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Guidelines for Collaborative Supply Chain System Design and Operation

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ABSTRACT

Over the past decade, firms have adopted *supply chain management* as a critical element of their corporate strategies. Despite these efforts, it is our observation that many firms do not realize the anticipated benefits of constructing *collaborative* operating relationships with supply chain partners. Our purpose in this paper is to establish a set of guiding principles for the effective design and execution of supply chain systems. These principles suggest why, what, and how collaborative relationships should be constructed.

While constructing and operating a competitive supply chain is the primary objective of supply chain management, we have observed several impediments to achieving this goal. First, demand uncertainty is so substantial in most supply chain environments that if it is not adequately addressed, it can severely degrade the anticipated performance of the supply chain as measured in terms of unit cost, speed, quality, and responsiveness to changing conditions. Second, supply chains with poor physical characteristics that operate with long and variable response times cannot take full advantage of collaborative relationships due to their inability to respond to changes in the environment. Third, firms with poor information infrastructures lack the capabilities necessary to acquire, store, manipulate, and transmit data effectively and quickly. Fourth, business processes are often not designed properly, both intra- and inter-organizationally, to adapt to evolving supply chain conditions. Finally, decision support systems and operating policies that guide day-to-day operating decisions may not be adequately designed to contend with supply chain uncertainty.

We also suggest that the strategic and tactical modeling paradigms employed in supply chain decision support systems are inadequate in many operational environments because their treatment of uncertainty is inappropriate. Furthermore, collaborative relationships that focus on reducing the uncertainty in operating environments by employing improved information systems and business processes will result in more efficient allocation of key resources, faster response times to market forces, and more reliable supply chain performance; however, these collaborative arrangements by themselves cannot compensate for fundamentally flawed and operationally ineffective manufacturing and distribution environments.

KEY WORDS: SUPPLY CHAIN MANAGEMENT, COLLABORATIVE PLANNING, PRODUCTION PLANNING AND CONTROL, OPERATIONS STRATEGY, MULTI-ECHELON INVENTORY SYSTEMS, CAPACITATED PRODUCTION.

1 Introduction

There are many definitions and interpretations of the term *supply chain management*. We define a supply chain to be the set of firms acting to design, engineer, market, manufacture, and distribute products and services to end-consumers. Equally confusing, the term *collaboration* has taken on several interpretations when used in the context of supply chain management. We use the term *supply chain collaboration* to refer to those activities among and between supply chain partners concerned with the cost effective, timely, and reliable creation and movement of materials to satisfy customer requirements.

Historically, many forces have had an impact on the evolution of supply chains. At the beginning of the twentieth century, the Ford Motor Company created an entirely vertically integrated supply chain that included mining, steel and glass fabrication; tire manufacturing, and the other manufacturing capabilities necessary to build and distribute an automobile. See Womack, Jones, and Roos (1990) for a complete discussion. While today's high standards of customers were not in play in the early 1900's, that supply chain proved to be extraordinarily effective and permanently changed the nature of business. With steadily increasing specialization in more recent times, there has been a shift in management focus and strategy toward trimming operations in order to focus on the firm's *core competencies*, as proposed in Prahalad and Hammel (1990). In many instances, this focus has resulted in a *dis-integration* of a firm's own internal supply chain.

As firms continue to focus on their core competencies, they have integrated their internal business processes and information flows well. Firms are working to make the most of their core competencies in order to maximize their competitive position as part of a larger supply chain. This forces the firm's leaders to understand the needs of its customers more completely. What do they want? Where do they want it? When do they want it? How do they want to receive it? What are they willing to pay for the products and services?

We believe it is essential to think of a supply chain in terms of five interconnected business systems, as shown in Figure 1.

- **Engineering Systems**. In order to create the products desired by customers, both the product, and its manufacturing and delivery process, must be designed and *engineered* properly.
- **Marketing Systems**. The market for products must be understood and the needs for the products must be created and nurtured. In creating needs in the mind of the customer for the firm's products, the marketing function also creates expectations of a reliable delivery mechanism and good customer service.
- **Manufacturing Systems**. Manufacturing processes must be aligned and maintained to produce products in a reliable and cost effective manner.
- **Logistics Systems**. Logistics systems must be capable of providing raw materials and components to supply chain partners, and finished goods to customers in a timely and cost effective way.
- **Management Systems**. Management planning, control, and reward systems must ensure that the operations are designed and executed properly.

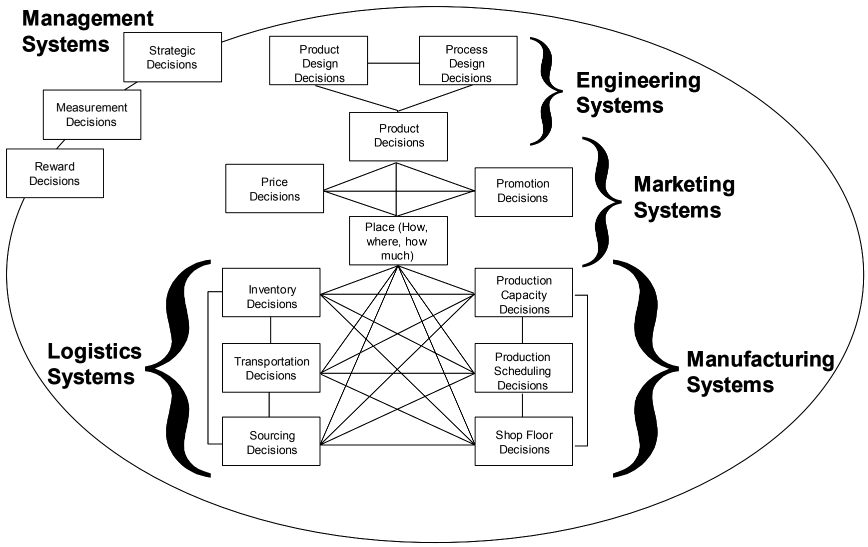

Figure 1. Five tightly connected business systems

Opportunities for supply chain efficiency tend to occur at the boundaries of these individual functions. As a result, we believe that the greatest competitive advantage comes to those firms that focus on both (1) integrating these five systems intra-organizationally and (2) integrating these business functions as much as possible with their collaborating supply chain partners.

Integration of these five systems alone is not sufficient to ensure competitive advantage. We think that firms must deal more explicitly with the impact of uncertainty on the supply chain decisions that they make. Poor supply chain decision-making in situations where uncertainty is present has broad negative impacts across a variety of industrial and military settings. See Muckstadt (1997) for a detailed discussion. As demonstrated in Lee, Padmanabhan, and Whang (1997) and in Cachon and Fisher (2000), the sharing of information can be extremely beneficial; however, in practice, simply passing data such as customer orders is not sufficient to reduce the impact of uncertainty substantially. We assert that manufacturing and distribution systems must be designed and operated in a manner that deals with uncertainty *explicitly*.

In this paper, we will illustrate the prevalence and magnitude of demand uncertainty in supply chains, propose an alternate operating philosophy capable of dealing explicitly with demand and capacity uncertainty, the *No B/C Supply Chain Design and Operating Strategy,* and illustrate with an industrial example the kind of supply chain collaboration required to produce sustainable competitive advantage.

2 Guidelines for Supply Chain Design

2.1 Forces Driving Change in Supply Chain Infrastructure

Several forces are currently driving change in supply chains. Some of these lead to greater efficiency while others increase operational uncertainty. On the positive side, advances in information technology continue to lower the cost of acquiring, storing, manipulating, and transmitting data. This makes it economical to integrate increased amounts of information in all aspects of business processes, both intra- and inter-organizationally, and decreases the cost of transactions. Prudent use of these integrated data can reduce operational uncertainties.

On the other hand, end-consumers continue to demand greater product variety, lower cost, and more agility from their suppliers. Product life cycles are shortening and the competitive time-to-market for new products is decreasing. Customers are requiring shortened lead times between the time when an order is placed and when an order is due. These shorter lead times render accurate demand forecasting over order lead times virtually impossible for many manufacturing and distribution planning purposes, thereby increasing operational uncertainty.

Many types of supply chains exist in the world economy. Most share some common elements. For example, within each supply chain, material flows from a raw material state to an end-user, and possibly flows in a reverse direction as recycling occurs. An example is depicted in Figure 2. In this diagram, there are four levels, or echelons, consisting of retailers, distribution locations, manufacturing facilities, and raw material suppliers.

At each level of the supply chain there can be many physical locations. For example, this supply chain could represent material flowing to The Gap clothing stores in the United States. The Gap has many retail locations that satisfy demand generated by end-users. One type of product sold at The Gap is blue jeans. Levi Straus may supply these jeans to The Gap. Levi Strauss, in turn, manufactures these jeans using denim that is supplied by Swift, or some other supplier. This denim is processed, in part, using chemicals from, say, DuPont or ICI. An important attribute of the supply chain is the *length of time* it takes both information and materials to flow through it.

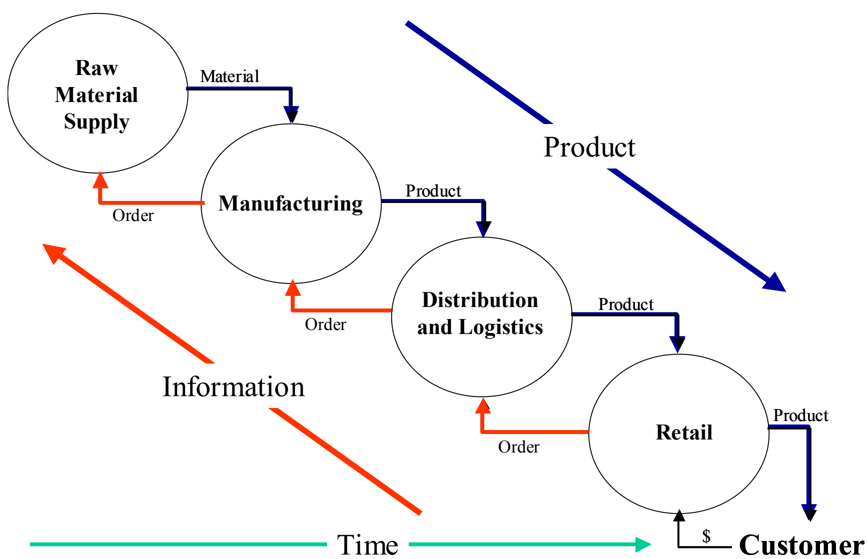

Figure 2. Traditional View of the Supply Chain

The balance of power among a supply chain's members plays a significant role in defining the supply chain. Fisher (1997) describes how very different supply chain structures may exist for seemingly similar products. These structures evolve over time depending on market, technological, and economic forces. Porter (1985) describes a framework for understanding a firm's competitive position and articulates how the balance of power between firms in a supply chain and between supply chains is critical to competitiveness.

The power relationships in supply chains are not necessarily static and may change quickly. For example, in the mid-1980's, Proctor & Gamble and Unilever dominated the supply chain for consumer soap in the United States. Today the basis of power in that supply chain has shifted away from these manufacturers to major retailers, such as Walmart. Thus, supply chains are dynamic, are created for specific purposes, and have finite useful lifetimes. They need to be carefully designed and operated recognizing the dynamic and uncertain nature of markets.

2.2 Five Principles of Supply Chain Management Excellence

The performance of a supply chain is influenced by the structure of business processes, information systems, and decision support rules as well as the nature of collaboration between supply chain partners. If the supply chain has not been structured properly, as measured by its physical attributes, little can be done to repair the resulting "damage." If the supply chain infrastructure has lengthy and variable lead times, poor understanding of customer demand patterns, poor product quality, or uncertain production capacity, then little competitive advantage can be achieved through more extensive adoption of information systems, decision support tools or efforts to collaborate with partners.

Thus, competitive advantage will exist only if several key elements exist in a supply chain. We believe there are five guiding principles that must guide the developments of these effective supply chains.

(1) Know the customer. First and foremost, without a clear understanding and definition of customer requirements, a supply chain cannot be effectively constructed. To gain this understanding requires the use of classical market research techniques, the construction of an information infrastructure to capture customer transaction data, and the storage and analysis of these data. The objective of these steps is to obtain a clear statement of the customer requirements relating to product desires, due date expectations, service requirements, method of acquisition and delivery, etc. The requirements of the supply chain will vary by customer, by product, and by location. The requirements must be thoroughly understood and must be the basis for the construction of the supply chain.

(2) Construct a lean supply chain organization that eliminates waste, variability, and uncertainty. During the past two decades, operationally excellent firms have focused on creating lean organizations. As a consequence, these firms have internally shortened lead times and have made them predictable and repeatable, reduced work-in-process inventories from months of supply to days of supply, implemented just-in-time delivery strategies for their most costly component materials, and have worked to reduce setup times dramatically. These actions have reduced indirect costs substantially, improved the utilization of physical space, and perhaps most importantly, have created cross-trained, empowered and more highly motivated workers. For a supply chain to be efficient, all partners must engineer, align, and execute their processes so that the entire chain has the attributes mentioned above. Even if the supply chain does have these attributes, it may not have competitive advantage because variability and uncertainty will erode its efficiency and profitability. Lean supply chains must also be designed as a system that is capable of responding to fluctuations in demand quickly and profitably. Thus, lean thinking must be extended beyond a firm's operations to the operations of an entire supply chain.

(3) Build tightly coupled information infrastructures. A necessary condition for a supply chain to achieve competitive advantage is the presence of an effective information infrastructure, both intra- and inter-organizationally. True B2B collaboration, using XML, permits supply chain partners to share up-to-date demand information, inventory status, requirements for capacity usage on a daily basis, evolving marketing plans, changes to product and process design, and logistics requirements to mention but a few. True collaboration requires more than the passing of data between successive supply chain members. Rather, it requires joint planning of inventory and production strategies, and the reliable execution of operational plans on a continuing basis. How capacity is used daily must be thought of from a systems perspective and not just from a local viewpoint. Simply passing data (even customer demand data) among partners only results in communication or coordination. It does not result in true collaboration.

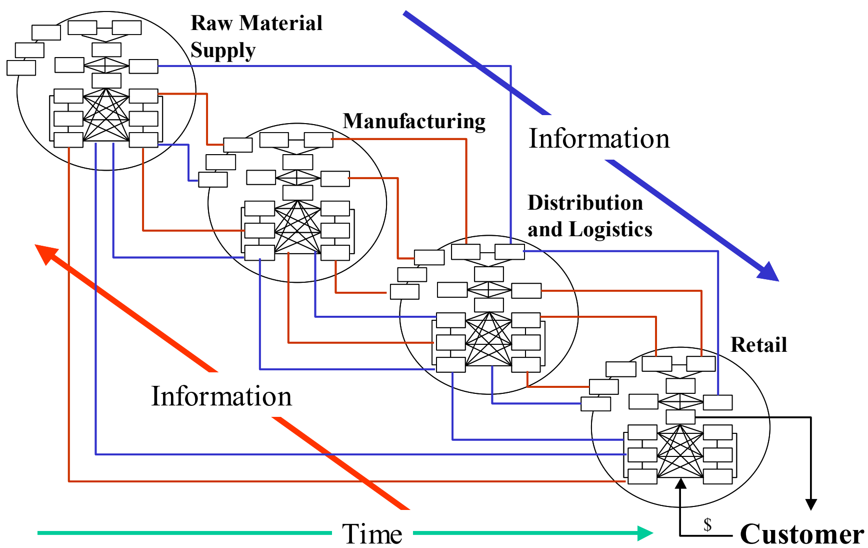

Figure 3. Tightly coupled information and business processes

(4) Build tightly coupled business processes. Business processes must be established both intra- and inter-organizationally to support the strategic objectives of the supply chain, as illustrated in Figure 3. These processes, coupled with the information infrastructure, support the efficient flow of material through the supply chain. While much attention has been placed on understanding business processes within organizations, it is essential to understand what processes must be built inter-organizationally to leverage and enhance the capabilities of the partners. These inter-organizational processes must be designed to take advantage of the increased information availability in driving daily supply chain activities.

(5) Construct tightly coupled decision support systems. Over the past thirty years, academics and software providers have concentrated on designing and building decision support environments (DSS) for individual firms and supply chains. These environments are based on different models of how supply chains operate. Also, they differ in how they forecast demand, and how they drive production and allocation decisions. Their goal is to generate plans that consider all elements of the supply chain simultaneously. No matter which approach is taken, these systems, and the rules embedded within them, drive many of the day-to-day supply chain activities. Therefore, they have a substantial impact on the operating behavior, and consequently on the overall performance of the supply chain. How much they enhance this performance depends both on the accuracy of their input data and on the modeling approaches employed. Specifically, these decision support systems need to address uncertainty explicitly.

2.3 Examples of Demand Uncertainty

We have stressed the importance of considering uncertainty throughout our discussion because it is prevalent in most supply chains. Certain characteristics of demand uncertainty can make it difficult to forecast reliably. To meet customer due dates, firms typically react in costly ways such as adding large quantities of buffer inventories, using overtime production, outsourcing production, or purchasing excess capacity or product on the spot market. To illustrate why we believe uncertainty must be addressed when making strategic, tactical, and operational decisions, we present three industrial examples. Other examples are given in Muckstadt (1997).

Example 1 – Consumer Package Goods. Consider the demand time series, shown in Figure 4, observed at a manufacturing facility for a popular consumer packaged good (CPG). Observe the degree of fluctuation in the demand process over time. While the mean daily demand is 104,423 units, the standard deviation of daily demand is 245,731 units. A measure of relative variation, called the coefficient of variation (CV), is defined as the ratio of the standard deviation to the mean. In this case, the CV is 2.35, or the standard deviation is 235% of the mean.

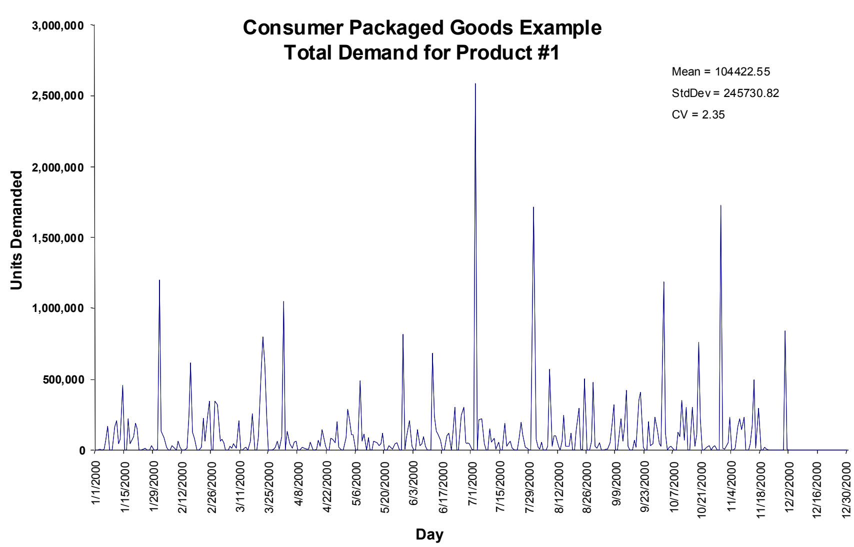

Figure 4. Daily demand for a consumer packaged good

In many planning systems, demand over a lead-time is modeled using a Normal probability distribution. Subsequently, this demand model forms the basis for several operating decisions, such as inventory stocking levels. This is sometimes a good approximation for the demand process when its CV is less than 0.30. The demand process over ever-shortening order lead times (customer due date minus order date) in the environment we have illustrated would not be modeled effectively using a Normal probability distribution, as is obvious by looking at the data. The consequences of this observation are substantial. For example, production lead times are not constant, safety stocks are not adequate, demand is not satisfied on time, and operating costs exceed expectations.

Example 2 - Aerospace. Consider another environment, where aggregate weekly demand data are shown in Figure 5. The products in this case are fabricated assemblies used in the aerospace industry. Even when the demand is aggregated into weekly time buckets, the relative variation in the demand process is very high. The CV is 0.85. We stress that it is extremely difficult for any forecasting mechanism to generate accurate forecasts on a part number basis for this environment. The coefficient of variation of demand over a lead-time is greater than 1.0 for almost all items. Hence, operational plans based on inaccurate forecasts result in poor supply chain performance.

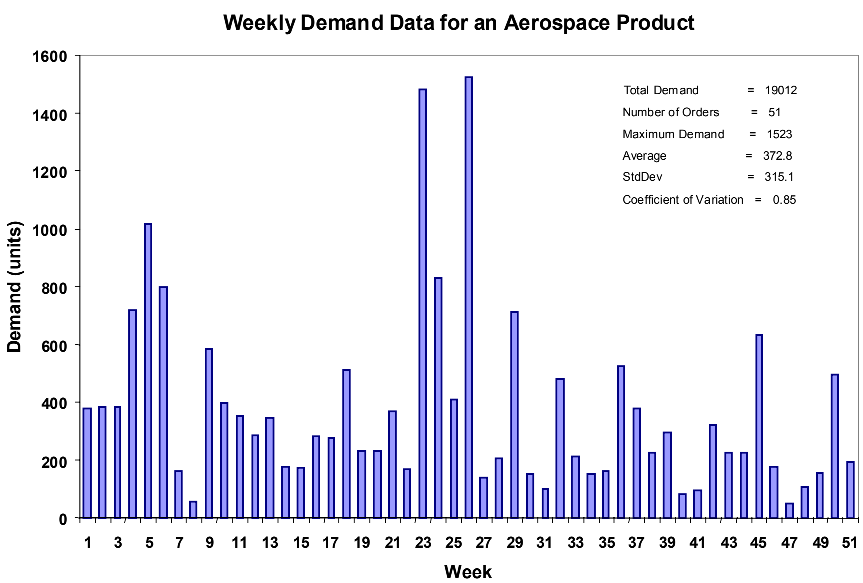

Figure 5. Weekly demand for an aerospace product

Example 3 – Industrial Products. Consider the aggregate demand time series for a product family produced by a manufacturer of consumable industrial equipment, as shown in Figure 6. The regular-time daily production capacity is 990 units per day. In order to meet promised shipment dates, products had to be produced in the same time period as the customer order. The per-unit processing times across different products are approximately the same and changeover times between different products are very small. Observe that while the average daily demand is 670 units per day, the actual demand is rarely, if ever, exactly 670 units. The capacity utilization of the facility is defined as the average demand divided by the available capacity. In this case, the capacity utilization is 74%, suggesting that there is plenty of available capacity to deal with demand uncertainty. The demand uncertainty, as measured by its standard deviation, is 764 units. The coefficient of variation is 1.10. Note that while a utilization of 74% may seem to be sufficient, demand frequently exceeds capacity over a lead-time. The system copes by either adding inventory, much of which may never be sold, or by not satisfying customer demand on time.

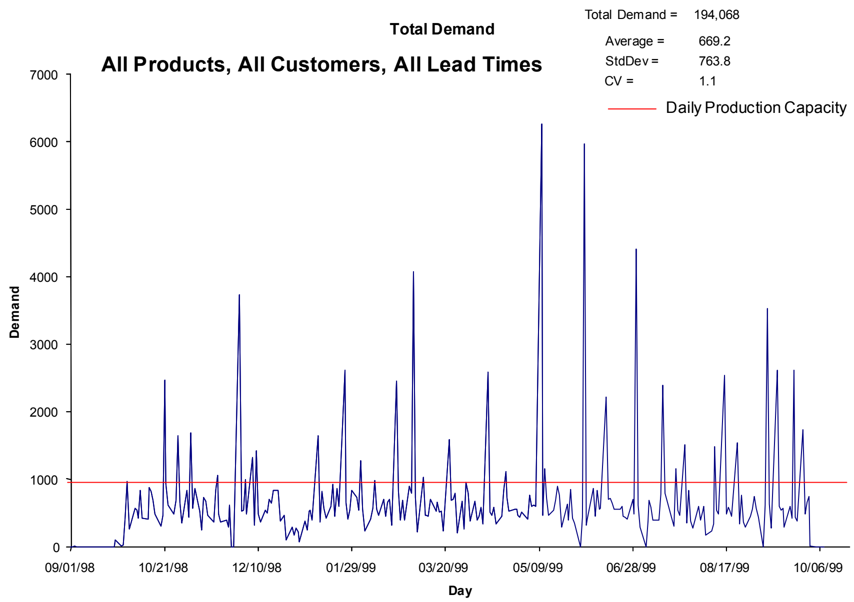

Figure 6. Time series of the total demand for capacity in the facility

The total demand on the facility, as depicted in Figure 6, is the sum over all products and all customers. The relative variation of demand generated from any given product and customer combination is much higher. This high degree of uncertainty makes accurate forecasting very difficult for the aggregate demand process across all items, let alone for specific products or customers. Figure 7 and Figure 8 illustrate this fact. These figures contain the demand time series and the inventory stocking levels for Products #1 and #26, respectively. For Product #1, the target inventory level was determined manually as a result of the system's inability to generate accurate forecasts. Note that this stock level as shown in the figure, is set just high enough to satisfy the large spikes in demand that occur periodically. For Product #26, the inventory level is set to 15 units by the planning system. This is approximately 12.5 days of average demand and would have been sufficient to satisfy only 57% of the demand on time. But, the customer service objective for this environment is a 93% customer on-time delivery. Consequently, the planning system policy is both ineffective and costly.

In summary, customer demands are a major source of uncertainty. As customer lead times shorten, the effect of this variation on supply chain performance has increased. Thus, this uncertainty must be carefully considered when designing supply chains. Since our data show that demand is usually concentrated in a small fraction of products and customers, careful attention must be given to this group of customers and products when designing supply chain strategy. We will give a specific example of how this was accomplished in one environment in section 4.

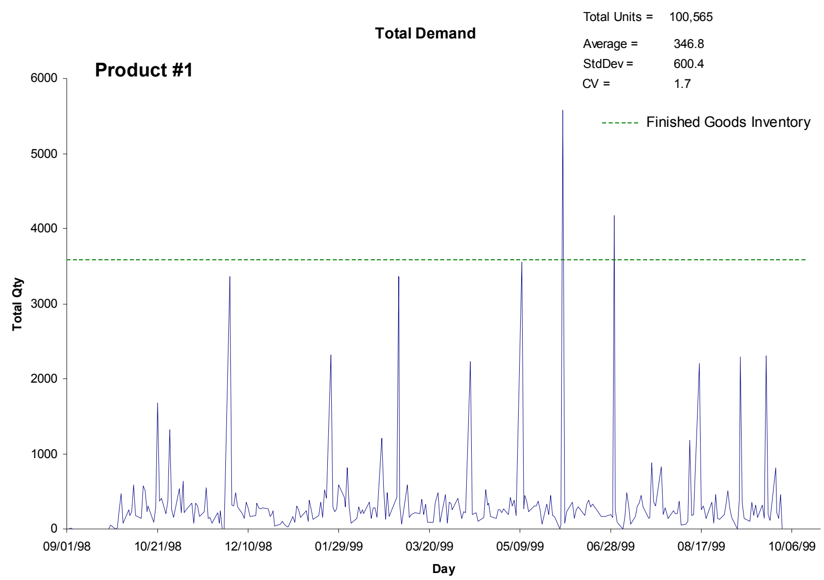

Figure 7. Time series of demand for the highest volume product

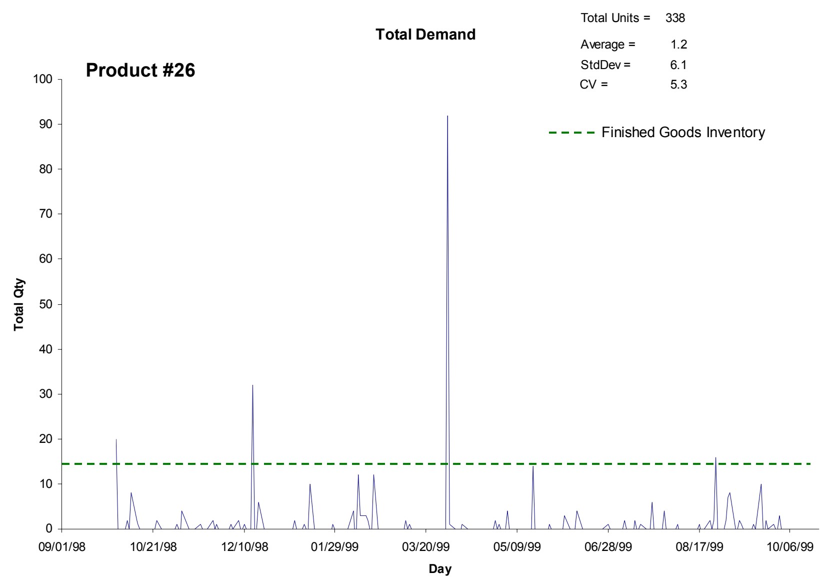

Figure 8. Time series of demand for product #26

2.4 Reducing Uncertainty Through Supply Chain Collaboration

We believe that a spectrum of supply chain relationship types must be established, as shown in Figure 9, and managed differently from one another. We have defined four categories or types. All of these relationship types may exist simultaneously in a supply chain. For example, a manufacturer will treat its customers differently. Moreover, it will treat its suppliers differently.

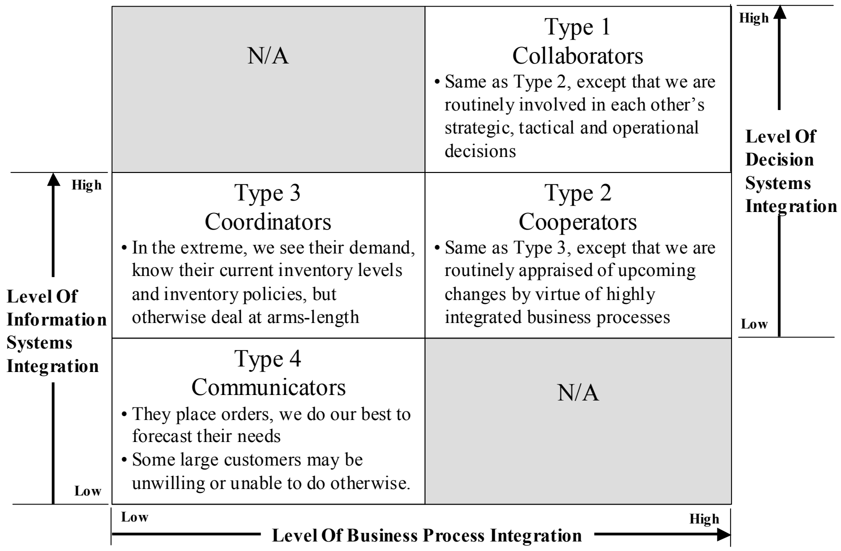

Figure 9. Four types of supply chain relationships

In the most basic of relationships, customers transmit orders to the firm and the firm is expected to respond to these orders in the lead-time requested by the customer. We call this type of relationship a Type 4 relationship, and call firms that interact in this manner *communicators*.

As firms evolve to share and capture more detailed operational data about inventory levels, stocking policies, and the customer's customer demand, a Type 3 relationship may result between supply chain members. An Electronic Data Interchange (EDI) 852 transaction, or stock-status report is an example of this type of information sharing. This level of sharing permits a higher degree of forecasting accuracy throughout a supply chain in terms of the size and timing of customer orders. Thus, we refer to these firms as *coordinators*. These data also permit a greater understanding of the customer's operations, which is important in constructing a collaborative supply chain value proposition.

While building the information infrastructure to support coordination is critical, it alone will help mitigate only a portion of the uncertainty that exists in these environments. Namely, it will help reduce the uncertainty surrounding a customer's order stream. To progress to a Type 2 relationship, customers must also communicate plans that are out of the ordinary. Examples are sales promotions that are likely to increase the demand rate or orders temporarily and plant or line closings that will decrease the demand rate or capacity for some period of time. We call firms that effectively communicate these types of anomalies *cooperators*. Achieving this level of interaction requires both a suitable information infrastructure and supporting business processes.

For supply chain partners to be considered *collaborators*, they must do more than cooperate. Together, they must carefully plan how capacity should be created throughout the system. They must decide jointly where and in what quantities inventories of various types should exist. They must also decide in advance what actions will be taken when various unplanned events occur. Thus, strategic and tactical plans must be created collaboratively by supply chain partners and executed collaboratively to achieve the maximum system effectiveness. These plans describe how the supply chain will respond to variations and uncertainty.

2.5 Capturing the Linkage Between Decision Levels in Supply Chain Design

Another requirement of a supply chain design that delivers competitive advantage is a decision making infrastructure that recognizes the linkages between the strategic, tactical, and operational levels of supply chain decision making, and the requirements for information flows.

A framework for viewing how strategic, tactical, and operational supply chain decisions relate to one another is depicted in Figure 10. Figure 11 provides examples of specific business decisions within each level of the hierarchy (examples vary from industry to industry). Strategic decisions typically deal with market entry and mobilizing resources needed to meet market requirements over time. The focus is largely on the creation and allocation of financial and human capital. Lead times required to implement these decisions can often be measured in years. A strategic planning model employed in the process may represent the entire chain of production and distribution capacities for a large business unit. It commonly measures the effect of employing alternative strategies by using data that represents point estimates of aggregated demand and capacities over long time periods.

As one moves downward in the decision-making hierarchy, planning horizons shorten. At the same time, the granularity of the decision models used in the planning process increases as the time horizon shortens so as to permit explicit representation of and timing of key events.

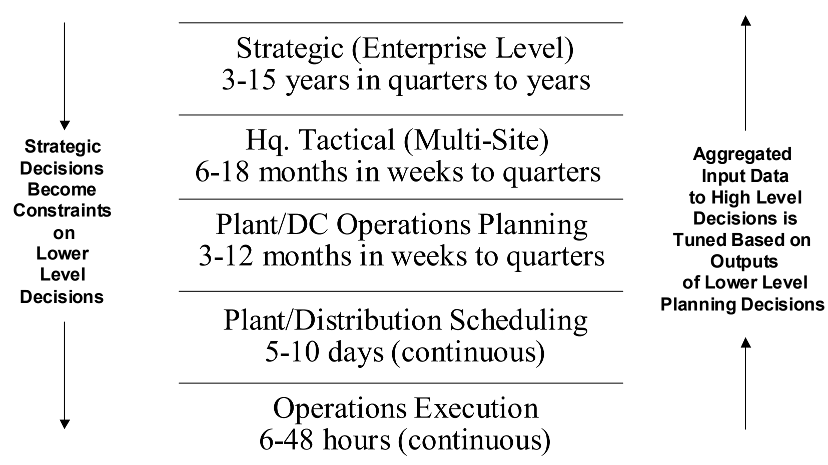

Figure 10. Hierarchy of Supply Chain Planning/Execution Decisions

<table>
<tr><td colspan="2">Strategic
• Merger / Acquisition
• Capacity rationalization (plants & distribution centers)
• Product mix optimization
• New product introductions</td></tr>
<tr><td colspan="2">Headquarters Tactical (Multi -Site)
• Sourcing of production
• Inventory positioning
• Ordering of long lead time materials</td></tr>
<tr><td>Plant Operation s Planning
• Overhaul, downtime planning
• Manpower/shift planning</td><td>Distribution Center Operations Planning
• Manpower/shift planning</td></tr>
<tr><td>Detailed Plant Scheduling
• Machine operations sequencing
• Detailed capacity balancing
• WIP to order matching</td><td>Detailed Distribution C enter Scheduling
• Shipping, receiving, and put away scheduling
• Vehicle load staging</td></tr>
<tr><td>Operations Execution
• Job dispatching</td><td>Operations Execution
• Vehicle loading and dispatching</td></tr>
</table>

Figure 11. Supply Chain Planning and Execution Decisions

A necessary condition for optimizing the supply chain is to recognize the required linkages between the hierarchy levels. Higher-level decisions, reflecting commitments over longer horizons, ultimately impose constraints when making lower level decisions. When constructing strategic objectives and plans, the operational dynamics of the supply chain are often ignored or assumed-away with estimated average figures. As many internet-based firms have found out, strategic plans may be well written, but unless the operational system is designed carefully by considering the interactions between processing capacity, demand uncertainty, inventory, customer service requirements, and unit cost, the strategic plan may not be executable and consequently the objectives may be unattainable.

Just as strategic decisions may be viewed as constraints placed on both tactical and operational decisions, operational decisions can influence the validity of the higher-level strategic decisions. The communication and representation of data from lower decision levels upward is less well understood. What output of lower level decisions should be used when making higher-level decisions? How should it be used? How should the information be organized in databases carrying it upward? What is the cost of ignoring this feedback loop in a supply chain-modeling framework?

A critical class of feedback information often missing is a representation of the uncertainty inherent in the parameter values used when making high-level strategic and tactical decisions. Point estimates of demand and processing capacity requirements are inadequate. The presence of uncertainty affects a system's ability to meet demand in a timely and profitable manner. Since higher-level models use aggregated point estimates as input data, higher-level model-generated plans are likely to suggest using production capacity inappropriately and to create inventories in the wrong items and locations. We now illustrate why this occurs.

2.6 Capacity, Inventory, and Service

One of the most commonly ignored relationships in the planning and management of production and inventory systems is the relationship among capacity utilization, inventory, and customer service. Capacity utilization is defined to be the average demand rate divided by the average production capacity rate. Inventory in this case refers to the amount of finished goods inventory. Customer service can be defined in multiple ways. For our purposes, we will define customer service as an off-the-shelf fill rate, or the expected fraction of demand that will be satisfied in the period in which customers wanted the material. As we shall demonstrate, capacity decisions, inventory decisions, and customer service objectives are inextricably linked. That is, once any two of the three are set, the other is determined. We illustrate this tradeoff with a simple example.

Consider a manufacturing facility that observes its customer demand and then makes its production decision. Customer orders received in a period must be satisfied within the same period. Production is limited by a maximum capacity in any period. The production policy each period is to produce enough material to raise its finished goods inventory level up to some predetermined value or up to its capacity, whichever is smaller. A fundamental question that arises in this environment is how much finished goods inventory needs to be carried in order to achieve some customer service level.

For our example, suppose customer demand is 100 units per period. We will examine the consequences of having different degrees of uncertainty in the demand process. Specifically, we assume that the standard deviation of demand is either 25 units, 50 units, or 75 units per period. The effect of capacity utilization will also be examined. We will assume that it is either 85%, 90%, or 95%, depending on how much equipment and labor are employed. The objective of this manufacturing facility is a 95% customer fill rate. That is, when a customer places an order for material in a period, the system must be able to ship an average of 95% of the units demanded on time. This service level will be achieved through a mix of capacity and inventory. Once the capacity utilization and customer service parameters have been determined, the required amount of inventory to support this environment is a direct consequence of these two decisions. Figure 12 below shows the amount of required inventory to achieve a 95% fill rate for various combinations of the standard deviations of demand per period and capacity utilization.

Observe that the amount of finished goods inventory required to support the customer service objective varies considerably, depending on the particular attributes of the system. Moreover, the relationship between inventory, utilization, and demand uncertainty is non-linear. If the manufacturing facility operates at an 85% capacity utilization and experiences demand that has a coefficient of variation of 0.25, the required amount of finished goods inventory to achieve a 95% customer fill rate is only 4 units. For the same system, trying to satisfy more uncertain demand with a coefficient of variation of 0.75 would require 406 units of inventory, or a 100 fold increase in inventory to achieve the same level of customer service.

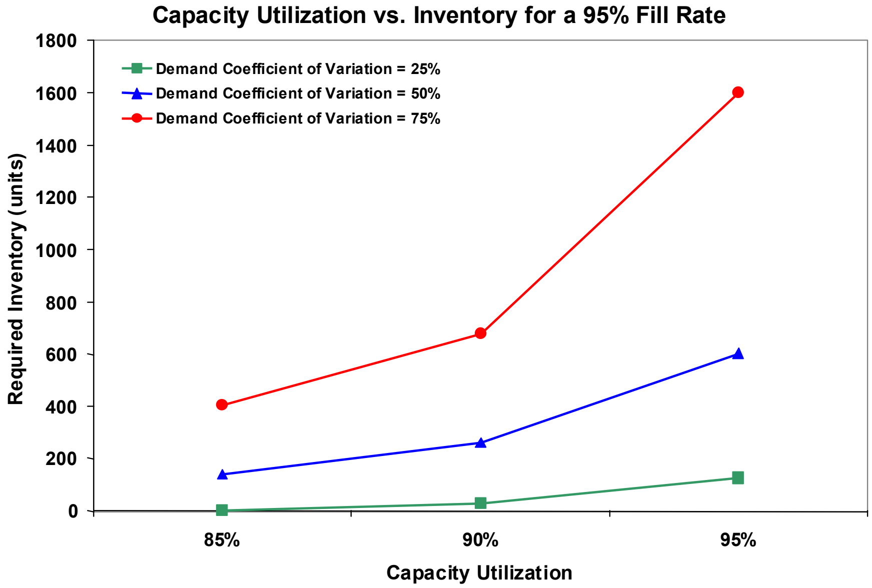

Figure 12. Required inventory levels under different scenarios

Increasing the capacity utilization, while intuitively financially attractive, may require an unacceptably high amount inventory to support the same level of customer service. Alternatively, increasing capacity utilization, while not adjusting the inventory level, will result in a deterioration of customer service. For example, suppose the demand coefficient of variation is 0.50 and we increase the capacity utilization from 85% to 95%. If we continue to hold 142 units of inventory, the customer service level will drop from a 95% fill rate to a 58% fill rate. This fundamental systems tradeoff should be considered when making strategic, tactical, and operational decisions, as it will directly impact the performance of the system.

This example illustrates how a system is negatively impacted by the presence of high degrees of uncertainty, but begs the question: *what can we do to affect the degree of demand uncertainty?* This is the essence of why collaborative supply chains must be built based on the five guiding principles that we have discussed.

3 Current Supply Chain Models: Theory versus Reality

How are supply chain decision support systems in use today designed? As is well known, these systems have evolved over time and often are based on operations research modeling paradigms. We now summarize a few of the more popular approaches.

3.1 MRP Models

Over the past thirty years, there have been many developments in inventory and production control concepts and their implementations in decision support systems. Some of them relate to the construction of models and some relate to finding answers from these models. One of the earliest approaches is the MRP model. In this model, demand is forecast for each item and, through a bill of materials explosion, time-phased requirements are determined for each finished product and raw material over a planning horizon. Capacity is assumed to be infinite, lead times are fixed and known, and customer demand predicted with certainty. The calculation of production and procurement decisions based on this model can be computed easily due to the special structure of the resulting set of linear equations. Uncertainty is not addressed directly in the model, even though attempts are made to do so indirectly through the calculation of safety lead times and safety stocks. Thus, for example, production lead times are both an input and an output of the model. They are an output because capacity is limited and demand is uncertain thereby causing production lead times to vary as well.

3.2 Mathematical Programming-Based Models

Subsequent modeling frameworks include mathematical programming-based models. In these models, capacities can be represented, complex production constraints can be used, and specific cost objectives can be stipulated. See Thomas, McClain and Mazzola (1992) and Silver, Pyke and Peterson (1998), and Nahmias (1997) for a discussion of these methods. Both heuristics and optimization methods are used in various implementations for sequencing and other decisions. However, demand in these environments is usually represented by point estimates over time with uncertainty modeled by including requirements for safety stocks. These safety stock levels are input parameter values to mathematical programming models. But, setting these safety stock levels properly requires a significant amount of analysis of the demand patterns. Unfortunately, this analysis is outside the scope of the optimization models and systems employed in practice. Important questions concerning the location and quantities of safety stocks are largely ignored in these mathematical programming models. As mentioned, production is often based on point estimates of demand for most products; however, these forecasts are highly inaccurate in many instances since demand fluctuates so substantially. The consequences of ignoring uncertainty directly in the modeling process often results in excess inventories, poor customer service, and operating costs that are higher than expected.

3.3 Inventory Models

In parallel, inventory modeling over the past four decades has advanced significantly. Several types of inventory models have proven themselves to be extremely useful in a variety of practical circumstances. See Clark and Scarf (1960), Muckstadt and Thomas (1980), Cohen and Lee (1988), Hausman and Erkip (1994), and Chen (1998) for some examples of such models. Excellent overviews of general inventory models can be found in Sherbrooke (1992), Axsäter (2000), and Zipkin (2000).

These models often include explicit representations of demand processes for individual items at particular locations in the supply chain. Calculations based on these probability models permit the estimation of safety stock requirements. Most often, an assumption is made in these models that lead times are fixed, are independent from item to item, are independent from time period to time period, and do not depend on variation in demand and capacity across time at different locations in the supply chain. However, there are exceptions. In some cases, uncertainty in lead times is considered. Except for the most simple of situations, for which (S–1, S) inventory policies are considered, multi-echelon models and computationally tractable algorithms are non-existent for large-scale systems. For all of these probabilistic models, there is an assumption that demand can be accurately represented by a probability distribution with a good estimate of both the mean and variance. As we have stated before, the demand over a lead-time is often-times characterized as following a Normal distribution for computational reasons. It is our observation, however, that in today's economic environment, the first moment of the demand process cannot be estimated accurately, much less the form of the probability distribution of demand, for most items in industrial supply chains.

3.4 Commercially Available APS Systems

While commercially available Advanced Planning and Scheduling (APS) systems have led to considerable improvements in supply chain efficiency in many companies, success in implementing these systems depends on the extent to which the Five Principles of Supply Chain Management Excellence are followed. Production and inventory control systems found in APS systems have various policies and rules embedded in them; however, when implementing such systems, firms rarely realize that they are in effect purchasing operating philosophies and business processes as well. The operating philosophies and business processes may work to a suitable level of performance; however, more often these systems and policies will not perform up to the customer's expectations when measured in terms of cost and service. This occurs because the models embedded within APS systems frequently do not adequately capture the dynamics of and the uncertainty of the operating environments. In a well-designed APS system, operating rules and policies must match the attributes of the physical operating environment. By imposing rules within an APS system, the physical environment may not necessarily operate effectively or profitably. Simply put, a physical environment cannot be expected to conform to the rules embedded in an APS system.

3.5 A New Decision Modeling Paradigm is Needed

Based on these observations, we suggest that the strategic and tactical modeling paradigms employed in supply chain decision support systems are inadequate. Hence, the structure of supply chain manufacturing and distribution systems are often poorly designed and operated. Typical consequences of poor design are inventories that are concentrated in the wrong products and in the wrong locations, and production efficiencies that do not match the projections of the models and thus do not meet the performance expectations of management. A fundamental cause for the failure of the paradigm is the uncertainty in the environment and the inability to construct accurate forecasts for most items. Given that creating accurate forecasts is difficult, if not impossible for most items at most locations, an entirely new paradigm must be used. The imperative is to create an integrated supply chain that quickly and repeatably moves the right quantities of materials to customers for those items that experience highly uncertain demand.

When designing a supply chain planning system, a clear process must be put in place that considers the operational dynamics that support the successful implementation of those plans. Planning model designs need to take into account both customer requirements and the physical structure of the supply chain. Reasonable customer lead-time expectations must be established so that the cost structure remains competitive. Supply chain operations must be designed around the specific customer service objectives. Other supply chain practices must consider flow times through facilities and, more importantly, through the entire supply chain. Inventories must be maintained in critical locations to support the overall operation of the supply chain.

While reducing demand uncertainty and decreasing lead-times are necessary for increasing operational effectiveness, it is equally critical that operational rules and policies be put in place to coordinate production and inventory effectively. Much research has been done in this area. Federgruen and Zipkin (1986) develop a fundamental operating policy that considers the presence of finite capacity. Tayur (1992) and Glasserman and Tayur (1994) provide a model and computational scheme for computing inventory levels in capacitated environments with random demand. Rappold and Muckstadt (2000) extend the use of these models to a multi-echelon system with finite production capacity. Sox and Muckstadt (1996) demonstrate how to compute production and inventory levels when demand is stochastic and non-stationary.

3.6 The No B/C Supply Chain Design and Operating Strategy

When considering how much inventory to carry and in which products, it is essential that inventory be carried in those items for which it will be most useful. Inventory held centrally by manufacturing is nothing more than stored production capacity, or stored time. By producing material and storing inventory in products whose demand is highly uncertain, manufacturers increase their financial risk, both in terms of un-sellable inventory and in terms of wasted capacity. No firm knowingly produces material that they do not expect to sell profitably. But much of this inventory is not sold profitably. Most firms have significant inventory write-downs each year, and have to sell off inventory at less than cost. This occurs because in most industrial environments, it is virtually impossible to predict customer demand over a short lead-time. So why must firms generate forecasts that are so prone to error? Inventory fundamentally exists in supply chain systems because customer order lead times are shorter than manufacturing and delivery lead times. If firms have long lead times, then they must stock some inventory. Here is where traditional planning systems fall short.

For analytic tractability, most planning systems break the supply chain up by product and by location. Demand is treated as known and fixed by period and is estimated through some forecasting mechanism. Capacity is often considered by specifying production lead-times, even though, as we have observed earlier, it is well understood that lead times are a consequence of systems design, and are not an input.

In thinking through the attributes of a new planning paradigm, the planning philosophies must simultaneously consider uncertain demand, customer lead-time requirements, finite production capacity, and inventory stocking decisions for different products and different customers. Not all products and customers behave identically. Not all customers for the same product behave identically, either.

We propose a hybrid make-to-stock and make-to-order planning strategy that stores inventory in products that will consider finite production capacity and highly uncertain demand. We call this philosophy the *No B/C Strategy,* and describe it detail in Muckstadt, Murray, and Rappold (2000). In this strategy, we categorize products into ABC categories (see Silver, Pyke, and Peterson (1998)), although not in the same manner as they describe. Inventory is carried primarily in the products for which the risk of not selling them quickly is minimized. Production priority is given to those products for which the demand uncertainty is high and for which there is little stock. To permit this, the production and business processes as well as the information systems must be designed in such a way so as to ensure short and predictable flow times of the make-to-order items. If there is insufficient capacity to produce all demand in a given period, the demand for *A* products may be largely satisfied from inventory. Thus the stock levels for an *A* type item must be established to meet not only the demand for that item, but also to compensate for the manner in which capacity will be used to implement this policy. Instead of creating forecasts for individual *B/C*-type products, a forecast is created for the aggregate capacity demanded across all *B/C* products. Typically, this forecast is much more accurate that ones for individual items.

The implementation of such a policy has numerous benefits. Firstly, instead of managing stock in a wide variety of different products, inventories are concentrated in a much smaller number of individual products. This permits considerable simplifications in material handling and inventory management requirements. Secondly, overall inventory levels are reduced dramatically. This occurs because production is focused on what is required rather than what might be required. Thirdly, since flow times are more predictable, customer service is improved. Finally, obsolete inventories are largely eliminated.

This type of policy can be implemented effectively only if all members of a supply chain can provide components in a timely manner. This requirement commands each supply chain member to plan inventories, capacities, and production execution rules consistent with the strategy. This consistency is at the heart of a truly collaborative supply chain system.

4 Applying the Five Guiding Principles: An Example

We have successfully implemented the No B/C Strategy in several environments. The precise form and structure of the No B/C Strategy depends on the attributes particular to an environment. In this section, we describe one example in which a firm follows the Five Principles of Supply Chain Management Excellence in designing and building a supply chain that yields competitive advantage. We focus on how the analysis of customer demand and operating data, as part of the collaborative process, brings about dramatic reduction in demand uncertainty. We present the key constructs of a decision support model that handles uncertainty explicitly and we explain the use of the principles of the No B/C Strategy.

4.1 Background

The supply chain shown in Figure 13 corresponds to the family of about 300 consumable industrial products previously discussed as Example 3 in the demand uncertainty section. Raw materials necessary for the production of a family of products are either fabricated by internal work centers or are procured from a set of external suppliers and are placed in a storage area convenient to the production of the final products. Output from a capacitated processing center is moved to a central storage facility. Customers place orders for varying mixes, quantities, and timings of deliveries of the products. If the products are available, they are shipped from the central storage area. Otherwise, the order is backlogged and, under extreme circumstances, may be produced and drop-shipped from the manufacturing facility. The customers of this firm are another echelon in the supply chain that serves a set of end-users that consume the products in the product family.

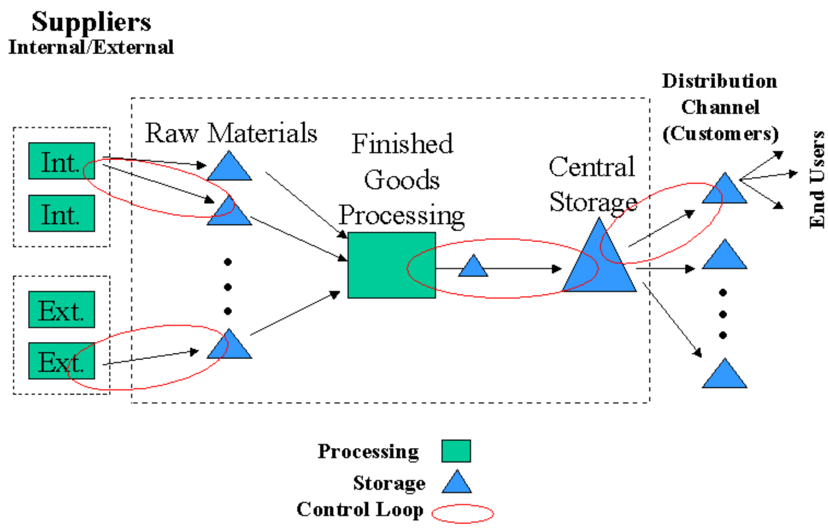

Figure 13. Overview of supply chain structure

Project Objectives. When we started creating the desired environment, the firm stocked approximately $200,000 worth of finished goods inventory in the central storage facility and achieved an 87% on-time delivery performance. This delivery performance was a weighted average of a 94% on-time delivery for stocked products and a 37% on-time delivery for make-to-order products. Our goal was to halve the finished goods inventory level while increasing the overall on-time delivery to 93%. The goal was achieved by implementing the Five Principles of Supply Chain Management Excellence.

4.2 Guiding Principle No. 2 – Lean Supply Chain Organization

The plant progressed through several lean improvement initiatives over the past five years. In particular, a considerable amount of time and money was invested in new equipment and in the training of personnel at this plant. To create this lean environment, the firm fundamentally changed the way in which it operated on a daily basis. The firm created a U-shaped material flow cells to produce all products in the product family. The firm uses dedicated equipment that has negligible changeover times within the product family. Personnel who operate the equipment on a daily basis are cross-trained to permit the flexible adjustment of capacity in response to changing conditions. Instead of producing large lot sizes of products in a functionally organized facility, small lot sizes now flow through a dedicated set of equipment. Raw materials are stored at their point-of-use. Inexpensive raw materials are stored in substantial quantities, while expensive raw materials are managed with more attention. The result of these efforts is that flow times through the plant are now both short and predictable. Flow times are now minutes in length instead of days or weeks. A significant benefit of this is that the firm's higher-level planning models are more accurate because the lead-times input into them are much more reliable.

The importance of creating this lean physical and responsive environment as part of a supply chain improvement strategy cannot be overstated. Without this improvement in the physical operating environment, the impact of other supply chain improvement efforts will be minimal.

4.3 Guiding Principle No. 3 – Information Infrastructure

In addition to ongoing lean improvements, the firm invested heavily in information technologies and created a team of highly talented information technology professionals. It has not implemented a large enterprise-wide system, but rather has integrated its internally developed systems. Planning information pertaining to booked orders, finished goods inventory levels, planned shipments, and raw material replenishment orders is readily accessible through a series of desktop computers throughout the production floor that are linked centrally to the firm's manufacturing system. Each day, a production planner responsible for the facility prints a paper work release and gives it to the team leader of the facility. The team leader is responsible for managing personnel and executing the production requirements for the shift. The facility's principle performance metric is on-time delivery.

Three years ago, the firm launched a vendor managed inventory-like system that captures and stores information about the customer's inventory levels and demand. It should be noted that after three years of discussion and relationship building, the majority of customers are now willing to share these data. These data gathered daily from customers can now be used in the planning and execution process.

4.4 Guiding Principle No. 4 – Business Processes

Materials management in this supply chain is driven by control loops drawn as ellipses in Figure 13. Many of the firm's customers control their inventories using standard reorder point and order quantity logic. When their inventory position (defined as on-hand inventory plus outstanding orders minus any backorders) falls to or beneath a reorder point, they place an order for replenishment. While the logic is clear, many customers often deviate from the logic in order to handle some impending circumstance (such as a large demand spike). As discussed in Example 3, the inventory level for Product #1 shown in Figure 7 is an example of such a manual intervention. Each day, a work list is generated by the firm's manufacturing system detailing precisely which products to produce in a capacitated finished goods processing facility. The work list is created from a mix of backlogged products and a list of products that are below their reorder points at the central storage facility. Provided that the necessary raw materials are available, the team leader decides the production priorities and production sequences through the facility. Similarly, orders are placed on the suppliers of the raw materials when the inventory position for a raw material drops to its reorder point. Reorder points at each location in the supply chain are calculated one product at a time as the forecasted demand over some fixed replenishment lead time, plus a few periods of safety stock. The production planner is responsible for managing the reorder points for raw materials and for finished goods inventory. When material shortages occur or when insufficient production capacity exists, the production planner attempts to resolve as many shortages as possible and works with the team leader to establish production priorities.

Based on the firm's ability to produce and move material quickly, on the accessibility to timely information, and on the management organization inside of the facility, the firm was able to achieve significant performance improvements by better understanding the demand characteristics of the customer and by rethinking the coordination of production and finished goods inventory.

4.5 Guiding Principle No. 1 – Know the Customer

To characterize the demand characteristics of the facility, we examined the nature of the demand process for this product family. Pareto charts of the demand for production capacity are created by product as well as by customer. As shown in Figure 14, the demand for the top 4 products consumed up to 80% of the total available time (capacity). Figure 15 shows that the demand for capacity originated from a total of 544 customers of which 12 constituted 50% of the total demand. Notice that Customer #1 demanded 28% of the total capacity.

Observe from the Pareto analyses that not all products and customers are equal. Each product-customer combination did not demand an equal portion of the total demand for capacity. This fact can significantly inhibit a statistical forecasting method from being able to construct an accurate forecast of demand.

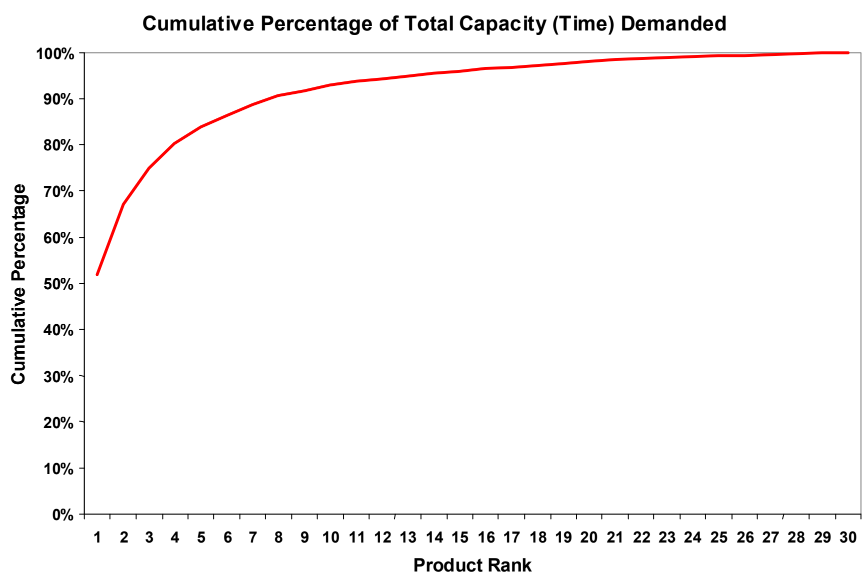

Figure 14. Pareto chart of the top 30 products in the product family

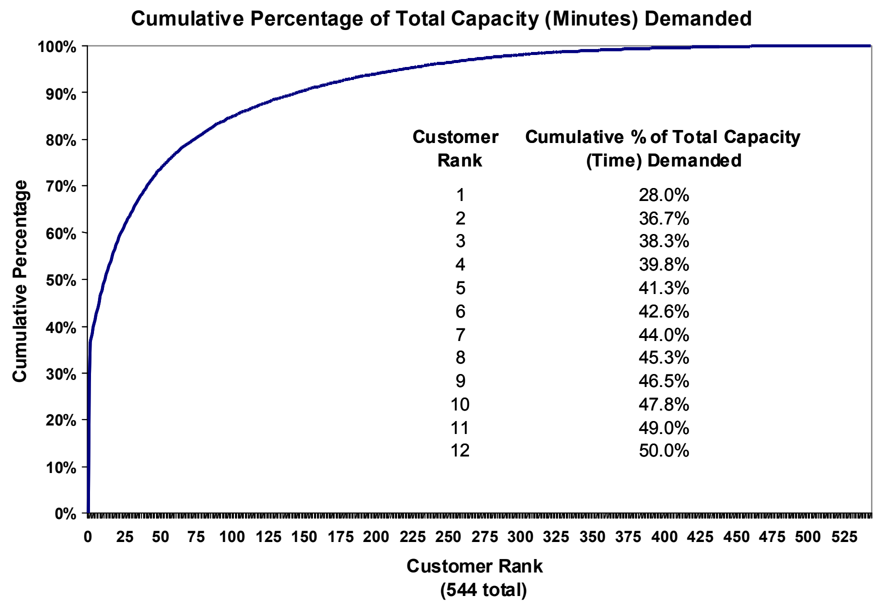

Figure 15. Pareto chart of customer demand for capacity

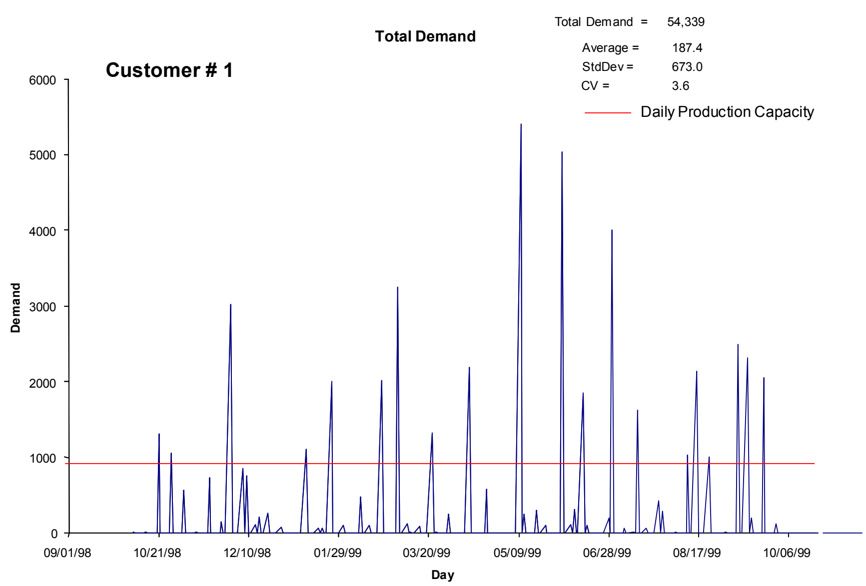

Figure 16. Time series of demand from the largest customer

Next, we explored the demand from a large contributor to the overall demand volatility in the facility – Customer #1, whose demand is shown in Figure 16. There appeared to be some periodicity to their orders and we conjectured that it was a result of their operating rules and policies. One opportunity became clear – if we could reduce or better understand the variability in the demand generated by Customer #1, we could significantly improve the overall operation of the facility both in terms of overall asset utilization and on-time customer delivery.

Using operational data the firm had been collecting through its vendor managed inventory system, we were able to examine Customer #1's operating environment. This included their customers' demand as well as their historical inventory status. This customer carried an average of 40 days worth of stock in its top 10 products. The customer stocked a large amount of inventory in order to both provide *its* customers with a high level of service and to protect against variable procurement lead times from the firm; however, it is substantially more inventory than it required when considering its demand uncertainty. The potential for a substantial reduction in its inventory investment formed the basis of the collaborative value proposition between the firm and Customer #1.

A time series of the inventory level for Product #3 at Customer #1 is shown in Figure 17. The customer normally ordered roughly 2000 units of this product every month. Notice that in the month of April there was no order. Rather, the customer doubled its order in March, since the purchasing manager was going on vacation. An order for 4000 units is approximately 4 days worth of production capacity in the firm's facility. Consequently, this type of large order had a significant impact on the production facility and on customer service for many other customers as well.

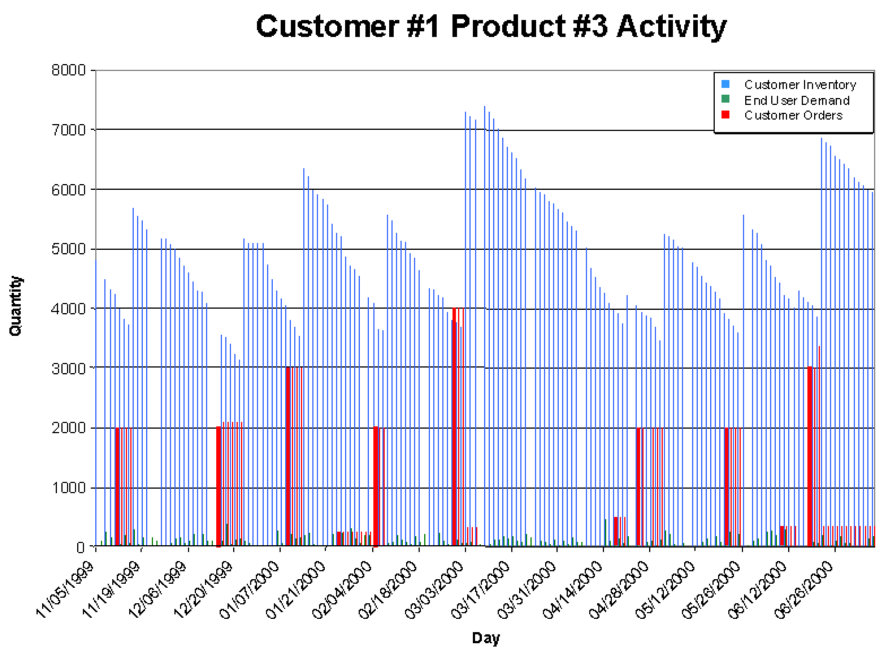

Figure 17. Finished goods inventory carried at customer

Consider the impact on the central storage facility's inventory when the large order spike from Customer #1 occurred, as shown in Figure 18. The shaded region represents the build up of finished goods inventory in the firm. The large saw-tooth shaped line is the amount of inventory at the customer for this product. The large vertical spike is the customer order. Notice that this customer caused a complete depletion of finished goods inventory for this item at the firm and exposed the system to backorders for other customers.

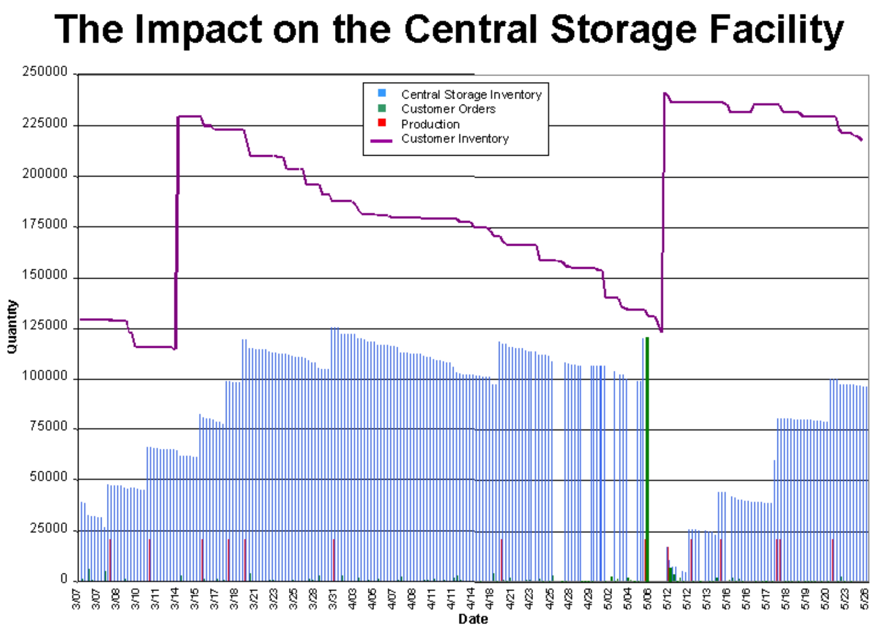

Figure 18. Impact of customer behavior on finished goods inventory

By meeting with the customer and presenting the financial benefits associated with collaborating, the firm was able to influence their ordering behavior in such a way as to reduce the volatility of the orders. This has two significant implications. For the customer, they hold far less finished goods stock. For the firm, they require far less safety stock and can respond to customer demand routinely with their available capacity.

4.6 Guiding Principle No. 5 – Decision Support Systems

The firm's manufacturing system had followed standard materials requirements planning (MRP) logic. Reorder points that control the movement of materials were recalculated periodically either by the computer system, or by manual intervention. Due to the highly uncertain nature of the customer demand processes, large inventories were created as a result of the MRP logic, which remained in the central storage facility for long durations of time. When a customer order arrived, the inventory often was not sufficient to satisfy demand. The presence of limited production capacity was not taken into account explicitly. Therefore, the use of production overtime was frequent in order to process production requirements on a daily basis. This operating philosophy neither resulted in an effective use of capacity and inventory, nor provided a high level of customer service.

To remedy this, we instituted the basic principles of the No B/C Strategy. We examined the total demand for capacity generated by each product and categorized the products into two categories. The Top 4 products are designated as *A* products and the remaining products are designated as *B/*C products. The aggregate demand for the *A* products is shown in Figure 19 and the aggregate demand for the *B/C* products is shown in Figure 20.

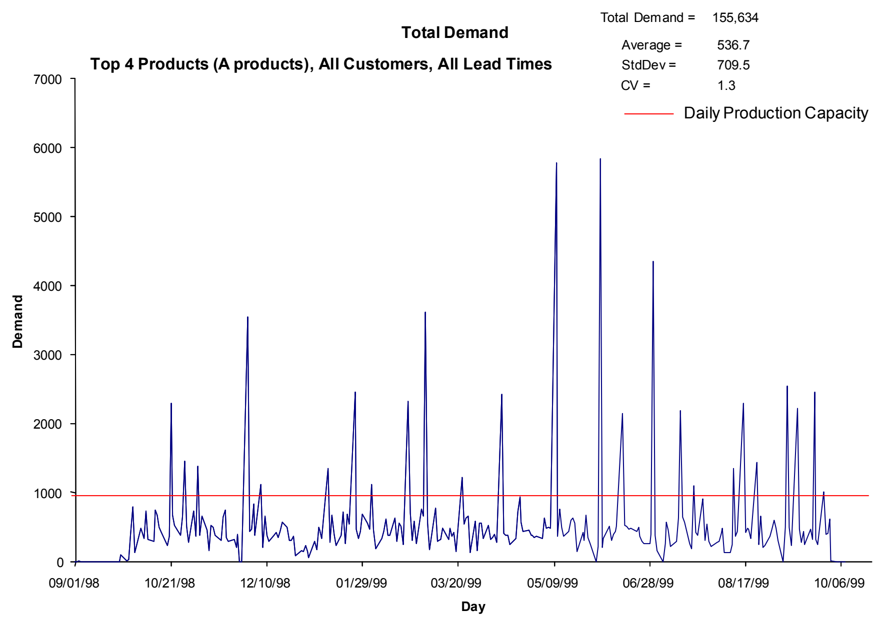

Figure 19. e aggregate demand for the top 4 products (A products)

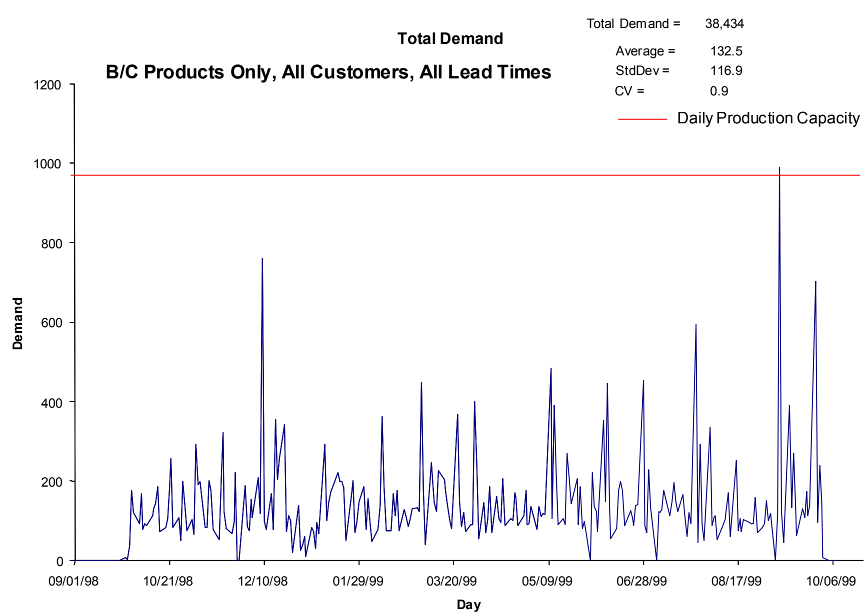

Figure 20. The aggregate demand for all products except the top 4 products (B/C products)

The first critical task was to reduce the demand variation in the *A* products. As a result of conducting a detailed demand analysis (Principle No. 1), we observed that Customer #1 caused a substantial portion of the total demand variability for these products. By constructing a collaborative relationship with this one key customer, the facility greatly reduced the overall demand variation in these top 4 products and was able to plan the use of its capacity more effectively. This simultaneously reduced the need for large amounts of safety stock across many products, reduced overtime production, and improved the on-time delivery performance for all customers. The operational improvements over time are shown in the next section.

Observe that while the demand for the *A* products often exceeded the daily production capacity, the demand for *B/C* products only exceeded the daily production capacity on one day over the course of one year. Thus, on a daily basis, the production facility has sufficient capacity to produce all of the requirements for the *B/C* products. Therefore, the *B/C* products received production priority on a daily basis. Any remaining production capacity was used to produce the *A* products. To compensate for giving the *B/C* products higher production priority, a considerable amount of finished goods stock will be needed in the *A* products.

By reducing the demand uncertainty generated by a single customer, by reprioritizing some basic production planning rules, and by stocking inventory in only *A* products, the firm was able to leverage its past investments in achieving several operational improvements for itself and for its customers.

4.7 Operational Improvements

Figure 21 shows the operational impact at Customer #1 over a four-month period. Its finished goods inventory in the top 10 products decreased 60% from \$2.5 million to just over \$1.0 million. At the firm's central storage facility, shown in Figure 22, finished goods stock levels dropped 40% to \$120,000 across the product family. At the same time, customer service levels, as measured in on-time delivery, increased to 95.2%. Most notably, the on-time delivery performance for make-to-order products increased from 37% up to 60% and is still increasing.

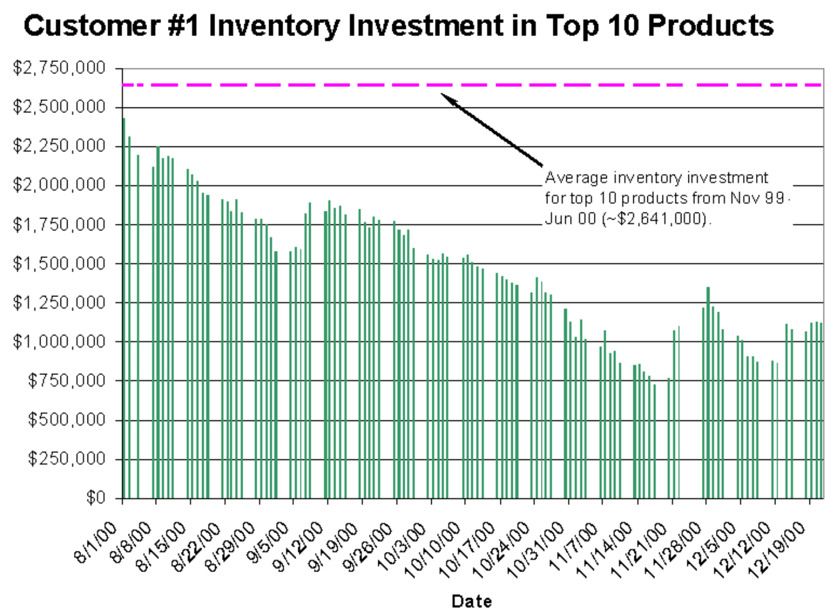

Figure 21. Supply chain partner's inventory levels over time

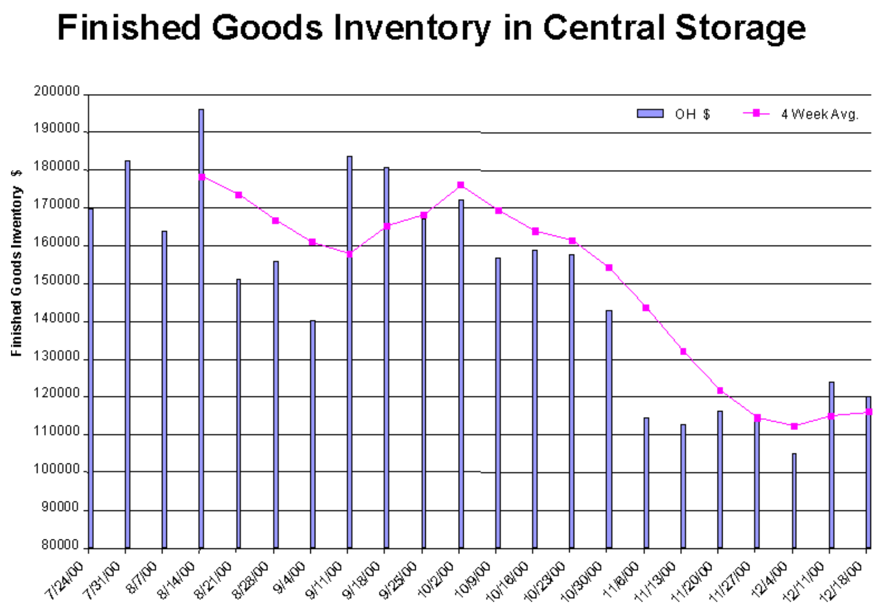

Figure 22. Finished goods inventory levels over time

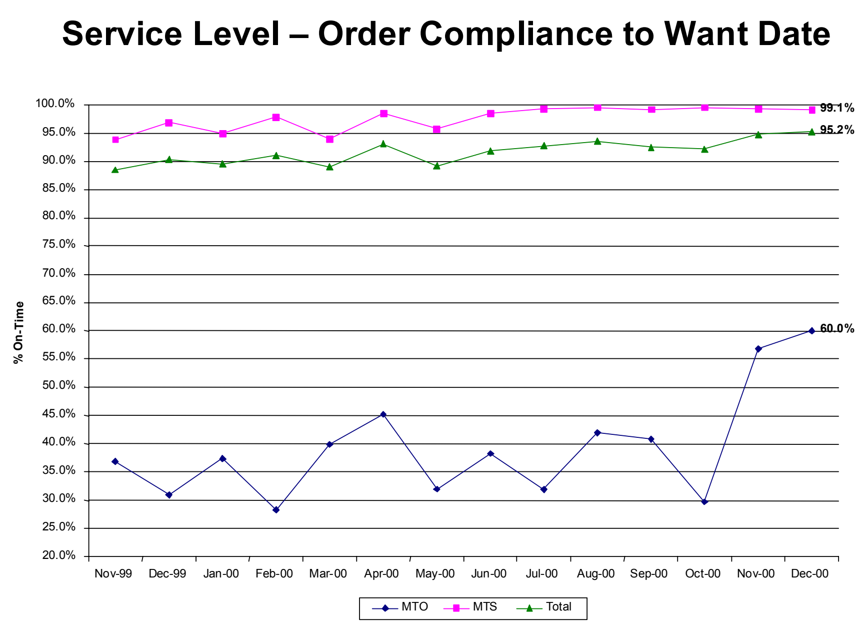

Figure 23. Customer service levels achieved for make-to-stock (MTS) and make-to-order (MTO) products

5 Concluding Remarks

In summary, a substantial degree of uncertainty exists in most supply chains. To create and sustain competitive advantages for a supply chain, this operational uncertainty must be reduced and dealt with explicitly by all supply chain partners. Current strategic and tactical paradigms employed in supply chain decision support systems are not well suited to handling decision making in the presence of substantial amounts of uncertainty. This leads to a poor overall utilization of the firm's assets in capacity and inventory while not necessarily providing a high and reliable level of customer service.

In order to remedy this, we proposed Five Principles of Supply Chain Management Excellence for the effective design and execution of supply chain systems must be followed in concert. By actively pursing only a subset of the principles, firms will not likely succeed in achieving their expected improvements in supply chain performance. Installing advanced information systems and streamlining business processes will not overcome a poorly designed physical operating environment, and vice versa. Business processes and rules must be tailored to the specific nature of the operating environments and to the objectives of the supply chain. Lastly, decision support systems and business processes must be capable of dealing with uncertainty explicitly. We discussed one such approach – the No B/C Strategy.

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