0	378	0	0	1,405	0
		IT_{pnjkt}	0	0	0	0	0	1,054	0	0	0	0	378	0	0	1,405	0
	3	Y_{pnjkt}	0	0	0	283	255	0	0	422	0	11	319	14	340	1,243	0
		IT_{pnjkt}	0	0	0	0	0	0	0	0	0	11	697	0	340	2,649	0
	4	Y_{pnjkt}	0	0	0	0	0	0	0	563	0	19	266	38	294	1,139	258
		IT_{pnjkt}	0	0	0	0	0	0	0	0	0	19	585	0	294	2,383	258

Table 24 (continued)

			Transportation Mode, j														
			1 (expedited truck)					2 (truck)								3 (rail)	
			Distribution Center, k					Distribution Center, k								Distribution Center, k	
Product Family, n	**Period, t**	**Variable**	**1**	**2**	**5**	**6**	**8**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**1**	**8**
4	**1**	Y_{pnjkt}	231	0	0	0	9	0	0	89	0	0	0	0	0	0	0
		IT_{pnjkt}	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	2	Y_{pnjkt}	1,281	0	0	1	217	1,695	0	387	0	0	82	0	0	1,763	0
		IT_{pnjkt}	0	0	0	0	0	1,695	0	0	0	0	82	0	0	1,763	0
	3	Y_{pnjkt}	0	0	0	62	287	496	0	513	0	1	75	28	382	1,965	0
		IT_{pnjkt}	0	0	0	0	0	496	0	0	0	1	158	0	382	3,728	0
	4	Y_{pnjkt}	0	0	0	0	0	0	0	683	0	24	74	43	320	1,741	262
		IT_{pnjkt}	0	0	0	0	0	0	0	0	0	24	149	0	320	3,706	262
5	**1**	Y_{pnjkt}	0	0	11	0	0	173	0	0	0	14	0	0	0	281	0
		IT_{pnjkt}	0	0	0	0	0	173	0	0	0	14	0	0	0	281	0
	2	Y_{pnjkt}	0	0	0	0	0	0	0	0	0	18	0	50	20	374	0
		IT_{pnjkt}	0	0	0	0	0	0	0	0	0	18	0	0	20	655	0
	3	Y_{pnjkt}	0	0	0	0	0	0	0	118	0	24	0	68	262	369	233
		IT_{pnjkt}	0	0	0	0	0	0	0	0	0	24	0	0	262	743	233
	4	Y_{pnjkt}	0	0	0	0	0	0	0	420	0	66	0	91	0	1,721	918
		IT_{pnjkt}	0	0	0	0	0	0	0	0	0	66	0	0	0	2,090	1,151

Table 25. Transportation consignments TU_{pjkt} assigned for mode $j=1,\ldots,3$ shipments from manufacturing facility $p=1$ to distribution center $k=1,\ldots,8$ in period $t=1,\ldots,15$

Period, t	Distribution Center, k																							
	1			2			3			4			5			6			7			8		
	Transportation Mode, j			Transportation Mode, j			Transportation Mode, j			Transportation Mode, j			Transportation Mode, j			Transportation Mode, j			Transportation Mode, j			Transportation Mode, j		
	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
1	12.23	11.09	10.90	0.22	0.06	0	0	17.03	0	0	0.26	0	0.81	0.58	0	2.02	0	0	0	2.00	0	11.97	1.78	0
2	7.22	9.55	22.44	0	0.08	0	0	6.58	0	0	0.12	0	0	0.76	0	0.75	1.60	0	0	1.54	0	7.33	10.44	0
3	0	1.73	21.40	0	0.11	0	0	9.86	0	0	0.15	0	0	1.06	0	1.20	1.37	0	0	2.21	0	1.88	18.73	8.82
4	0	0	30.93	0	0.08	0	0	15.72	0	0	0.20	0	0	1.54	0	0	1.18	0	0	3.12	0	0	3.73	14.77
5	0	0	29.93	0	0.03	0	0	14.37	0	0	0.19	0	0	1.04	0	0	1.65	0	0	3.14	0	0	0	11.63
6	0	0	24.35	0	0.07	0	0	13.99	0	0	0.17	0	0	1.53	0	0	2.19	0	0	3.56	0	0	0	15.43
7	0	0	34.68	0	0.11	0	0	19.59	0	0	0.27	0	0	2.37	0	0	1.98	0	0	4.97	0	0	0	4.34
8	0	0	21.59	0	0.15	0	0	25.99	0	0	0.41	0	0	2.09	0	0	1.17	0	0	6.59	0	0	15.42	0
9	0	0	11.71	0	0.15	0	0	26.81	0	0	0.38	0	0	1.14	0	0	0.82	0	0	5.12	0	1.19	11.22	0
10	0	4.75	12.96	0	0.10	0	0	19.36	0	0	0.23	0	0.04	0.83	0	0	0.70	0	0	2.11	0	1.76	9.09	1.82
11	0	0	15.12	0	0.09	0	0	13.55	0	0	0.17	0	0	0.72	0	0	0.85	0	0	1.49	0	0	5.27	5.09
12	0	0	13.02	0	0.10	0	0	11.62	0	0	0.15	0	0	0.83	0	0	0.96	0	0	1.27	0	0	2.00	5.77
13	0	0	0.00	0	0.07	0	0	18.49	0	0	0.30	0	0	0.76	0	0	0	0	0	2.34	0	0	0	0
14	0	0	0.00	0	0.00	0	0	6.13	0	0	0.03	0	0	0.00	0	0	0	0	0	0.71	0	0	0	0
15	1.94	0	0.00	0.01	0.00	0	0	1.06	0	0	0.01	0	0.11	0.00	0	0.05	0	0	0	0.25	0	0.49	0	0

Table 26. Inventory I_{pnkt} and safety stock level $(\lambda D_{pnk(t+1)}+DS_{pnk})^*$ at distribution center $k=1,\ldots,8$ for product family $n=1,\ldots,5$ produced at manufacturing facility $p=1$

Product Family, *n*	Period, *t*	Variable	Distribution Center, *k*								Safety Stock Policy
			1	2	3	4	5	6	7	8	
1	1	I_{pnkt}	520	5	560	9	99	110	31	31	Centralized
		$\lambda D_{pnk(t+1)}+DS_{pnk}$	42	1	12	1	6	0	5	23	
	2	I_{pnkt}	436	4	536	7	87	110	21	32	
		$\lambda D_{pnk(t+1)}+DS_{pnk}$	60	1	18	1	9	0	8	32	
	3	I_{pnkt}	316	2	501	5	70	110	9	40	
		$\lambda D_{pnk(t+1)}+DS_{pnk}$	75	1	22	2	11	0	9	40	
	4	I_{pnkt}	167	1	458	2	49	110	12	56	
		$\lambda D_{pnk(t+1)}+DS_{pnk}$	105	2	30	2	15	0	13	56	
2	1	I_{pnkt}	2512	44	4048	91	304	623	509	2794	Decentralized
		$\lambda D_{pnk(t+1)}+DS_{pnk}$	2512	44	4048	91	304	48	509	2794	
	2	I_{pnkt}	2840	46	4192	95	319	594	545	3055	
		$\lambda D_{pnk(t+1)}+DS_{pnk}$	2840	46	4192	95	319	54	545	3055	
	3	I_{pnkt}	3113	47	4312	98	332	553	575	3272	
		$\lambda D_{pnk(t+1)}+DS_{pnk}$	3113	47	4312	98	332	59	575	3272	
	4	I_{pnkt}	3660	51	4552	105	357	502	636	3706	
		$\lambda D_{pnk(t+1)}+DS_{pnk}$	3660	51	4552	105	357	69	636	3706	
3	1	I_{pnkt}	879	2	879	83	70	598	108	455	Decentralized
		$\lambda D_{pnk(t+1)}+DS_{pnk}$	879	0	879	27	34	598	71	455	
	2	I_{pnkt}	1019	2	935	77	60	636	90	489	
		$\lambda D_{pnk(t+1)}+DS_{pnk}$	1019	0	935	28	36	636	75	489	
	3	I_{pnkt}	1136	2	982	69	46	667	78	517	
		$\lambda D_{pnk(t+1)}+DS_{pnk}$	1136	0	982	29	38	667	78	517	
	4	I_{pnkt}	1371	2	1076	59	40	730	84	574	
		$\lambda D_{pnk(t+1)}+DS_{pnk}$	1371	0	1076	31	40	730	84	574	
4	1	I_{pnkt}	527	24	159	28	52	65	39	89	Centralized
		$\lambda D_{pnk(t+1)}+DS_{pnk}$	527	1	159	2	5	20	10	89	
	2	I_{pnkt}	753	23	228	24	42	27	19	127	
		$\lambda D_{pnk(t+1)}+DS_{pnk}$	753	1	228	3	7	27	15	127	
	3	I_{pnkt}	942	21	285	18	28	34	18	159	
		$\lambda D_{pnk(t+1)}+DS_{pnk}$	942	1	285	4	9	34	18	159	
	4	I_{pnkt}	1318	19	398	11	12	48	25	223	
		$\lambda D_{pnk(t+1)}+DS_{pnk}$	1318	2	398	5	12	48	25	223	
5	1	I_{pnkt}	127	7	533	19	6	119	23	387	Centralized
		$\lambda D_{pnk(t+1)}+DS_{pnk}$	88	0	98	1	6	1	22	62	
	2	I_{pnkt}	125	7	337	17	8	117	30	264	
		$\lambda D_{pnk(t+1)}+DS_{pnk}$	125	0	140	2	8	2	30	88	
	3	I_{pnkt}	156	7	175	14	10	114	38	109	
		$\lambda D_{pnk(t+1)}+DS_{pnk}$	156	0	175	2	10	2	38	109	
	4	I_{pnkt}	218	7	245	11	14	110	53	153	
		$\lambda D_{pnk(t+1)}+DS_{pnk}$	219	0	245	2	14	3	53	153	

* Pre-specified percentage of next weeks demand $\lambda D_{pnk(t+1)}$ + decentralized safety stocks DS_{pnk}

CHAPTER 5. SENSITIVITY ANALYSIS

The study of the model's sensitivity is divided into two sections: First, several tests were conducted with the objective of further investigating the impact of such parameters and variables as timeliness, periodic-review policy and risk pooling, independently. Second, we conduct a series of runs in which variations to parameters such as labor costs and lead-times were studied; these parameters were chosen based on the consideration of which one contained more uncertainty, or which one was likely to change because of the volatile Mexican market. The objective of this study was to further evaluate the system's behavior regarding the allocation of information resources under different circumstances.

5.1 Sensitivity of the Model to Changes in the Information Parameters

For this analysis, scenarios 3 and 4, as described in Chapter 4, were used and the appropriate initial values were supplied to the model in order to independently evaluate the following parameters/decision variables: information timeliness, periodic-review policy and risk pooling. Additionally, rather than comparing the total costs to evaluate the model's sensitivity, we use the convention of comparing the estimated profit, which is calculated by subtracting, in each case, the objective function value from the estimated total revenue, which for AG, Inc. is approximately \$184,373,060[†] for the planning horizon considered. Using the net profit as a measure helps us rescale, in a valid way, the effects that each information parameter has on the model. In this manner, we were able to isolate the impact and value of each information parameter within the total supply chain, complementing some of the observations made previously in the case study.

Initially, 6 additional runs were performed in order to compare the current status of the system with that which is attained under optimal levels of the information parameters. These runs, along with scenarios 3 and 4 are shown in Table 27. The logic behind the generation of this table was to fix the three information-related parameters (inventory review policy, information timeliness and safety stock policy) at two levels each, and run the model for all possible combinations (2^3=8). The two levels of information were called current (related to the settings in scenario 3) and optimal (relative to the settings of scenario 4) for the inventory review policy and information timeliness, and decentralized (scenario 3) and centralized (scenario 4) for the safety stock policy. For example, in terms of the inventory review policy, "current" refers to a cycle length of TP_{pi}=.25 ($\forall p=1\ldots7$ & $i=2$) and "optimal" to TP_{pi}=.125 ($\forall p=1\ldots7$ & $i=1$).

[†] The method of calculation is kept confidential due to the proprietary nature of the information.

Table 27. Sensitivity analysis to changes in information parameters

Run #	Inventory Review Policy	Information Timeliness	Safety Stock Policy	Profit	Premium Transportation and Information Cost	Periodic Review Policy Cost	Information Timeliness Cost	Total Information Cost
Scenario. 3	Current	Current	Decentralized	$27,252,403	$0	$49,000	$24,000	$73,000
1	Current	Current	Centralized	$31,056,303	$272,286	$49,000	$24,000	$345,286
2	Current	Optimal	Decentralized	$27,257,191	$0	$49,000	$34,500	$83,500
3	Current	Optimal	Centralized	$31,064,646	$277,636	$49,000	$34,500	$361,136
4	Optimal	Current	Decentralized	$28,678,624	$0	$84,000	$24,000	$108,000
5	Optimal	Current	Centralized	$32,352,694	$252,296	$84,000	$24,000	$360,296
6	Optimal	Optimal	Decentralized	$28,683,378	$0	$84,000	$34,500	$118,500
Scenario. 4	Optimal	Optimal	Centralized	$32,358,840	$256,929	$84,000	$34,500	$375,429

Table 27 shows the profit obtained for each run. It should be noted that the minimum profit (MP) obtained was \$27,252,403 for scenario 3; this quantity is also used as a reference in our analysis. First, by comparing the profits at the current and optimal levels of the information timeliness parameter (while all others remain constant) we realize the following:

In going from Run 1 to Run 3 the information timeliness parameter changes from "current" to "optimal". The result is a profit increase of only \$8,343 (or 0.03% of MP), which is achieved by investing \$10,500 in IT upgrades. Similarly, going from Run 5 to Scenario 4 results in a profit increase of \$6,145 (or 0.02% of MP) at an investment of \$10,500. These results indicate that information timeliness does not have a significant impact on the profits, and that the return on the information technology investment is unacceptable. As a final confirmation of this finding we run 3 more tests using a different information system *m* for each run. This was based on the assumption that all the plants have the same information system *m*, reflecting to the extent that is possible, the standardization of systems throughout the organization. Table 28 shows the results of the 3 runs.

Table 28. Information system *m* comparison (detail)

Run #	Information System, *m* for all Manufacturing Facilities	Profit	Total Information Timeliness Cost
7	1	\$31,608,102	\$10,000
8	2	\$32,045,779	\$22,000
9	3	\$32,347,838	\$47,000

It is noted that by comparing run 8 versus run 7 we realize that the profit increase opportunity is of $437,678 (1.61% of MP) when investing $12,000 additional dollars in IT to increase timeliness. On the other hand, run 9 versus run 8 results in a $302,059 (1.11% of MP) profit increase with an additional expense of $25,000. In total, the company had a profit increase potential when going from a manual information system to an automated system of $739,736 (2.71% of MP) with an investment of $37,000. From here we may conclude that in the case of AG, Inc. the timeliness systems that are currently being used are appropriate or nearly appropriate because changing to more timely systems would only result in very low savings (less than 0.03% of MP). However, the profit increase potential, relative to the additional disbursement with varying information systems indicate a much higher impact of the information timeliness parameter. We consider this to be an important finding, because if this were not the case, the inclusion of this variable into the model would have not been justified.

Table 29. Inventory review policy comparison

Runs	Profit Increase	% of MP	Information System Expense
5 vs. 1	$1,296,391	4.76%	$35,000
Scenario 4 vs. 3	$1,294,193	4.75%	$35,000

Second, we look at the review cycle length; Table 29 shows two comparisons that can be made when changing the periodic-review policy while all other information variables remain constant. In this realm, by comparing run 5 versus run 1 and scenario 4 versus run 3, we realize that the sensitivity of the model to changes in the periodicity of information is higher (i.e., approximately 4.75% of MP) than that of timeliness.

In order to further evaluate the impact of higher levels of periodicity, and for the sake of completeness of our analysis, we include two more inventory review policies, and their estimated profits and costs (i.e., TP_{p4}=.05 and TP_{p5}=0 corresponding to runs # 10 and 11, respectively). Table 30 denotes the computed profits in each case, as well as the periodic-review policy costs. Table 31 provides a pair-wise comparison among the different levels of periodicity, with all other information parameters set at the optimal level, in order to isolate the effect of periodicity. It is observed that additional profits could indeed be obtained by increasing the periodicity level, however, as we approach 0 (TP_{p5}=0), the marginal profit increase is reduced and the corresponding costs increase, increasing the risk of the investment. For example in going, from a periodic-review policy of TP_{p3}=.125 (Sc. 4) to TP_{p4}=.05 (run 10) we would invest $91,000 for a return of $1,086,446, whereas in going from TP_{p4}=.05 to TP_{p5}=0 the return would reduce to $616,774 with an investment of $175,000. Similarly, the marginal profit increase from run 3 to run 11 would be $2,997,308 for a $301,000 dollar investment.

Table 30. Review policy comparison (detail)

Run #	Periodic-review policy, *i* for all Manufacturing Facilities	Profit	Periodic-review policy Cost
3	0.25	$31,064,752	$49,000
Sc. 4	0.125	$32,358,840	$84,000
10	0.05	$33,445,286	$175,000*
11	0	$34,062,060	$350,000*

* New costs that have been assumed

Table 31. Review policy pair-wise comparison

Runs	Profit Increase	Information System Expense
Sc. 4-3	$1,294,088	$35,000
10-Sc. 4	$1,086,446	$91,000
11-10	$616,774	$175,000
11-3	$2,997,308	$301,000

Finally, we evaluate the application of the safety stock policy by noting the following in Table 27:

- Run 1 versus scenario 3 indicates a profit increase of $3,803,899 (13.96% of MP) when $272,280 additional dollars in premium transportation and information are disbursed.
- Scenario 4 versus run 6 indicates a cost reduction of $3,675,682 (13.49% of MP) in return for a $256,929 additional expense in premium transportation and information.

Therefore, we can conclude that, in the case of AG, Inc., the highest impact on profits is due to the application of risk pooling. However, the risk of this investment is also high given the significant disbursements required to implement this strategy. Considering the results more closely, we realize that the profit improvement is obtained primarily because of the inventory reductions achieved, leading to a reduction in labor, holding, transportation and raw materials costs.

The second highest impact on profits is due to the periodic-review policy, where we see that the expenses are much lower than those in risk pooling, which would make this investment more attractive.

Finally, as it was noted, the effect of timeliness on profits is much smaller, however, under certain conditions the investment may become attractive, considering the low expenses involved in this case.

5.2 Sensitivity of the Model to Changes in Lead-times, Cost and Standard Deviation Parameters

Additional sets of runs were performed to evaluate the impact of lead-times, cost and standard deviation parameters on the behavior of the model. In this case, only scenario 4 was used as the basis for the study in order to fully evaluate the original model as presented in Chapter 3. Lead-times (TLT_{pk}, MLT_{pn} and TP_{pi}), premium transportation and information costs (PTC_{pn}), labor costs (L_p), transportation costs (TC_{pjk}), and standard deviations (σ_{pn} and σ'_{pnk}) were changed within a range of feasible alternatives, given the conditions of the Mexican environment and the probable errors made when computing the values for these parameters. In this case, although the profits were the primary measure of performance of the system, in some instances it was necessary to analyze the cost elements in the objective function in order to gain insight into the underlying mechanisms that govern the allocation of resources. Figure 4 and Figure 5 show the effect of changes in standard deviation, lead-time and cost parameters on the profits.

Figure 4. Profit impact of changes in lead-time and standard deviation parameters

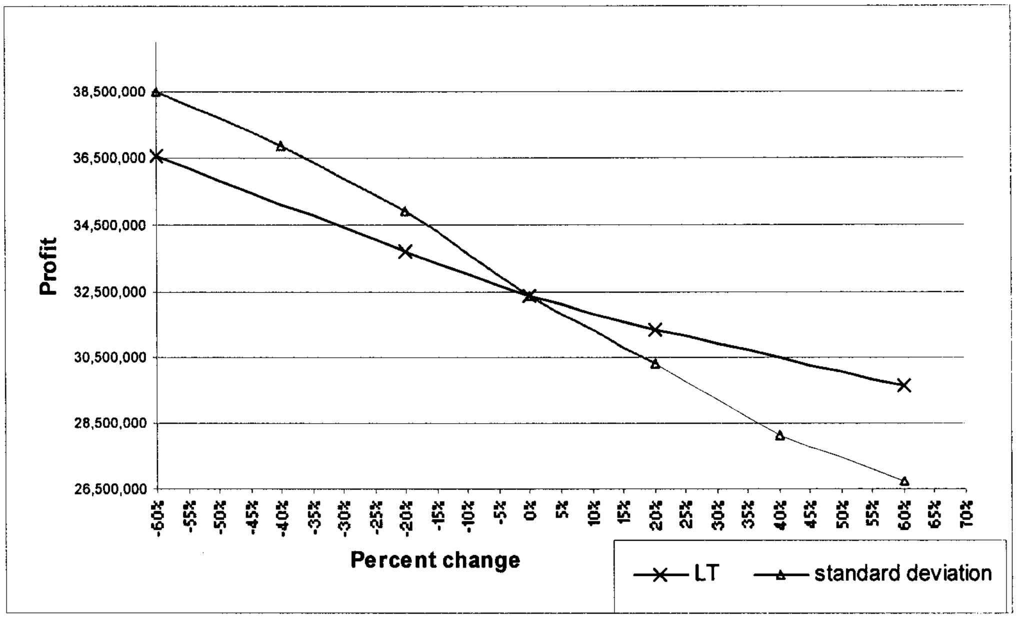
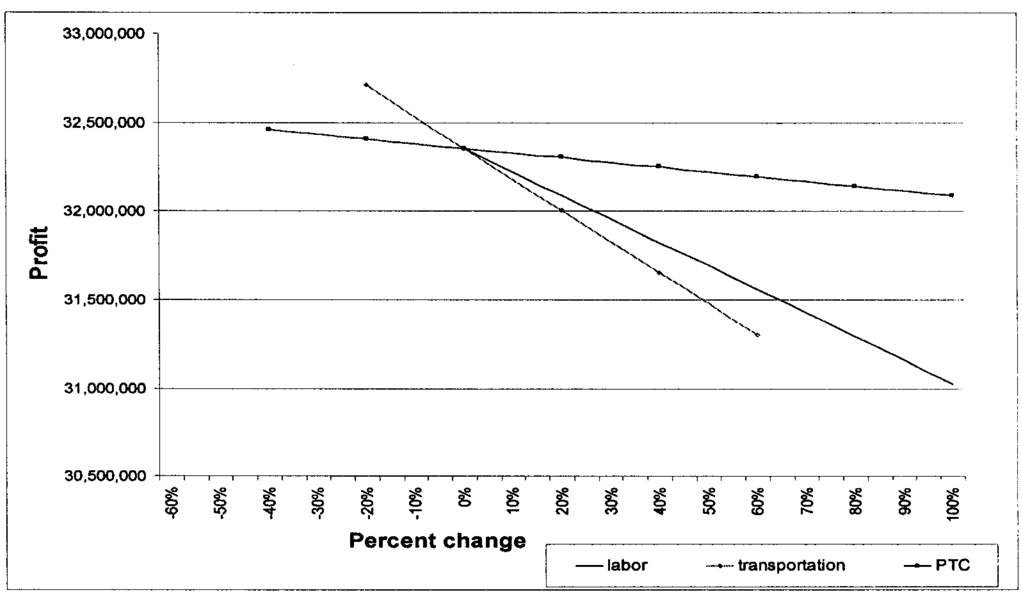


Figure 5. Profit impact for changes in cost parameters



As is apparent, the highest impact results when reducing/increasing standard deviations and lead-times (LT), followed by labor, transportation, and premium transportation cost (PTC). To study the effect of these changes on the optimal solution and information variables, we consider the parameters separately. Our main scope, as discussed previously, is to evaluate the effect of the changes in these parameters on the information variables of premium transportation, timeliness and periodic-review policy.

Table 32. Sensitivity to changes in lead-time

Run #	Percentage of Reduction/increase in Lead-time	Profits
Run 12	-60%	$36,559,038
Run 13	-20%	$33,693,811
Sc. 4	0%	$32,359,060
Run 14	20%	$31,355,885
Run 15	60%	$29,628,060

5.2.1 Effect of Lead-times

In terms of the lead-time, the changes were made to the cycle length (TP_{pi}), standard transportation lead-times (TLT_{pk}) and manufacturing lead-times (MLT_{pn}) ($\forall$ $p=1...P;$ $n=1...N(p);$ $k=1...K;$ $i=1...I(p)$) simultaneously. Table 32 shows the results obtained when increasing/reducing the original case study's lead-times (corresponding to scenario 4) by the percentages shown. The transportation lead-times for each mode (LT_{pjk}) were not considered based on the assumption that their calculations are accurate and unlikely to change. As it can be seen in Figure 4, the resulting graph is non linear, suggesting a change in the allocation of resources. This can be further studied by considering Table 33 where the individual cost elements are shown. Specifically, we are interested in changes in the premium transportation and information, and timeliness costs.

In terms of timeliness, it is interesting that the model is indeed changing the selection of the systems when lead-times are varied. From Table 34 it is noted that in going from run 12 to run 13 two changes occur: plant $p=3$ with system $m=3$ and plant $p=5$ with system $m=1$ change to systems $m=2$ and $m=2$, respectively. This results in a cost reduction of $2,000 for timeliness. Additionally, in going from minus 20% to 0% lead-time reduction, there is an increase of $5,000, which is caused by the change in system $m=2$ to $m=3$ at manufacturing facility $p=3$. These subtle changes reinforce the previous finding of low sensitivity in the timeliness variables, however, the fact denotes the need to monitor and evaluate their effect if changes in lead-times should arise.

In terms of premium transportation and information costs, the difference is much more significant among the different runs, as shown in Table 33. For example, in going from run 12 to run 15, the difference in premium transportation and information cost is of $64,376.30 ($298,274.90-$233,898.60). Although intuitively we know that the safety stocks increase as lead-times increase, it is necessary to study the model's behavior in detail. Table 35 shows the safety stock allocation for the set of runs in Table 33 in which it is noted that 45% of the 27 families had at least one change in the safety stock allocation policy when lead-times changed from –60% to +60%.

Table 33. Cost elements for sensitivity to changes in lead-times

	Percentage of Reduction/increase in Lead-time				
Category	-60% (Run 12) Cost	-20% (Run 13) Cost	0% (Sc.4) Cost	+20% (Run 14) Cost	+60% (Run 15) Cost
Labor	$1,302,100.00	$1,323,982.00	$1,333,932.00	$1,342,501.00	$1,356,329.00
Increasing labor	$1,494.87	$1,590.45	$1,590.45	$1,992.81	$1,622.86
Reducing labor	$345,430.10	$335,328.70	$328,813.80	$326,578.70	$317,588.80
Refreshment	$51,634.34	$52,541.21	$53,563.48	$54,166.72	$54,882.00
Transportation	$1,693,128.00	$1,746,906.00	$1,774,075.00	$1,796,354.00	$1,844,583.00
Manufacturing facility inventory	$246,806.00	$264,367.90	$266,026.70	$275,853.40	$289,933.70
In-transit inventory	$205,661.40	$203,566.60	$202,481.20	$200,743.70	$194,513.70
Distribution center inventory	$947,078.00	$1,115,867.00	$1,180,909.00	$1,245,268.00	$1,323,365.00
Overtime	$0.00	$0.00	$0.00	$0.00	$0.00
Premium transportation and information	$233,989.60	$263,599.20	$256,929.10	$268,117.40	$298,274.90
Periodic-review policy	$84,000.00	$84,000.00	$84,000.00	$84,000.00	$84,000.00
Timeliness	$31,500.00	$29,500.00	$34,500.00	$31,500.00	$31,500.01
Raw materials	$142,671,200.00	$145,258,000.00	$146,497,400.00	$147,390,100.00	$148,947,900.00
Total	**$147,814,022.31**	**$150,679,249.06**	**$152,014,220.73**	**$153,017,175.73**	**$154,744,492.97**

Table 34. Sensitivity of timeliness to changes in lead-times (detail)

	Percentage of Reduction in Lead-time								
	-60% (run 12)			-20% (run 13)			0% (Sc. 4)		
Manufacturing Facility, p	Information System, m	Timeliness Factor, γ_{pm}	Information System Cost, CI_{pm} (\$/15-weeks)	Information System, m	Timeliness Factor, γ_{pm}	Information System Cost, CI_{pm} (\$/15-weeks)	Information System, m	Timeliness Factor, γ_{pm}	Information System Cost, CI_{pm} (\$/15-weeks)
1	3	0.99	\$10,000	3	0.99	\$10,000	3	0.99	\$10,000
2	1	0.8	\$1,000	1	0.8	\$1,000	1	0.8	\$1,000
3	3	0.99	\$7,000	2	0.95	\$2,000	3	0.99	\$7,000
4	3	0.99	\$5,000	3	0.99	\$5,000	3	0.99	\$5,000
5	1	0.85	\$4,000	2	0.95	\$7,000	2	0.95	\$7,000
6	3	0.98	\$3,500	3	0.98	\$3,500	3	0.98	\$3,500
7	1	0.8	\$1,000	1	0.8	\$1,000	1	0.8	\$1,000
			\$31,500			\$29,500			\$34,500

Table 34 (continued)

	Percentage of Increase in Lead-time					
	+20% (run 14)			+60% (run 15)		
Manufacturing Facility, *p*	**Information System, *m***	**Timeliness Factor, γ_{pm}**	**Information System Cost, CI_{pm}** ($/15-weeks)	**Information System, *m***	**Timeliness Factor, γ_{pm}**	**Information System Cost, CI_{pm}** ($/15-weeks)
1	3	0.99	$10,000	3	0.99	$10,000
2	1	0.8	$1,000	1	0.8	$1,000
3	3	0.99	$7,000	3	0.99	$7,000
4	2	0.95	$2,000	2	0.95	$2,000
5	2	0.95	$7,000	2	0.95	$7,000
6	3	0.98	$3,500	3	0.98	$3,500
7	1	0.8	$1,000	1	0.8	$1,000
			$31,500			$31,500

Table 35. Safety stock allocation given by RP_{np}^{*} for different lead-time levels

Product Family, *n*	Manufacturing Facility, *p*	Percentage of Reduction/increase in Lead-time -60% (run 12)	-20% (run 13)	0% (Sc. 4)	+20% (run 14)	+60% (run 15)	
1	1	0	1	1	1	1	change
2	1	1	0	0	0	0	change
3	1	0	0	0	1	1	change
4	1	0	1	1	0	0	change
5	1	1	1	1	1	1	
1	2	1	1	1	1	1	
1	3	1	1	1	1	1	
2	3	0	1	1	1	1	change
3	3	1	0	0	0	0	change
4	3	1	1	1	1	1	
5	3	0	1	0	0	0	change
6	3	0	1	1	0	0	change
7	3	0	1	1	1	0	change
1	4	0	0	0	0	0	
1	5	1	1	0	0	0	change
2	5	1	0	1	1	1	change
3	5	1	0	1	1	1	change
4	5	1	1	1	1	1	
1	6	0	0	0	0	0	
2	6	1	1	1	1	1	
1	7	0	0	0	0	0	
2	7	1	1	1	1	1	
3	7	1	1	1	1	1	
4	7	1	1	1	1	1	
5	7	1	1	1	1	1	
6	7	1	1	1	1	1	
7	7	1	1	1	1	1	
		17	19	19	18	17	

* $RP_{np} = 1$ if a centralized safety stock policy is applied, 0 otherwise

In order to explain the underlying phenomenon and given the amount of information generated we first consider Figure 6, which summarizes the warehouse capacity usages at each manufacturing facility *p,* computed for run 12 which corresponds to a –60% reduction in the original lead-time. It may be seen that manufacturing facilities $p=2$ and $p=7$ are under utilizing warehouse capacity throughout the planning horizon, which provides an insight into why there are no changes in the allocation of safety stocks in these two plants as lead-times change. In both plants the excess of warehouse capacity is enough to cover the space requirement needed to centralize all product families. That is, as lead-times change, there is enough space for the safety stocks to remain centralized, which is the most profitable policy in this case. Additionally, from Table 35 we note that at manufacturing facility $p=4$ the decentralized policy does not change as lead-times change. In this case, this manufacturing facility has only 400 units of warehouse capacity, which is not enough for a centralized policy.

In order to further study the behavior of safety stocks, we select manufacturing facility $p=3$, which shows the largest number of changes in the allocation of safety stocks. From Table 36 it is possible to appreciate the sensitivity of the safety stock policy selection. For example, at a lead-time reduction of –60%, the model has chosen a centralized policy for product families $n=1$, $n=3$ and $n=4$, adding up to a total safety stock in the manufacturing facility of 4,380, which is constrained by the total capacity of 4,500 units. At –20% reduction, the system centralized product families $n=1$, $n=2$, $n=4$, $n=5$, $n=6$ and $n=7$, adding up to a total safety stock of 4,150 in the manufacturing facility, which is also constrained by the maximum capacity.

Figure 6. Manufacturing facility *p* warehouse capacity usage for run 12

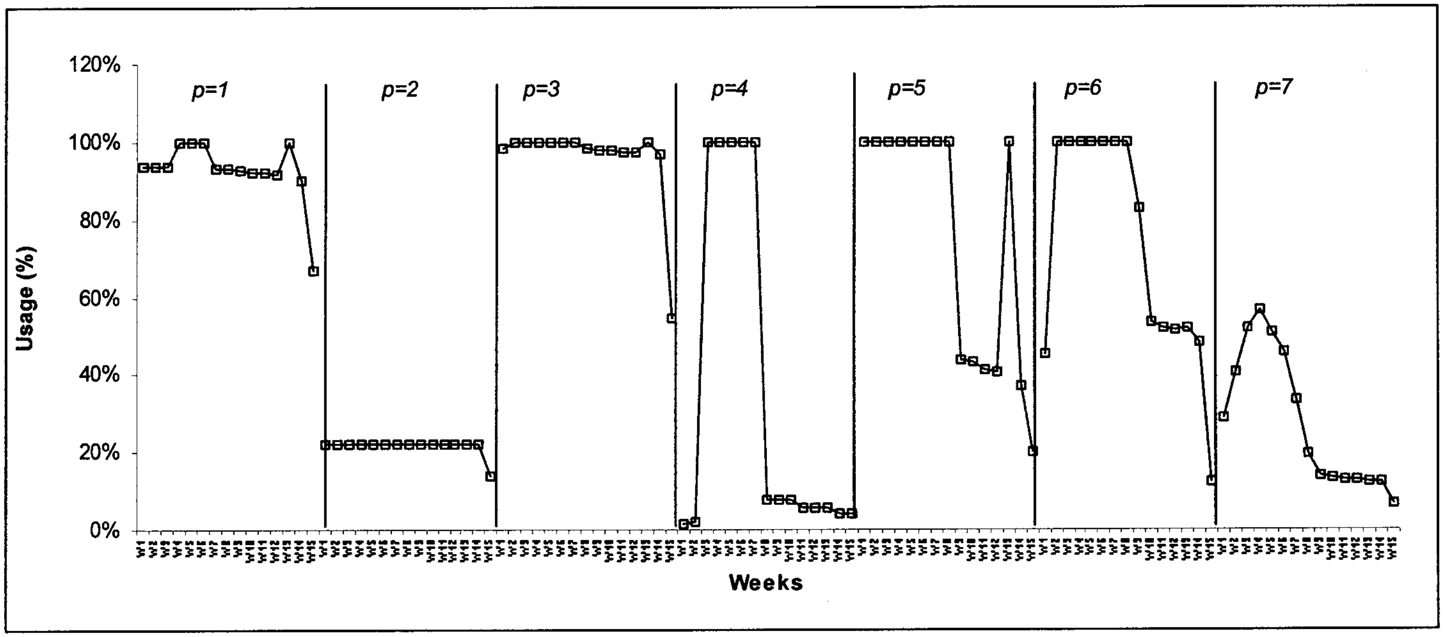


Table 36. Safety stock allocation at manufacturing facility $p=3$ with respect to changes in the lead-time

Product Family, n	Percentage of Reduction/increase in Lead-time									
	-60% (run 12)		-20% (Run 13)		0% (Sc.4)		+20% (Run 14)		+60% (Run 15)	
	PS_{pn} ‡	$\sum_{k=1}^{K} DS_{pnk}$ §	PS_{pn}	$\sum_{k=1}^{K} DS_{pnk}$	PS_{pn}	$\sum_{k=1}^{K} DS_{pnk}$	PS_{pn}	$\sum_{k=1}^{K} DS_{pnk}$	PS_{pn}	$\sum_{k=1}^{K} DS_{pnk}$
1	897	0	1,269	0	1,419	0	1,555	0	1,795	0
2	0	385	393	0	440	0	482	0	556	0
3	2,546	0	0	4,636	0	5,182	0	5,678	0	6,556
4	937	0	1,325	0	1,481	0	1,622	0	1,874	0
5	0	210	254	0	0	332	0	363	0	420
6	0	346	376	0	421	0	0	599	0	692
7	0	461	533	0	596	0	653	0	0	923
Total	**4,380**	**1,402**	**4,150**	**4,636**	**4,357**	**5,513**	**4,312**	**6,640**	**4,225**	**8,591**

‡ Centralized safety stock for product family $n=1,\ldots 7$ produced at manufacturing facility $p=3$

§ Aggregate decentralized safety stock for product family $n=1,\ldots,7$ produced at manufacturing facility $p=3$ over all distribution centers

Our analysis leads us to the conclusion that the sensitivity of the model to changes in lead-times is mainly due to the changes in the allocation and levels of safety stock, which protect against uncertainty during the lead-time. It is important to note that changes in lead-times should be closely monitored and controlled in order to minimize variation; however, in some cases, this is not possible. This is why, at the operational level, it is necessary to coordinate with all the supply chain areas any such changes in lead-time. For example, under the premise that inventory levels will change, it would be necessary to closely monitor and control the location of products in the warehouses under a flexible scheme (see Dominguez et al., 2001).

5.2.2 Effects of Costs

In terms of costs, several additional runs were carried out by changing a particular cost parameter by a given percentage while keeping all other parameters constant. For the range of values considered in our study, Figure 5 indicates that the graphs are linear, denoting that other than the increases/reductions in the respective costs, one should not expect significant changes in the allocation of resources.

The labor costs were varied in a range from 0 to 100 percent, emulating the probable range of changes in cost that could occur over the planning horizon studied. The runs and their cost elements are shown in Table 37.

Table 37. Sensitivity to changes in labor cost

	Percentage of Reduction/increase in Labor cost				
Category	0% (Sc. 4) Cost	+25% (Run 16) Cost	+50% (Run 17) Cost	+75% (Run 18) Cost	+100% (Run 19) Cost
Labor	$1,333,932.00	$1,667,415.00	$2,000,887.00	$2,334,363.00	$2,667,844.00
Increasing labor	$1,590.45	$1,590.45	$1,590.45	$1,590.45	$1,590.45
Reducing labor	$328,813.80	$328,813.80	$328,820.00	$328,822.00	$328,822.00
Refreshment	$53,563.48	$53,563.48	$53,563.11	$53,562.99	$53,562.99
Transportation	$1,774,075.00	$1,774,075.00	$1,774,076.00	$1,774,076.00	$1,774,076.00
Manufacturing facility inventory	$266,026.70	$266,026.70	$266,108.00	$266,163.80	$266,163.80
In-transit inventory	$202,481.20	$202,481.20	$202,480.90	$202,480.80	$202,480.80
Distribution center inventory	$1,180,909.00	$1,180,909.00	$1,182,455.00	$1,182,943.00	$1,182,943.00
Overtime	$0.00	$0.00	$0.00	$0.00	$0.00
Premium transportation and information	$256,929.10	$256,929.10	$256,929.10	$256,929.10	$256,929.10
Periodic-review policy	$84,000.00	$84,000.00	$84,000.00	$84,000.00	$84,000.00
Timeliness	$34,500.00	$34,500.00	$34,500.00	$34,500.00	$34,500.00
Raw materials	$146,497,400.00	$146,497,400.00	$146,495,800.00	$146,495,200.00	$146,495,200.00
Total	**$152,014,220.73**	**$152,347,703.73**	**$152,681,209.56**	**$153,014,631.14**	**$153,348,112.14**

As is observed, the premium transportation and information, periodic-review policy, timeliness and most of the cost elements show no significant change throughout the analysis. Labor costs, however, change significantly, proving our preliminary conclusion. Similar observations were found for the transportation and premium transportation and information cost parameters. To avoid repetitiveness, the runs and results are provided in appendix VI.

For the premium transportation and information cost, additional runs were performed in order to search for a threshold at which the premium transportation cost is such that it is no longer attractive to centralize safety stocks. These runs are also shown in appendix VI. It was surprising to see that even for an increase of +200% to the original premium transportation cost, the safety stock allocations did not change. However, one must remember that essentially through the application of postponement it is possible to reduce the average inventory (i.e., safety stock), therefore only very high, unrealistic increases in the premium transportation cost would offset the amount of savings generated by reducing this inventory.

The above findings indicate that the model is robust, a desirable characteristic given its tactical nature and the volatility of costs in the Mexican market. Had the model been found sensitive to these parameters, plans would have to be modified constantly, increasing the perceived variability, and making the model less useful, or even impractical, for managing the supply chain.

5.2.3 Effects of Standard Deviation of the Forecast Error

Due to the changing nature of the standard deviation of the forecast error, it was necessary to investigate the effects of changes in this parameter. Eight additional runs were performed and compared by simultaneously changing σ_{pn} and σ'_{pnk} for all of the product families ($\forall p=1...P;\ n=1...N(p)$). Table 38 shows the cost elements and the increase in profits relative to scenario 4 for the set of runs when the standard deviation of the forecast error changes from –100% to +60% of the original standard deviation. This range is not very realistic in the sense that large negative values are related to perfect information of forecasts, which is ideal. The range chosen is considered in order to quantify the upper bound (value) of perfect information. A range of –60 to +60 percent is deemed more achievable and realistic. Murray (1996) shows that by entering into more information-intensive relationships with customers, it is possible to eliminate the perceived variation (variance) with some key customers. In our case, we are conservatively assuming that there is always a source of uncertainty, which can be reduced but not eliminated. As may be noted, the value of perfect forecasts (0 variance) is estimated to be \$7,191,714.17, which is the maximum amount that AG, Inc. should be willing to pay for this information. The plot of the corresponding profit changes in Figure 7 shows that the value of improvements in the accuracy of the forecast follows a diminishing-return pattern with respect to scenario 4 (i.e., 0% of change in the standard deviation of the forecast error). This means that one would expect to have greater returns when embarking upon improved forecasting systems, but once these systems are implemented, further improvements would be less profitable. In Figure 7 it is also noted that as the standard deviation of the forecast error is increased from scenario 4, the amount of marginal loss in profit is also being reduced. It is important to note, however, that runs 37 and 38 were initially infeasible and it was necessary to slightly modify the model to consider the warehouse capacity constraints as elastic constraints that could be violated at a given linear penalty cost per unit violation. This modification is not shown herein due to space limitations; however, it is worthwhile to note that, in our case, very high penalty values (≥10,000 \$/sq-ft) were given and therefore, the exceeding inventory levels were the minimum required in order to attain feasibility. In summary runs 37 and 38 would be expected to reduce their profits even further, due to storage capacity costs, which were not considered implicitly in the model because of their strategic implication in terms of fixed and variable costs.

As may be observed from Table 38, the periodic-review policy, premium transportation, timeliness and most of the cost elements undergo significant changes in their values. Such changes in cost denote changes in the allocations made by the model. We focus only on those changes related to information parameters in order to gain insight into the factors underlying the model's behavior and to be consistent with the scope of the thesis.

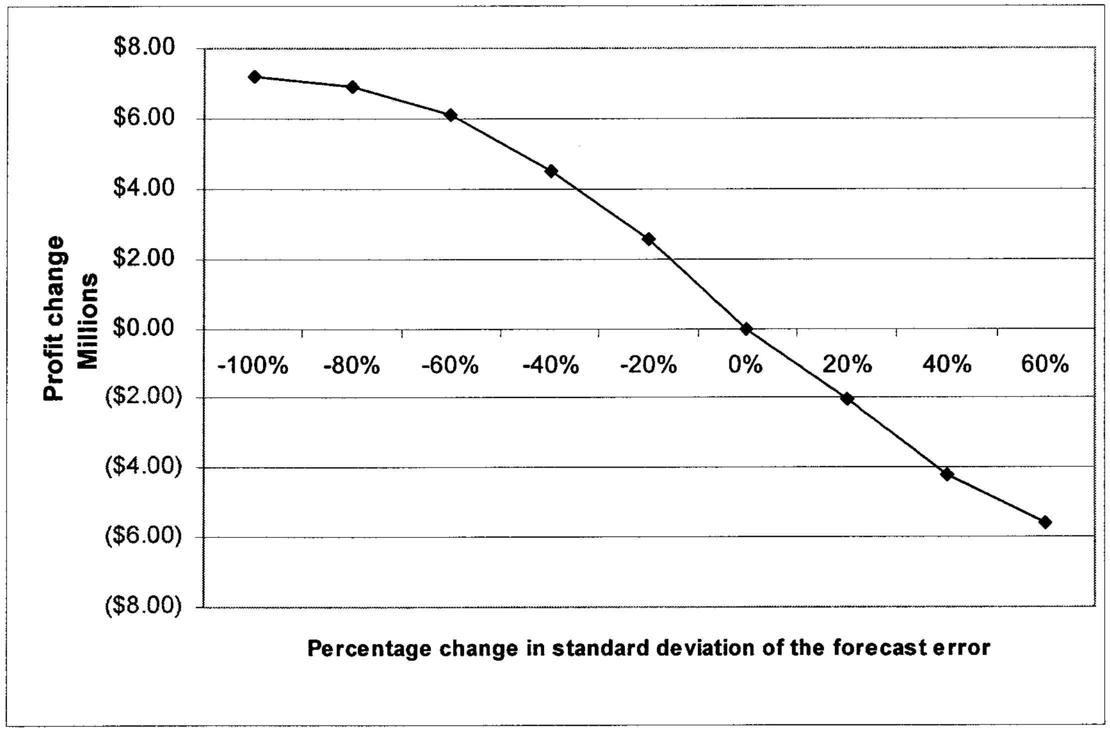
Table 38. Sensitivity to changes in standard deviations of the forecast error

	Percentage of Reduction in Standard Deviations of the Forecast Error				
	-100% (Run 31)	-80% (Run 32)	-60% (run 33)	-40% (Run 34)	-20% (Run 35)
Category	Cost	Cost	Cost	Cost	Cost
Labor	$1,279,960.00	$1,281,057.00	$1,286,876.00	$1,299,627.00	$1,315,201.00
Increasing labor	$2,191.80	$2,189.22	$1,773.62	$1,541.12	$1,553.04
Reducing labor	$336,499.50	$347,242.00	$351,498.80	$346,060.50	$334,838.40
Refreshment	$50,454.56	$50,706.08	$51,030.54	$51,509.80	$52,057.57
Transportation	$1,655,872.00	$1,661,454.00	$1,677,125.00	$1,688,610.00	$1,730,457.00
Manufacturing facility inventory	$154,461.50	$191,375.00	$215,727.90	$240,699.90	$263,432.20
In-transit inventory	$209,564.20	$207,960.80	$205,345.80	$205,659.70	$205,105.50
Distribution center inventory	$815,003.00	$823,463.40	$854,564.20	$937,013.50	$1,052,215.00
Overtime	$0.00	$0.00	$0.00	$0.00	$0.00
Premium transportation and information	$0.00	$96,078.01	$169,937.30	$228,370.30	$243,880.50
Periodic-review policy	$35,000.00	$69,000.00	$84,000.00	$84,000.00	$84,000.00
Timeliness	$34,000.00	$18,000.00	$18,500.00	$31,500.00	$29,500.00
Raw materials	$140,249,500.00	$140,336,000.00	$140,977,200.00	$142,393,900.00	$144,125,600.00
Total	**$144,822,506.56**	**$145,084,525.51**	**$145,893,579.16**	**$147,508,491.82**	**$149,437,840.21**
PROFIT	$39,550,553.74	$39,288,534.79	$38,479,481.15	$36,864,568.48	$34,935,220.09
Increase in profit vs Sc. 4	$7,191,714.17	$6,929,695.22	$6,120,641.57	$4,505,728.91	$2,576,380.52

Table 38 (continued)

	Percentage of Increase in Standard Deviations of the Forecast Error			
	0% (Sc. 4)	20% (Run 36)	40% (Run 37)	60% (Run 38)
Category	Cost	Cost	Cost	Cost
Labor	$1,333,932.00	$1,351,023.00	$1,367,338.00	$1,380,144.00
Increasing labor	$1,590.45	$1,764.88	$1,650.64	$1,650.64
Reducing labor	$328,813.80	$320,807.10	$312,363.90	$303,173.00
Refreshment	$53,563.48	$54,612.23	$55,405.04	$55,995.99
Transportation	$1,774,075.00	$1,825,137.00	$1,873,525.00	$1,896,798.00
Manufacturing facility inventory	$266,026.70	$285,319.60	$300,076.90	$351,366.50
In-transit inventory	$202,481.20	$196,925.00	$192,020.30	$191,727.00
Distribution center inventory	$1,180,909.00	$1,292,014.00	$1,374,135.00	$1,397,221.00
Overtime	$0.00	$0.00	$0.00	$0.00
Premium transportation and information	$256,929.10	$287,070.40	$325,779.40	$388,588.40
Periodic-review policy	$84,000.00	$84,000.00	$84,000.00	$84,000.00
Timeliness	$34,500.00	$31,500.00	$31,500.00	$31,500.00
Raw materials	$146,497,400.00	$148,346,000.00	$150,319,000.00	$151,534,900.00
Total	**$152,014,220.73**	**$154,076,173.21**	**$156,236,794.18**	**$157,617,064.53**
PROFIT	$32,358,839.57	$30,296,887.10	$28,136,266.12	$26,755,995.77
Increase in profit vs Sc. 4	$0.00	($2,061,952.48)	($4,222,573.45)	($5,602,843.80)

Figure 7. Profit impact when increasing/reducing standard deviations relative to scenario 4



In the case of the periodic-review policy, it is noted that changes in the standard deviation are the only ones that cause the periodic-review policy to vary. Table 39 shows the assignments and costs for each run in terms of the periodic-review policy; for reasons of space economy we only display the information up to run 33 given the fact that the remainder of the runs (34-38) have the same periodic-review policy as run 33 and thus the same cost. As is illustrated, the periodic-review policy changed from policy $i=3$ ($\forall p=1...7$) in run 31 to a mixed review policy (i.e., $i=1$ ($\forall p=1,3,5$ & 7) and $i=2$ ($\forall p=2,4$ & 6)) in run 32 and then to review policy $i=1$ ($\forall p=1...7$) in run 33; these changes denote a significant impact on the periodic-review policy, however, in the range of –60% to 60% no changes were detected in the assignment of policies, denoting the fact that the periodic-review policy selection responds to changes but is not overly sensitive.

With further analysis, it is easy to infer that in the case of run 31, the model selects the inventory review policy with lowest periodicity given the fact that no uncertainty is present. As uncertainty is increased, the model makes a trade off between the cost of information (i.e., CP_{pi}) and the cost associated with safety stocks (i.e., raw materials, labor, transportation and holding costs) and chooses the appropriate balance. Our results show that, in general, the cost of information is not significant and therefore high periodicity is chosen.

In summary, the periodic-review policy selection shows a stable behavior, which is beneficial, due to the difficulty to quantify intangible organizational issues when changes in the periodic-review policy are forced.

Table 39. Periodic-review policy assignments for changing levels of the standard deviation parameters

	Percentage of Reduction in Standard Deviations of the Forecast Error								
	-100% (Run 31)			-80% (Run 32)			-60% (run 33)		
Manufacturing Facility, *p*	**Review policy, *i***	**Cycle length, TP_{pi} (months)**	**Periodic review policy cost, CP_{pi}**	**Review policy, *i***	**Cycle length, TP_{pi} (months)**	**Periodic review policy cost, CP_{pi}**	**Review policy, i**	**Cycle length, TP_{pi} (months)**	**Periodic review policy cost, CP_{pi}**
1	3	0.5	$5,000	1	0.125	$12,000	1	0.125	$12,000
2	3	0.5	$5,000	2	0.25	$7,000	1	0.125	$12,000
3	3	0.5	$5,000	1	0.125	$12,000	1	0.125	$12,000
4	3	0.5	$5,000	2	0.25	$7,000	1	0.125	$12,000
5	3	0.5	$5,000	1	0.125	$12,000	1	0.125	$12,000
6	3	0.5	$5,000	2	0.25	$7,000	1	0.125	$12,000
7	3	0.5	$5,000	1	0.125	$12,000	1	0.125	$12,000

In the case of the premium transportation and information cost, the changes shown in Table 38 suggest modifications in the allocation as well as in the level of the safety stocks. Table 40 shows the sensitivity of the safety stock levels and allocation to variations in the standard deviation of the forecast error. The table reveals an interesting behavior in the safety stock levels and allocation: With reduced uncertainty, the model tends to adopt a centralized safety stock policy (e.g., at –80% (run 32) the number of product families that are centralized is equal to 26); as uncertainty increases, several product families become decentralized, reducing the number of centralized families to a minimum of 15 for the run with +60% standard deviation increase (run 38). From the table and our past conclusion regarding lead-time sensitivity it is possible to conclude that, again, the manufacturing facility's warehouse capacity is a major factor influencing the sensitivity of the safety stock allocation to changes in standard deviation. For example, at manufacturing facility $p=3$ for run 32, we observe that all product families have a centralized safety stock policy, which is possible because the storage capacity of 4,500 units is quite adequate to hold the 1,731 units of products as the centralized safety stock. As the standard deviation is increased, the centralized safety stock is also increased. Run 33 shows only 133 units of decentralized safety stocks compared to 3,351 units of centralized safety stock. Note that this is the only case throughout our analysis in which there is a decentralized rather that a centralized safety stock allocation given that the manufacturing facility warehouse capacity constraint is not binding; we assume that these 133 units were allocated given the complex tradeoffs of the model with regard to the overall system costs considered and given that this quantity is negligible we do not further address the underlying mechanism by which these were allocated in a decentralized rather than a centralized manner. Runs 33-38, clearly show the effect of the storage capacity as no centralized stock for manufacturing facility $p=3$ exceeds the 4,500 units even though the total safety stocks (centralized plus decentralized safety stocks) is increased in order to buffer against the uncertainty that is being added. As mentioned previously, runs 37 and 38 exceed the capacity limitation due to the elastic warehouse capacity constraint. With table 40 it becomes apparent that the only manufacturing facility in this condition is $p=1$, because, excluding all other inventories, only the centralized safety stock exceeds the storage capacity by 482 units (3,982-3,500) in run 37 and by 3,285 units (6,785-3,500) in run 38. This fact indicates that additional storage space (with associated costs) would have to be made available in order to allow manufacturing facility $p=1$ to continue production. This is further appreciated with the capacity usages for manufacturing facility $p=1$ plotted in figure 8 which show an approximate 120% space usage for run 37 and a 200% for run 38. This means that if the forecasts had a +40% of increased error, we would require an additional 20% of warehouse space at the manufacturing facility, and if the forecasts had a +60% increase in the error, a warehouse of double capacity would be required.

Finally, in terms of timeliness, it is evident from Table 38 that the sensitivity of this parameter is higher when changes in standard deviation are effected than with any other parameter. Table 41 provides the details of the information system allocation in which runs 31 through 36 are shown; Runs 37 and 38 have the same timeliness levels as run 36 and thus are not shown. In most cases there are changes in the assignment of the information systems. The trend toward the selection of timeliness systems is obvious when analyzing Table 40, Table 41 and the capacities of the manufacturing facility's warehouses. Initially, with no uncertainty (run 31), no buffer stocks are required and therefore having additional inventories due to low timeliness would only increase the cost. This is why, in most of the manufacturing facilities, the timeliness factor γ_{pm} is relatively high. As uncertainty is increased, so are the centralized safety stocks and, in some cases, the need for timely systems is reduced because products can be shipped to the distribution centers from the existing safety stocks. This is clearly seen in run 32 where 5 manufacturing facilities ($p=1$, $p=2$, $p=5$, $p=6$ and $p=7$) change their information systems to ones with lower timeliness factors. For example, in manufacturing facility $p=2$ the information system changed from $m=3$ to $m=2$ (i.e., γ_{23}=0.98 to γ_{22}=0.85). As safety stocks continue to grow due to uncertainty, and the manufacturing facility warehouses get filled up and further reductions in inventory are required in order to create additional space by enhancing flow with increased shipping speed, timeliness is increased. For example, from run 33 to run 34, manufacturing facility $p=1$ changes from information system $m=1$ to $m=3$, and manufacturing facility $p=3$ changes from $m=2$ to $m=3$.

In summary, we may see that the timeliness variable is highly sensitive to changes in the standard deviation. This verifies the need for the existence of the variable in the model and reinforces the need for flexible information systems so as to achieve the maximum flow of materials and to avoid deadlocks in the system.

Figure 8. Storage space usage for manufacturing facility *p=1* in runs 37 and 38

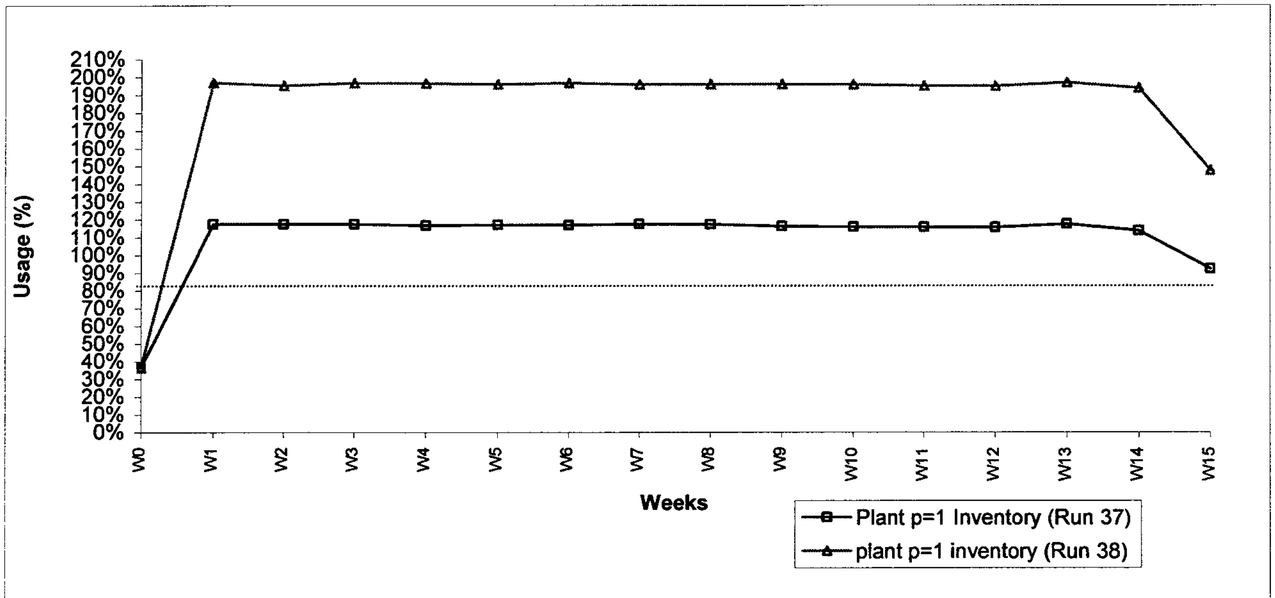


Table 40 Safety stock allocation and levels for standard deviation sensitivity

Manufacturing Facility, p	Percentage of Reduction in Standard Deviations of the Forecast Error											
	-100% (run 31)			-80% (run 32)			-60% (run 33)			-40% (run 34)		
	$\sum_{n=1}^{N(p)} PS_{pn}$ *	$\sum_{n=1}^{N(p)}\sum_{k=1}^{K} DS_{pnk}$ **	$\sum_{n=1}^{N(p)} RP_{pn}$ #	$\sum_{n=1}^{N(p)} PS_{pn}$	$\sum_{n=1}^{N(p)}\sum_{k=1}^{K} DS_{pnk}$	$\sum_{n=1}^{N(p)} RP_{pn}$	$\sum_{n=1}^{N(p)} PS_{pn}$	$\sum_{n=1}^{N(p)}\sum_{k=1}^{K} DS_{pnk}$	$\sum_{n=1}^{N(p)} RP_{pn}$	$\sum_{n=1}^{N(p)} PS_{pn}$	$\sum_{n=1}^{N(p)}\sum_{k=1}^{K} DS_{pnk}$	$\sum_{n=1}^{N(p)} RP_{pn}$
1	0	0	5	1,709	0	5	3,419	0	5	3,291	3,529	3
2	0	0	1	406	0	1	704	0	1	1,056	0	1
3	0	0	7	1,731	0	7	3,351	133	6	4,418	965	4
4	0	0	1	368	0	1	0	1,144	0	0	1,715	0
5	0	0	4	738	0	4	1,479	0	4	2,220	0	4
6	0	0	2	471	0	2	108	1,149	1	163	1,724	1
7	0	0	7	1,277	377	6	2,558	755	6	3,837	1,132	6
Total	**0**	**0**	**27**	**6,700**	**377**	**26**	**11,619**	**3,181**	**23**	**14,985**	**9,065**	**19**

* Aggregate centralized safety stock for all product families produced at manufacturing facility $p=1,...,7$.
** Aggregate decentralized safety stock for all product families produced at manufacturing facility $p=1,...,7$ over all distribution centers.
\# Number of product families produced at manufacturing facility $p=1,...,7$ in which a centralized safety stock policy was chosen.

Table 40 (continued)

	Percentage of Reduction/increase in Standard Deviations of the Forecast Error															
	-20% (run 35)			0% (sc 4)			+20% (run 36)			+40% (run 37)			+60% (run 38)			
MF, p	$\sum_{n=1}^{N(p)} PS_{pn}$	$\sum_{n=1}^{N(p)}\sum_{k=1}^{K} DS_{pnk}$	$\sum_{n=1}^{N(p)} RP_{pn}$	$\sum_{n=1}^{N(p)} PS_{pn}$	$\sum_{n=1}^{N(p)}\sum_{k=1}^{K} DS_{pnk}$	$\sum_{n=1}^{N(p)} RP_{pn}$	$\sum_{n=1}^{N(p)} PS_{pn}$	$\sum_{n=1}^{N(p)}\sum_{k=1}^{K} DS_{pnk}$	$\sum_{n=1}^{N(p)} RP_{pn}$	$\sum_{n=1}^{N(p)} PS_{pn}$	$\sum_{n=1}^{N(p)}\sum_{k=1}^{K} DS_{pnk}$	$\sum_{n=1}^{N(p)} RP_{pn}$	$\sum_{n=1}^{N(p)} PS_{pn}$	$\sum_{n=1}^{N(p)}\sum_{k=1}^{K} DS_{pnk}$	$\sum_{n=1}^{N(p)} RP_{pn}$	Storage Space, IC_p
1	3392	6805	1	3,155	10,790	3	2,882	14,487	3	3,982	15,994	2	6,785	13,609	1	3,500
2	1408	0	1	1,760	0	1	2,112	0	1	2,464	0	1	2,816	0	1	8,000
3	3712	4147	6	4,357	5,513	5	4,349	7,752	4	4,061	10,361	2	4,028	12,782	3	4,500
4	0	2287	0	0	2,858	0	0	3,431	0	0	4,002	0	0	4,574	0	400
5	2410	921	3	963	4,381	3	1,156	5,259	3	1,349	6,136	3	1,542	7,013	3	2,615
6	217	2299	1	271	2,873	1	326	3,448	1	380	4,023	1	434	4,598	1	600
7	5117	1509	6	6,397	1,886	6	7,677	2,264	6	8,956	2,641	6	10,237	3,018	6	55,000
Total	**16,256**	**17,967**	**18**	**16,903**	**28,301**	**19**	**18,502**	**36,640**	**18**	**21,192**	**43,157**	**15**	**25,842**	**45,593**	**15**	

Table 41 Sensitivity of timeliness to changes in standard deviations of the forecast error (detail)

	Percentage of Reduction in Standard Deviations of the Forecast Error											
	-100% (run 31)			-80% (run 32)			-60% (run 33)			-40% (run 34)		
Manufacturing Facility, p	Information System, m	γ_{pm}*	CI_{pm}**	Information System, m	γ_{pm}	CI_{pm}	Information System, m	γ_{pm}	CI_{pm}	Information System, m	γ_{pm}	CI_{pm}
1	3	0.99	$10,000	2	0.85	$5,000	1	0.8	$1,000	3	0.99	$10,000
2	3	0.98	$7,000	2	0.85	$2,000	1	0.8	$1,000	1	0.8	$1,000
3	2	0.95	$2,000	2	0.95	$2,000	2	0.95	$2,000	3	0.99	$7,000
4	1	0.9	$1,000	1	0.9	$1,000	3	0.99	$5,000	3	0.99	$5,000
5	2	0.95	$7,000	1	0.85	$4,000	1	0.85	$4,000	1	0.85	$4,000
6	3	0.98	$3,500	2	0.93	$2,000	3	0.98	$3,500	3	0.98	$3,500
7	3	0.98	$3,500	2	0.92	$2,000	2	0.92	$2,000	1	0.8	$1,000
	Total		**$34,000**			**$18,000**			**$18,500**			**$31,500**

* Timeliness factor
** Information system cost in $/15-weeks

Table 41 (continued)

	Percentage of Reduction/increase in Standard Deviations of the Forecast Error								
	-20% (run 35)			0% (Sc. 4)			+20% (run 36)		
Manufacturing Facility, *p*	**Information System, *m***	γ_{pm}	CI_{pm}	**Information System, *m***	γ_{pm}	CI_{pm}	**Information System, *m***	γ_{pm}	CI_{pm}
1	3	0.99	$10,000	3	0.99	$10,000	3	0.99	$10,000
2	1	0.8	$1,000	1	0.8	$1,000	1	0.8	$1,000
3	2	0.95	$2,000	3	0.99	$7,000	3	0.99	$7,000
4	3	0.99	$5,000	3	0.99	$5,000	2	0.95	$2,000
5	2	0.95	$7,000	2	0.95	$7,000	2	0.95	$7,000
6	3	0.98	$3,500	3	0.98	$3,500	3	0.98	$3,500
7	1	0.8	$1,000	1	0.8	$1,000	1	0.8	$1,000
	Total		**$29,500**			**$34,500**			**$31,500**

5.2.4 Summary of the Sensitivity Analysis to Changes in Lead-times, Cost and Standard Deviation Parameters

The above analyses point out the following results:

1. The highest impact on profit is due to variations in standard deviations of forecast error and lead-times followed by labor, transportation, and premium transportation costs.
2. Changes in lead-times impact the allocation of premium transportation and information, and timeliness parameters, but do not affect the review policies allocated by the model.
3. The allocation of information related resources are insensitive to small changes in labor, transportation, and premium transportation and information costs, and even fairly large changes in premium transportation and information cost show no major impact on the allocation of these information related resources.
4. Standard deviation changes show no serious effect on the periodic-review policy assignments. Premium transportation and information variables are affected by changes in standard deviation, as well as the timeliness variables.
5. Manufacturing warehouse capacity constraints have a major influence on the application of postponement, and thus in the allocation of safety stocks, especially when changes in the lead-times and standard deviations are effected.

6. In general, the model shows the required robustness and predicted response, which validates its applicability for the real world environment.

5.3 Computational Experience

The model was solved using LINGO version 7.0 on a PC having 128 MB RAM and a 700 MHZ Pentium 4 processor. It took, on average, 3,448 seconds to run the model. There were 24,564 variables (258 integer), 16,109 constraints and it took, on average, 810,000 iterations to reach the global optimum solution.

CHAPTER 6. SUMMARY AND PROPOSED FUTURE DIRECTIONS

6.1 Summary of the Present Work

The basic premise in the development of this thesis was to evaluate how the economies of inventory and production change as we integrate the supply chain functions by means of information. We noticed that there is a consistent trend among researchers and practitioners in that information is assumed given and the costs of acquisition are seldom considered or assumed fixed. In order to be able to measure information, a suitable definition was given in terms of its ability to reduce uncertainty and its characteristics of accuracy, timeliness, periodicity and availability. It was also noted that two types of information technology –analytical and transactional- are useful as a means of supply chain integration and that an appropriate balance of both is required in order to improve decision-making.

Our objective was, therefore, to apply a modeling approach that includes and balances both analytical and transactional information technologies in order to improve the management of the supply chain.

Before proceeding, it was intended that this modeling approach be done in the context of a real world, large-scale business operation, namely AG, Inc., an appliance manufacturer located in Mexico, in order to insure that the model would be capable of handling realistic supply chain environments.

The basic MIP model by Dominguez et.al. (2000) was extensively enhanced and modified in order to account for uncertainty so that information variables related to accuracy, timeliness and periodicity could be included and large scale problems be handled. The resulting model was also a MIP model. The solver used was lingo 7.0. This solver was chosen because of its user friendliness, low cost, high flexibility and possibility to solve the model.

The case study presented served as a means of validating of the inputs, processes and outputs, and the results helped to measure the impact of supply chain integration in terms of production flexibility and information flexibility. Additionally, the case study showed the flexibility and applicability of the model as an evaluation tool for "what-if" scenarios in a dynamic testing environment. The input data for the case study was thoroughly explained and the assumptions regarding this data were clearly stated. In some cases, required transactional data was not available and estimations had to be made, however, this highlighted the need for functional integration in order to even start the systems-wide approach. Another set, demand forecast information, was not available either and thus a modified version of the Winter's forecasting method was presented and applied.

In summary, the results of the case study presented showed that the model can be successfully used by the physical distribution, logistics, production planning and financial areas of the firm as a planning tool for managing the supply chain; however, further evaluation and fine tuning would be required at the time of implementation in order to fully validate its outcomes.

The sensitivity analysis was performed in order to evaluate the impact of information parameters and decision variables on the total cost, and to analyze the impact of changes in other parameters on the allocation of timeliness, periodic-review policy, and premium transportation and information resources. In our analysis it was concluded that the highest impact on profits is due to the application of risk pooling followed by changes in the periodic-review policy, and finally the lowest impact was due to changes in the timeliness variable. These results helped validate the value of the information variables, which otherwise would be eliminated from the model. In the same fashion, by changing the values of several parameters chosen on the basis of their inherent uncertainty or inaccuracy, it was concluded that the model shows the required level of robustness[**] and response in order to validate its applicability to the real world environment. It is important to mention, however, that our sensitivity analysis was by no means exhaustive and our conclusions should be further verified. For example, it would be interesting to further analyze the effect of the rolling horizon on the allocation of resources, especially those related to information.

The MIP programming approach used in the study has many advantages. First, it provides a systematic framework in which a very large number of details can be accommodated. Second, it is adaptive to changing conditions in the business environment; for example changes in production flexibility could easily be handled, and although the model is specific to AG, Inc., its flexibility makes it suitable as a starting point for analyzing and modeling other supply chains. The important aspect, however, is that it permits the analyst to view the problem from a systems standpoint. Thus, the elements in the supply chain were optimized not with respect to a few specific functional costs, but rather as part of the overall supply chain network. In this study we have not dealt with the complete supply chain by any

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[**] Robustness has been defined as the insensitivity of a system towards stochastic disturbances (Heisig, 2002) (Heisig, G. (2002), "Planning Stability in Material Requirements Planning Systems", Springer-Verlag, Berlin, Germany.

means; however, the approach could be further extended in order to include suppliers, customers and other functions related to the supply chain.

In conclusion, the research described herein represents an important step towards the integration of functions and hierarchies within a supply chain. In this context the model aids the decision-maker in detecting areas of improvement, and the extent to which these improvements or changes impact the supply chain as a whole. The major contribution of the work is to include information as an implicit decision variable and a cost parameter in the large-scale real-world model based in the Mexican environment.

6.2 Future Research

The summary presented above shows the current understanding of an integrated large-scale supply chain model. It is certainly true that there are more issues to be explored and the expansion of the knowledge of these types of systems will continue. There are several potential directions in which the research reported here can be continued:

1. As was noted, only internal integration of the supply chain was considered. It is necessary to extend the scope of such large-scale systems to include suppliers and retailers as well as their information elements.
2. As was discussed, the present model is a tool for planning at the tactical level of the supply chain. A logical extension to this would be its use as a tool for the operational level planning, as well as for the strategic level planning of the

supply chain. Issues to be considered could include, for example, scheduling and routing at the operational level, and manufacturing facility location, distribution center location and capacity planning at the strategic level. Another logical extension to the model could be in terms of extending the functions considered at the three planning levels, for example, to include production issues such as work-in-process and raw materials inventory control or marketing issues such as dynamic pricing and promotions or even financial issues such as time value of money, exchange rates and speculative practices. It is important to say that as the complexity of the model increases, its tractability may be adversely affected. We therefore envisage the need to develop efficient algorithms to solve the model. The issue of the implementation of the model also remains to be addressed and the mechanisms by which the strategic, tactical and operational planning functions are to be linked needs to be considered in a well-defined framework.

3. The assumption that items in product families have similar behavior in terms of demand variations in many cases is not realistic. Therefore, we see the need for the consideration of items instead of product families. This may also increase the size of the model to the point where the use of decomposition techniques may be necessary.
4. The model presented is limited in application because it was designed for the environment of the appliance company. However, due to its flexible nature, it may be easily modified to accommodate other types of industries, or even other types of processes. We suggest that further research be conducted in order to

develop a general modeling framework that is easily applicable to different situations.

5. It was assumed herein that lead-times are deterministic. In reality it is known that lead-times show an easily identifiable stochastic behavior that could be included in the model. This is not an easy task, however, given the complexity of the present model.
6. The current model assumes that there are no transshipments. The model could be further enhanced to consider the economic convenience of these types of shipments, which occur quite often in real world systems when production problems arise or when there is an excess of inventory that can be sold at another location.
7. In order to monitor the proposed supply chain optimization system we propose the implementation of a set of performance measures to adequately track the extent to which the supply chain is performing up to expectations. Our premise is that traditional measurement systems may be either adversely affected or completely unaffected by supply chain improvements. Appendix VII shows an example of a holistic measurement system called the Balanced Scorecard.

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APPENDICES

Appendix I. Input information

Appendix II. Calculation of D_{pnkt} and σ'_{pnk} for all the families-DC's-plants and σ_{pn} for all families-plants

Appendix III. Lingo Program File

Appendix IV. Special Structures in Large Scale Mathematical Programming problems

Appendix V. Solution to the production-distribution problem (FPS-FIS)

Appendix VI. Cost elements for the sensitivity analysis

Appendix VII. The Balanced Scorecard.

Note: In order to save space and paper, the appendices are all included in the CD ROM attached at the end of the Thesis.

VITA AUCTORIS

Hugo Dominguez was born in 1968 in Mexico City, Mexico. He graduated from The Instituto Juventud High School in 1987. From there he went on the Universidad Anahuac where he obtained a B.Sc. in Industrial Engineering in 1991. He is currently a candidate for the Master's degree in Industrial Engineering at the University of Windsor and hopes to graduate in Fall 2002.