Data-Driven Logistics Planning

by

Christopher Aaron Richard

B.S., Electrical Engineering, United States Military Academy, 1989

Submitted to the Sloan School of Management and the Department of Electrical Engineering
in Partial Fulfillment of the Requirements for the Degrees of

Master of Science in Management
and
Master of Science in Electrical Engineering
at the
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ABSTRACT

Rapidly growing, high-technology industries face especially difficult challenges in the realm of logistics management. Short product life cycles and capricious markets create conditions of great uncertainty in both supply and demand. Material planners manage inventory in an attempt to maintain a fine point of balance between satisfying customer demand and controlling inventory levels. There are costs associated with failing to fill orders within the customers' desired lead time as well as with procuring and holding inventory. Material planners spend their days attempting to minimize these costs. The inventory system which they try to manage is one that is characterized by complex and non-linear cause and effect relationships. Human beings have difficulty understanding the effects of non-linearities, feedback and cause and effect relationships that are separated in space and time. Planners function in this confusing environment having developed their intuition over many years. They often make decisions based on what they term "gut feel", "hard to quantify" and "soft" data.

This thesis is based on the premise that the proper and consistent use of available data in logistics planning can lead to a better balance between customer satisfaction levels and quantity of inventory held in stock.

I present a model of the total cost of the inventory system. I present a framework that allows planners to input various pieces of relevant decision making data. The model is used to analyze current operating procedures and recommend improvements.

Thesis Advisors:
Professor Alvin W. Drake
Senior Lecturer Donald B. Rosenfield

Table of Contents

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Chapter 1: Introduction and Overview

Preface

> Management is in transition from an art, based only on experience, to a profession, based on an underlying structure of principles and science.
>
> Any worthwhile human endeavor emerges first as an art. We succeed before we understand why. The practice of medicine or of engineering began as an empirical art representing only the expertise of judgment based on experience. The development of the underlying sciences was motivated by the need to understand better the foundation on which the art rested.
>
> Without an underlying science, advancement of an art eventually reaches a plateau. Management has reached such a plateau. If progress is to continue, an applied science must arise as a foundation to support further development of the art. Such a base of applied science would permit experiences to be translated into a common frame of reference from which they could be transferred from the past to the present or from one location to another, to be effectively applied in new situations by other managers.
>
> -- Jay Forrester, Industrial Dynamics

The purpose of my thesis is to further the advancement of the science of management by contributing to the understanding of how we can translate art into science. One tool for managing this translation is explicit modeling. Explicitly modeling the actual situation forces us to understand and evaluate our current policies. Explicitly modeling the desired situation forces us to form a clear picture of the paradigm which we strive to achieve[1]. The comparison of these two models reveals the differences and helps us create a plan to reconcile them.

[1] Randers, 1980

In the world of a rapidly growing, high technology company, where everyone is running as fast as they can just to keep up, and where the money is rolling in hand over fist, it is easy to overlook the need for careful analysis of current practices. While technology and first mover advantage may give a high tech company a comfortable position for some time, analysis, evaluation and improvement of business practices are necessary to survive over the long run.

Problem Statement

PictureTel Corporation has stated that making supply chain management a core competency is a fundamental component of its strategy. Currently, PictureTel has no adequate methodology to evaluate the costs associated with the policies that control the operation of its supply chain. If PictureTel is to gain advantage by effective supply chain management, the company must have better methods for evaluating supply chain costs, particularly those costs associated with the company's own policies.

Background

PictureTel is a young, technology-based company that is experiencing rapid growth. Since 1990 the company's revenue has grown at an average annual rate of 68%. As sales have expanded, both in quantity and in geographical spread, the logistics system has been strained in an attempt to keep pace.

Over the years, policies have evolved for managing pieces of the supply chain. From time to time decisions have been made to incrementally expand its capacity and its capabilities. Though these decisions were locally logical and rational, they were not necessarily globally optimal. In fact it would be extremely difficult to determine which decisions would be best for the overall system, as there exists no measurement system that can adequately quantify the costs and benefits of such decisions.

In the summer of 1995 PictureTel reviewed its supply chain operations. An analysis by the author of the existing European distribution operation revealed that significant cost reductions could be realized by improving the inventory management and replenishment policies. This project revealed the need for an analysis of the entire supply chain system and the need for a tool that can be used to assist in inventory management. The decisions facing the company are:

- In what locations should inventory be stored?
- In each of these locations, how much inventory should be stored?
- How does each inventory storage location reorder goods?
- In what shipment sizes are orders for goods satisfied?

In this thesis I address the latter three questions.

PictureTel is moving towards a business model in which it does not perform any of its own manufacturing. The company will purchase subassemblies from various vendors which will then need to be packaged and shipped to customers. In this sense, the company is mainly concerned with the integration and distribution of finished goods (of some form). However, since the lead times on some of its custom products currently exceed seven months, the slow response of the supply side of the chain must be carefully considered when planning finished goods inventory levels. The supply chain, as defined here, consists of both the incoming supply and outgoing distribution chains.

As the company moves toward this new business model, the supply chain needs to change to support it. The current practice of routing all goods through PictureTel's warehouse in Peabody, MA is not necessarily the best practice, as the value added by this step will be questionable in the future.

Company Background

PictureTel Corporation is the market and technology leader in the videoconferencing industry. The company has three categories of products. These are room or group systems, personal or desktop systems and network systems. Each of these product types is administered by a corresponding business division. The Room Systems Division (RSD), the Personal Systems Division (PSD) and the Network Systems Division (NSD). PictureTel is attempting to capture almost all of the identified market segments with the products from these divisions.

PictureTel's technology allows videoconferencing to be conducted over switched digital telephone lines. These lines are available in most locations in the world today, though the particular type of hardware interface may vary from place to place. The heart of the technology is a proprietary video compression algorithm. This algorithm allows video signals on the order of megabits per second to be compressed, with minimal loss of picture quality, to signals on the order of hundreds of kilobits per second.

The company structure is moving towards what they term a "leveraged" model. In this business model the manufacturing and distribution of products is outsourced. PictureTel will continue to design and market their products, but most of their operational activities will occur outside of the corporation's boundaries, with direction being provided from within. Manufacturing is included in this set of outsourced activities. Currently, PictureTel's personal and network systems are manufactured entirely by third parties. Some of the room system products undergo final assembly and test procedures at PictureTel, but all of the components and subassemblies are manufactured by third parties. In the future even these systems will be completely outsourced.

In support of this leveraged model, PictureTel operations has stated that its two core competencies will be product life cycle management and supply chain management.

The Videoconferencing Industry

The videoconferencing industry is growing rapidly. The short product life cycles are on the order of 18 months. These factors combine to create a business environment that is challenging to manage.

Since 1990 PictureTel's revenue has been increasing at an average[2] annual rate of 68%. This trend is graphically portrayed in Chart 1, below.

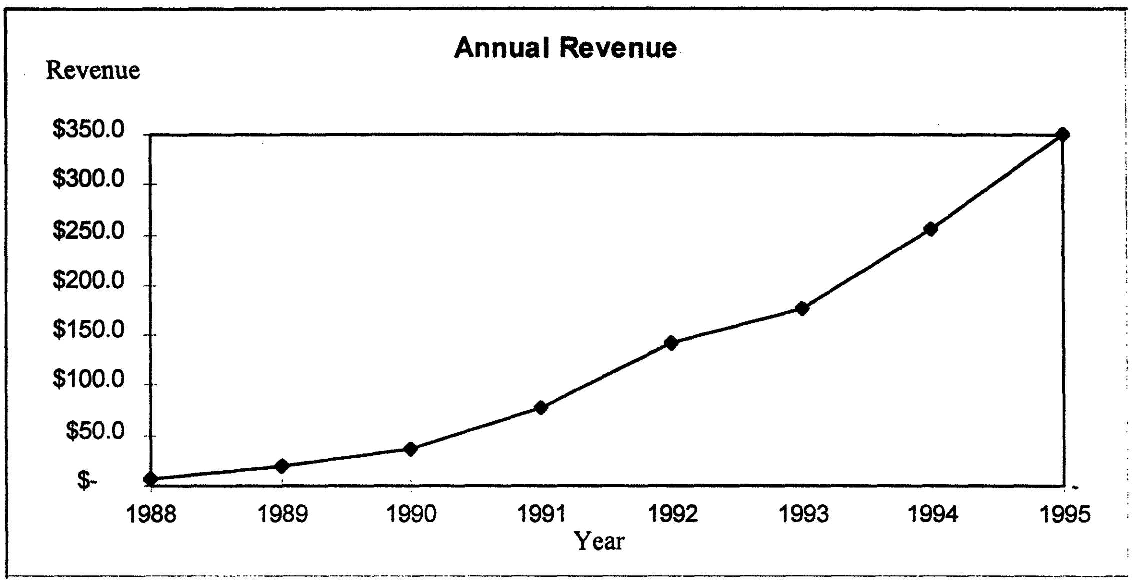

Chart 1 - PictureTel Revenue Trend

There is an obvious seasonal pattern and trend exhibited in sales in this industry. There is a notable seasonal pattern within the quarter and a trend within the year. The first month of the quarter represents approximately 17% of the total quarterly sales, the second month of the quarter represents approximately 24% of the total quarterly sales and the third month of the quarter represents approximately 59% of the total quarterly sales. The first quarter of the year represents approximately 20% of the total yearly sales, the second quarter of the year represents approximately 24% of the total yearly sales, the third quarter of the year represents approximately 27% of the total yearly sales and the fourth quarter of the year represents approximately 29% of the total yearly sales. The seasonal pattern and trend are represented graphically in Chart 2, below.

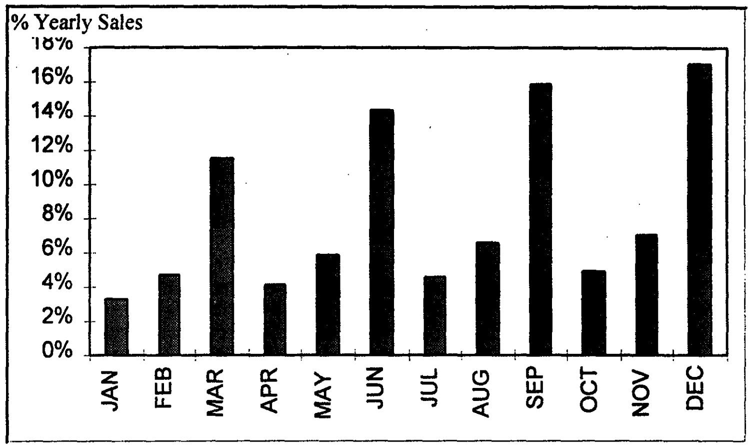

Chart 2 - Historical Monthly Sales as a Percentage of Yearly Sales

Systems and Control: Engineering and Business

A business is a complex system designed by man. Like any other system designed by man, a business exists for a specific purpose. This purpose is to make money for its stakeholders.

When man designs an engineering system, he includes control mechanisms. These mechanisms exist in order to keep the system performing correctly, that is, to keep the system producing the desired output. Without such mechanisms the system will almost definitely go out of control and stop producing the desired output (for which it was created). So without reliable control mechanisms, the system is not of much use.

[2] Geometric average.

In an engineering system, a simple controller compares the actual output of the system to the desired output. If a discrepancy exists, it then adjusts the inputs and/or the process to bring the actual output in line with the desired output[3]. Such a controller is shown below, in Figure 1.

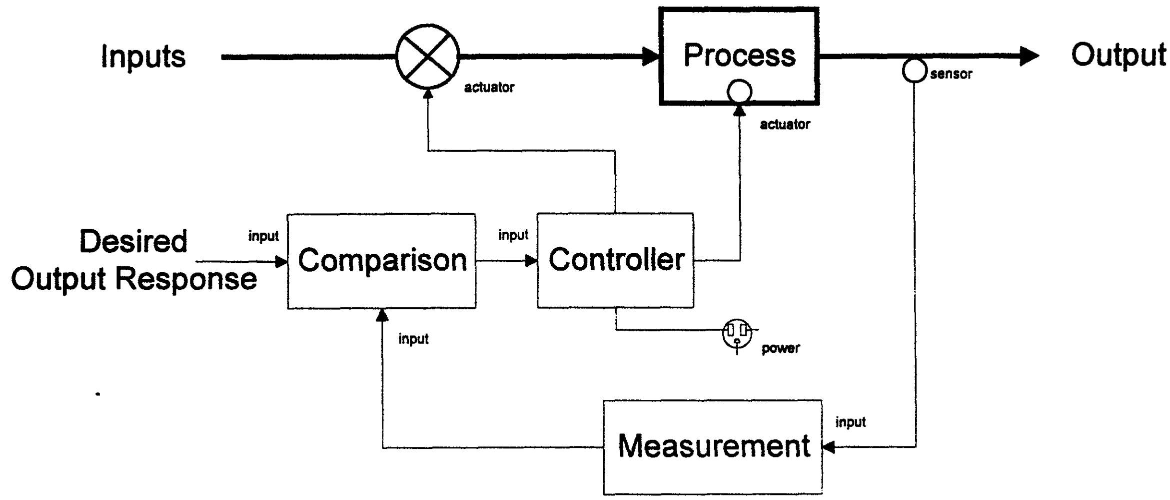

Figure 1 - Engineering Control System

Of course, appropriate control action requires that the controller's designer know enough about the cause and effect relationships between the system output and its inputs and processes to take the correct actions at the correct times. Indeed, most engineering systems that we encounter in our daily lives are understood well enough to make this happen under quite a variety of conditions. If they were not, we would certainly give much more thought before boarding an airplane or stepping onto an elevator.

Like engineering systems, businesses have control mechanisms. Like engineering systems, these control mechanisms exist in order to bring each output of the system in line with the desired output. The big difference between engineering systems and business systems is the degree of understanding that the respective controller designers have about the cause and effect relationships in the system. While these relationships are often understood quite well in engineering systems, they are frequently not at all well understood in business systems[4].

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[3] Dorf, 1987
[4] "An Informal Note on Knowledge and How to Manage It", 1986

This lack of understanding makes it hard to design business control systems that cause the system to respond to the wishes of the designer. In fact, many times in business we encounter de facto control systems that were never explicitly designed into the system. They have come into existence because of a local need and do not necessarily act in the best interests of the broader system. Indeed, a business is so complex and the conditions in which it operates so uncertain that the concept of designing a fully integrated, holistic centralized control system to optimize the performance of a business is pretty unlikely. However, control systems do not need to be centralized to be effective. In fact, in complex systems, an attempt at centralized control will almost never work. The attempt to centrally control the economy of the former Soviet Union is a good example of such a failure[5].

While it is extremely difficult to make complex systems function properly with centralized control, it is very possible to make them function well with distributed control. Simple, local controllers can often function well to accomplish specific outcomes under diverse circumstances. Similar simple, local control mechanisms at the next level in the hierarchy can control how two lower level parts of the system interact. This model of control has been repeatedly proven in complex engineering systems ranging from technically mature chemical refineries and experimental mobile robots.

So how do we take these lessons from engineering and transfer them to business? One way is to examine the procedure that a control engineer might use to for an engineering system and use an equivalent procedure for business. Certainly such a procedure would, in the very least, provide the manager a tool for the systematic evaluation of the business system.

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[5] Kelly, 1994

Procedure for Designing a Controller

During the course of my internship at PictureTel, I, from time to time, found business systems that did not appear to be functioning as intended. As a tool to aid in the systematic evaluation of a business control system, I developed the following procedure. This procedure, which was developed from my own experience in designing engineering and business control systems, provides a logical and thorough template for evaluating business control systems.

Controller Design Procedure[6]

1. Identify the outputs in which you are interested.
2. Identify the desired values of these outputs.
3. Identify ways to measure the actual values of these outputs.
4. Identify the inputs and process variables that affect the outputs.
5. Identify ways to measure the actual values of these inputs and process variables
6. State your understanding of the cause and effect relationships between the inputs, process variables and the outputs.
7. Create a controller[7] that, in response to a discrepancy between the desired and actual system output, causes a change in the appropriate inputs or process variables such that the discrepancy will go away.
8. Connect the controller to a source of power, its inputs and actuators.
9. Calibrate the sensors (of the outputs, inputs and process variables) to ensure that the signals they are generating are correct.
10. Test the control system in its environment and make adjustments as necessary.

At first glance the reader may suppose that a big challenge to implementing such a procedure in a business environment is understanding of the cause and effect relationships between the inputs,

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[6] They key terms used in this procedure are diagrammed in Figure 1.

[7] A controller in the engineering context is a mechanical, electrical or logical device. In the business context, it can take many forms. It can be a person, perhaps one who is following a procedure. It can be a system of people and

process variables and the outputs as this will determine the effectiveness of the controller. Trying to put this mental puzzle together can be overwhelming. And at this point many people would say that this task is too daunting, that these relationships can not be understood to a sufficient degree. However, I propose that, in some situations, major benefits may be realized without such a thorough understanding. In other situations, this understanding of cause and effect already does exist, and the reason that the system does not behave as desired is that one of the other conditions necessary to achieve proper controller action has not been met.

For example, the lack of business reporting tools in a business system is equivalent to not having inputs to the controller in an engineering system. Having business reporting tools of mediocre quality is equivalent to having the wrong or uncalibrated inputs. We would not expect an engineering control system to work with wrong, uncalibrated, or lack of inputs. Why should we expect a business control system to work under these conditions?

The factor that contributes the most to making control in business difficult is uncertainty. Uncertainty is ubiquitous in the business environment. Uncertainty is present in forecasts, in supplier reliability and in the performance of every humanly executed action in the system.

We do not have to accept a given level of uncertainty as inevitable. In the spirit of continuous improvement we should strive to qualify, quantify and reduce the causes of uncertainty. But while we continue to work to reduce uncertainty, we must deal with its current level wisely. This is accomplished by the proper use of techniques from the fields of probability and statistics.

Chapter Conclusions

It is the formal process of transforming the art of management into the science of management that enables a company to learn as an organization. A powerful tool that can be used in this process is modeling. While PictureTel is not currently undertaking such long term business

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procedures working, whether they realize it or not, in related areas. It can be a computer program. Or it can be some combination of all of these.

improvement efforts, such efforts must be commissioned at some point if the company is to sustain its market position against such manufacturing powerhouses as Intel and Hitachi.

A business should be thought of as a system. It requires controls to function properly. Translating engineering controller design process knowledge into the realm of business provides a powerful framework to help model and design the business.

Overview of the Remaining Chapters

In the remaining chapters I shall examine PictureTel's logistics system using the concepts discussed above.

In chapter two I describe the logistics system as it exists today.

In chapter three I present the complex inventory management problem, reduce it to a simpler form and develop an inventory cost model which can be used to help in decision making given the available information.

In chapter four I analyze the current logistics system using the controller design procedure as a logical analysis framework and the inventory cost model as a tool for evaluating inventory decisions. In this chapter I focus on the main inventory drivers: the forecast procedure and inventory control mechanisms.

In chapter five I make further analyses to include secondary inventory drivers and other aspects of the logistics system.

In chapter six I present conclusions and recommendations.

Chapter 2: The Existing State of the Supply Chain

Introduction

In this chapter I briefly describe the supply chain as it exists today. I cover the material flow as well as the information flow throughout this system.

Definition of Terms

Supply Chain: This term refers to the route that goods follow from PictureTel's suppliers to its customers. It includes the physical locations at which goods are stored, the transportation streams that connect those locations and the business processes which cause the movement of goods throughout this system.

Material Flow

The flow of materials through the supply chain is as represented in Figure 2, below.

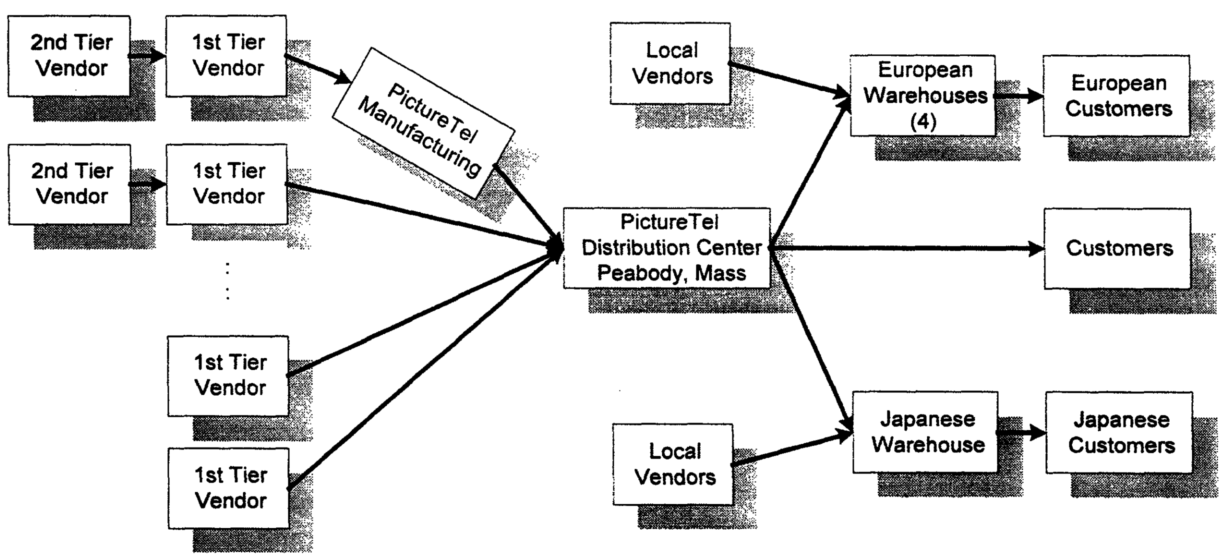

Figure 2 - PictureTel's Material Flow

First Tier Vendors

PictureTel has over a thousand[8] vendors which directly supply goods to them. Most of these vendors are located in the United States. A large number of these vendors are located within several hours of the Peabody, Massachusetts Distribution Center (DC), though some key vendors are quite far removed (California, North Carolina, Idaho, Wisconsin, Japan). With the exception of some of the local vendors, PictureTel pays the freight for these shipments. Lead times for products vary from days to months.

Second Tier Vendors

First tier vendors purchase materials from second tier vendors. Though functional relationships primarily exist between the first and second tier vendors, in some cases PictureTel becomes involved with the second tier vendors. This involvement is primarily through engineering as they design products and work out specifications. PictureTel is also concerned with the lead times between these first and second tier vendors as they are frequently a major component of the total product lead time.

PictureTel Distribution Center

PictureTel has one distribution center located in Peabody, Massachusetts. The vast majority of goods that eventually arrive at the customer site flow through this location. Goods are received, stored until needed and the picked, packed and shipped.

Manufacturing

PictureTel performs a limited amount of manufacturing. This manufacturing process consists of final assembly and test on their room system products. Materials that undergo these processes are received by the manufacturing facility in Peabody, Massachusetts and then shipped, via PictureTel's truck, to the distribution center, which is less than one mile away.

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[8] Total of first and second tier vendors.

Warehouses

There are finished goods warehouses located in Europe and Japan. The European warehouses are located in the U.K., Germany, Switzerland and Sweden. These are public warehouses in which PictureTel rents space as needed. These warehousing companies also coordinate delivery of the product to the customers. The vast majority of the materials that flow through these warehouses are received from the Peabody DC. Some items are purchased from local vendors though, and received at these warehouses in preparation for shipment to the customers.

Local Vendors

Local vendors supply a small number of items that can be procured locally and are geographically specific. There are about a half dozen of these local vendors per region.

Information Flow

The information flows that control the movement of materials throughout the supply chain are presented in Figure 3. For diagrammatic simplicity, the second and first tier vendors have been consolidated from Figure 2, as have the manufacturing facility and the distribution center. The shadowed boxes and heavy lines represent material flow. The unshadowed boxes and thin lines represent information flow.

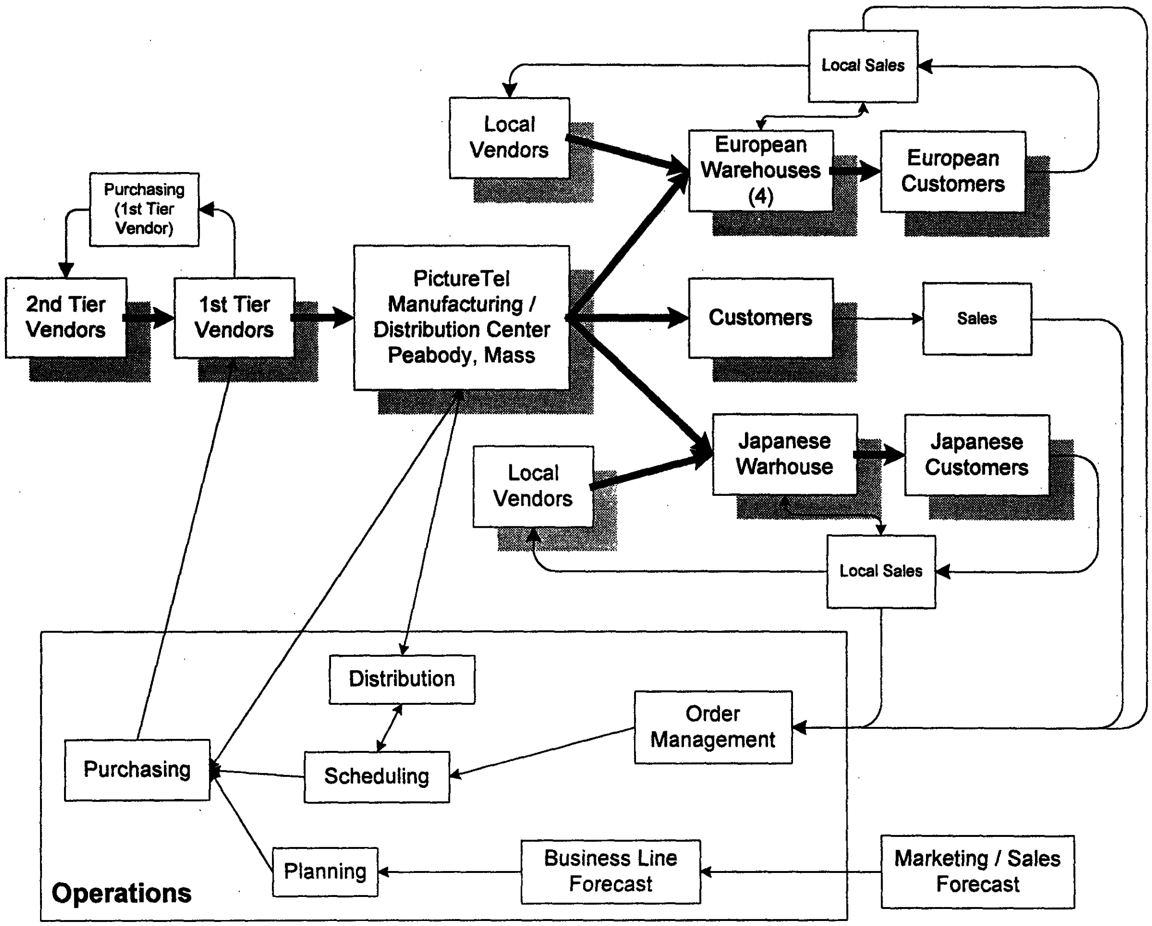

Figure 3 - PictureTel's Information Flow

Forecast and Planning

Sales prepares a monthly forecast by revenue and product line. This forecast is passed to marketing which adjusts the forecast for new product introductions and pricing changes. This forecast is then compared to historical sales and detailed to represent specific product configurations. This forecast is loaded into the MRP system. The transfer of this forecast across business functions is a manual process.

Purchasing

The purchasing agents (buyers) receive their information from the MRP system. They purchase materials so as to have the quantity on hand at a given time equal to the quantity that the MRP system tells them will be required. Buyers are assigned groups of products which are usually of the same general class. Multiple part types from one vendor are handled by one buyer. Blanket purchase orders have been established with most vendors. PictureTel provides the vendors long range forecasts (typically six months) and commits to specific orders at the lead time for the part. There is some flexibility in adjusting specific order quantities. Orders may be "pulled in " when the actual quantity needed exceeds the original order quantity or "pushed out" when the actual quantity needed does not meet the original order quantity. The degree to which these adjustments may be made varies from vendor to vendor and from part to part, but is negatively correlated with lead time. On short lead time, commodity-like items there is a great deal of flexibility. On long lead time, more customized items there is much less flexibility. Communication with vendors is accomplished by fax and phone.

Purchasing (First Tier Vendors)

The first tier vendors are responsible for procuring the materials necessary to manufacture the material they supply to PictureTel. PictureTel is responsible for providing a forecast to the vendors with a time horizon sufficient for the vendors to procure these materials. If the materials are specific to PictureTel and the actual demand is less than forecasted, PictureTel is responsible for the excess purchased material.

Local Sales (PictureTel Subsidiaries)

The local (country / region specific) sales forces set inventory levels in their regions. They procure materials from local vendors as they see fit. They maintain some level of inventory from which they can satisfy some portion of customer demand. They place orders on the order management department as necessary. These orders may be to replenish warehouse stock or to directly fill a specific customer order. The orders may ship from PictureTel's distribution center to the local warehouse or directly to the customer. Orders may be filled directly from the finished goods inventory or may be built to order.

Sales

For worldwide locations, with the exception of Europe and Japan, the sales representatives place orders on order management for specific customer orders. These orders are filled from the finished goods inventory in the distribution center or may be built to order.

Order Management

The order management department receives incoming purchase orders from the sales representatives by FAX. These purchase orders are audited for correctness and entered into the MRP system. When the purchase order is entered, it becomes a sales order. Once a sales order has been assigned a ship date (by scheduling), order management notifies the sales representative. Order management also handles all special requests, such as expediting.

Scheduling

Once the order has been entered into the MRP system by order management, the scheduler assigns it a ship date. This date is the later of the customer requested ship date and the longest lead time item (for items not in stock). The scheduler communicates any special material requirements to the appropriate buyer.

Distribution

Each day a ship list is printed in the distribution center. This list specifies the items that will be shipped on each sales order. For each sales order a pick list is generated. The pick list specifies each individual item that will be shipped as part of that order. Each order is packed according to the pick list and shipped. All room system orders are double checked by the distribution center manager or assistant manager before they are shipped. Personal system orders are not double checked. Audits are conducted on approximately 5% of all shipments. On a given day, orders are randomly selected for auditing from the set of all orders scheduled to ship for that day. These audits compare the actual contents of the order to those specified on the paperwork. These audits are not conducted randomly over time. They are concentrated in the first weeks of the quarter when the work load is lesser. Audits are not conducted in the last weeks of the quarter when the majority of the product is being shipped.

Information System

The existing enterprise resource planning (ERP) system is MANMAN. MANMAN supports all of the activities described above with the exception of European sales, which uses an accounting and inventory management program called *Platinum*.

PictureTel is currently in the process of selecting a new ERP system to replace MANMAN.

Chapter Conclusions

PictureTel's supply chain is characterized by relatively simple, unidirectional flows of material and information. The vast majority of materials are currently routed through PictureTel's Peabody, MA distribution center. Information flows sequentially from function to function through manual processes, by phone and by fax.

Chapter 3: Total Cost Model

Introduction to the Model: Dealing with Complex Systems

> "Over the last two decades, engineering has developed an articulate recognition of the importance of systems engineering. Systems engineering is a formal awareness of the interactions between parts of a system. A telephone is not merely wire, amplifiers, relays and telephone sets to be considered separately. The interconnections, the compatibility, the effect of one upon the other, the objectives of the whole, the relationship of the system to the users, and the economic feasibility must receive even more attention than the parts, if the final result is to be successful.
>
> "In management as in engineering, we can expect that the interconnections and interactions between the components of the system will often be more important than the separate components themselves.
>
> -- Jay Forrester, Industrial Dynamics

In the turbulent environment of this rapidly growing, high-tech industry, short product life cycles and capricious markets create conditions of great uncertainty in both supply and demand. Material planners manage inventory in an attempt to maintain a fine point of balance between satisfying customer demand and controlling inventory levels. There are costs associated with failing to fill orders within the customers' desired lead time as well as with procuring and holding inventory.

Material planners spend their days attempting to minimize these costs. The inventory system which they try to manage is one that is characterized by complex and non-linear relationships. Human beings have difficulty understanding the effects of non-linearities, feedback and cause and effect relationships that are separated in space and time. Planners function in this confusing environment having developed their intuition over many years. They often make decisions based on what they term "gut feel", "hard to quantify" and "soft" data. It is truly an art they practice. Their actions are guided by intuition they have developed over years of experience.

This thesis is based on the premise that the proper and consistent use of available data in logistics planning can lead to a nearly optimal balance between customer satisfaction levels and quantity of inventory held in stock. But to use this data, we have to first understand the system. The inventory system is a complex system. Its nature is as Forrester describes in the quote presented above. The individual parts of the system can not be considered independently of each other. The system must be considered as a whole. We seek to understand such systems by forming models. It is by this process that we can help to turn the *art* of logistics management into the *science* of logistics management.

As humans we create models of the world in an attempt to understand it. These models can be either implicit or explicit. We all have implicit mental models. We use these constantly as we make decisions in the course of our daily lives. These mental models enable us to survive and function in a complex world. However, a danger with these implicit models is that we do not usually *actively* manage their quality and development, that is, we normally do not *actively* question whether they are correct and make efforts to improve them. We usually do this maintenance in a *passive* manner. When some event occurs that we can not explain with our mental model, we seek an explanation. If we realize that our mental model was flawed, i.e. we did not have an accurate model of reality, then we change our model. This is called (passive)double loop learning[9,10].

There is nothing necessarily wrong with this passive maintenance. It is our default mode of operation. But we can enhance the quality of our models, and hence our decisions, by making them explicit. An explicit model is one that publicly presents our understanding of the system. We typically make a model explicit by documenting[11] it. By making a model explicit we accomplish at least two things. First, when we force ourselves to document a model we are *actively* developing it. The process of documentation causes us to question the quality and

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[9] Morecroft, 1994
[10] Senge, 1990

quantity of every relationship as we write it down. This process helps ensure that model is accurate. Second, when we put the model in a form that others can see, we make the model available for others to examine and question. Additional input from qualified persons can greatly enhance the quality of the model.

Explicit models become especially helpful when the system we are attempting to understand is large and/or complex. When the relationships between model variables are likewise complex (and especially if they are non-linear), mathematical models can be especially valuable as they can aid the user in understanding the counterintuitive effects of altering variables or relationships within the system. An employee who is responsible for inventory management could make use of such a mathematical model to help understand the effects of his decisions and hence improve the quality of those decisions.

Chapter Preview

In the remainder of this chapter I present the general multi-location, multi-item, inventory management problem, discuss some of the complex issues associated with this problem, show how simpler models can be used to help solve this problem and present a such model. This model is called the "Total Cost Model" as it attempts to fully capture all costs associated with inventory.

This model allows the materials manager to use available data to assist him in his decision making. It serves the dual purpose of allowing the user to evaluate the costs of the system (current or proposed) with an Activity Based Costing methodology and to optimize the decision variables for the selected policy. The model is formulated as an optimization model with the objective function being to minimize cost. However, it has an interface that allows the user to switch off the optimization function and make his own policy decisions so as to evaluate the effects of these. There is also a simulation function which allows the user to visualize the

[11] Documentation can take many forms. Examples of these forms could be narratives, diagrams, mathematical equations or simple statements of cause and effect.

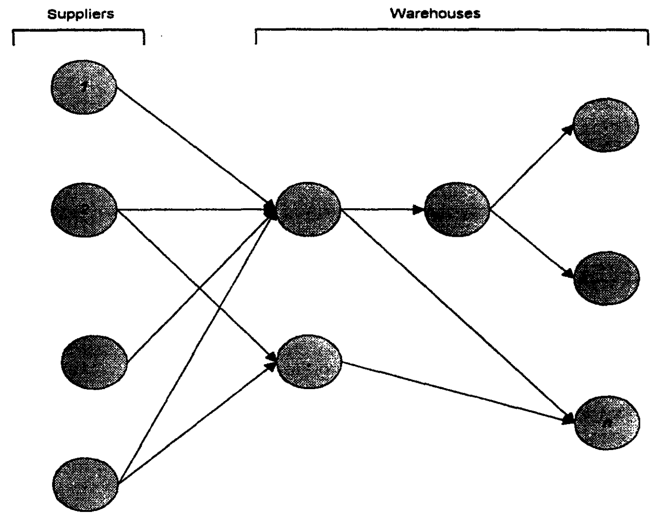
behavior of inventory levels over time and to validate the results of the optimization. The outputs of the model include recommended inventory levels, order / replenishment quantities, expected service level, and expected costs.

General Inventory Management Problem Description

I'll begin by describing the most complex and difficult to manage of inventory worlds. I talk about this for two reasons. First, a major learning for me during my internship experience occurred as I discovered the extreme difficulty involved in attempting to model and optimize such a system. I considered techniques ranging from linear programming to genetic algorithms in a search to find a general solution to a general problem, finally realizing that I had to narrow the problem to make it tractable. Second, I discuss this scenario because, even though PictureTel's inventory system is not currently so complex, it could become this way if no preventive action is taken. The company should take active measures to ensure it does not unintentionally wind up with such a complex and unwieldy system.

A general multi-echelon inventory system can be modeled as a graph, $G = (N, A)$, which is a directed network defined by the set N of n nodes and the set A of a directed arcs. Each of the nodes represents an inventory site at which can be stored up to m inventory items, where m is the total possible number of inventory stocking items[12].

[12] Ahuja et al., 1993



$G = (N, A)$

Figure 4: General Multi-Echelon Inventory System

At each inventory site, items are stored to satisfy demand from downstream locations. Items are removed from inventory and shipped to satisfy the demand. Items are added to inventory as they arrive from upstream locations. There is some time that elapses between the placement of the order and the arrival of the item. We refer to this time as the lead time. Demand is stochastic as are lead times.

For a single inventory location, I will consider a type of system that requires two decisions to be made for each item at each node: the quantity of inventory carried[13] and the lot size ordered.

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13 A note on inventory: For a given planning period, the total planned inventory can be broken into two classifications. The first is that inventory that is held to meet the expected demand, i.e. the forecast of demand for that period of time. The second category is that inventory that is held to protect against random variations in supply and demand, i.e. given that our forecast will always contain some error, and that there is some cost associated with not having the inventory in stock (underage or stockout cost) and some cost associated with having too much inventory in stock (overage cost) we wish to carry an amount of inventory, called *safety stock*, that minimizes our total cost for that period. Typically the underage cost is greater than the overage cost, i.e. the cost to the company of not having a piece of inventory on hand when the customer wants it is greater than the cost of carrying that piece of inventory, for one period, in the case that the customer doesn't want it. In this case, we would want to have on hand a positive amount of safety stock. So in each planning period, the total amount of inventory at the beginning of the period is equal to the expected demand plus the safety stock. Since the expected demand will always be ordered, the only real decision variable is the quantity of safety stock.

When the inventory level is being monitored continuously (as opposed to periodically) we refer to the system as being under *continuous review*. The advent of modern information technology systems has made continuous review inventory control systems very practical as computers can be programmed to generate an alert message, or even a purchase order, when an inventory item drops below a determined level. The type of inventory control system I have described is referred to as a *continuous-review, order-point, order-quantity* inventory control system. It is also referred to as a (Q, r) system where Q is the order quantity and r is the safety stock. The order point, R, is the sum of the safety stock and the expected demand over the lead time. This inventory control policy is illustrated in Figure 5: Inventory Level Over Time with (Q,r) Continuous Review Control. When the inventory level drops below the reorder point, R, an order is placed for the order quantity, Q. We expect the inventory level to be at r when the order arrives, since we anticipate only the expected demand to be consumed over this lead time interval. However, since both the demand and lead times are stochastic, the inventory level at the time of order arrival is itself a random variable. From time to time this inventory level will drop below zero before the order arrives. This creates a backlog condition and it is in these situations that the company incurs a stockout cost[14].

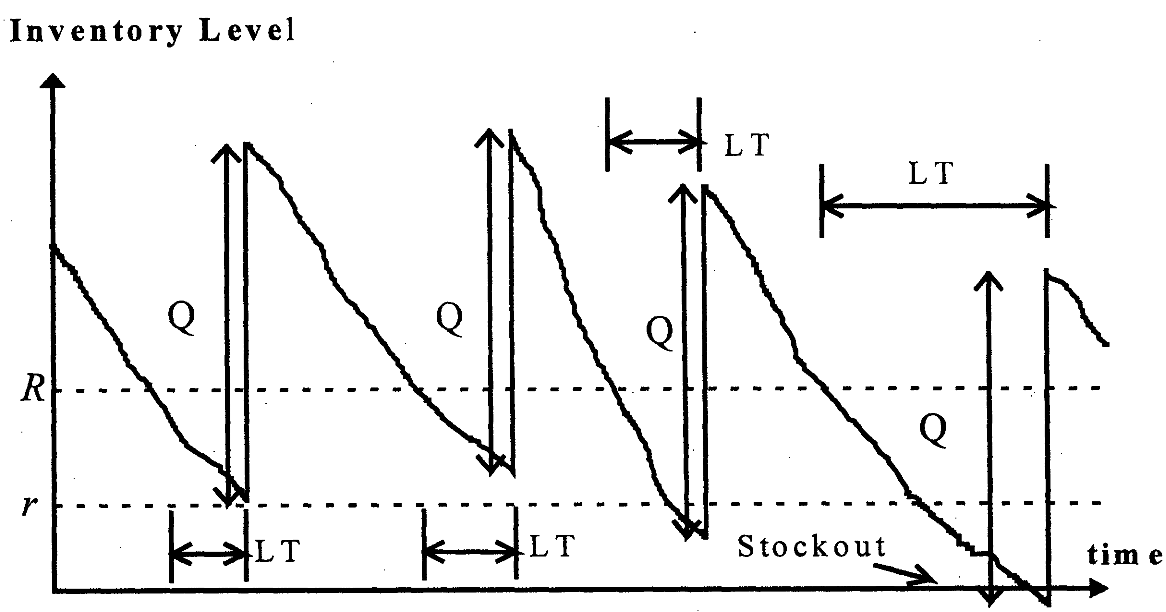

Figure 5: Inventory Level Over Time with (Q,r) Continuous Review Control

[14] For further discussion of these inventory models see Silver, 1979; Nahmias, 1993; Taha, 1987

We make inventory control decisions with the ultimate goal of maximizing the profitability of the company. Profit is the difference between revenue and cost. Some decisions that we make concerning the inventory system may have effect on both revenue and cost. For example, say we choose to not carry any inventory of a certain item. In this case we will have no cost associated with holding that item, but neither will we have any revenue from its sale (assuming that since we did not carry it, we could not sell it) resulting in a net profitability, for that item, of zero dollars. Since our inventory decisions have effect on both revenue and cost, if we characterize the costs properly, we can achieve the result of maximizing profitability by minimizing cost. We do this by assigning a cost to lost revenue. This maximization of profitability by the minimization of cost is the approach I shall take throughout this thesis in considering inventory decisions.

Types of Inventory Costs

All of the costs associated with the inventory system may be grouped into three categories:

- *order costs*
- *holding costs*
- *stockout costs*

The relationship between these costs and the decisions we can make about inventory are shown, below, in Figure 6. As mentioned above, the decisions we can make concern only the level of inventory carried and the lot size ordered. As mentioned in footnote 13, when making our inventory level decisions we really are only making a decision about the level of safety stock. The other decision we make concerns the lot size for each order. Since we are assuming some finite level of demand, this is equivalent to specifying the number of orders per time period. I will refer to the safety stock level, r, and the number of orders or order quantity, Q, as *decision variables*. We note from Figure 6 that the expected number of stockouts is determined solely by the decision variables.

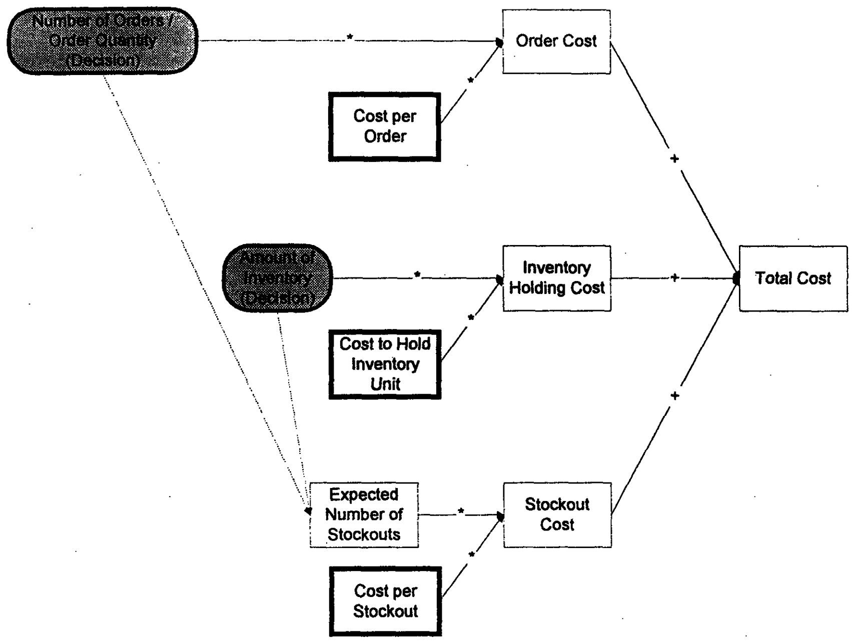

Figure 6: Relationship Between the Costs of Inventory and the Decision Variables

There is some cost associated with holding an item of inventory at each location per time period, this is referred to as the *holding cost*. The holding cost includes the cost of capital, the cost of insurance, the cost of warehousing facilities the cost of shrinkage and the cost of obsolescence. There is some fixed cost associated with placing an order for an item from an upstream location, this is referred to as the *order cost*. The order cost includes the time spent by all employees to place and receive the order and any fixed cost imposed by the supplier and/or the shipping company. There is some cost associated with failing to satisfy demand for an item, this is referred to as the *stockout cost*. The stockout cost includes the lost revenue and customer ill will. As shown in Figure 6, the *total cost* is the sum of these three costs.

Minimizing Total Cost

As many authors have shown, the task of minimizing inventory costs can therefore be formulated as an optimization problem where we are minimizing the total cost. A mathematical formulation of this optimization problem formulated for a single item at a single location over one year is presented below in Equation 1.

$$Min \quad TC(Q,r) = \frac{D}{Q}S + IC\frac{Q}{2} + ICr + \frac{D}{Q}ksN(z)$$

Equation 1

where $z = \frac{r}{s}$

and

D	is the annual demand [items]
Q	is the order quantity [items/order]
S	is the order cost [$/order]
I	is the inventory carrying cost as an annual percentage [%]
C	is the cost of the item [$/item]
r	is the safety stock level [items]
k	is the stockout cost [$/stockout]
s	is the standard deviation of demand over the lead time
$N(z)$	is the unit normal loss function
$sN(z)$	is the expected number of stockouts in an order interval [stockouts/order]

the components of total cost are:

$\frac{D}{Q}S =$	annual procurement cost [$]
$IC\frac{Q}{2} =$	annual carrying cost to meet the average demand [$]
$ICr =$	annual carrying cost to hold safety stock [$]
$\frac{D}{Q}ksN(z) =$	annual stockout cost [$]

and thus $TC(Q,r) = \frac{D}{Q}S + IC\frac{Q}{2} + ICr + \frac{D}{Q}ksN(z)$ is the sum of these cost components.

We make the assumption that demand is random and stationary.

Multi-Echelon Complexity

The multi-echelon system[15], as described above, is a network of *n* individual inventory sites. At each of these sites up to *m* inventory items may be stored. Since we have two decisions to make for each item at each site, we have a total of $2mn$ decision variables. It would be nice if we could simply sum the total costs of each item at each site to come up with the complete inventory system total cost. This would be possible if each inventory item and site was independent of the remainder of the items and sites, but this is not the case. The items and sites are, in actuality, dependent upon each other. Modeling this type of system is very difficult, or, as Silver puts it, "probabilistic demand ... creates extreme modeling complexities in a multi-echelon inventory situation." Next I examine some of these complexities.

First let's consider the implications of having multiple-items in the system. With multiple line items on an order, the treatment of stockout costs can become extremely complex. Typically, when an order is being prepared for shipment and it is discovered that there are one or more line items out of stock, a decision will be made to either delay the entire shipment until all items are available for shipment, or to make a partial shipment immediately of the goods on hand and ship the remainder of the items at a later date. This is referred to as a *short shipment*. The decision about how to ship is usually made after consultation with the customer. In either case, assigning a stockout cost to the items becomes more confusing. Arguments can be made that the stockout cost should be the same, less than, or greater than the stockout cost for the independent item. Also, if there are multiple items out of stock and the entire shipment is delayed, the stockout cost would not necessarily be the sum of the stockout costs of the individual items.

Next let's consider the implications of having multiple upstream sites that feed a common item into a single site. This is the case when there are several suppliers of an item to one inventory site. For each of these upstream sites there will probably be a different order cost and a different lead time distribution. Multiple suppliers may be retained to maintain price and service

[15] For further information see Graves, 1989; Lee at al., 1992; Magee et al., 1985; Nahmias, 1993; Rosenfield et al., 1980; Shapiro et al., 1985

competitiveness, or because one supplier possesses insufficient capacity to satisfy all of the demand. The optimization model presented above would need to be expanded to allow these factors to be taken into account.

Another challenge that arises is estimating the distribution of demand over the lead time. Even if we assume a Gaussian distribution we face the challenge of estimating the parameter s, the standard deviation of demand over lead time. As Nahmias says, "in general, it is very difficult to incorporate the variability of lead time into the calculation of optimal inventory policies." There are two reasons for this. First, lead times from a single supplier may not be independent. The lead time for an order may very well depend on the size of the current and recent prior orders. Second, if we assume that the lead times are independent random variables, such as would be the case if we had several suppliers of a given item, then it is possible for the lead times to cross, i.e. orders may not be received in the same order in which they were received. Equation 1 assumes that the distribution of demand over the lead time interval is Gaussian. In reality, determining the proper distribution of demand over the lead time interval could be difficult. Even if the demand distribution is Gaussian, the distribution of demand over lead time will not be, if the lead time distribution has a non-zero variance. This distribution will be complex and would be best estimated from empirical data and then the model would have to be modified to account for this distribution.

Finally let's consider a more general implication of having a complex, interconnected inventory system. This implication is that actions at the sites are no longer independent. Local optimization by individual sites can result in far reaching negative effects and suboptimal behavior for the system as a whole. These phenomena have been well documented by scholars such as Forrester and Senge from a System Dynamics perspective and Silver from a purely mathematical perspective.

In summary, accurately modeling a multi-echelon, multi-item inventory system is a task that is exceedingly difficult. As Graves puts it, progress in this field has been slow and most of the advances have been made for very specialized situations such as the cases of deterministic demand, serial systems with stochastic demand and one-for-one systems with stochastic demand. For more general multi-echelon inventory control problems, most of the work has been focused on two-echelon distribution systems with identical retail sites with Poisson demand processes[16].

A Simpler Model: Single Item, Single Location

As I have pointed out, finding a solution to the multi-item, multi-echelon inventory, cost minimization problem for a realistic inventory system is a virtually impossible task. Indeed, if there were a tractable[17] solution to this problem, there would not be inventory management challenges, as inventory managers could just program a computer to determine the optimal levels of inventory at any given location and time. In reality, managers must grapple with this problem daily.

There are numerous approaches that could be taken to tackling this problem. One approach could be to model the entire supply chain as thoroughly and accurately as possible and use some sophisticated optimization routine to arrive at a good solution. Some companies, such as Digital Equipment Corporation (DEC)[18] and AT&T, have taken this approach. During my internship this was also my first approach. I investigated using a software product developed at DEC called the *Global Supply Chain Optimizer*, which is a mixed integer program that uses penalty costs to arrive at solutions very rapidly. What I found, though, is that a program of this magnitude requires the full time dedication of many employees to maintain and use the model. Unlike DEC, PictureTel can not currently support the use of such a model. They do not have the internal competency in operations research necessary to support the mode, nor does the scope of their global business (yet) justify such an expenditure.

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[16] Graves,1989
[17] Ahuja et al., 1993; Cormen et al., 1990; Winston, 1991
[18] Arntzen et al., 1994

After abandoning this approach, but still desiring to solve this large scale problem with a large scale approach, I investigated the potential of using genetic algorithms[19] as a tool for finding a near optimal solution. I chose this approach because the multi-item, multi-site, inventory problem is full of complex, non-linear mathematical relationships, and genetic algorithms can provide good solutions to these types of problems as they broadly search the solution space and don't become trapped at local optima[20]. However, I found that this approach, as well, required too much support within the company for its continued use, and was too sensitive to model structure and parameter accuracy. Most importantly, though, I felt that this approach decoupled the user from the problem too much. The genetic algorithm searches are truly "black box" searches that randomly search the solution space. I felt that PictureTel's problem was of a scope that was best dealt with a modeling technique that heavily involved the user, forcing him to really understand the model, its inputs and assumptions.

"You cannot conceive the many without the one." -- Plato

In order to effectively deal with this complex problem I have chosen to take the approach of decomposing it into simpler parts. For example, if portions of the system can be decoupled from each other so that they do not affect one another, then they could be treated separately. These "portions" of the system refer to both the inventory items and the sites. PictureTel's inventory network is structurally simple enough that, with the proper assumptions, we can reduce the inventory control problem to a single item, in a single location, with stationary demand. So we reduce the complex multi-item, multi-echelon system presented in Figure 2 to a group of simple single-item, single-site systems as presented in Figure 7.

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[19] Goldberg, 1989

[20] The current paradigm is to use a combination of genetic algoritm and hill climbing techniques to locate promising regions and then quickly locate the local optima.

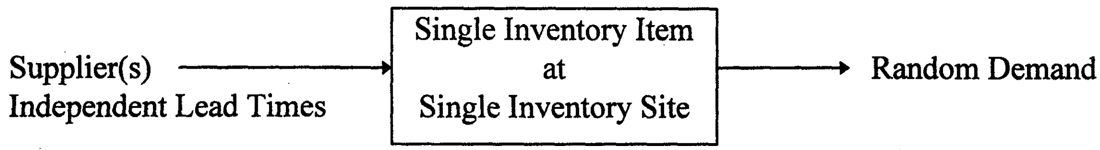

Figure 7 - Single Item, Single Site Model

For these systems Equation 1 applies for each item. The equation can be solved by solving Equation 2 and Equation 3 through an iterative procedure, as described by authors such as Nahmias and Silver.

$$Q^* = \sqrt{\frac{2D[S + ksN(z)]}{IC}}$$

Equation 2

and

$$z = \Phi^{-1}\left(\frac{Q^* IC}{Dk}\right) \qquad \text{where} \qquad r = zs$$

Equation 3

Model Simplification

As mentioned above, PictureTel's inventory system can be reduced and this simpler model can be intelligently used to aid in inventory control. I will now explain why this problem simplification is possible, including the assumptions necessary. I will then discuss the model in detail.

PictureTel Peabody Distribution Center

Even though from an examination of Figure 2 it appears that PictureTel's inventory system is quite long and complex, approximately 90% of the inventory is held in one location, the Peabody Distribution Center (DC). Because the bulk of the inventory is held at this location, this is the site where the largest potential improvements in inventory control and costs can be made. While the model presented below may used at other inventory sites within the PictureTel supply chain, in this thesis I will only examine it use at the Peabody DC. Use in other locations would require only the modification of the appropriate model parameters and adherence to the stated assumptions.

Now PictureTel's inventory system is modeled in the form presented in Figure 8. The interactive effects of the different sites and the different items are assumed to be of negligible magnitude for this model to be valid. I will explain the assumptions made for this approximation and discuss ways to use this model even when items can not be considered independently.

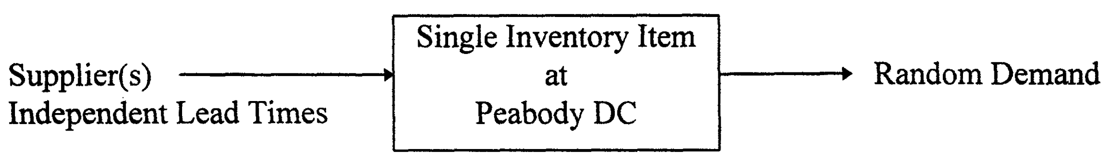

Figure 8 - Single Item, Single Site Model

Model Assumptions

The Downstream Distribution Centers (Europe and Japan) Can Be Ignored: Only minimal quantities (less than 10% of total investment) of inventory are stored at these locations. The biggest cost saving are to be realized at the Peabody DC. For the model to be valid we must have a random demand process drawing inventory from the Peabody DC. This is indeed the case, as discussed below.

The Demand at the Peabody DC is Random: The seasonality of PictureTel's sales was discussed in Chapter 1: Introduction and Overview, and graphically depicted in Chart 2. The (historical) aggregate demand can be decomposed into a trend, a seasonal, a constant and a normally distributed random component. A linear regression was performed on the aggregate GSD shipments for a 101 week time period (July 1993 to June 1995). The independent variables that were significant were *time*, measured as the week of the series (from 1 to 101), the *first week of the month*, the *last week of the month*, the la*st month of the quarte*r and a *special order* from a large customer. These variables capture a good deal of the trend and seasonal components of the demand pattern. The results of the regression are presented in Table 1: Regression Output for Aggregate GSD Shipments July 1993 - June 1995. The residuals are normally distributed. A histogram of the raw residuals is presented in Chart 3 and a normal probability plot is presented in Chart 4. The raw data is presented in Appendix H.

Regression Summary for Total GSD Shipments

R= .8096 R^2= .6554 Adjusted R^2= .6371

F(5,94)=35.8 p<.00000 Std.Error of estimate: 82.3

Ind Var	Beta	St. Err of Beta	B	St. Err of B	t(94)	p-level
Interept			71.28	18.151	3.927	.0002
Time	.2386	.0607	1.11	.282	3.930	.0002
First Week of the Month	-.1629	.0622	-81.63	31.173	-2.618	.0103
Last Week of the Month	.4708	.0691	250.87	36.825	6.813	.0000
Last Month of the Quarter	.2162	.0664	60.89	18.693	3.257	.0016
Special Order	.2729	.0651	372.84	89.018	4.188	.0001

Table 1: Regression Output for Aggregate GSD Shipments July 1993 - June 1995

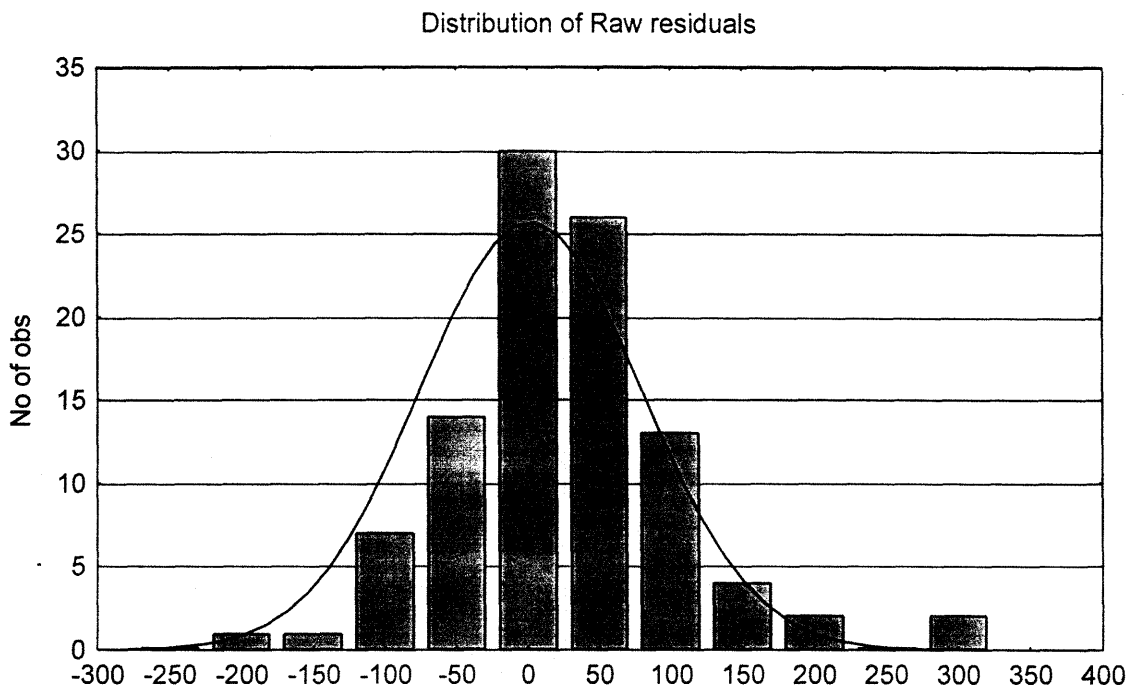

Chart 3

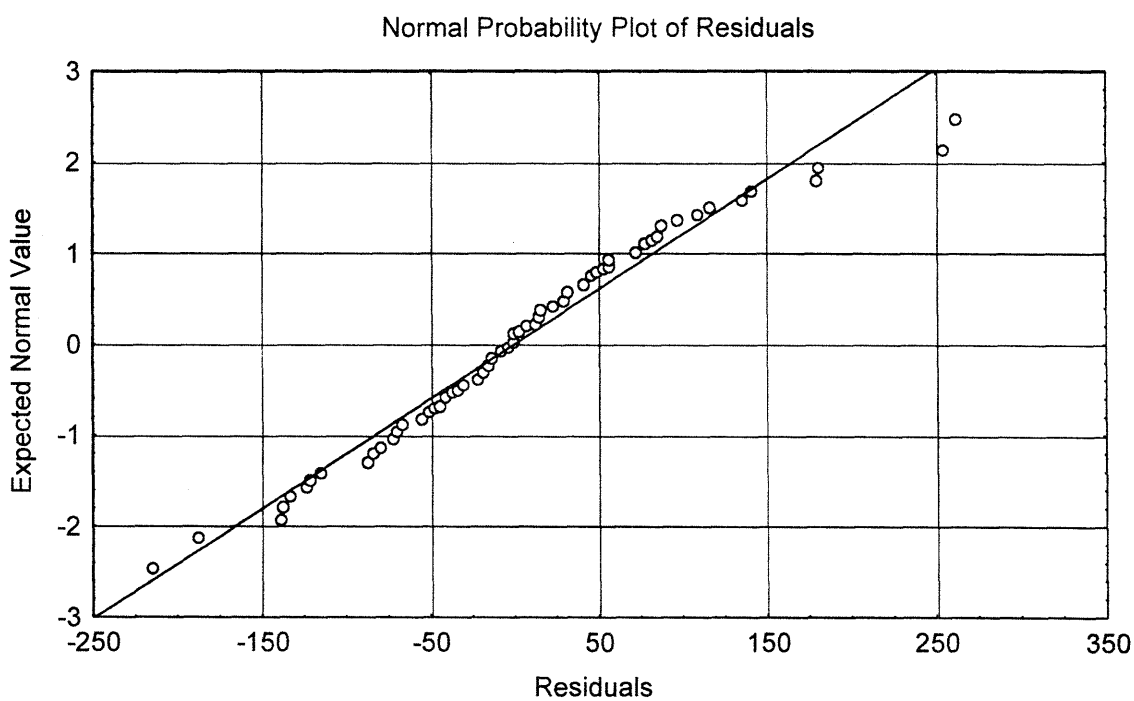

Chart 4

The Supply Chain for an Item Upstream of the Peabody DC May be Treated as One Site: Even though there are second tier vendors that supply materials to the first tier vendors (refer to Figure 2), PictureTel does not deal with the second tier vendors operationally. The interface is only with the first tier vendor. Lead times for parts supplied by the second tier vendors are included in the first tier vendor quoted lead times. Though this is not necessarily the optimal arrangement from a logistics management viewpoint, it is the current state of affairs. This point will be re-addressed later in this thesis.

Supplier Lead Times are Independent of Each Other and of Demand: This assumption has to be carefully considered before using the model. While off the shelf inventory items that are readily available from a number of vendors will almost always meet this requirement, specialized, long lead time items may not. However, if the lead times are assessed correctly, they will almost always meet this requirement. This correct assessment requires working with the (chain of) vendor(s) to understand the true lead time. I found that even though production planning is aware of the true total lead time, when the control gets down to the level of the individual purchasing agent, strange things happen to the lead times. As a case in point, one system with a total lead time of approximately 200 days was treated as having a 40 day lead time by the purchasing agent who "wasn't going to let them [the vendor] get away with that kind of lead time." This purchasing agent actually understood the constraint on lead time, which was a set of custom manufactured integrated circuits, and in reality he worked with this long lead time by releasing purchase orders to authorize the requisition of these materials with the proper advance notice. The 40 day lead time that he entered into the MRP system was a lead time that he used to "lock in" orders for delivery to PictureTel. The point is that the recorded lead times must be questioned before they are used. In this case the 200 day lead time should be used, not the 40 day time (which does not meet the definition of lead time for the model.)

One case in which the independent lead time requirement will not be met is the case in which the vendor is capacity constrained. If the vendor is already delivering goods as fast as he is able, then orders may be placed at a rate faster than the vendor is capable of filling them. In this case the model will not generate accurate results. I will present a method to use the model to estimate the cost of this capacity constraint.

Individual Inventory Items are Independent of Each Other: This assumption has potential impacts in each of the three cost categories. In the category of order cost there are two issues. First, if multiple items are ordered from the same vendor and there are economies of scale in ordering (i.e. the order cost for ordering two items at once from the same vendor is less than the order cost for ordering a single item) then this should be reflected in the order cost. A mechanism for this is included in the model . Second, if the same item may be ordered from multiple vendors, then the order cost may be different for each of these vendors. In this case the user must use one order cost in the model. As long as the order costs are similar, this assumption will have negligible effect. If the costs are significantly different, and all vendors must be used (due to capacity constraints, etc.), the user may manually take a weighted average of the different order costs[21] and use this data in the model.

In the category of holding costs I assume that there are no interactive effects. Though there may be effects in a capacity constrained facility where there may be higher incremental costs of storage for certain items, I assume that this is not the case. Since capacity is assumed to be unconstrained, holding costs are assumed to be proportional to item cost and independent of the levels of other items.

Stockout costs are hard to estimate to begin with, and the interactive effects of multiple items confuse the issue. This becomes an issue when there are multiple line items on a purchase order, which is almost always the case, where one item may hold up an entire shipment. However, items can be considered independent for this model if the stockout costs for each item are assigned with this dependency taken into account, i.e. when assigning a stockout cost to an item, the user must estimate the stockout cost of an individual item based on the effect of that item on a multiple item shipment. For example, a ten dollar power cord for a $50,000 videoconferencing system would probably carry a stockout cost closer to the stockout price of the system than to the incremental lost revenue of this single power cord. Stockout costs will be discussed in more detail later in this chapter.

While many assumptions must be met for this model to be used, in many cases these assumptions are all already met. In other situations, which will typically be the cases of high cost, long lead time items, more care must be exercised in the use of the model. But the user would naturally exercise more care in dealing with these items, so this is not an alarming revelation. It is in these cases that sensitivity analyses will be especially valuable as they will help the user to understand the major cost drivers and hence the leverage points for system improvement.

Translating Equation Variables Into Meaningful Quantities

While we have reduced the problem to a manageable form, the parameters specified above must be specified in terms that have meaning to people who actually make the decisions. While terms such as "reorder point" and "cost" have easily interpretable meanings in both the mathematical equations and in the real world of inventory management, terms such as "holding cost" and "standard deviation of demand over lead time" do not have meanings that can be directly and easily interpreted in the real world.

Total Cost Model

A model is a representation of a portion of the real world. We can use a model to test a hypothesis we have about the real world. If the hypothesis is proven to work in the model, then

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[21] As will be discussed later in this chapter, the order cost has many components. The user should be careful to include all components in such a weighted average.

we can try it in the real world with more confidence. In this sense a model is a proving ground for policies we intend to use in the real world.

For a model to be useful then, the model must be built to accurately represent the world in areas that affect us. The model must interface well with the world. It must take as its inputs data that are available in the real world and must deliver results that have meaning in the real world.

With this in mind I describe the total cost model that is built off of the mathematical equations presented above.

The fundamental components of the total cost model were presented in Figure 6, but while this level of detail may be sufficient for theoretical consideration, it does not reflect the form in which data are available in the real world. A diagram that represents the data elements and their relationships within the model is presented in Figure 9.

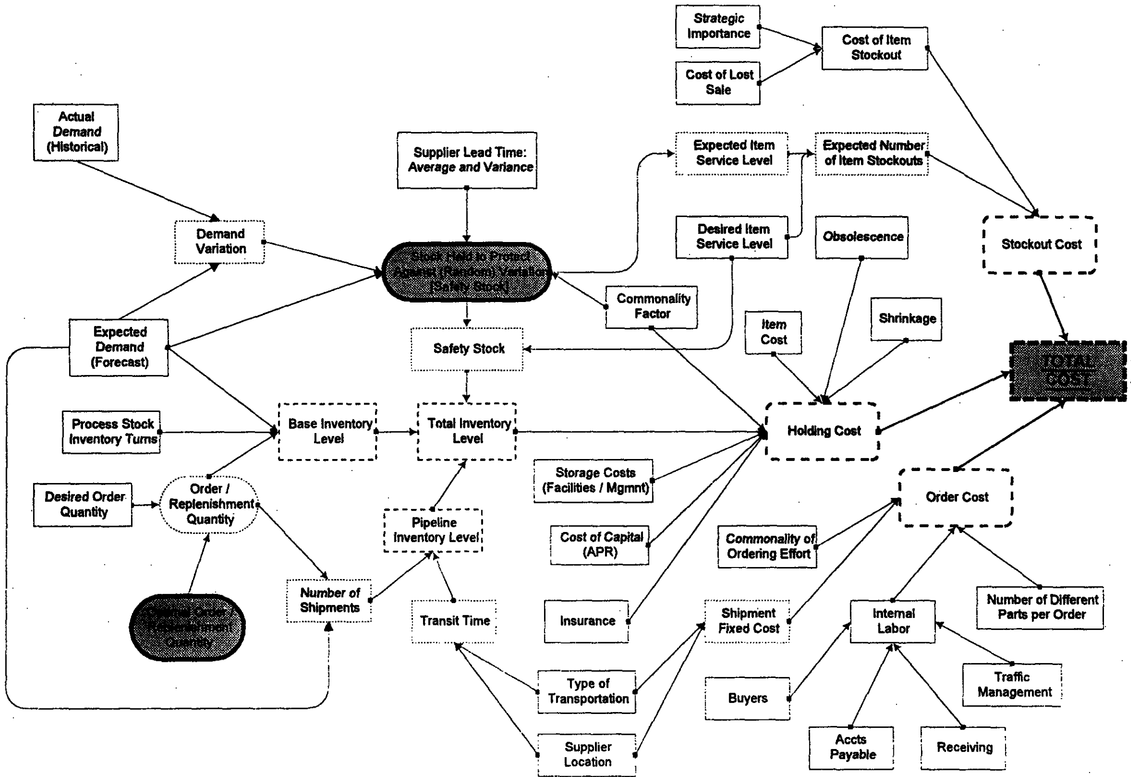

Figure 9 - Total Cost Model Diagram

The user is ultimately concerned with the total cost, which is represented by the dark box on the right hand side of Figure 9. The total cost here, as in Figure 6, consists of the holding cost, the order cost and the stockout cost.

Solid boxes represent pieces of data that are input by the user. These data are put into the model in forms that are available to the user. Dashed boxes represent variables that are calculated from this data. The dark, oval boxes represent the two optimized decision variables, order quantity and safety stock level.

Model Form

The model is in the form of a Microsoft Excel© workbook. This format was chosen because it is a standard for PictureTel and its employees are familiar with it.

The model is composed of three integrated sections. The first section is an Activity Based Costing model. By entering various data about the logistics system, the user can understand the impact on costs, inventory levels, service levels, etc. The second section is an optimization algorithm (based on Equation 1) for determining the optimal safety stock and order quantity for the item, given the user entered data. The user can choose to use the optimization function, or to choose his own order quantity and service level. The third section is a simulation model. Given the information entered in the other model sections, the user can simulate the behavior of inventory levels over a two year period. This section serves two purposes. First, it gives the user the added benefit of being able to visualize the behavior of the inventory as opposed to just looking at the numbers. Second, it allows the user to test the ABC / optimization models. The user may choose the "simulate" function which runs a selected number of simulations and compares simulation results to the predicted optimization model results.

Model Parameters

In this section I will describe the model inputs, as diagrammed in Figure 9, and their relation to the parameters of Equation 1, which is the root of the model and is reproduced below for convenience.

$$TC(Q,r) = \frac{D}{Q}S + IC\frac{Q}{2} + ICr + \frac{D}{Q}ksN(z)$$

where $z = \frac{r}{s}$ is the unitized value of safety stock and

D	is the annual demand [items]
Q	is the order quantity [items/order]
S	is the order cost [$/order]
I	is the inventory carrying cost as an annual percentage [%]
C	is the cost of the item [$/item]
r	is the safety stock level [items]
k	is the stockout cost [$/stockout]
s	is the standard deviation of demand over the lead time [items]
$N(z)$	is the unit normal loss function
$sN(z)$	is the expected number of stockouts in an order interval [stockouts/order]

All of the following parameters are entered into labeled cells on the sheet titled "User Interface" in the Microsoft Excel© Workbook. This interface is reproduced below in Figure 10, Figure 11 and Figure 12. Cells with values are user changeable values. Other cells explain the variable and its unit of measure.

Basic Data

Part Number	520-0510-02	(optional)
Description	pc box, isdn, 1.(	(optional)
Inventory Class	A	A,B,C,D
Value of Part	$ 2,684.11	dollars
Demand Data		
Annual System Demand	5200	systems / year
Additional Demand	0	parts / year
Part Qty per System	0.47	parts / system
Demand Std Dev	27	systems / week
Supplier/Trans Data		
Lead Time Average	40	days
Lead Std Dev	0	days
Distance from Supplier	3000	miles
Transportation Type	A	L,S,A,O,V
Stockout Costs		
System Stockout Cost	$ 2,000	dollars
Extra Order Cost	$ -	dollars / order

User Specified Quantities

Service Level	90%
Order Quantity	100

Figure 10

Advanced Data

Inventory Process Time	0	weeks	
Commonality of Purchasing Effort	0%	0 - 100%	
# P/Ns Purchased from Vendor	2	parts	
Strategic Importance	5	1=Low; 5=Average; 10=High	

CONTROLS

Optimized = 1; NOT Optimized = 0	1	Toggle

Update

Output

$400,112	inv level
$153,564	ann cost
98.88%	service level
55.8	EOQ
101.1	safety stock
129	avg whse inv lev
8.3	days btwn order
2444	ann dmd
40	LT
$2,684.11	cost

Figure 11

Model Reference Data

Procurement Costs

Item Class	A	B	C	D	Hourly Rate
Purchasing hours	5.00	3.00	2.00	2.00	$ 40
Accounts Payable hours	0.25	0.25	0.25	0.25	$ 40
Receiving hours	0.25	0.25	0.25	0.25	$ 40
Traffic Management hours	1.00	0.50	0.00	0.00	$ 40
Total	$ 60	$ 40	$ 20	$ 20	

Transportation Costs

Code	Transportation Type	Fixed Cost / Shipment	Trans Time
L,S,A,O,V	L,S,A,O,V	$	miles / day
L	Land	$ 10	250
S	Sea	$ 100	500
A	Air, Standard	$ 20	1000
O	Air, Overnight	$ 30	3000
V	Vendor	$ -	250

Holding Costs

Obsolescence	9.7%
Cost of Capital	23.0%
Storage	2.7%
Insurance	0.069%
Shrinkage	1.0%
Total	36.5%

Figure 12

Annual Demand, *D*: Annual demand is the expected value of demand from the forecast. Though the terminology reflects the assumption that the user is planning over a one year (annual) time horizon, this is not a constraint. Any time horizon is appropriate as long as all variables (*D*, *s* and *l*) are scaled accordingly. There are three pieces of data that determine the annual demand. In Figure 10 they are "Annual System Demand", "Additional Demand" and "Part Qty per System". This format is designed to support the focus of planning around videoconferencing systems, as this is the level of aggregation at which the forecast is created. The expected annual demand for the system is entered in the cell titled "Annual System Demand". Since there is usually not a one-for-one correspondence of individual items to systems, the expected ratio of this inventory item usage to total system demand is entered in the cell titled "Part Qty per System". This ratio can be found in MANMAN. Any demand for the item beyond the quantity used in the system under consideration is entered in the cell titled "Additional Demand". This entry accounts for the item's use as part of other systems, spare parts consumption, etc. If the item is not part of a system, then the entire expected demand may be entered into the "Additional Demand" cell and the other cells left blank.

Order Quantity, *Q*: This is one of the two decision variables in the model. The user can select to use the optimized value which the model calculates or a user chosen value which is entered in a separate cell. The optimal quantity is displayed in the cell labeled "EOQ" in Figure 11. The user specified quantity is entered in the cell titled "Order Quantity" in Figure 10.

Order Cost, *S*: There are two main components of order cost: labor and transportation. The internal PictureTel labor is expended in four business areas: purchasing, accounts payable, receiving and traffic management. Interviews indicated that, in certain areas, the amount of time spent per order could vary greatly, but that the time spent was proportional to the inventory item classification[22]. The "Procurement Costs" matrix in the model, as shown in Figure 12, contains the average hours spent per order, by inventory class. It also contains the hourly rate for employees in these areas. The "Total" is the sum of the time spent in hours multiplied by the hourly rate in dollars per hour. The user indicates the inventory classification by entering the code letter (A,B,C,D) in the cell titled "Inventory Class" as shown in Figure 10. This causes the model to select the appropriate cost from the "Procurement Costs" matrix.

Also in Figure 12 are listed the transportation data, under the title "Transportation Costs". Under the column titles "Fixed Cost / Shipment" are the estimated fixed costs per shipment. The values displayed in Figure 12 are for small package type shipments. These are the costs incurred regardless of shipment size or location. There are five categories: Land, Sea, Air, Standard Air, Overnight Air and Vendor. "Vendor" indicates that the vendor delivers the goods F.O.B[23]. PictureTel's receiving dock. The user indicates the mode of transportation by entering the code letter (L,S,A,O,V) in the cell titled "Transportation Type" as shown in Figure 10. This causes the model to select the appropriate cost from the "Transportation Costs" matrix. These costs will change infrequently and are expected to remain constant for most of the items, so I expect that these data will not be changed very often. I therefore include a third component of order cost in this model to allow the user to easily adjust this cost to a particular situation. The category "Extra Order Cost", as shown in Figure 10, is added to the other order cost. A positive value will increase the order cost used in the model and a negative value will decrease it.

Inventory Carrying Cost, *I*: This parameter, measured as an annual percentage rate, is the cost to the company of having their cash tied up in inventory. It is composed of four parts as can be seen by examining Figure 12. These are obsolescence, cost of capital, storage and shrinkage. These individual rates are calculated in Appendix A.

Cost of the Item, *C*: This variable is entered in the cell titled "Value of Part" as shown in Figure 10. It is the cost that the vendor charges to PictureTel the current price may be found on MANMAN.

Safety Stock Level, *r*: This is the other of the two decision variables in the model. The user can select to use the optimized value which the model calculates or a user chosen value which is entered in a separate cell. The optimal quantity is displayed in the cell labeled "safety stock" in Figure 11. The corresponding service level is displayed in the cell labeled "service level" in Figure 11. The user specified quantity is entered indirectly by specifying a service level in the cell titled "Service Level" in Figure 10.

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[22] I am referring to the "ABC" type of inventory classification commonly used in operations management and discussed later in this thesis.
[23] Free On Board

Standard Deviation of Demand Over Lead Time, *s*: The standard deviation of demand over lead time is affected both by the demand distribution and the lead time distribution. Assuming the demand and lead times are independent random variables, if the lead times are deterministic, then the standard deviation of demand is scaled by the square root of the lead time. (See Equation 5, below) In interviews with purchasing agents I could rarely find an example of a non-deterministic lead time. PictureTel's vendors, in the vast majority of cases, deliver the item at the quoted lead time. The variables required to determine *s* are entered in the cells "Demand Std Dev", "Lead Time Average" and "Lead Std Dev"[24] as shown in Figure 10. The calculation of the standard deviation of demand is discussed in Appendix I.

Treatment of Deterministic vs. Stochastic Lead Times

Though in the current situation almost all of the lead times can be treated as deterministic I have included the provision for stochastic lead times in the model so that the user can experiment with them to understand their (adverse) consequences. If lead times are deterministic, then, in Equation 1, the parameter *s*, the standard deviation of demand over the lead time, is easily determined from the customer demand distribution[25]. If lead times are stochastic, and if we assume that the lead time, *l*, and the demand rate, *d*, are independent random variables (and that time increments are independent), then it can be shown[26], as by Drake[27] and others, that

$$E[x] = E[l]\,E[d]$$

Equation 4

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[24] Note: in the model the demand *s* is entered in items/week while the lead time data is entered in days, the units conversion is made inside the model. The different units were chosen to reflect the normal units of consideration in the company: lead time is entered in units of days in MANMAN while demand planning is done in buckets of (at least) weeks.

[25] See Appendix I.

[26] As pointed out by Silver, the preferred method for determining the distribution of *x* is to estimate it from empirical data.

[27] Drake, 1967

and

$$s = \sqrt{E[l]s_d^2 + E[d]^2 s_l^2}$$

Equation 5

where:

l:	lead time [days]
s_l:	standard deviation of lead time [days]
d:	demand rate [items/day]
s_d:	standard deviation of demand [items/day]
x:	total demand over the lead time [items]
s:	standard deviation of total demand during lead time [items]

Upon inspection of Equation 5 the reader will note that when the variance of the lead time is zero, then the standard deviation of demand over lead time is equal to the standard deviation of the demand rate scaled by the square root of the lead time, as we would expect.

Unit Normal Loss Function, ***N(z)***[28]**:** The unit normal loss function is used to calculate the expected number of inventory items stocked out, given the fact that a stockout did occur. In other words, the expected value of demand is the forecasted value[29], but if we just carried this expected value, then 50% of the time, we would not have enough inventory in stock to satisfy demand. For this reason we carry safety stock. Now, we try to carry an optimal amount of safety stock,. i.e., not too little and not too much. From time to time though, demand will exhaust even our safety stock supplies and we will be in a stockout situation. When we get in this situation we want to know how many backorders we expect to have before the next shipment arrives. The unit normal loss function is used to determine this quantity. Given that we are in a stockout situation, it tells us how many backorders we expect to have. This function is entered in the model as a lookup function on a hidden worksheet.

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[28] For further information see Magee et al., 1985; Nahmias, 1993

[29] If the forecast is unbiased then 50% of the time the actual value of demand should be less than the forecast value and 50% of the time the actual value of demand should be greater than the forecast value.

Stockout Cost, *k*: The stockout cost is probably the most difficult model parameter to estimate. I will present some factors to consider in this estimation process and discuss a sensitivity analysis that will help contain the problem. Regardless of the estimation process, the value of stockout cost is entered in the model in the cell titled "System Stockout Cost" as shown in Figure 9. Since stockout cost is difficult to estimate, most companies avoid the issue by directly selecting a service level. This selection is typically based upon some benchmarking study where the company compares themselves to the industry norm and the industry best-in-class. While this method certainly has its merits, I would argue that everyone who has a say in determining inventory levels has in his head some implicit stockout cost. I believe that it is better to make this cost explicit, as this facilitates more consistent decision making and forces the person to question his own assumptions.

As an example of this, I present the concept of "strategic stock" as described to me by the materials manager at PictureTel. During my conversations with this manager I learned that in addition to his safety stock, he also maintained a "strategic stock" of some items. I initially assumed that, since it was an augmentation to the safety stock (which is maintained to protect against random variation), it was used when a supplier was more unreliable than normal or when demand for that item had a greater variance than the norm. As I tried to quantify this variable though, I found that this was not at all the reason for holding strategic stock. Rather, the reason was that if these items were not in stock, the manufacturing process would be seriously disrupted, meaning that product assembly could not be completed and the product shipped. I believe that what this manager was really saying was that the ratio of stockout cost to value for these items was greater than average. In his implicit mental model, he dealt with this discrepancy by jumping straight to the solution of adding more safety ("strategic") stock. In an explicit model we would deal with this by assigning the proper stockout cost. If the item was critical to the system assembly, we would probably assign it the same stockout cost as the system. If the item is inexpensive, the model will recommend a high safety stock level, just as this manager knew he had to have. The advantage of using this model in a case such as this is that the user can quantify the effects of his decisions and estimations.

Estimating Stockout Cost: A good starting point for the process of estimating stockout cost is the average selling price of a system. The price of the system, less the cost of the goods gives the gross margin for this system. Now let's suppose that a single stockout resulted in the loss of exactly this one sale and hence this margin, would this be the stockout cost for the system? Many people would argue that the stockout cost is actually greater than this because by not having the system in stock when the customer wanted it, you have created long term ill will with that customer, which will result in future lost revenue.

I argue that the stockout cost is greatly affected by the maturity of the product. If the product is very mature, such that it is commodity-like and can be procured readily from any number of vendors, I would argue that the stockout cost is very close to the forgone gross margin. As a consumer, if I can't buy a commodity at the first place I shop, I can easily turn to another supplier for that good. If I have a vendor which I normally turn to and this stockout situation happens only rarely with this vendor, I will probably bear no long term ill will against this particular vendor, and this stockout instance will not dissuade me from turning to this vendor the next time I need a good. At the other end of the spectrum, if a good is very new, and there are a limited number of vendors that can provide this good, these vendors each will have near monopoly power[30]. In this case I would argue that the cost of a stockout would be less than the gross margin foregone. Over some time horizon[31], the more monopoly power the vendor has, the less the stockout cost. The existence of a backlog lends support to this, as it shows that, at least some, customers are willing to wait for their orders. So it is within some region between these extremes that the stockout cost would be greater than the foregone gross margin. This concept is illustrated in Figure 13.

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[30] Other factors may increase this near monopoly power. One such factor in PictureTel's case is a first mover advantage. Many companies have already made a relatively large investment in PictureTel equipment. In order to maintain compatability with the previously purchased systems, they must continue to purchase PictureTel equipment in the future. At the current time these companies really have little choice but to wait for equipment to become available.

[31] Continuing the topic of footnote 30, if, at some point in the future, the compatability issue becomes a non-issue, a company that has been forcing customers to wait long periods of time to get their orders may rapidly lose market share. Therefore, it is dangerous to carry this reasoning too far.

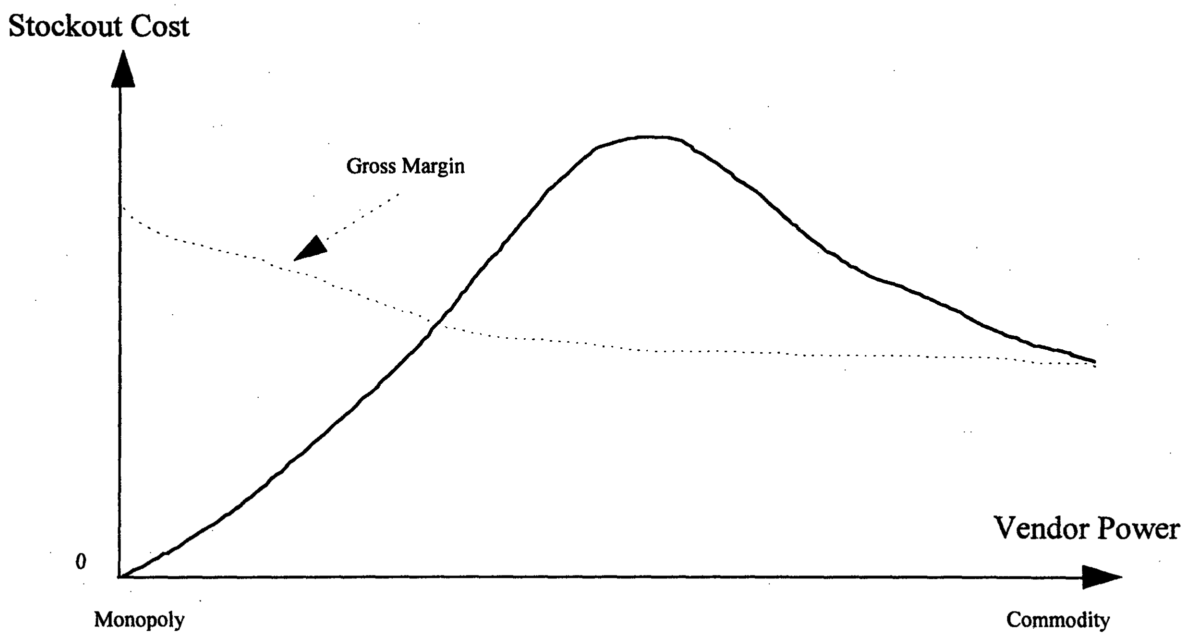

Figure 13

Because of PictureTel's strong position (approximately 50%) in the market I would argue that they are currently positioned towards the left hand side of this graph and have a system stockout cost that is less then the gross margin. However, as the market becomes more competitive and product substitution becomes possible, they will move to the right side of the graph.

Regardless of the assumed stockout cost, sensitivity analyses should be used to understand the sensitivity of inventory policy decisions (especially safety stock levels) to the stockout cost. Such a sensitivity analysis is graphically displayed in Chart 5, below.

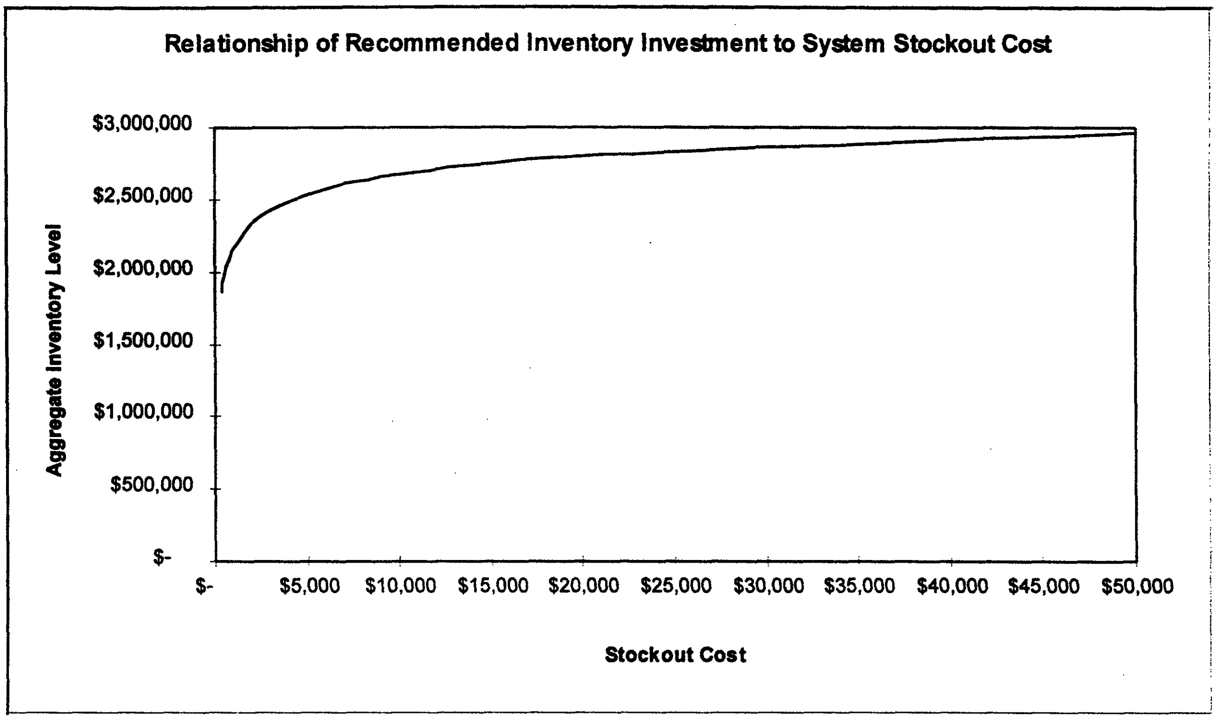

Chart 5

This chart shows the relationship between recommended inventory investment and stockout cost for one of the GSD product families. The inventory investment includes all items listed on the first level bill of materials for the product family. Inspection of this figure reveals that inventory level is more sensitive to changes in stockout cost when stockout cost is low than when it is high. This product sells for $9,000 to $15,000 and has a gross margin of $6,000 to $10,000. When people argue that the stockout cost should be several times the sales price as opposed to just the sales price, the difference in the result is only a few percent. The big changes come when the estimation of the stockout cost is less than the gross margin. A stockout cost equal to a gross margin of $6,000 corresponds to an inventory investment of approximately $2.5M, while a stockout cost of $1,000 corresponds to an inventory investment of approximately $1.8M.

Individual Item Stockout Cost: I have been discussing the system stockout cost to this point. Individual inventory items may have very different stockout costs from the system stockout cost. Some items can be safely estimated to have the same stockout cost as the system. These components are those that are critical to the shipment of the system and might include such items as the system box, the camera, the power cord, etc. Other items may be judged to not be critical to shipment and hence be assigned a smaller stockout cost. This downward adjustment should be made only after carefully considering the customer requirements, not just the company's policy on when a shipment may be made. For example, the company may say it is all right to ship product without an auxiliary microphone or without the documentation for the system. Not receiving one or the other of these items may have very different consequences for the customer. While the customer can operate the system without the auxiliary microphone, he may not be able to use the system at all without setup and operating instructions. So these items, while they may be in the same category for deciding whether to ship or not, they do not necessarily have the same stockout cost. The system stockout cost is a good reference point for estimating item stockout cost, but the implications of stocking out of that items should be carefully considered before adjusting the stockout cost downward.

Another factor to consider in estimating item stockout costs is the interactive effect mentioned earlier in the chapter. While several ancillary items may each be assigned a small stockout cost because any one of them will not stop a shipment by itself, several of these items stocked out at once may stop a shipment. While the model will calculate optimal service levels for items considered independently, these do not necessarily reflect the aggregate service level. The user needs to consider the service level from a systems perspective, not from an item perspective. In the best case, if the inventory levels of these items are perfectly positively correlated, then the aggregate service level will be equal to the lowest service level of an the individual items. In the worst case of perfect negative correlation of some components, it will be impossible to ever make a complete shipment. If the items levels are considered to be independent random variables, then the service level for a group of items will be the product of their individual service levels.

This multiplicative effect can reduce the effective service level quickly. For example, if the service level for each of 15 independent items is 99%, the aggregate service level will be 86%. Large improvements in aggregate service level may be realized though by correct investment in inventory. To continue this example, say that ten of these 15 items are fairly inexpensive. If we increase the service the service levels of these parts to 99.9% and maintain a 99% service level of the other parts, then the aggregate service level rises to 94%. These types of considerations can help in estimating stockout costs and while using the model in general.

Stockout cost is indeed very difficult to estimate. I have provided some guidelines for thinking about system stockout cost relative to the nature of the product and the competition. I have also discussed some factors to consider when estimating the stockout cost of an individual item. The responsibility for estimating a stockout cost ultimately lies with the decision maker within the company. Everyone has some implicit stockout cost they use when making inventory decisions. I argue that it is better to make these estimates explicit and to leverage the knowledge of many different parts of the organization in trying to estimate stockout costs.

Advanced Data: "Inventory Process Time" allows the user to enter the time required to process inventory that is received at the inventory site. Though this quantity will most likely be zero, at the current time it is included to allow the user to understand the effect of having inventory wait in a queue to be processed.

The "Commonality of Purchasing Effort" and "#P/Ns[32] Purchased from Vendor" are included to capture the economies of scale in order multiple items from one vendor. A commonality of 0% means that there is no economy of scale, i.e. the items may just as well be ordered separately. A commonality of 100% means that the incremental cost to order another item is zero, i.e. it costs the same to order one, two or ten items on one order. In this (100%) case, the current item is assigned an order cost of (1/ # items). For example, if there are two items ordered from this vendor, the order cost for the current item is cut in half. The relationship between the two commonality endpoints (0 - 100%) is linear.

Controls: This section of the model provides an interface for the user to control the model behavior and the calculation of the model[33]. Clicking the "Update" button causes the model to

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[32] P/Ns stands for part numbers. A part number has the same meaning as "item" in this thesis.

[33] Since the simulation feature of this model requires lengthy calculation, the calculation mode of the workbook has been set to manual. It is recalculated when the update button is clicked.

recalculate and must be clicked after new data is entered. The "Toggle" button causes the model to toggle between using the optimized decision variables and the user selected decision variables. The current mode is displayed. The update button must be clicked to update the model after a change to the mode.

The model also has a simulation feature. When this feature is used, the model runs a simulation of inventory levels, in daily increments, for a two year period. The simulation is based off of the current model parameters and follows the reorder policy described in the section titled "Reorder Point". The daily demand is a random variable drawn from the normal distribution with the parameters specified on the "User Interface" sheet for mean and standard deviation of demand. (See Figure 10.) The lead times are also random variables drawn from a normal distribution with the parameters specified for the lead time on the "User Interface" sheet. To run, and watch, a series of simulations, select "Simulate" from the Tools menu.

Other Model Variables, Parameters and Outputs: "Part Number" and "Description", while not used in the calculations, are included in the model (Figure 10) so the user can keep track of the item he is modeling. "Distance from Supplier" is used, in conjunction with the transportation type to calculate average pipeline stock. The carrying cost for this pipeline inventory is included in the total annual cost ("ann cost", Figure 11). Other model outputs include: the average number of dollars tied up in this item of inventory in the warehouse "inv level"; the corresponding number of items, "avg whse inv lev"; the average number of days between order placement, "days btwn order", to give the user a feel for the frequency of ordering; the total annual demand, "ann dmd", which is calculated from the demand raw data; mean lead time and item cost are also reproduced in the output section of the model.

Reorder Point

The model user is ultimately concerned, from an inventory control standpoint, with two outputs the order quantity and the reorder point. The reorder point, *R*, is the inventory level at which an order is placed. It is equal to the expected demand over the lead time interval, $E[x]$, plus the (optimal) safety stock, r, as shown in Equation 6.

$$R = E[x] + r$$

Equation 6

The purchasing agent must continuously[34] be looking at the expected demand over the lead time horizon and comparing this to the current inventory level[35]. When the current inventory level drops below the reorder point an order must be placed for the order quantity, Q.

For a stationary demand process, $E[x]$ will be constant as will the safety stock, and therefore so will be the reorder point. For a non-stationary demand process, the reorder point is described in the same way, except that the expected demand over the lead time interval, x, is not constant, but will vary as does the forecast. Therefore the reorder point will also vary.

Model Use

The model is designed to be used by persons responsible for managing inventory. Rather than present an exhaustive description of its use here, descriptions of its use will be presented throughout the remainder of this thesis.

The user should be careful to keep in mind that this model, like any model, is a **model** of the real world. As such, it is a simplification of reality. Though I have designed this model to be as accurate and complete as possible, it is only as good as the data and assumptions that go into it. The user should not treat this model as a black box that is guaranteed to give the optimal answer without fail. It should be used for the purpose for which it was designed: to **help** the inventory manager make intelligent, profit maximizing decisions. It helps the manager by forcing him to

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[34] Hence the term "continuous review" in the title of the inventory control policy. Continuous review certainly is interpreted within reasonable limits. Depending on the consumption rate, this could be several times a day, or once a month. The use of modern information technology systems can help to automate this process as the computer can generate an alarm whenever the level drops below the reorder point.

make explicit and quantify his implicit estimations of parameters and allowing him to understand the, sometimes, counterintuitive effects of varying these parameters.

This model is used to aid in controlling inventory at a location very near the end of the supply chain. The user needs to keep the entire system in perspective and realize that some of the greatest leverage points for inventory control are at upstream (supplier) locations.

Chapter Summary

In this chapter I presented the general multi-location, multi-item inventory management problem, discussed some of the complex issues associated with this problem, showed how simpler models can be used to help solve this problem and presented a such model. This model is called the "Total Cost Model" as it attempts to capture all costs associated with inventory.

I chose this modeling technique because I believe it to be the best for PictureTel's current situation. The material flows are simple enough to model this way and this technique tightly couples the decision maker to the problem.

As this model decomposes a complex, interrelated system into a set of independent models, the interactive effects in the system must be dealt with by the user. I have presented some considerations and guidelines to help the user think about these things.

This model, like any other model, is only valid under certain assumptions. These assumptions were laid forth, as were certain guidelines to help in estimating the model parameters.
This model allows the materials manager to use available data to assist in decision making.

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[35] The inventory level is defined as the quantity on hand plus the quantity on order.

It allows him to evaluate the costs of the system (current or proposed) with an Activity Based Costing methodology and to optimize the decision variables if he so chooses. The simulation function allows the user to visualize the behavior of inventory levels over time. This feature provides a richer interface and allows the user to gain a more intuitive feel for the effects of his policy decisions on inventory levels.

Chapter 4: Analysis of Forecast and Inventory Control

Introduction

Although PictureTel's supply chain is structurally simple, it has proven difficult to control. Signs of this are evident in analysis of inventory levels as well as in inventory turns, benchmarking studies and accounting write-offs for obsolescence.

In this chapter I discuss two business functions that that have large effects on inventory levels: the forecast and the inventory control policies.

Indicators of Inventory Problems

Inventory Turns: Over the years 1990 - 1995 PictureTel had an average inventory turn of 3.6. Though it appeared that the turns ratio was improving until 1994, the turns for 1995[36] (3.3) were significantly less than 1994 (4.7) and less than the average. Even in its best year, PictureTel's turns were not good by industry standards. This data is presented in Figure 15, below, and in Appendix B.

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[36] 1995 data based on January - October 1995 data.

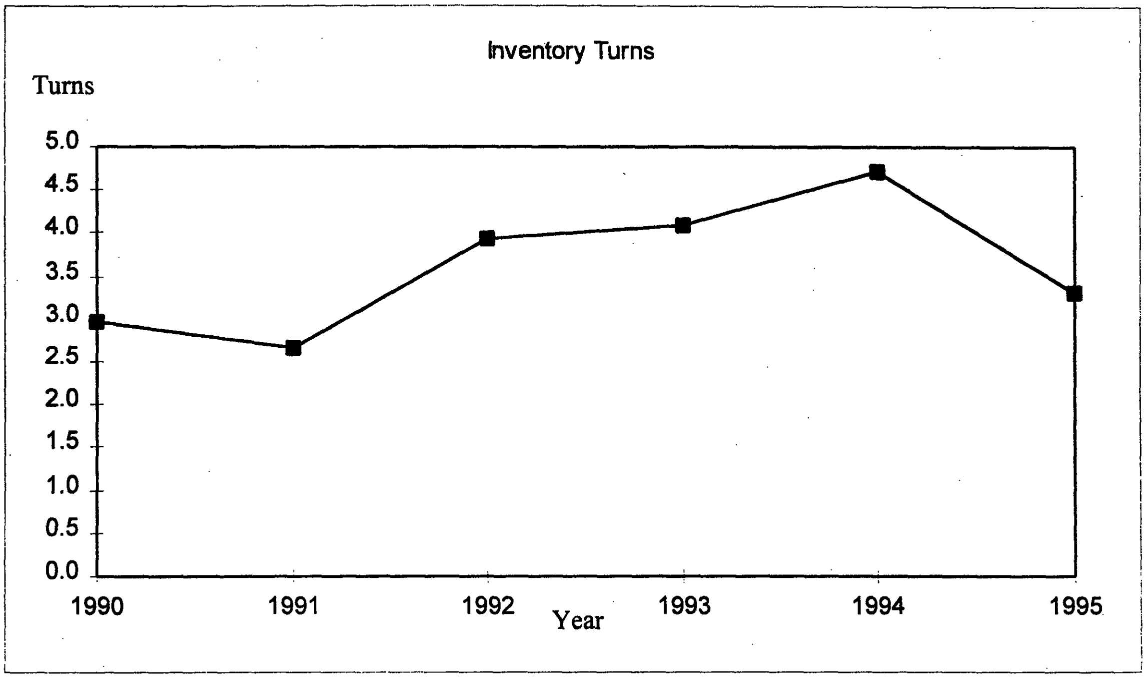

Figure 14

Benchmarking Study: A study performed by the management consulting firm Pittiglio, Rabin, Todd & McGrath (PRTM) found that for their "Delivery to Commit" metric, PictureTel's Personal Systems Division's performance was 55% and their Group Systems Division's performance was 82% compared to industry averages of 83.5% and 90%, respectively.

Accounting Write-Offs: PictureTel has been writing off large dollar amounts of obsolete inventory every year. The annual write-off has been almost 10% of the average annual inventory value. Data and analysis are presented in Appendix C.

Inventory Levels: Like most companies, PictureTel faces the problem of having inventory levels of some goods that are too high, resulting in excess costs, and having inventory levels of other goods that, from time to time, are too low, resulting in stock outs. The latter cases are often the only ones recognized. When the company has stocked out of a component, it becomes obvious because that stock out holds up a shipment. At this point, the purchasing agent (and at least his immediate boss) begin a firefighting procedure, attempting to expedite the arrival of that component so that the shipment may be made. Inventory shortages cause these people to operate in a reactionary mode as they attempt to minimize the perceived stockout cost. Meanwhile, hundreds or thousands of other components rest in the warehouse at levels that are too high, tying up expensive capital and wasting away their useful lives. Costs are incurred in both cases, stock out costs for the former and holding costs for the latter.

Explanation

There are two major operational policy problems that are contributing to excessive inventory costs. These are the forecast procedure and the inventory level management policies. We will see that the forecast is biased, and, although PictureTel has a good method in place for collecting data on the forecast accuracy, they are not using this data to improve their forecast procedure. I will suggest a double-loop learning process that the company can use to adjust the forecast procedure and hopefully eliminate the bias and other problems. We will see that the inventory level controls have been insufficient and make recommendations for improvement using the total cost model.

Area 1: Forecast

The components of PictureTel's major product families have lead times that exceed seven months. With such long lead times, forecast accuracy is a significant driver of inventory costs. Forecasts that are over-optimistic result in excess inventory and hence holding and obsolescence costs. Forecasts that are too pessimistic result in inventory shortages and hence stockout costs. Forecasting is complicated by the fact that each product family has many possible configurations. These different configurations exist to make the system compatible with different types of communications equipment and available in different languages.

As can be seen in Figure 3, PictureTel operations personnel are responsible for inventory management. The business lines deliver the forecast to the planning and purchasing functions.

Ideally these forecasts would be unbiased and the materials manager would make decisions about inventory levels based on the expected value of demand and the variance of demand. An analysis of forecast accuracy for January to August 1995, however, reveals that the forecasts are biased. Examining the one month out, forecast error over these eight months for five products revealed only three instances (out of forty) of underforecasting. In other words, 92.5% of the forecast points were greater than actual, leaving 7.5% of the forecast points that were less than actual. In an unbiased forecast we would expect these numbers to be 50% / 50%.

Why is this the case? While PictureTel has a detailed forecast procedure, there are no mechanisms in place to monitor forecast accuracy and make adjustments. The forecast procedure is purely linear. The forecast originates with sales and is eventually handed over to the operations people who are responsible for planning inventory levels. The people who are responsible for maintaining the proper level of inventory are handed an overly optimistic forecast without having been given the opportunity to adjust it. An example of this shown in Figure 15 which graphs the forecast of GSD total sales one month out (upper line) and the actual sales (lower line). The reader can clearly see the bias in the forecast.

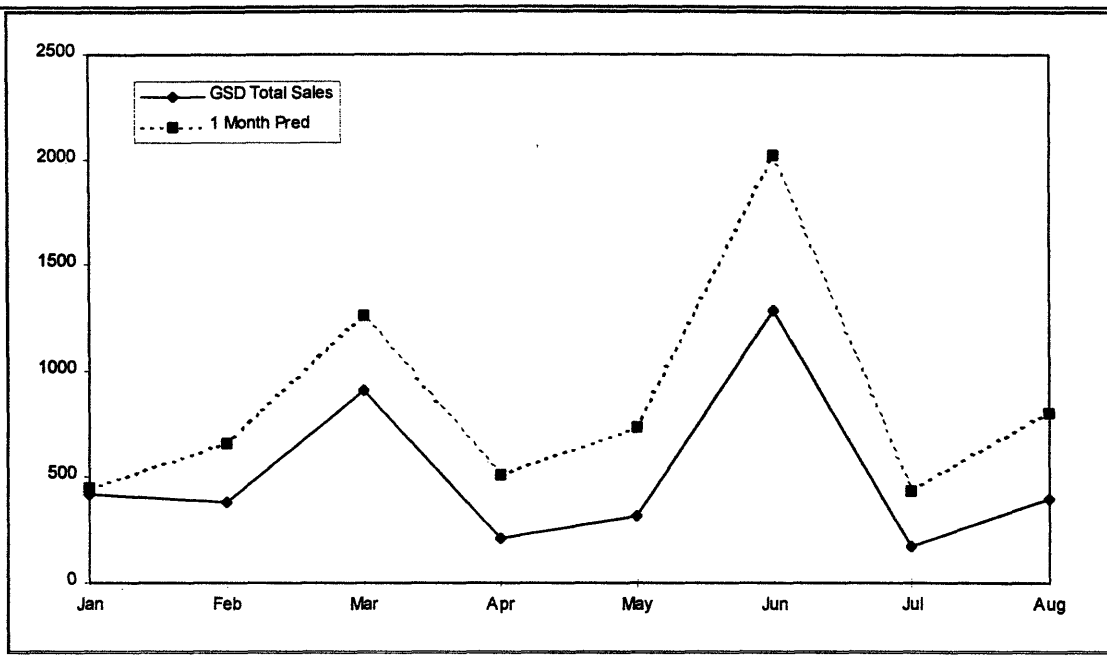

Figure 15 - Forecasted and Actual Total GSD Systems Sales

This bias is significant. Forecast bias data is presented in Table 2 for each of the major GSD product lines. The reader will note that, in three of the five product lines, the average forecast error is over 100%, which means that, one month out, the forecast was to sell more than twice as many videoconferencing systems as actually sold. For an average month, actual sales were 908 systems, but the forecast was for 1,444 systems (908 + 536). This amounts to more than $3,000,000 in inventory, which is approximately 9% of the average inventory level for 1995. If operations does not back this bias out, the result is that PictureTel carries this as excess inventory at a carrying cost of over $1,000,000[37] per year.

37 ($3,096,875)(36.5%) = $1,130,359 [see Appendix for 36.5% holding cost explanation]

1 Month Forecast Error (FE)					
System	Mean Sales	Mean FE	FE as % of Sales	Estimated System Cost	Total Cost
S1000	56	-99	-177%	$ 8,000	$ 789,000
S2000	50	-57	-115%	$ 6,000	$ 341,250
S4000EX	276	-172	-62%	$ 9,000	$ 1,550,250
S4000ZX	121	-9	-8%	$ 7,000	$ 63,875
Total S4000	397	-187	-47%		$ 1,614,125
M8000	9	-12	-138%	$ 30,000	$ 352,500
Total GSD	511	-349	-68%		$ 3,096,875

Table 2 - 1 Month Forecast Error and Inventory Investment Resulting from the Bias

One reason that the bias is so severe is that when the forecast for a month within the quarter is not met, the balance is pushed into the latter months of the quarter. For example, say that 200, 200 and 400 systems are forecast to be sold in months one, two and three of the quarter. If only 100 are sold in month one, instead of keeping the forecast the same or adjusting it down for months two and three, the balance of 100 systems is pushed into month two, making the revised forecast for months two and three, 300 and 400 systems. When only 100 systems are sold in month two, the balance is carried into month three.

This activity is a result of the quarterly revenue goal. PictureTel sets quarterly revenue goals for itself. This appears to be, in reality, the most important metric in the organization. If there is one thing that everybody at PictureTel knows, it is that they must make the quarterly revenue goal, no matter what it takes. This revenue goal drives the original forecast for a quarter, and a refusal to revise sales estimates throughout the quarter. This can be seen in the forecast waterfall chart[38] presented in Table 3. For example, look at the actual for May (190) compared to the previous month's forecast (464) the difference is 274. This added to June's forecast from April (775)

[38] The waterfall chart is a chart that is used to track forecasts of demand and actual demand. In this chart each column corresponds to a month, as does each row. Looking down each column you will find the forecasted values of demand for each future month in that year, as forecasted in the month named at the top of the column. When the column and row denote the same month, the value in the intersecting cell is the actual value of demand for that month. These cells are outlined. The falling diagonal pattern of these outlined cells gives the waterfall chart its name.

equals 1049, which is June's forecast in May. This does not happen without exception, but the pattern repeats itself across many months and many product forecasts.

S4000EX	Plan	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
Jan	290	338								
Feb	434	420	313							
Mar	725	691	817	712						
Apr	123	292	233	193	97					
May	185	438	350	290	464	190				
Jun	309	730	583	483	775	1049	394			
Jul	96	185	164	124	124	124	130	39		
Aug	145	277	246	186	186	186	195	225	127	
Sep	241	463	410	310	310	310	325	386	484	

Table 3 - Waterfall Chart of Forecast and Actual Sales

The effect of this problem on forecast accuracy is that, on average, the three and two month forecast accuracy's are better than the one month accuracy. This can be seen in Table 4, below.

1 Month Forecast Error (FE)			
System	**Mean Sales**	**Mean FE**	**FE as % of Sales**
S1000	56	-99	-177%
S2000	50	-57	-115%
S4000EX	276	-172	-62%
S4000ZX	121	-9	-8%
Total S4000	397	-187	-47%
M8000	9	-12	-138%
Total GSD	511	-349	**-68%**

2 Month Forecast Error (FE)			
System	**Mean Sales**	**Mean FE**	**FE as % of Sales**
S1000	56	-65	-116%
S2000	50	-81	-163%
S4000EX	276	-124	-45%
S4000ZX	121	-17	-14%
Total S4000	397	-141	-36%
M8000	9	-6	-66%
Total GSD	511	-292	**-57%**

3 Month Forecast Error (FE)			
System	**Mean Sales**	**Mean FE**	**FE as % of Sales**
S1000	56	-55	-98%
S2000	50	-110	-221%
S4000EX	276	-100	-36%
S4000ZX	121	-42	-34%
Total S4000	397	-142	-36%
M8000	9	-1	-14%
Total GSD	511	-308	**-60%**

Table 4 - 1, 2 & 3 Month Out Forecast Error

It is an interesting phenomenon that, in spite of this, PictureTel has always made its revenue goal. Even though the forecast is based off of the revenue goal, and the forecast is consistently not met, the revenue goal, which drove that forecast, is met. This question begs further investigation. Possible explanations for this phenomenon include that the average selling price for these products is not being accurately assessed in the revenue number that drives the forecast (i.e. PictureTel receives a higher average selling price than that which they plan to receive) and/or that the extra revenue is made up from services or other revenue generating activities. While this author did not investigate this matter, it certainly deserves further attention.

Improving the Forecast Procedure Using Controller Design Process

Operations personnel must have an unbiased forecast if they are to perform their jobs properly. In this section I shall evaluate the existing forecast process and make recommendations for improvement using the controller design procedure as a template. The short answer is that the sales force needs incentive to make accurate forecasts. Examining the situation systematically:

1. *Identify the outputs in which you are interested*: forecast accuracy measured by forecast error.
2. *Identify the desired values of these outputs*: unbiased forecast, i.e. expected value of the forecast error is zero.
3. *Identify ways to measure the actual values of these outputs*: use the existing waterfall chart, but add cells to track forecast error one month out, two months out, etc. as shown in Appendix D.
4. *Identify the inputs and process variables that affect the outputs*: the inputs and process variables are the personnel in finance, sales, and the business lines who formulate the forecast.
5. *Identify ways to measure the actual values of these inputs and process variables*: in addition to the current waterfall chart, an identical chart should be kept for each step in the forecast process that tracks the forecast accuracy at that stage.
6. *State your understanding of the cause and effect relationships between the inputs, process variables and the outputs*: in this process the personnel at each step can adjust the forecast however they choose.
7. *Create a controller that, in response to a discrepancy between the desired and actual system output, causes a change in the appropriate inputs or process variables so that the discrepancy will go away*: this controller is the key to getting an unbiased forecast. Since operations is ultimately responsible for the inventory levels which are affected by the forecast, they must push to get this controller process instituted. The process must interface properly with the sales personnel, as they are the people that are closest to the customer and should have the best reading on expected sales. The problem with the current forecast system

is that the sales force has it in their best interests to overforecast (so that systems are available in case they should happen to find customers for them). Unfortunately, under this system the originators of the forecast (sales) are not at all responsible for its accuracy and the people who suffer the consequences of a biased forecast (operations) have almost no say in it. The solution is to tie the sales force's bonuses to their forecast accuracy so that they have incentive to create forecasts that are in the best interests of the corporation.

8. *Connect the controller to a source of power, its inputs and actuators*: since the sales force, which controls the forecast, will be responsible for its accuracy, the controller is empowered to actuate change. They need to monitor forecast accuracy with the improved waterfall charts. The sales force should also have access, through operations, to the current and planned inventory levels so that they can understand the current state of inventory and hence view the system in a holistic manner.
9. *Calibrate the sensors (of the outputs, inputs and process variables) to ensure that the signals they are generating are correct*: the waterfall charts should be correct, but should be audited from time to time as a check
10. *Test the control system in its environment and make adjustments as necessary*: ongoing.

Double Loop Learning

What I have described in the previous section is a single loop control process. The sales force, now being incented to make accurate forecasts has taken the output signal, forecast error, and used it to adjust their inputs, proclaimed expected sales of videoconferencing systems. Here we are counting on the sales force to revise their mental models of PictureTel's costs of doing business so that the corporation is more profitable overall. We are hoping that they will take a more holistic view that transcends the organizational boundaries. Of course this will be easier with the cooperation of operations and other functions. This matter should be used as a learning tool for PictureTel's Corporate Management Council (CMC) which is composed of the president of the company and all of his functional vice-presidents. This issue shows the need for interdepartmental cooperation to improve the overall profitability of the company.

Area 2: Inventory Control

Like most companies, PictureTel carries inventory in three forms: raw materials inventory (RMI); work in process (WIP); and, finished goods inventory (FGI). Raw materials are those materials on which some operation is performed that adds value. For PictureTel, raw materials take the form of subassemblies, cabinets, printed circuit boards, etc. WIP inventory consists of all those goods that began their existence within PictureTel as raw materials but are now in the process of having value added to them. Finished goods are those goods which are ready to be shipped to customers and hence generate revenue for the company.

PictureTel currently performs only a limited amount of manufacturing internally. They are moving towards a business model where none of their manufacturing will be performed internally. In this model, PictureTel will outsource 100% of the manufacturing of their products. PictureTel will serve the role of integrating various items into a package which constitutes a videoconferencing system. (Actually, PictureTel is moving to a business model that is even more "leveraged" than this. They will not even perform the integration, which is really just picking the correct components and packing the boxes, but will outsource this function to a logistics company.) In this business model, the traditional categories of raw material, WIP and FGI all blur into one category of inventory.

Currently PictureTel has moved part of the way towards their fully "leveraged" business model. Their high end group videoconferencing system product line, the S4000, is assembled and tested internally. Some assembly and test of their other group system, the S2000, is performed internally, as well as some testing of various other components for special reasons[39]. All of the personal, desktop, systems are fully manufactured and tested outside of PictureTel's walls. PictureTel's only role in preparing these systems for delivery to customers is to pick, pack and ship the orders. In the current state then, PictureTel has the traditional categories of RMI, WIP

[39] For example, the proving of the quality of new products. This function will also move outside as the new product introduction process is optimized.

and FGI and they have inventory that is received from vendors, stored and then shipped to customers. We shall call this latter category "pass through"[40] inventory.

Although PictureTel has only four major product families, they have over 10,000 components which they stock. These components range from sophisticated electronic assemblies valued at tens of thousands of dollars down to simple stickers valued at less than a dollar. As discussed in Chapter 3: Total Cost Model, there are really only two decisions to be made regarding inventory: 1) how much safety stock to maintain; and, 2) in what quantities to place the orders. An inventory control system is a system that examines the current levels of inventory, compares them to the desired levels and takes appropriate action to resolve any discrepancy.

Most inventory control systems involve a great deal of human effort. This is certainly the case with PictureTel, as described in Chapter 2: The Existing State of the Supply Chain. Much of this human effort is spent in checking current inventory levels. Because this time costs money, and there is a limited amount of time available to control the inventory system, we would want to distribute the time spent on controlling inventory in the most profitable way. It would make sense to spend a greater proportion of time on those items that are more expensive (have more potential negative impact on the total carrying cost) and those items that contribute more to the company's profitability, while spending a lesser proportion of time on those items that are not as costly or as profitable. This allocation is traditionally made by using an "ABC" categorization[41] of inventory. The ABC categorization is based on the *Pareto effect*, which states that a large proportion of the dollars held, will be accounted for by a small proportion of items. Typically, the top 80% of dollars are accounted for by only 20% of the items. This rule holds at PictureTel where, historically, 80% of the inventory dollars are accounted for by approximately 14% of the items[42]. A plot of the number of inventory components versus the cumulative value of inventory is presented in Chart 6, below.

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[40] "Pass through" inventory because all the goods do is pass through the warehouse. There is no physical value added to the goods, and WIP and FGI are only created minutes before leaving the warehouse.
[41] Nahmias, 1993
[42] This is based off of the inventory associated with the S2000 product line. Tablular data is presented in Appendix .

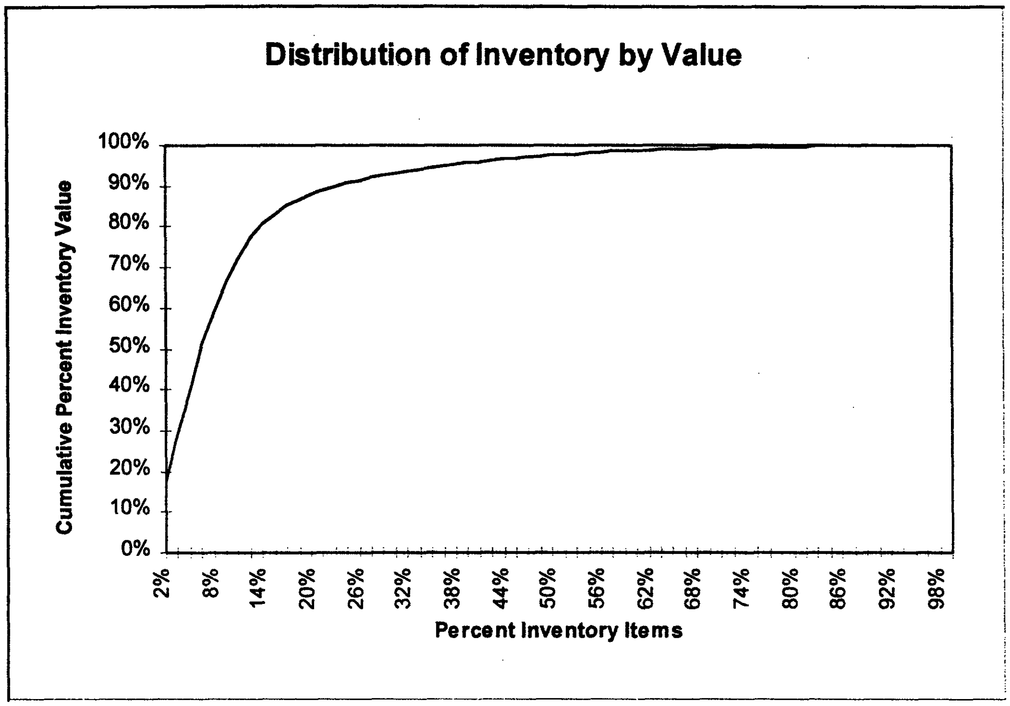

Chart 6

PictureTel actually uses an "ABCD" classification, i.e. four categories rather than three. In PictureTel's system, when you rank order (in ascending order) the inventory items according to the amount of money invested in each item, and tabulate the cumulative inventory, the "A" items are those items that account for the first 90% of cumulative inventory dollars. The "B" items account for the next six percent, bringing the cumulative total to 96%. The "C" items account for the next three percent, bringing the cumulative total to 99%. The "D" items account for the next one percent, bringing the cumulative total to 100%.

Using such a system, the personnel responsible for maintaining the correct inventory levels would devote the majority of their attention to the items in category A and the least amount of their attention to the items in category D.

Instead of just looking at the absolute value of inventory stocked we might try to examine some more meaningful metric to determine where effort is best devoted in inventory control. One metric at which we could look is a ratio of the cost to procure the component to its value. Another metric might be the ratio of the annual procurement cost to the total annual cost of inventory. These ratios are calculated and tabulated in Appendix F. A lower ratio would indicate that the inventory control cost is a lower portion of the overall value or cost, and it would make sense to devote more attention to these items. From Appendix F we can see that the A and B items have the lowest percentages, though there is not much distinction between the two categories. This data generally supports the ABCD classification system. So it is probably good to keep using this classification system as a method of allocating inventory control effort. But while the effort may be directed in the right place, the inventory control actions could be refined.

The employees at PictureTel who are responsible for controlling inventory currently lack adequate reporting and planning tools. MANMAN has limited reporting capability and no graphical capability. There is also a lack of formal planning rules and decision criteria for determining safety stock levels and order quantities[43]. There are so many factors to consider when making these types of decisions that it is nearly impossible to make optimal decisions without using some mathematical tools. The total cost model presented in Chapter 3: Total Cost Model, is a tool that can help in planning inventory. Using available data in an explicit model will enhance the quality of inventory decisions.

I will illustrate this use of the model with two examples of areas where improvements may be made. The total cost model's simulation function allows the user to visualize the behavior of inventory levels using the calculated optimal values for safety stock and order quantity. Below, I compare simulations of inventory levels using recommended optimal reorder points and order quantities to the actual historical inventory levels. I do this for two cases to illustrate two different situations. The first is the case of carrying too much inventory (hence paying too much

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[43] For example: When PictureTel was in the early stages of planning a new European Distribution Center (EDC), one employee was asked by the author how much safety stock he planned to carry at the EDC. The reply was "I don't believe in safety stock." When asked how he planned to manage the inventory he replied: "We'll keep about two weeks of inventory there and ship replenishments." When asked what 'two weeks' meant (the week to week variance can be quite large, see Chart 2) he replied "two average weeks." When asked what 'two average weeks' meant he replied: "two normal weeks."

holding cost). It is shown in Chart 7. The case of holding too little inventory (hence paying too much stockout cost) is shown in Chart 8.

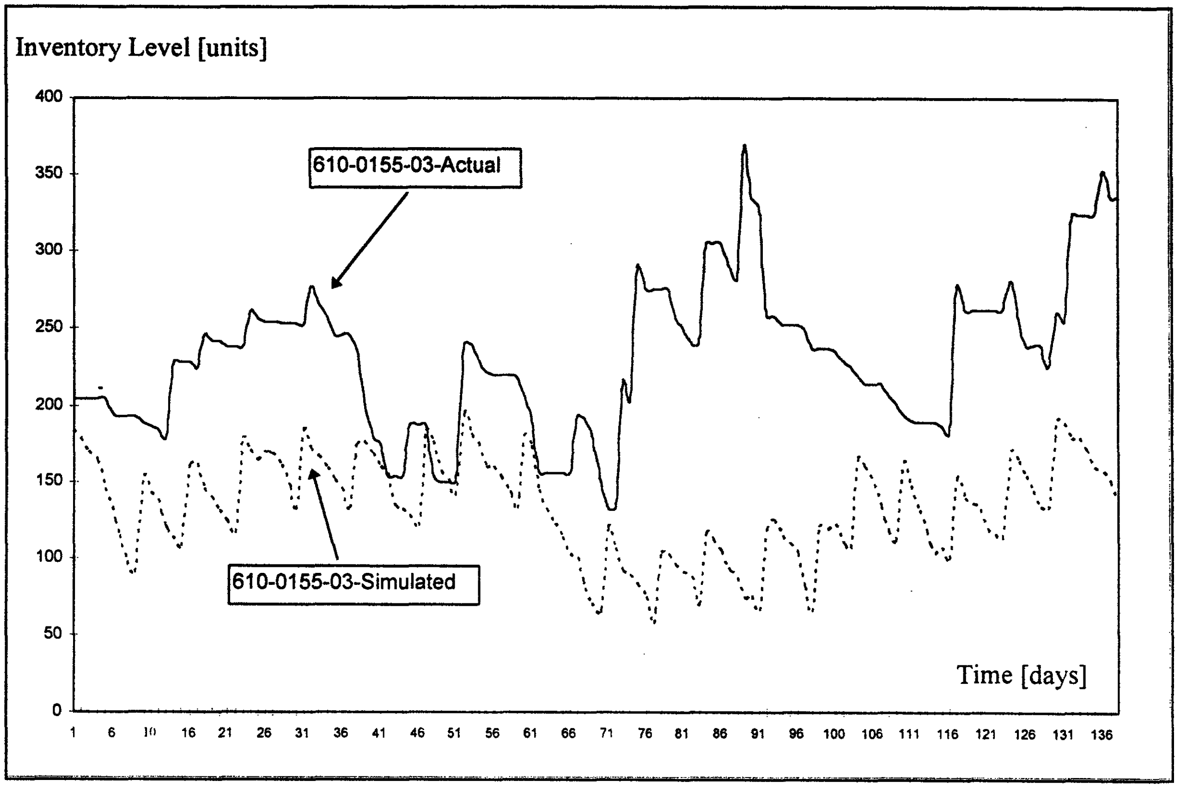

Chart 7 - Historical and Simulated Inventory Levels for Part Number 610-0155-03

The historical average inventory level is 231 units, the average simulated inventory level is 133 units. This difference in average level of 98 units represents a potential decrease in average inventory of approximately $200,000 for this item.

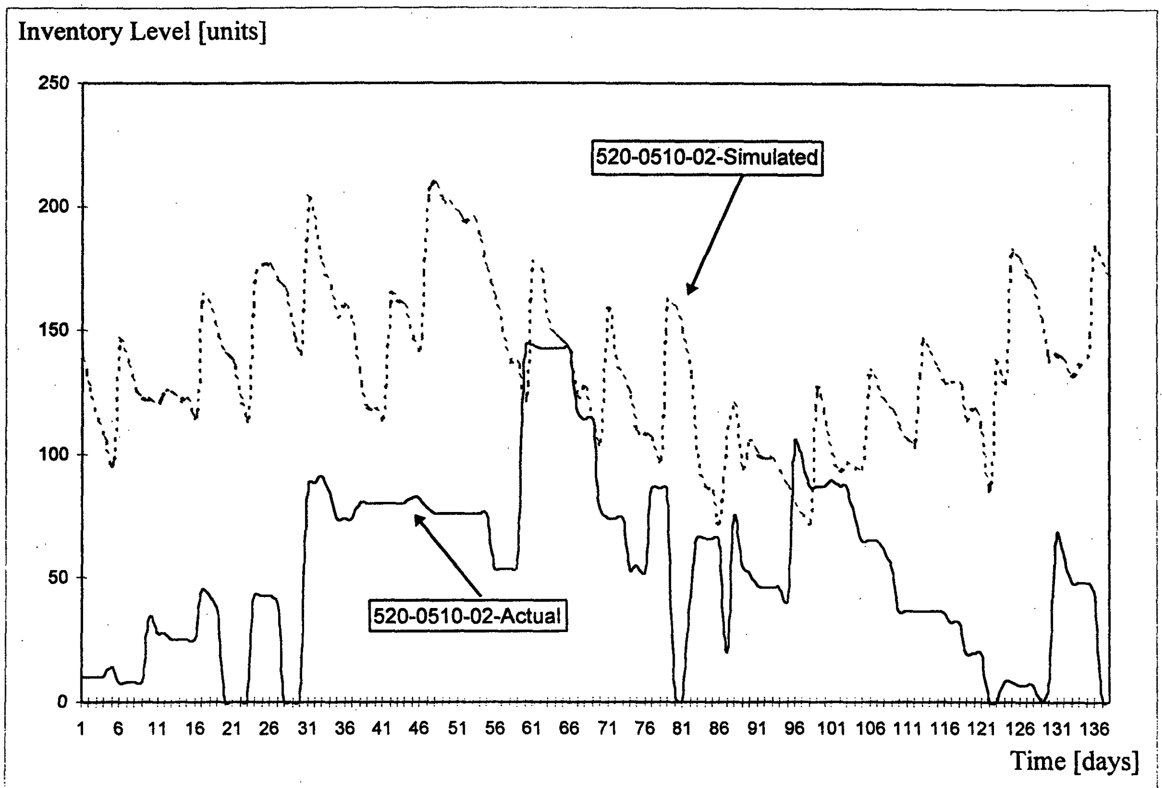

Chart 8 - Historical and Simulated Inventory Levels for Part Number 520-0510-02

The actual average inventory level is 54 units, the average simulated inventory level is 129 units. Because of the stockout problem with this item an additional investment in average inventory level of 87 units should be considered. This investment represents an increase in average inventory of approximately $230,000.

Improving the Inventory Control

PictureTel has a quality group of people that are working very hard to manage the inventory. While they direct their efforts well, the quality of their decisions could be enhanced by using modeling tools to make use of the available data. There exist many informal decision rules and inventory policies that should be tested, refined and formalized.

Currently, PictureTel employees manage inventory off of a rough ABCD system. But the rules followed here need to be tested and formalized. The current policies try to keep "A" item inventory as low as possible while attempting to meet demand. "A" items get a lot of attention and orders to suppliers are "pulled in" or "pushed out" to adjust to demand fluctuations. Purchasing agents are on the phone daily to "A" item vendors adjusting orders. The policy is to carry about a week of "A" item inventory. "D" items, at the other end of the spectrum, are checked infrequently and large orders are placed. There exists no rule or system to check levels for correctness.

Using the total cost model, PictureTel employees can test the inventory rules and enhance their decisions. For a given inventory item, the model's recommendations will include an order quantity and a safety stock level. The purchasing agent must keep track of inventory levels on hand and quantity on order and compare their sum to the sum of the expected demand and safety stock for one lead time period into the future (which is the reorder point). If the inventory falls below the reorder point, then another order is placed for the recommended order quantity.

Of course in this case, the reorder point changes or floats with the change in expected demand. A floating reorder point can make matters confusing, however. Though a properly designed modern information technology system that could automatically generate purchase orders should be able to handle such a task, most companies, including PictureTel, are not equipped with such an elaborate system. While purchasing agents should be able to maintain floating reorder points on a limited number of part numbers, they certainly would have a difficult time doing so with PictureTel's thousands of part numbers.

This distinction can be made with the ABCD inventory classification system. However, the current ABCD system should be revised. Currently the "A" items account for the cumulative first 90% inventory dollar investment. These “A” items account for 23% of the total number of inventory items. "B" items make up the next six percent of the cumulative inventory investment and another 18% of the inventory items (bringing the total cumulative percentage of items to 41%. There are too many components grouped into these categories. PictureTel should re-designate the class boundaries. The “A” items should be those items that account for the first 80% of the inventory investment. The “B” items should be those items that account for the next

15% of cumulative inventory investment. The “C” items should be those items that account for the remaining five percent of inventory investment.

This re-designation includes the deletion of the "D" category. There is really nothing to be gained by distinguishing the last 1% of inventory dollars. This re-designation groups the inventory into more manageable and useful categories.

The "A" items are costly enough that their inventory status should be tracked daily and controlled as specified above with floating reorder points.

The "C" items, which make up only 5% of the inventory value do not warrant such focused attention. It would seem that for those items ("C" items) that constitute a low percentage of the total inventory value, it might pay to just carry levels a bit beyond those that you would expect to use, i.e. some extra stock, so that you would not have to worry about getting the order quantities and safety stock levels exactly right. In other words, absolute stocking levels of these items could be maintained instead of worrying about coordinating the inventory levels with demand (floating reorder points). Since these items make up only a small percentage of the total inventory value, it would seem that the extra cost incurred would not be unreasonable.

To use the total cost inventory model in this situation the standard deviation in demand, *s*, which was measured as the *standard deviation of forecast error* must be replaced with the (larger) *total standard deviation of demand*[44].

Even though the variance, and hence safety stock levels, and hence carrying costs will increase, the increase is minor in the grand scheme of things. For PictureTel the total standard deviation of demand is between one and three times greater than the standard deviation of forecast error. Increasing the standard deviation by a factor of three for (current) "C" and "D" (or new "C") items results in an increase in total inventory cost of approximately only 1.2% . If PictureTel

[44] These terms are explained in detail in Appendix .

carries about $2.5M of S2000 inventory, 1.2% amounts to in increase of only $30,000 in S2000 inventory investment.

The "B" items, of course, lie in the middle somewhere. As discussed above, and presented in Appendix F, the order cost to value ratios for some "B" items are very low, indicating that these items may warrant the same type of attention as the "A" items. And of course, other "B" items border on the "C" range. The inventory manager will have to make a decision on how to handle "B" items. The total cost model can be used in this decision process.

Improving Inventory Control Using the Controller Design Process

Ultimately PictureTel is concerned with minimizing the cost of inventory. As mentioned in Chapter 3: Total Cost Model, there are three types of cost: carrying cost, order cost and stockout cost. In addition to controlling costs the company must also perform the task of keeping inventory at the proper levels. Control schemes for these functions are presented below.

Controlling "A" item inventory levels:

1. *Identify the outputs in which you are interested*: inventory levels, the sum of quantity in the warehouse and on order.
2. *Identify the desired values of these outputs*: above the reorder point. The reorder point is equal to the safety stock level plus the expected demand (from the forecast) over the period of time into the future which is equal to the vendor lead time[45]. The safety stock is calculated using the total cost model and using the standard deviation of forecast error for the parameter *s*.
3. *Identify ways to measure the actual values of these outputs*: warehouse and on order inventory levels are measured with MANMAN; these quantities must be summed manually

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[45] For example, if the lead time for an item is 40 days, the forecast states that 100 items should be sold in the next 40 days, and the safety stock level is 50 items, then the current reorder point is 150 items. If the the number of items in the warehouse plus the number of items on order is less than 150, the purchasing agent should order the appropriate quantity.

by the purchasing agent. They should be monitored very frequently, every day or couple of days.

4. *Identify the inputs and process variables that affect the outputs*: the main factors affecting the inventory level are the receipts and the shipments. There are other factors that may affect inventory levels from time to time. These included engineering change orders (ECOs) which may freeze inventory, rendering it unshipable (in effect, in the customer's eyes, this is a stock out situation) and inventory used by customer service for repairs.
5. *Identify ways to measure the actual values of these inputs and process variables*: all receipts and shipments are measured and monitored on MANMAN. Special attention should be paid to other factors as they arise from time to time.
6. *State your understanding of the cause and effect relationships between the inputs, process variables and the outputs*: receipts increase inventory levels, shipments decrease inventory levels.
7. *Create a controller that, in response to a discrepancy between the desired and actual system output, causes a change in the appropriate inputs or process variables so that the discrepancy will go away*: when the inventory level (on hand plus on order) falls bellow the reorder point an order is placed for the order quantity. The order quantity can be determined with the aid of the total cost model.
8. *Connect the controller to a source of power, its inputs and actuators*: the controller, who in this case is a purchasing agent, must have access to the necessary data on MANMAN, must have access to timely forecast data, must know how to calculate floating reorder points, must know what the order quantity is and must have the authority to place orders as necessary.
9. *Calibrate the sensors (of the outputs, inputs and process variables) to ensure that the signals they are generating are correct*: the data displayed on MANMAN must be reliable. Though this is generally the case, there have been problems with this in the past[46].
10. *Test the control system in its environment and make adjustments as necessary*: ongoing effort.

[46] At times, especially when levels get low, physical counts of inventory have had to have been made by the schedulers as they could not trust the number on MANMAN.

Controlling "C" item inventory levels:

The same procedure should be followed as specified for the "A" items with the following changes: the reorder point is constant. The safety stock is calculated using the total cost model with the parameter *s* equal to the total standard deviation of demand, not the (smaller) standard deviation of forecast error. The reorder point, *R*, is equal to the sum of the safety stock level and the expected demand over the lead time. This is calculated as:

$$R = \frac{AnnualDemand(units)}{365days} * lead\_time(days) \quad + \quad safety\ stock$$

The level of "C" items should only have to be checked at intervals on the order of weeks to months.

Controlling Costs:

1. *Identify the outputs in which you are interested*: stockout cost, carrying cost and order cost.
2. *Identify the desired values of these outputs*: minimize the sum.
3. *Identify ways to measure the actual values of these outputs*: since the total cost model is based on minimizing these costs, these costs should be tracked so that they can be compared to the model's predictions. This will allow the model to be improved as the understanding of the inventory system improves. Carrying cost can be calculated from currently available data by multiplying the year's average inventory level by the inventory carrying cost percentage. Data needs to be gathered on stockouts and orders. This data can be recorded on simple logs. Purchasing agents should record the number of orders placed per time period and the total amount of orders spent. Data on stockouts should be gathered by order management. For every order that can not be filled at the time the customer desires, the component that is holding up the order should be recorded, as well as the customers reaction, i.e. did the customer take his business elsewhere, if not, how long was the order delayed, etc. These data can be used to improve the model and test reality against model predictions.
4. *Identify the inputs and process variables that affect the outputs*: these are specified in Chapter 3: Total Cost Model, diagramatically in Figure 9.
5. *Identify ways to measure the actual values of these inputs and process variables*: see next point (6).

6. *State your understanding of the cause and effect relationships between the inputs, process variables and the outputs*: while it is beyond the scope of this thesis to investigate all of the cause and effect relationships between variables, this total cost model can be used as a focus for a continuous improvement effort, with the goal of reducing costs in the logistics system.
7. *Create a controller that, in response to a discrepancy between the desired and actual system output, causes a change in the appropriate inputs or process variables such that the discrepancy will go away*: when costs appear to be greater than expected, root cause analyses should be performed in order to understand the problem and provide solutions. When costs are lower than expected, revisions to the model parameters should be contemplated.
8. *Connect the controller to a source of power, its inputs and actuators*: the manager responsible for controlling inventory needs to have the authority to gather the necessary cost data and make adjustments to inventory levels as he deems necessary.
9. *Calibrate the sensors (of the outputs, inputs and process variables) to ensure that the signals they are generating are correct*: the data gathered on costs must be rigorously examined to ensure its validity.
10. *Test the control system in its environment and make adjustments as necessary*: ongoing.

Double Loop Learning

Several points regarding double loop learning have been made in the preceding paragraphs. The double loop learning here is all about revising PictureTel's model of how the inventory system works. The total cost model is the first attempt at specifying the causes and relationships that affect inventory. This model is the result of many hours of interviews with decision makers in the logistics system coupled with academic theory. This is an explicit model that can be challenged and revised as more and better data is gathered as time goes by and as the system changes.

Like any model, the total cost model is a simplification of reality with the aim of improving performance in the real world. The model should be continuously questioned and updated as the logistics world, or PictureTel's understanding of it changes.

Chapter Four Conclusions

PictureTel has two large problems with its inventory system. The first of these is the key input in planning inventory: the forecast. It is unquestionably biased and right now there is no feedback system to adjust it. Data is currently being recorded that would allow the company to monitor and adjust their forecast process. It just needs to be used. The second problem is the inventory control system. There is data available on many of the factors that affect inventory costs. This has been assembled in the total cost model. This model can be used to understand the complex, non-linear relationships between these factors. Use of available data in this model can enhance the two inventory decisions: how much safety stock to carry and for what quantities to place orders.

The current forecast procedure does not support PictureTel's strategy. Supply chain management has been proclaimed a core competency necessary to support PictureTel's leveraged business model. A biased forecast does not support effective supply chain management, but rather inhibits it. With PictureTel's leveraged business model, where only 6% of the cost of doing business will be incurred internally, the company should be much leaner than competitors. This should permit PictureTel to create short and efficient lines of communications across functions, resulting in more timely and accurate information dissemination throughout the organization. Improvements in information quality, resulting in the reduction of demand uncertainty (represented mathematically as variance) will be explored further in the next chapter.

Likewise, inventory control needs to be further developed in order to support the company's strategy. It is hard enough for any company to control inventory levels within its own walls. PictureTel's challenge will only increase in magnitude as the company outsources it logistics operations. Good models of the inventory system need to be created and used in order to better understand where the costs are.

The forecast system is a key input into the inventory control system. Sales and marketing generate the forecast. Operations is tasked with maintaining proper inventories. These parts of the company need to be closely tied together and jointly work towards reducing inventory costs. As Forrester says, “In management as in engineering, we can expect that the interconnections and interactions between the components of the system will often be more important than the separate components themselves." Neither operations nor sales and marketing can effectively perform their functions alone. Each needs feedback from the other for the system to work effectively.

Chapter 5: Further Analysis and Recommendations

Learnings from Model Construction and Internship In General

The process of constructing the total cost model was one of discovery. The path of discovery led outwards from the three cost categories which are the root of the model. As I attempted to qualify and quantify the factors that composed these costs I encountered people from many different parts of the PictureTel organization. All of these people and their organizations affect the logistics costs. Many are unaware of this fact.

Some of the discoveries I made were academically interesting as they enriched my understanding of logistics systems. Some of the discoveries were alarming. There are many "little" opportunities for improvement throughout the company[47]. These "little" areas combined can have a large effect of the performance of the logistics system as a whole.

In this chapter I discuss several of these "little" areas and make recommendations for improvement.

Obsolescence

PictureTel is writing off almost 10% of their inventory each year due to obsolescence. The main factors contributing to this problem are the short product life cycles and engineering change orders. Engineering change orders can render large stocks of inventory obsolete overnight. The PictureTel videoconferencing technology is cutting edge and continues to be developed after product is released. As the product reaches the market place, unanticipated problems come back to engineering for solutions. Some of these problems are solved by hardware changes that result in rework of current inventory, or obsolescence. Short product life cycles also contribute to the problem. As mentioned before, a positively biased forecast is delivered to operations. Even if operations planned (by following the forecast) to have a zero inventory level at the product's end of life the bias could leave them holding on the order of $3,000,000 of last generation videoconferencing equipment.

Supplier Dependability

PictureTel's ability to deliver product to their customers is very much affected by the dependability of their suppliers. The only way to buffer the customer from fluctuations in supplier delivery and quality is to carry more inventory. Of course, this solution will only make the turns metric worse and is not a solution to the root cause of the problem. The only sustainable solution is to improve supplier dependability. Most of PictureTel's suppliers are dependable, where dependable is defined to mean that they deliver product when they say they will and to the level of quality which they promise.

There are some notable exceptions to this rule though. Perhaps the best example is that of one vendor's ability to supply to PictureTel a particular electro-mechanical device. This device is now being used on the group system products. It is a mechanically complex device that rotates about two axes and is mounted in an aesthetically pleasing enclosure. There are, however, problems with its design, namely that the design does not support ease and quality in manufacturing. This is evidenced by the low yield of product delivered by the manufacturer as it was being introduced. PictureTel was forced to inspect quality into this product, testing each unit that was received.

Supplier dependability has an appreciable impact on the annual logistics cost. A sensitivity of the annual cost versus supplier reliability (measured as the standard deviation in lead time) was performed using the total cost model. The results are displayed in Chart 9, below. The baseline analysis was performed with a standard deviation in lead time of zero. The mean lead time is 40 days. Increasing the standard deviation of lead time to 10 days, which is 25% of the mean lead

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[47] Lee et al., 1992

time, approximately doubles the annual cost. A standard deviation equal to half of the lead time results in an increase in annual cost of approximately 250%.

The increase is so drastic because of the compounded difficulty of trying to meet a varying demand with a varying supply.

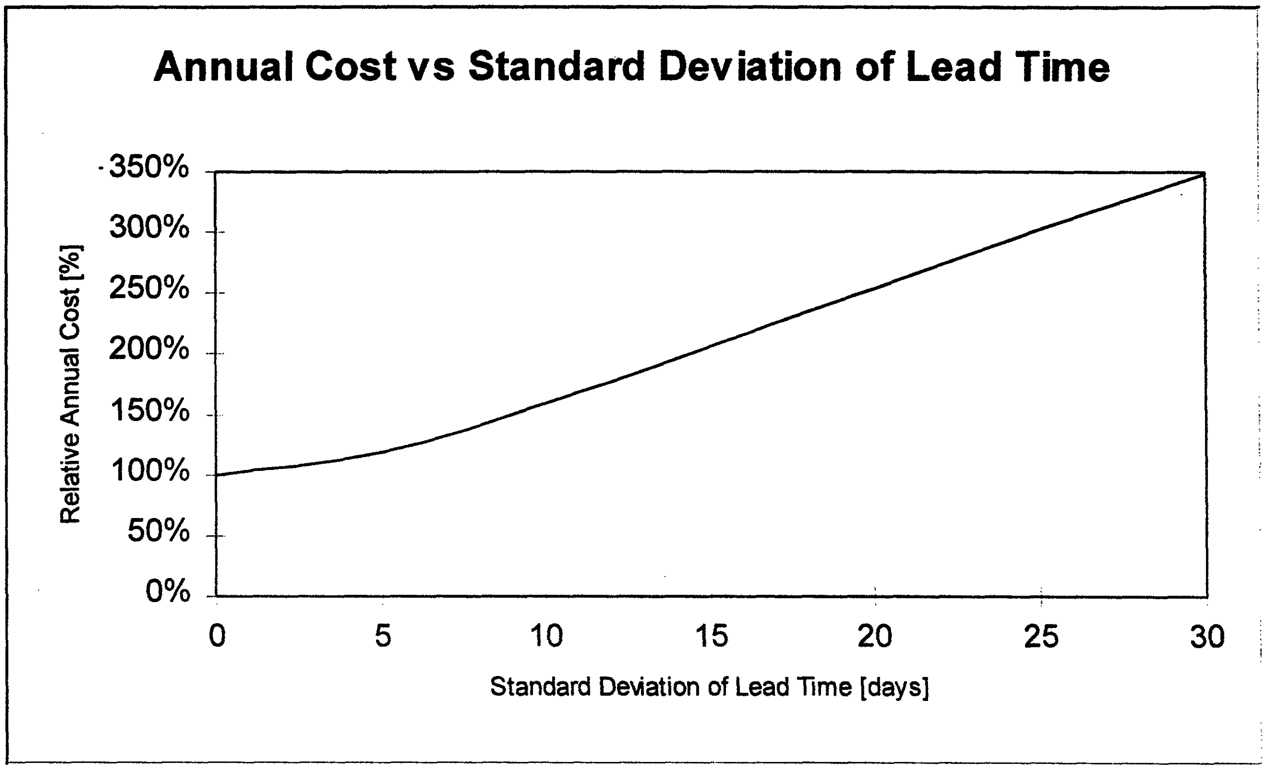

Chart 9 - Sensitivity of Annual Cost to Standard Deviation of Lead Time

Though supplier dependability has not been a general problem at PictureTel, the company has felt the pain of the few problems they have had. The effect of an unreliable supplier is grave. There are large potential benefits to be gained by heavily weighing this factor when choosing suppliers.

Supplier Lead Time

Probably one of the big reasons that PictureTel has not had more problems with supplier lead time is that the lead times, in general, are long. Some of these long lead times give the suppliers flex time to work with. Even though the flex time is not explicit in the details they have provided PictureTel, it exists. For example, consider the S2000 model production schedule provided by PictureTel's vendor, Solectron. The critical path consists of a 26 week lead time on the ASICS[48] and a three week manufacturing cycle time, for a total of 29 weeks, or 203 days. It appears to me that Solectron and their upstream vendors should be able to reduce these cycle times and pass these reductions through to PictureTel.

Currently PictureTel releases an initial purchase order 25 weeks out for these systems. Solectron purchases the ASICS at this point. Ten weeks out PictureTel commits to a certain number of systems. Some time in the next few weeks, at their convenience, Solectron builds these systems, puts them in their warehouse and charges PictureTel for them. PictureTel takes delivery on the scheduled date, unless they "pull the orders in". Solectron has a huge amount of power in this relationship. This is a result of the way the contracts were first negotiated. PictureTel's ability to compete in the future will be hampered if products on an 18 month life cycle are burdened by such significant lead times.

Much more complicated integrated circuits are fabricated in a fraction of the time allowed in this product. Solectron, who values PictureTel's business, and views it as a huge growth opportunity, should be producing product almost continuously, reducing the three weeks cycle time to on the order of three days. PictureTel has done a great job of creating strategic alliances with development and distribution partners. Similar alliance should be formed with their supply chain partners.

The effect on annual cost of changing the mean lead time is displayed in Chart 10, below. The baseline case was run with a mean lead time of 40 days.

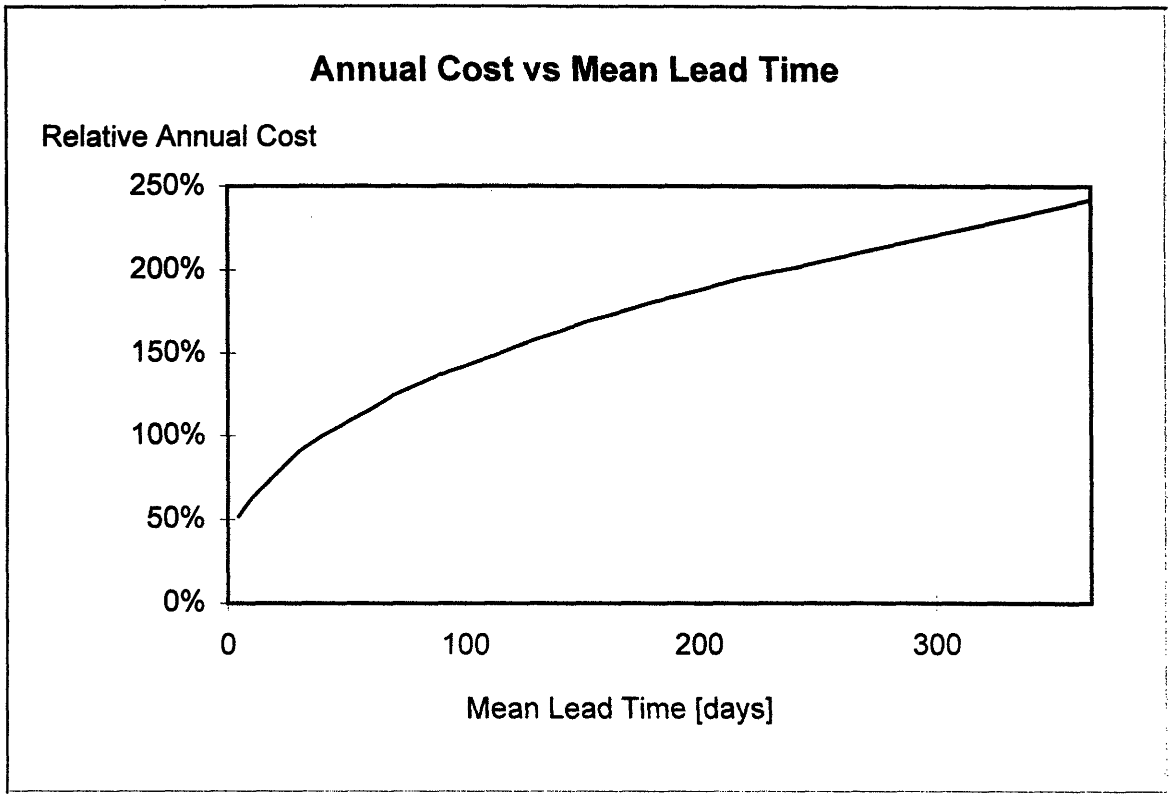

Chart 10

Product Design

PictureTel need not accept any lead time as fixed. There are many ways to reduce lead time. As mentioned, pressure on the suppliers is one way to improve lead times. A very high leverage method is to design the products to reduce lead time[49].

An example of this is the Infrared Keypad that PictureTel uses with its group systems. The keypad is a remote control (the same principle as a television set remote control) for the system. Since this device rests on the center of a conference table, a major design consideration is that it be aesthetically pleasing. For this reason, they have the keypads labeled by the manufacturer,

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[48] Application Specific Integrated CircuitS
[49] Whitney, 1988

who is located in Idaho. PictureTel purchases five varieties of this keypad, printed in five different languages.

As predicted by theory[50], PictureTel's aggregate forecast is much better than its forecast for individual items. At one time during the summer of 1995, some S2000 systems could not ship because they were stocked out of some of the language varieties of keypad. They had other language keypads in stock though. If this keypad had been designed with more flexibility in mind they may have been able to avoid this stock out situation. Possible alternatives are to manufacture the keypads with symbols instead of words or to label the keypads internally or using a local vendor.

In the design of products and manufacturing processes, these issues should be considered[51].

Forecast

As mentioned above, PictureTel's forecast, while still biased, is much better in the aggregate than it is for individual products. Since PictureTel is making good progress towards sharing components[52] between various products, they can take advantage of their aggregate forecast being more accurate to reduce inventory levels.

The effect of reducing the uncertainty in demand is displayed graphically in Chart 11, below. Cutting the standard deviation of forecast error in half will cut the inventory costs approximately in half.

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[50] Nahmias, 1993
[51] For further reference see Lee et al., 1993
[52] Cameras, microphones, cables, and accessories can all easily be shared.

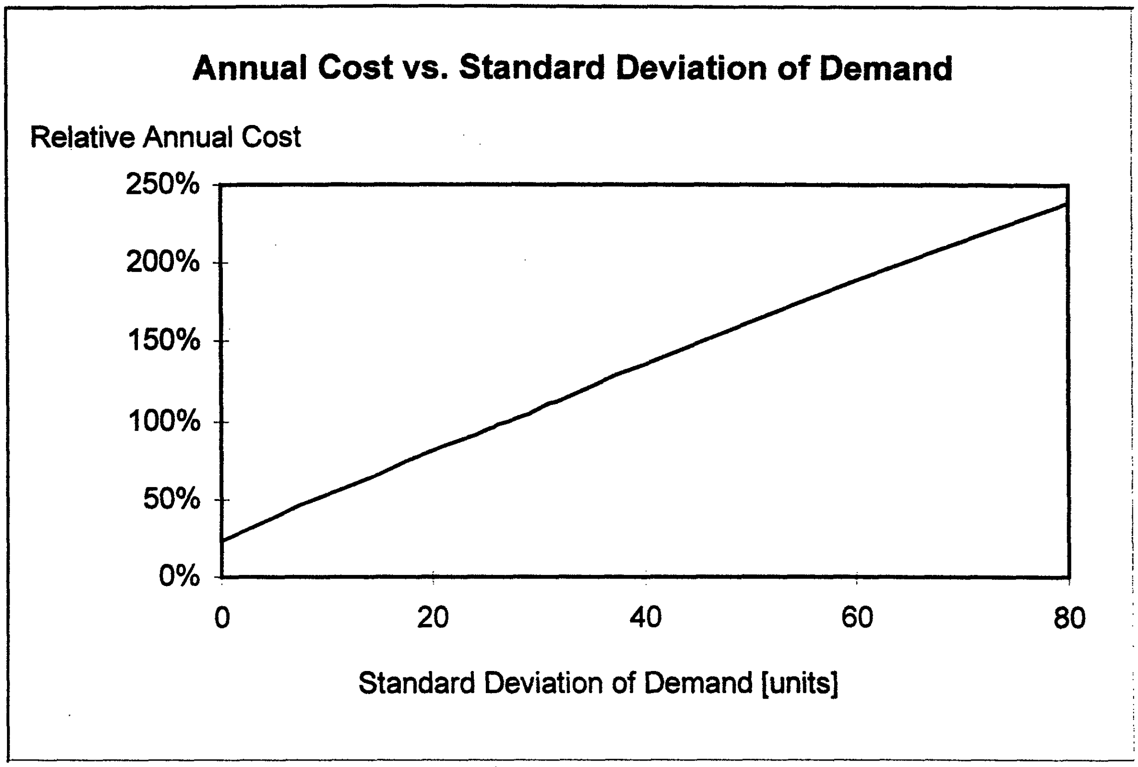

Chart 11

Order Management

In many large companies the time required to get an order processed through the order management department can be a significant proportion of the total lead time to the customer. This is not the case at PictureTel. Most orders are processed fully within an hour. A long delay is three days, and this is a rare occurrence. As PictureTel moves towards its leveraged business model, it will give them a competitive advantage if they can maintain such excellent order processing times.

Sales

The sales force generates the orders that are received by order management. Though order management does a terrific job of processing orders, the sales force does not do such a good job of preparing them correctly. Fully half of the orders received by order management are incorrect in some significant way. During the course of my internship this matter was raised repeatedly with the sales force, but I noticed no improvement. It escalated to the point that the VP of Operations met with the VP of Sales regarding this matter.

Though this matter was outside the scope of my project, it is a very important matter and there are huge potential benefits to be gained in this area. Operations is frequently blamed for not getting the order out of the door on time, but is the sales force blamed for not getting it in on time? By not submitting a correctly completed order, the lead time to the customer is being increased unnecessarily. The persistence of this problem indicates insufficient cooperation and a lack of shared vision between sales and operations.

Post Pack Audit

As described in Chapter 2: The Existing State of the Supply Chain, the Post Pack Audit (PPA) was established in order to sample product that was about to be shipped. The PPA was originally created to help locate potential sources of customer dissatisfaction arising from incomplete orders and/or faulty goods. The problem with the PPA is that it is only performed early in the month or quarter, when shipment activity is low. To get an accurate measure of the quality of shipped goods, the PPA should be conducted at purely random times. Since most of the product is shipped in the latter parts of the months and quarters, audits should differently be performed during these intervals. With the increase in activity, there is less time available to inspect in quality and I would therefore hypothesize that there is a higher probability of defect in the shipments in this time frame.

In general, when gathering data, careful thought should be given while considering the ultimate use of the data, and hence the proper statistical sampling technique to use in the process of gathering it.

Information Systems

PictureTel is using a very old information system (MANMAN) that is very limited in its capability as implemented. Data is very hard to access for reporting and analysis purposes. When I wanted to look at data during my internship, it almost always required the special services of a person from the information technology group to write special programs to extract the data I needed. The reporting system is so inflexible in MANMAN that I once encountered one of the purchasing agents printing a 130 page report of which he was interested in a half dozen lines of information, but could not access in any other way.

The company, recognizing the need to analyze its business, has started to use a datamining product called *CrossTarget*. However, this tool is limited by the MANMAN system. For each analysis, special *CrossTarget* models need to be constructed to look at the data in the requested manner.

PictureTel is in the process of bringing a modern Enterprise Resource Planning (ERP) system into the company, but the implementation will take years. Such a system will give the users many more tools to aid in the execution of their daily tasks.

In addition to the new ERP system PictureTel should also add a datamining capability. There are great areas for improvements in the company. In the future, as competition becomes more intense, it is going to become absolutely necessary to make these improvements. This is going to require analysis of current operating practices and historical trends. PictureTel should position themselves now with the capability to perform such profit enhancing analyses.

Information Delay

Delays in the transfer of information throughout a system add phase shifts and amplification[53]. The result of this is increased uncertainty. We saw in Chart 11 what the consequences of increased uncertainty were on inventory cost. An assumption that underlies this chart though, is that there is infinite capacity in the system to meet the varying demand. In reality this is not at all the case. In reality the costs would be much greater and the effects would be felt throughout the organization. As demonstrated by Bitran, when capacity utilization becomes high, the sensitivity of the system to variance becomes very large[54].

Currently there is little information delay within the U.S. operations organization, but there are significant delays and barriers to getting operationally relevant information into this organization. Operations has no visibility to the inventory that the foreign subsidiaries carry. Orders come in from these organizations in bulk, so operations has no idea what the detailed consumption patterns look like. As the company becomes larger and larger, visibility to this inventory is going to become more and more crucial to the efficient operations of the firm. A good way to accomplish this is with a modern information system.

Organizational boundaries also provide significant barriers to communication. Many people at PictureTel reminisce about the days where the entire company was housed in one building. "When there was a problem in those days you just walked down the hall and talked to whomever you needed to solve it," one employee said. Some employees feel that with the company's coming move to one facility in Andover, MA, the cross boundary communications problems will be solved.

I doubt that the move to Andover will solve these problems. The company continues to grow at a significant rate. It is an international company with subsidiaries and offices distributed throughout the planet. Though co-location will certainly help to solve communications

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[53] Forrester, 1961; Senge, 1990; Silver, 1979
[54] Bitran, 1995

problems, it is not the solution to all of the problems. What worked several years ago when the company was small will not necessarily work as the company grows.

PictureTel has recently implemented Lotus® Notes®. Unfortunately, its only real use has been as an electronic mail system. The use of Notes® databases and shared workplaces to increase communications and cooperation between functions should help improve the general state of communications within the company.

More importantly, there is a cultural problem that continues to inhibit effective communications between functions. It would help to make cross functional cooperation an integral part of the culture. As mentioned in other parts of this thesis, sales and operations do not seem to communicate effectively, but there are big potential gains the company if this communications channel is opened up.

Revenue Drives the Company

There is one rule that everybody at PictureTel lives by. Each period the company has to meet its revenue goal. Every month and quarter there is a revenue goal. Every month and quarter it is met. Every last week of the month and quarter the orders come flooding in from the sales force. On the last day of each month and quarter the operations people work until midnight to pack and ship product. People work double and triple shifts to accomplish the work. Incomplete orders are sometimes shipped with the balance sent later at profit killing costs.

This spike in activity at the end of the period is referred to as a "hockey stick" by the employees.

The hockey stick is a reality at most companies, especially high tech companies. Most companies throw their shoulders up and say there is nothing that can be done about it. This is one attitude that management can take. The other is that they can try to understand the system well enough to do something about it.

Some of the hockey stick is externally generated. Funds for purchasing expensive videoconferencing equipment become available at the end of the spending cycle when they have not been consumed by other activities. Some of the hockey stick is internally generated though. It is internally generated because management has not taken action to control it. Incentives placed on the sales force may help smooth this pattern. Pricing the product with discounts at the beginning of the quarter and premia at the end of the quarter may help to smooth the external hockey stick.

If PictureTel can smooth its hockey stick it will have a significant competitive advantage. This topic was beyond the scope of this thesis, but it is a very important topic that should receive vigorous management attention. The company is able to deal with the hockey stick now, but will it be able to when it is twice the size it is now?

Chapter Conclusions

In this chapter I described some of the areas in the company where I saw opportunity for improvement. Some of the key areas were: design for manufacturability, design for flexibility in product routing, communications processes and information systems. By continuously modeling and evaluating business systems the company can maintain a steady course down the path of continuous improvement.

Chapter 6: Conclusions and Recommendations

I stated in the introduction that the purpose of this thesis was to contribute to the translation of the art of management into the science of management. I presented explicit modeling of business processes as a general method for effecting this translation. I presented a template to aid in modeling business systems and a specific model of inventory costs. The first was the controller design process, which provides a systematic analysis template for analyzing business control systems. The second was the total cost model which attempts to capture all of the costs of inventory. Both are tools that help the user understand the inventory system in more scientific ways.

PictureTel's logistics system is growing in complexity. Though the system is technically a multi-echelon inventory system, currently, it can be reasonably well modeled as a set of single-item, single-site mathematical models that are considered by the user as part of a larger, interactive system. Multi-echelon inventory systems are exceedingly complex to model and control. As the company grows it should take great care to contain the complexity of its logistics system.

The total cost model, as a computer model and as a system diagram, allows the user to leverage data that is available today to make better decisions. Over the longer term it is a road map for continuous improvement. Understanding where the costs come from in the system is the first step in reducing these costs. During my internship I demonstrated the use of modeling in both of these contexts as I modeled the European distribution system and its costs. This model continues to used at PictureTel. The total cost model, like any model, is a simplification of a complex world. Interrelationships between inventory items and inventory sites are not explicitly modeled, but must be considered by the user. I presented some frameworks for such considerations.

PictureTel currently has some inventory management problems. The main drivers of these problems are the forecast and the inventory control policies. I discussed their current states and made recommendations for improvement.

Lastly, an important thing to keep in mind is that PictureTel is a company that is growing rapidly. The systems that made the company run well yesterday most likely will hinder its performance tomorrow. Open minds, shared vision and an active effort to learn as a company will give PictureTel a sustainable advantage over the long run.

"Begin at the beginning ... and then go on till you come to the end: then stop." - Lewis Carroll

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List of Appendices

Appendix A

Inventory Carrying Cost Calculation

Holding Cost:

The holding cost was calculated at 36.3%.

Category	Annual Percentage	Information Source
Cost of Capital	23%	Calculated Below (1)
Storage	2.7%	Calculated Below (2)
Insurance	0.069%	Quote: Donna Bellanger, PictureTel Corporation, 12/8/95
Shrinkage	1.0%	Author's Estimate
Obsolescence	9.7%	Calculated Below (3)
Total	36.5%	

(1) Cost of Capital

The Weighted Average Cost of Capital (WACC) was calculated to be 23%. The formula for the WACC is presented below[55], where:

D ≡ Market Value of Debt = \$6,969,000
E ≡ Market Value of Equity = \$1,300,000,000 (32.5M shares * \$40/share)
r_D ≡ Interest Rate on Debt = 6.8%
r_f ≡ Risk Free Interest Rate = 5.6% for 1-year Treasury Bills
r_m ≡ Market Rate of Return
$r_m - r_f$ ≡ Market Risk Premium = 8.4%
β ≡ Risk Premium = 2.10

$$WACC = \frac{D}{D+E} r_D (1-T) + \frac{E}{D+E}(r_f + \beta(r_m - r_f))$$

Notes: Debt and interest rate on debt from PictureTel annual report for 1994; risk free rate of return from the *Wall Street Journal*, March 1996; risk premium (for stock market) from Brealy

[55] Brealy and Myers, 1991

and Myers; Market Value of Equity from Standard & Poor's Small Cap 600 Stock Report, 28 February 1996; Beta from *Morningstar, Inc.*, March 1996.

Note: Tax shields on debt payments were neglected as debt makes up less than one percent of the WACC. (In fact the leverage is so slight on PictureTel that it can be approximated as 100% equity financed.)

(2) Storage

Storage cost is composed of the cost of facilities (rental) and the cost to manage those facilities and the material held within. The cost of storage was estimated from PictureTel's accounting data for 1995. This estimate placed the annual cost of storage at approximately 2.7% of the average inventory value.

Method 1: PictureTel accounting data for 1995

Peabody distribution center (DC)facilities:	$724,844
30% of labor/operations[56]:	<u>$200,351</u>
	$925,195
Average Peabody DC inventory 1995:	$34,496,000

($925,195) / ($34,496,000) = 2.68% ≈ 2.7%

(3) Obsolescence

Obsolescence is calculated in Appendix C.

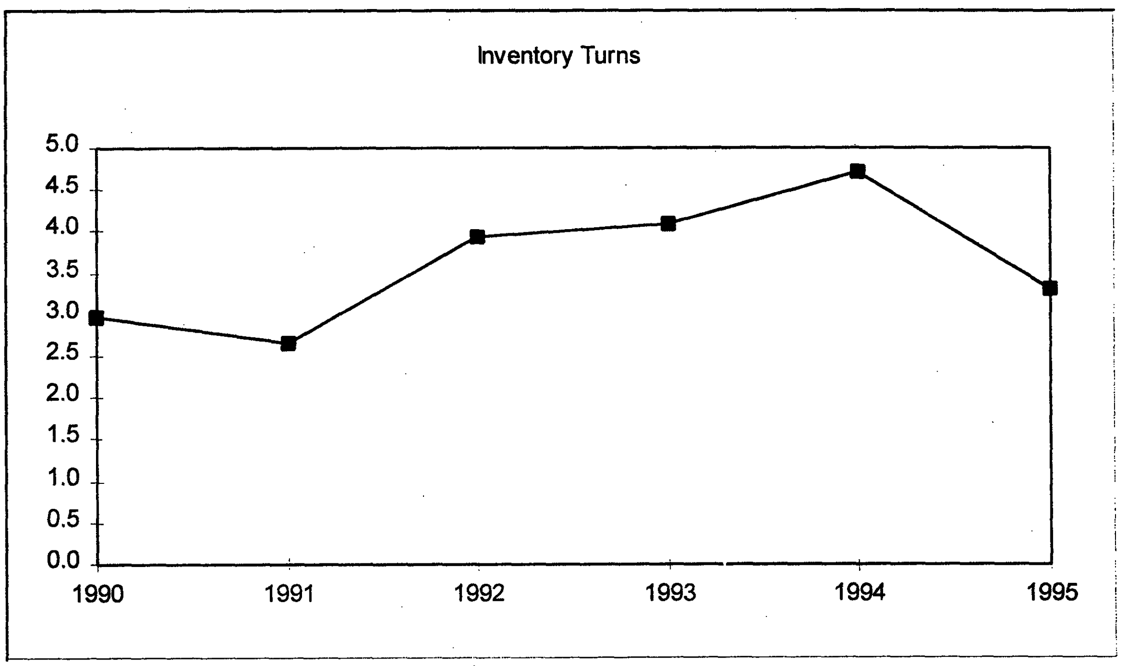
[56] Assume that 30% of budgeted resources are used for management of the goods in the warehouse and 70% of the budgeted resources are used to receive and ship goods.

Appendix B

Inventory Turns Calculation

Inventory turns data calculated from PictureTel annual reports.

Year (12/31/XX)	1989	1990	1991	1992	1993	1994	1995	Average
Inventory[57]	3,911	8,821	17,823	15,030	23,201	31,679	37,000	--
Cost of Sales	10,945	18,832	35,381	64,529	78,011	129,039	114,000	--
Turns	--	**3.0**	**2.7**	**3.9**	**4.1**	**4.7**	**3.3**	**3.6**



[57] Inventory and Cost of Sales figures in thousands of dollars.

Appendix C

Obsolescence Accounting Write Off Calculations

Year	1991	1992	1993	1994	1995	Total	Avg[58]
Method One							
End of Year Inventory ($M)	17.823	15.030	23.201	31.679	37.000	106.910	
Yearly Inventory as % of Total		14.1%	21.7%	29.6%	34.6%	100%	
Average Yearly Inventory ($M)		16.427	19.116	27.440	34.340		
Obsolete Inventory Write Off ($M)		2.000	2.000	2.000	2.000		
Extra Inventory Write Off to Account for Build Up ($M)					1.500		
Extra Inventory Write Off Allocated for Year ($M)		0.211	0.326	0.444	0.519	1.500	
Adjusted Inventory Write Off ($M)		2.211	2.326	2.444	2.519		
Obsolescence as % of Average Inventory		13.5%	12.2%	8.9%	7.3%		**9.7%**
Method Two							
Average Yearly Inventory ($M)		16.427	19.116	27.440	34.340	97.322	
Obsolete Inventory Write Off ($M)		2.000	2.000	2.000	2.000	8.000	
Extra Inventory Write Off to Account for Build Up ($M)					1.500	1.500	
Total Inventory Write Off ($M)						9.500	
Obsolescence as % of Average Inventory						9.8%	**9.8%**

58 Average for *Method One* is a weighted average.

Appendix D

Forecast / Actual Values of Demand with Recommended Forecast Error Tracking Method

GSD	Plan	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Jan	450	418											
Feb	679	658	385										
Mar	1216	1035	1261	907									
Apr	427	402	378	511	212								
May	971	877	846	911	739	315							
Jun	1149	1223	1179	1308	1525	2016	1282						
Jul	502	575	570	570	570	530	437	172					
Aug	755	829	828	828	828	788	655	805	397				
Sep	1255	1299	1312	1312	1312	1312	1090	1169	1769	0			
Oct	678	718	715	715	715	715	647	508	521	0	0		
Nov	848	907	904	904	904	904	820	761	779	0	0	0	
Dec	1527	1625	1619	1619	1619	1619	1165	1271	1302	0	0	0	0

Fcst Error	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Mean	Stdev
1 month	-32	-273	-354	-299	-424	-734	-265	-408	-349	185
2 month		-294	-128	-166	-596	-243	-358	-258	-292	143
3 month			-309	-190	-531	-26	-398	-391	-308	162
Total Sales	418	385	907	212	315	1282	172	397	511	359
Predicted	450	658	1261	511	739	2016	437	805		

Appendix E

Historical ABC Inventory Class Calculations

% Inventory Items	Part Number	Description	Cash	Cumulative Cash	% Inventory Dollars	Historical ABC
2%	610-0155-03	Part Description Omitted	$472,486	$472,486	18%	A
3%	520-0513-01	Part Description Omitted	$309,838	$782,323	29%	A
5%	540-0057-03	Part Description Omitted	$294,643	$1,076,966	40%	A
6%	520-0511-01	Part Description Omitted	$290,924	$1,367,890	51%	A
8%	540-0058-03	Part Description Omitted	$228,817	$1,596,707	59%	A
9%	520-0512-02	Part Description Omitted	$189,962	$1,786,670	67%	A
11%	520-0510-02	Part Description Omitted	$144,456	$1,931,125	72%	A
12%	370-0285-01	Part Description Omitted	$144,075	$2,075,201	77%	A
14%	540-0094-01	Part Description Omitted	$90,247	$2,165,448	81%	A
15%	540-0060-01	Part Description Omitted	$62,872	$2,228,320	83%	A
17%	370-0190-02	Part Description Omitted	$54,945	$2,283,265	85%	A
18%	540-0064-01	Part Description Omitted	$40,985	$2,324,250	87%	A
20%	540-0080-01	Part Description Omitted	$32,356	$2,356,605	88%	A
21%	520-0527-01	Part Description Omitted	$32,111	$2,388,717	89%	A
23%	610-0071-05	Part Description Omitted	$22,370	$2,411,086	90%	A
24%	610-0328-03	Part Description Omitted	$21,743	$2,432,829	91%	B
26%	540-0096-01	Part Description Omitted	$19,255	$2,452,084	91%	B
27%	540-0067-01	Part Description Omitted	$18,615	$2,470,700	92%	B
29%	510-0184-01	Part Description Omitted	$15,945	$2,486,645	93%	B
30%	540-0074-01	Part Description Omitted	$14,765	$2,501,410	93%	B
32%	540-0071-01	Part Description Omitted	$13,471	$2,514,881	94%	B
33%	180-0005-01	Part Description Omitted	$12,701	$2,527,582	94%	B
35%	540-0073-01	Part Description Omitted	$10,914	$2,538,496	95%	B
36%	510-0181-02	Part Description Omitted	$10,790	$2,549,286	95%	B
38%	540-0088-01	Part Description Omitted	$9,978	$2,559,264	95%	B
39%	510-0173-01	Part Description Omitted	$8,709	$2,567,972	96%	B
41%	370-0213-01	Part Description Omitted	$8,438	$2,576,410	96%	B
42%	510-0214-01	Part Description Omitted	$7,653	$2,584,063	96%	C
44%	810-0307-02	Part Description Omitted	$7,409	$2,591,472	97%	C
45%	180-0159-02	Part Description Omitted	$7,227	$2,598,699	97%	C
47%	810-0226-01	Part Description Omitted	$6,702	$2,605,401	97%	C
48%	800-0338-01	Part Description Omitted	$5,997	$2,611,398	97%	C
50%	540-0072-01	Part Description Omitted	$5,955	$2,617,353	98%	C
52%	510-0220-01	Part Description Omitted	$5,251	$2,622,604	98%	C

53%	180-0158-02	Part Description Omitted	$5,012	$2,627,616	98%	C
55%	380-0004-01	Part Description Omitted	$4,972	$2,632,589	98%	C
56%	180-0121-01	Part Description Omitted	$4,230	$2,636,819	98%	C
58%	540-0115-01	Part Description Omitted	$4,144	$2,640,963	98%	C
59%	510-0223-01	Part Description Omitted	$4,115	$2,645,078	99%	C
61%	540-0084-01	Part Description Omitted	$3,130	$2,648,208	99%	C
62%	180-0157-03	Part Description Omitted	$2,913	$2,651,122	99%	C
64%	510-0163-01	Part Description Omitted	$2,662	$2,653,783	99%	C
65%	540-0083-01	Part Description Omitted	$2,621	$2,656,404	99%	C
67%	180-0139-01	Part Description Omitted	$2,620	$2,659,024	99%	D
68%	180-0049-01	Part Description Omitted	$2,568	$2,661,592	99%	D
70%	540-0086-01	Part Description Omitted	$2,440	$2,664,032	99%	D
71%	180-0001-01	Part Description Omitted	$2,259	$2,666,291	99%	D
73%	510-0199-01	Part Description Omitted	$2,107	$2,668,398	99%	D
74%	180-0144-01	Part Description Omitted	$1,823	$2,670,221	99%	D
76%	540-0085-01	Part Description Omitted	$1,821	$2,672,042	100%	D
77%	380-0221-01	Part Description Omitted	$1,430	$2,673,472	100%	D
79%	180-0143-02	Part Description Omitted	$1,316	$2,674,789	100%	D
80%	180-0142-01	Part Description Omitted	$1,164	$2,675,953	100%	D
82%	180-0140-01	Part Description Omitted	$1,148	$2,677,100	100%	D
83%	380-0238-01	Part Description Omitted	$1,129	$2,678,229	100%	D
85%	810-0246-02	Part Description Omitted	$1,103	$2,679,332	100%	D
86%	180-0141-01	Part Description Omitted	$1,088	$2,680,420	100%	D
88%	260-0431-03	Part Description Omitted	$821	$2,681,241	100%	D
89%	260-0040-01	Part Description Omitted	$738	$2,681,979	100%	D
91%	810-0264-02	Part Description Omitted	$624	$2,682,603	100%	D
92%	810-0250-02	Part Description Omitted	$493	$2,683,096	100%	D
94%	810-0265-02	Part Description Omitted	$453	$2,683,548	100%	D
95%	810-0249-02	Part Description Omitted	$341	$2,683,889	100%	D
97%	810-0305-02	Part Description Omitted	$190	$2,684,079	100%	D
98%	800-0339-02	Part Description Omitted	$173	$2,684,252	100%	D
100%	810-0304-02	Part Description Omitted	$135	$2,684,388	100%	D

The "Cash" column contains the average dollar level of inventory held by PictureTel in the first seven months of 1995.

Appendix F

Alternative Inventory Priority Measure Calculations

Part Number	Description	Value	order/ value	order/ total	inv class
520-0512-02	Part Description Omitted	$ 3,637.41	5%	8%	B
520-0527-01	Part Description Omitted	$ 3,492.00	5%	8%	B
520-0513-01	Part Description Omitted	$ 3,893.07	7%	9%	A
520-0511-01	Part Description Omitted	$ 3,492.00	8%	9%	A
520-0510-02	Part Description Omitted	$ 2,684.11	10%	10%	A
540-0058-03	Part Description Omitted	$ 1,194.64	11%	4%	A
540-0057-03	Part Description Omitted	$ 1,194.64	11%	5%	A
610-0155-03	Part Description Omitted	$ 2,049.12	13%	11%	A
610-0205-03	Part Description Omitted	$ 2,049.12	13%	14%	A
540-0080-01	Part Description Omitted	$ 943.00	18%	12%	B
370-0285-01	Part Description Omitted	$ 1,450.00	19%	10%	A
540-0094-01	Part Description Omitted	$ 1,194.64	22%	9%	A
610-0071-05	Part Description Omitted	$ 712.44	36%	18%	A
370-0190-02	Part Description Omitted	$ 471.19	57%	19%	A
CART-1	Part Description Omitted	$ 430.06	63%	20%	A
540-0115-01	Part Description Omitted	$ 177.61	96%	26%	B
540-0072-01	Part Description Omitted	$ 117.23	102%	22%	C
540-0071-01	Part Description Omitted	$ 117.23	102%	22%	D
540-0074-01	Part Description Omitted	$ 117.23	102%	22%	D
540-0073-01	Part Description Omitted	$ 117.23	102%	23%	D
540-0096-01	Part Description Omitted	$ 117.23	102%	25%	C
540-0060-01	Part Description Omitted	$ 117.23	154%	21%	B
370-0213-01	Part Description Omitted	$ 105.00	162%	29%	B
540-0088-01	Part Description Omitted	$ 64.50	171%	29%	C
800-0338-01	Part Description Omitted	$ 57.00	175%	36%	C
610-0328-03	Part Description Omitted	$ 90.88	187%	18%	B
540-0083-01	Part Description Omitted	$ 49.50	202%	28%	D
540-0084-01	Part Description Omitted	$ 49.50	202%	28%	D
540-0086-01	Part Description Omitted	$ 49.50	202%	28%	D
540-0085-01	Part Description Omitted	$ 49.50	202%	28%	D
540-0064-01	Part Description Omitted	$ 49.50	323%	25%	B
180-0158-02	Part Description Omitted	$ 30.62	359%	32%	C
180-0159-02	Part Description Omitted	$ 30.62	359%	32%	C
180-0157-03	Part Description Omitted	$ 30.56	360%	32%	D

810-0226-01	Part Description Omitted	$	25.77	388%	33%	C
510-0184-01	Part Description Omitted	$	26.89	409%	29%	C
540-0067-01	Part Description Omitted	$	33.76	504%	32%	B
510-0163-01	Part Description Omitted	$	18.70	588%	31%	C
510-0181-02	Part Description Omitted	$	14.28	770%	34%	C
180-0140-01	Part Description Omitted	$	13.42	820%	37%	D
510-0220-01	Part Description Omitted	$	11.99	917%	38%	C
510-0173-01	Part Description Omitted	$	11.82	931%	35%	C
180-0142-01	Part Description Omitted	$	11.51	956%	38%	D
810-0304-02	Part Description Omitted	$	9.02	1109%	42%	D
810-0305-02	Part Description Omitted	$	9.02	1109%	42%	D
810-0306-01	Part Description Omitted	$	9.02	1109%	42%	D
810-0307-02	Part Description Omitted	$	9.02	1109%	42%	D
180-0144-01	Part Description Omitted	$	9.28	1185%	39%	D
380-0238-01	Part Description Omitted	$	8.75	1257%	41%	D
510-0214-01	Part Description Omitted	$	8.62	1276%	35%	C
510-0199-01	Part Description Omitted	$	8.50	1294%	41%	D
180-0121-01	Part Description Omitted	$	8.28	1329%	39%	D
510-0223-01	Part Description Omitted	$	8.25	1333%	36%	D
180-0141-01	Part Description Omitted	$	8.25	1333%	39%	D
180-0143-02	Part Description Omitted	$	8.10	1358%	39%	D
180-0139-01	Part Description Omitted	$	8.04	1368%	39%	D
380-0004-01	Part Description Omitted	$	7.99	1377%	35%	C
50000911	Part Description Omitted	$	7.38	1491%	39%	D
810-0246-02	Part Description Omitted	$	6.34	1577%	42%	D
260-0431-03	Part Description Omitted	$	6.00	1833%	42%	D
380-0003-01	Part Description Omitted	$	4.90	2245%	38%	D
380-0221-01	Part Description Omitted	$	4.20	2619%	39%	D
810-0265-02	Part Description Omitted	$	3.64	2747%	44%	D
180-0005-01	Part Description Omitted	$	3.22	3416%	42%	D
810-0249-02	Part Description Omitted	$	2.91	3436%	45%	D
810-0250-02	Part Description Omitted	$	2.91	3436%	45%	D
180-0001-01	Part Description Omitted	$	3.15	3492%	42%	D
810-0264-02	Part Description Omitted	$	2.67	3745%	45%	D
180-0049-01	Part Description Omitted	$	1.99	5528%	44%	D
800-0339-02	Part Description Omitted	$	0.63	15873%	48%	D
260-0040-01	Part Description Omitted	$	0.16	70064%	47%	D

Appendix G

Sample First Level Bill of Material Inventory Level Evaluation

P/N	Actual	Mean	Diff	Cost	(Savings)	Description
610-0155-03	231	133	-98	$2,049.12	($200,418)	Part Description Omitted
520-0512-02	52	19	-33	$3,637.41	($121,069)	Part Description Omitted
540-0060-01	536	350	-186	$117.23	($21,806)	Part Description Omitted
540-0064-01	828	594	-234	$49.50	($11,600)	Part Description Omitted
180-0005-01	3944	620	-3324	$3.22	($10,703)	Part Description Omitted
810-0307-02	821	71	-751	$9.02	($6,771)	Part Description Omitted
540-0096-01	164	123	-42	$117.23	($4,891)	Part Description Omitted
540-0073-01	93	59	-30	$117.23	($3,563)	Part Description Omitted
540-0074-01	126	93	-26	$117.23	($3,027)	Part Description Omitted
540-0067-01	551	438	-86	$33.76	($2,899)	Part Description Omitted
180-0121-01	511	243	-261	$8.28	($2,157)	Part Description Omitted
540-0071-01	115	93	-15	$117.23	($1,734)	Part Description Omitted
180-0139-01	326	146	-175	$8.04	($1,405)	Part Description Omitted
510-0199-01	248	121	-124	$8.50	($1,052)	Part Description Omitted
510-0181-02	756	661	-61	$14.28	($869)	Part Description Omitted
180-0049-01	1291	945	-326	$1.99	($649)	Part Description Omitted
180-0157-03	95	72	-20	$30.56	($620)	Part Description Omitted
510-0173-01	737	658	-47	$11.82	($559)	Part Description Omitted
180-0144-01	196	139	-53	$9.28	($490)	Part Description Omitted
540-0084-01	96	81	-10	$49.50	($475)	Part Description Omitted
180-0143-02	163	146	-12	$8.10	($96)	Part Description Omitted
260-0040-01	4610	5148	594	$0.16	$95	Part Description Omitted
540-0083-01	84	81	2	$49.50	$115	Part Description Omitted
180-0141-01	132	145	18	$8.25	$147	Part Description Omitted
540-0085-01	56	56	4	$49.50	$180	Part Description Omitted
180-0001-01	717	811	116	$3.15	$365	Part Description Omitted
180-0142-01	101	129	32	$11.51	$373	Part Description Omitted
510-0214-01	888	889	44	$8.62	$377	Part Description Omitted
540-0086-01	78	81	8	$49.50	$402	Part Description Omitted
260-0431-03	137	202	72	$6.00	$430	Part Description Omitted
800-0338-01	105	108	9	$57.00	$512	Part Description Omitted
510-0220-01	438	459	44	$11.99	$527	Part Description Omitted
180-0140-01	86	122	41	$13.42	$555	Part Description Omitted
800-0339-02	275	1194	933	$0.63	$588	Part Description Omitted
540-0088-01	155	156	10	$64.50	$673	Part Description Omitted
810-0305-02	37	109	76	$9.02	$689	Part Description Omitted

810-0265-02	124	322	206	$3.64	$750	Part Description Omitted
810-0304-02	26	109	87	$9.02	$784	Part Description Omitted
810-0250-02	169	455	297	$2.91	$865	Part Description Omitted
180-0159-02	236	252	29	$30.62	$892	Part Description Omitted
810-0264-02	234	558	339	$2.67	$904	Part Description Omitted
380-0238-01	129	229	108	$8.75	$942	Part Description Omitted
810-0249-02	117	455	349	$2.91	$1,017	Part Description Omitted
510-0184-01	593	607	50	$26.89	$1,345	Part Description Omitted
380-0004-01	622	837	253	$7.99	$2,020	Part Description Omitted
810-0246-02	174	483	326	$6.34	$2,064	Part Description Omitted
510-0223-01	499	763	299	$8.25	$2,466	Part Description Omitted
380-0221-01	340	952	647	$4.20	$2,715	Part Description Omitted
610-0328-03	413	448	35	$90.88	$3,202	Part Description Omitted
810-0226-01	260	365	127	$25.77	$3,271	Part Description Omitted
180-0158-02	164	266	117	$30.62	$3,576	Part Description Omitted
520-0513-01	80	74	1	$3,893.07	$5,732	Part Description Omitted
540-0072-01	51	114	72	$117.23	$8,386	Part Description Omitted
510-0163-01	142	603	494	$18.70	$9,234	Part Description Omitted
370-0285-01	99	97	7	$1,450.00	$9,693	Part Description Omitted
370-0213-01	80	191	124	$105.00	$12,978	Part Description Omitted
520-0527-01	9	12	4	$3,492.00	$14,247	Part Description Omitted
540-0080-01	34	46	16	$943.00	$15,214	Part Description Omitted
540-0115-01	23	125	111	$177.61	$19,690	Part Description Omitted
540-0057-03	247	245	22	$1,194.64	$25,727	Part Description Omitted
610-0071-05	31	88	64	$712.44	$45,799	Part Description Omitted
370-0190-02	117	229	130	$471.19	$61,292	Part Description Omitted
520-0511-01	83	96	21	$3,492.00	$73,809	Part Description Omitted
540-0094-01	76	144	82	$1,194.64	$97,528	Part Description Omitted
520-0510-02	54	129	87	$2,684.11	$233,111	Part Description Omitted
540-0058-03	192	422	271	$1,194.64	$324,141	Part Description Omitted
					$592,566	Total

Top level Bill of Materials for the S2000 product family. Optimal mean values calculated with the following parameters:

annual S2000 demand: 5200
system demand standard deviation: 27/week
standard deviation of lead time: 0
system stockout cost: $2000
inventory class: A, B, C, D
inventory carrying cost: 36.5%

Appendix H

Regression Analysis of Aggregate GSD Demand

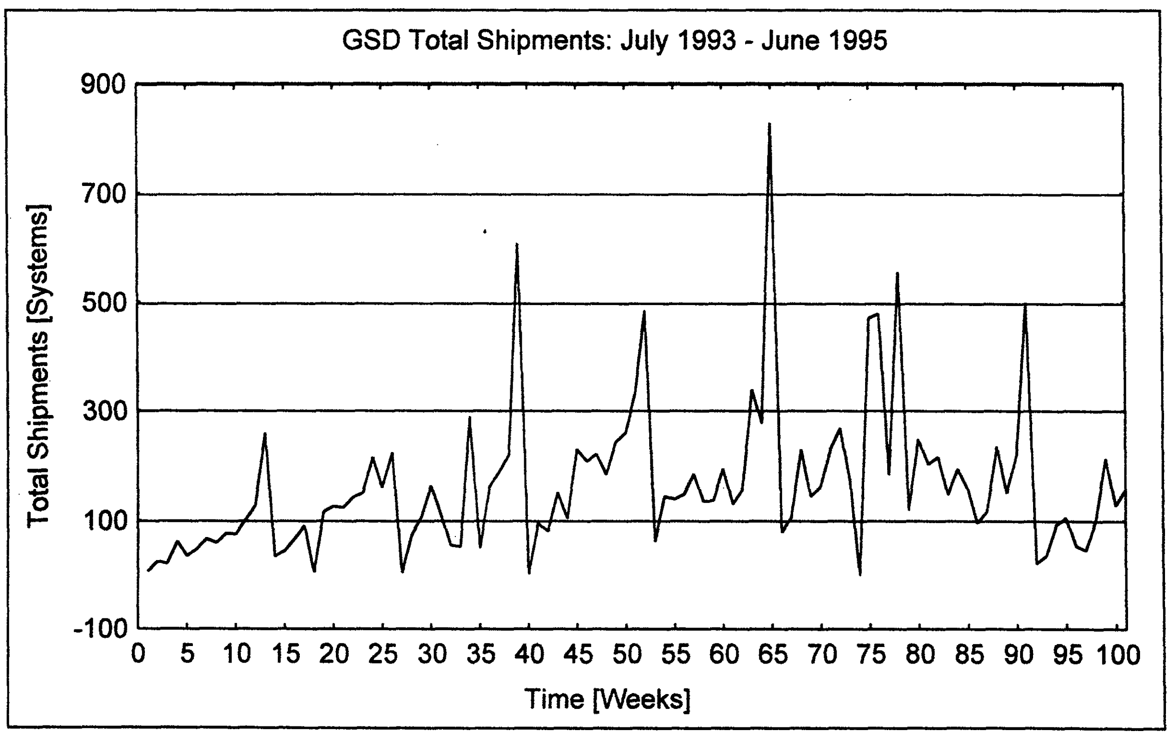
Regression Summary for Total GSD Shipments

R= .8096 R^2= .6554 Adjusted R^2= .6371

F(5,94)=35.8 p<.00000 Std.Error of estimate: 82.3

Ind Var	Beta	St. Err of Beta	B	St. Err of B	t(94)	p-level
Interept			71.28	18.151	3.927	.0002
Time	.2386	.0607	1.11	.282	3.930	.0002
First Week of the Month	-.1629	.0622	-81.63	31.173	-2.618	.0103
Last Week of the Month	.4708	.0691	250.87	36.825	6.813	.0000
Last Month of the Quarter	.2162	.0664	60.89	18.693	3.257	.0016
Special Order	.2729	.0651	372.84	89.018	4.188	.0001

Table 5: Regression Output for Aggregate GSD Shipments July 1993 - June 1995



Raw Data

	S1000	S2000	S4000	M8000	WK	WK_1	WK_L	M1	M3	MCI	TOTAL
930701	6	0	1	0	1	1	0	1	0	0	7
930702	2	0	24	0	2	0	0	1	0	0	26
930703	1	0	20	1	3	0	0	1	0	0	22
930704	2	0	60	0	4	0	0	1	0	0	62
930801	0	0	36	0	5	0	0	0	0	0	36
930802	0	0	44	4	6	0	0	0	0	0	48
930803	17	0	49	1	7	0	0	0	0	0	67
930804	0	0	57	3	8	0	0	0	0	0	60
930901	0	0	76	1	9	0	0	0	1	0	77
930902	0	0	74	2	10	0	0	0	1	0	76
930903	10	0	89	2	11	0	0	0	1	0	101
930904	7	0	115	5	12	0	0	0	1	0	127
930905	10	0	245	5	13	0	1	0	1	0	260
931001	3	0	31	1	14	1	0	1	0	0	35
931002	2	0	43	0	15	0	0	1	0	0	45
931003	1	0	66	0	16	0	0	1	0	0	67
931004	5	0	85	0	17	0	0	1	0	0	90
931101	0	0	6	0	18	0	0	0	0	0	6
931102	1	0	114	1	19	0	0	0	0	0	116
931103	15	0	108	3	20	0	0	0	0	0	126
931104	45	0	79	0	21	0	0	0	0	0	124
931201	20	0	120	3	22	0	0	0	1	0	143
931202	64	0	82	4	23	0	0	0	1	0	150
931203	56	0	156	3	24	0	0	0	1	0	215
931204	22	0	123	15	25	0	0	0	1	0	160
931205	13	0	204	7	26	0	1	0	1	0	224
940101	3	0	1	0	27	1	0	1	0	0	4
940102	15	0	56	3	28	0	0	1	0	0	74
940103	34	0	68	4	29	0	0	1	0	0	106
940104	20	0	138	5	30	0	0	1	0	0	163
940201	9	0	102	0	31	0	0	0	0		111
940202	8	0	47	1	32	0	0	0	0	0	56
940203	1	0	46	6	33	0	0	0	0	0	53
940204	1	0	280	8	34	0	0	0	0	0	289
940301	6	0	42	2	35	0	0	0	1	0	50
940302	6	0	150	4	36	0	0	0	1	0	160
940303	61	0	124	4	37	0	0	0	1	0	189
940304	46	0	171	3	38	0	0	0	1	0	220
940305	19	0	576	12	39	0	1	0	1	0	607
940401	0	0	2	0	40	1	0	1	0	0	2
940402	8	0	87	0	41	0	0	1	0	0	95
940403	11	0	70	0	42	0	0	1	0	0	81
940404	10	0	141	0	43	0	0	1	0	0	151
940501	23	0	74	7	44	0	0	0	0	0	104
940502	67	0	161	2	45	0	0	0	0	0	230
940503	54	0	154	0	46	0	0	0	0	0	208
940504	63	0	153	5	47	0	0	0	0	0	221
940601	40	0	140	4	48	0	0	0	1	0	184
940602	34	0	203	6	49	0	0	0	1	0	243
940603	86	0	166	8	50	0	0	0	1	0	260
940604	76	0	248	6	51	0	0	0	1	0	330
940605	35	0	419	30	52	0	1	0	1	0	484
940701	1	0	61	0	53	1	0	1	0	0	62
940702	50	0	93	1	54	0	0	1	0	0	144
940703	42	0	95	2	55	0	0	1	0	0	139
940704	26	0	113	9	56	0	0	1	0	0	148
940801	13	0	171	0	57	0	0	0	0	0	184
940802	47	0	88	0	58	0	0	0	0	0	135
940803	49	0	87	0	59	0	0	0	0	0	136
940804	27	0	167	0	60	0	0	0	0	0	194
940901	9	0	116	5	61	0	0	0	1	0	130
940902	30	0	126	1	62	0	0	0	1	0	157

940903	103	0	229	6	63	0	0	0	1	0	338
940904	75	0	175	27	64	0	0	0	1	0	277
940905	182	0	619	27	65	0	1	0	1	1	828
941001	3	0	76	0	66	1	0	1	0	0	79
941002	21	0	81	3	67	0	0	1	0	0	105
941003	41	0	187	1	68	0	0	1	0	0	229
941004	12	0	130	2	69	0	0	1	0	0	144
941101	21	0	127	13	70	0	0	0	0	0	161
941102	32	0	193	3	71	0	0	0	0	0	228
941103	75	0	187	6	72	0	0	0	0	0	268
941104	49	0	124	2	73	0	0	0	0	0	175
941201	0	0	0	0	74	0	0	0	1	0	0
941202	40	0	416	14	75	0	0	0	1	0	470
941203	71	0	387	21	76	0	0	0	1	0	479
941204	27	0	144	13	77	0	0	0	1	0	184
941205	69	0	467	20	78	0	1	0	1	0	556
950101	10	0	109	0	79	1	0	1	0	0	119
950102	23	0	224	1	80	0	0	1	0	0	248
950103	74	0	125	4	81	0	0	1	0	0	203
950104	17	0	199	0	82	0	0	1	0	0	216
950201	11	0	126	10	83	0	0	0	0	0	147
950202	28	0	163	3	84	0	0	0	0	0	194
950203	24	0	121	13	85	0	0	0	0	0	158
950204	15	1	76	4	86	0	0	0	0	0	96
950301	33	4	70	9	87	0	0	0	1	0	116
950302	30	4	195	6	88	0	0	0	1	0	235
950303	21	7	121	2	89	0	0	0	1	0	151
950304	65	1	150	3	90	0	0	0	1	0	219
950305	69	2	412	16	91	0	1	0	1	0	499
950401	8	0	9	5	92	1	0	1	0	0	22
950402	9	10	15	2	93	0	0	1	0	0	36
950403	1	26	64	1	94	0	0	1	0	0	92
950404	8	4	90	3	95	0	0	1	0	0	105
950501	11	0	42	1	96	0	0	0	0	0	54
950502	13	5	30	-2	97	0	0	0	0	0	46
950503	1	1	98	0	98	0	0	0	0	0	100
950504	26	5	181	1	99	0	0	0	0	0	213
950601	10	2	114	2	100	0	0	0	1	0	128
950602	5	30	115	7	101	0	0	0	1	0	157

Appendix I

Estimation of the Standard Deviation of Demand

The standard deviation of demand has a large effect on the results of the model. The standard deviation of demand is a measure of the unpredictability of demand. It is the driver of safety stock level. If you can predict demand perfectly, you need to carry no safety stock. If you are extremely inaccurate in your prediction of demand, you will have to carry a large amount of safety stock. Therefore, it is important to estimate the standard deviation of demand as accurately as possible.

PictureTel's forecasted demand can be decomposed into three components that sum linearly: a *trend*, a *seasonality* and a *constant*. When these components are added, we see a pattern similar to that presented in Figure 16. The actual demand contains a fourth component, referred to as the *error* component.

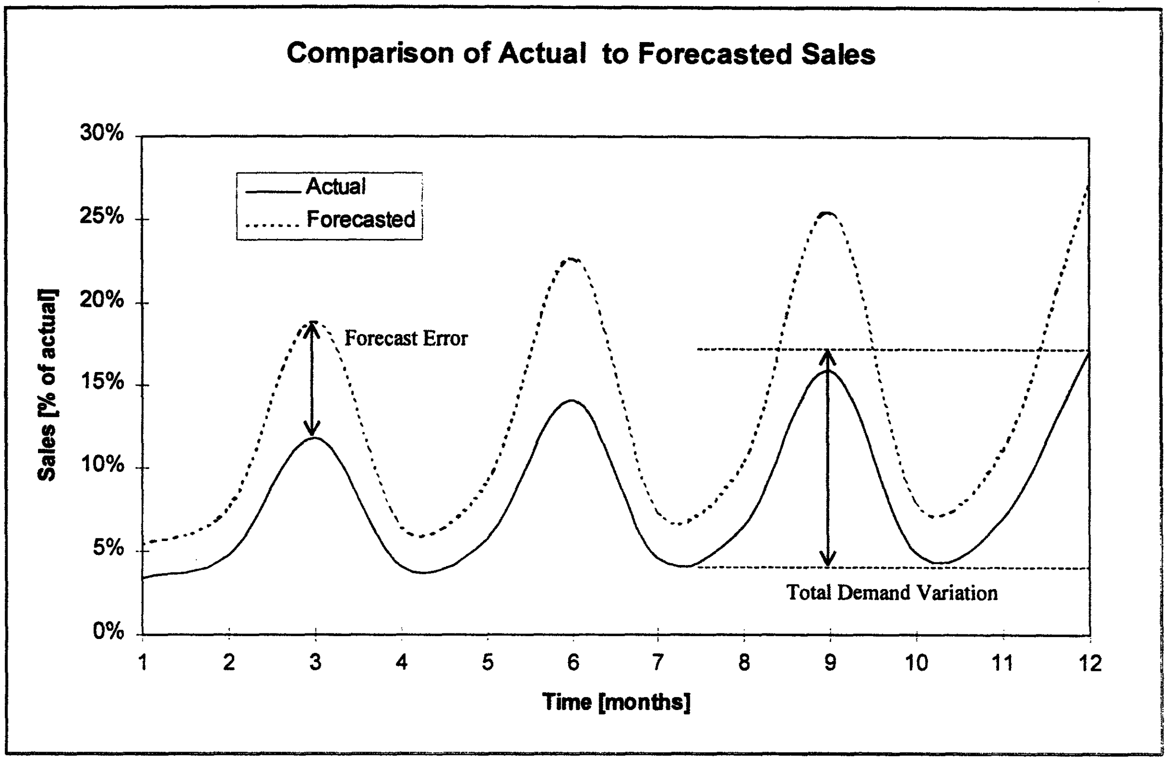


Figure 16

We note from Figure 16 that the demand is not constant. The variation in demand is a result of the trend, the seasonal and the error components. If we take each data point of a historical demand series (which are random variables) we can calculate the standard deviation of this series. We will call this value the *total standard deviation of demand.* The total standard deviation of demand includes some components of variation in demand that we can explain, however, these are the trend and seasonal components. We are really interested only in those components of variation that we can not explain. We get to this point by removing the trend and seasonal components. If we remove these components, we are left with the constant and error components, as illustrated below in Figure 17.

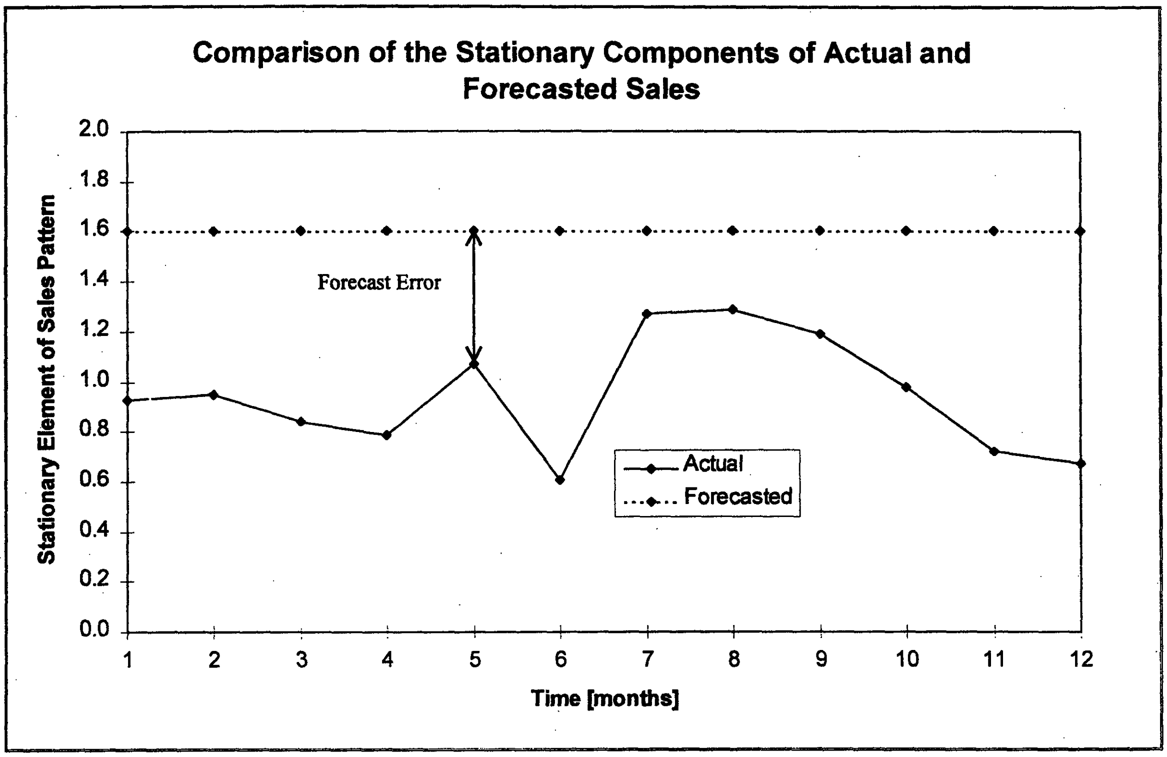


Figure 17

We will refer to the error component as the *forecast error*. As can be seen in Figure 17, the forecast error is a random variable which will have some distribution. This distribution is approximately normal, as was described in Chapter 3: Total Cost Model. Any normal distribution can be fully described with two parameters, the mean and standard deviation. The mean of the forecast error represents the bias. (An unbiased forecast will have a mean of zero.) The standard deviation is a measure of the unpredictability of the demand. It is this standard deviation of forecast error that we will use as our measure of the standard deviation of demand. It is the most accurate representation of the (historical) unpredictability in demand. Note, that our measure, the standard deviation of forecast error, is different from the Mean Square Forecast Error.