Optimized Distribution Supply Chain for Improved Customer Service

by

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Submitted to the Engineering Systems Division and the MIT Sloan School of Management in partial fulfillment of the requirements for the degrees of

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Abstract

In an attempt to attract consumers, companies are offering an increasingly wide range of product varieties to cater to each consumers individual needs and desires. This behavior leads to fragmentation of demand that increases supply chain complexity and cost. At Company X, this behavior is also visible. There is a proliferation of product types and sizes as these are increasingly used for product differentiation by both the company and original equipment manufacturers that use its products. This, in turn, lowers demand per product and disaggregates it, resulting in higher variability.

Some of Company Xs products that are affected by the changes in demand patterns, and consequently have relatively low demand, are also highly profitable. This relatively small, but increasingly important segment of the market is not well served by the existing supply chain that has been optimized for large, steady flows of products. Service levels for products with the new demand patterns are low, leading to customer dissatisfaction and lost sales.

We hypothesize that Company X can improve its customer service, as measured by service level, fill rate, and on time delivery rate, for consumer products by adopting a segmented supply chain. The current supply chain is optimized for products that have a steady and large demand, but it undersupplies products with low or variable demand. A segmented supply chain would allow each segment of products to be served by a supply chain that is optimized to that segments demand characteristics. Traditional manufacturing would provide a low-unit-cost source of products, while a new, agile small-scale manufacturing source would provide a responsive source of products.

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Acknowledgments

Yet another two years at the Institute have passed by more quickly than I could imagine. While this thesis is a culmination of my internship work, it represents but a small part of the entire two-year journey. Thus, I would like to extend these acknowledgments beyond just the thesis.

Most importantly, Katherine has been by my side providing loving support throughout the journey. From reading application essays to moving to Cambridge and putting up with a hectic schedule, she has persevered throughout.

My parents have provided me with their everlasting support, even when I forget to call. They provided the foundation and encouragement to get me to where I am, and I value this immeasurably.

A good part of my time was spent at my host company where I expanded my horizons with new professional experiences that I consider a key part of my learning. There I would like to thank John Brainerd, Jim Euchner, Phil Dunker, Josh Elsass, David Mintz, and Tom Mooney for their guidance and support.

Similarly, I would like to thank my two advisors, Don Rosenfield and David Simchi-Levi, for their guidance and support throughout the project. Additional gratitude goes out to Don for building and leading the LGO program.

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Chapter 1

Introduction

1.1 Company X

This study was conducted in conjunction with an undisclosed company, referred to in this thesis as "Company X". Company X is a US-based manufacturer with a global manufacturing, distribution, and customer footprint. It is in the middle of a transformation to adapt to changing business conditions, including changing customer demand patterns and financial pressures. As part of this transformation, one of the company's goals is to become more agile in meeting customer demands. A lean supply chain is seen as one way to achieve this goal, but the current supply chain design has limited ways in which it can be improved. Figure 1-1 shows a representation of the fundamental trade-off that can be made in the current supply chain. A supply chain transformation will help Company X move off the current trade-off curve and onto an improved one.

1.2 Project Background

In an attempt to attract consumers, companies are offering an increasingly wide range of product varieties to cater to each consumer's individual needs and desires. This behavior leads to fragmentation of demand that increases supply chain complexity and cost. At Company X, this behavior is also visible. There is a proliferation of product types and sizes as these are increasingly used for product differentiation by both the company and original

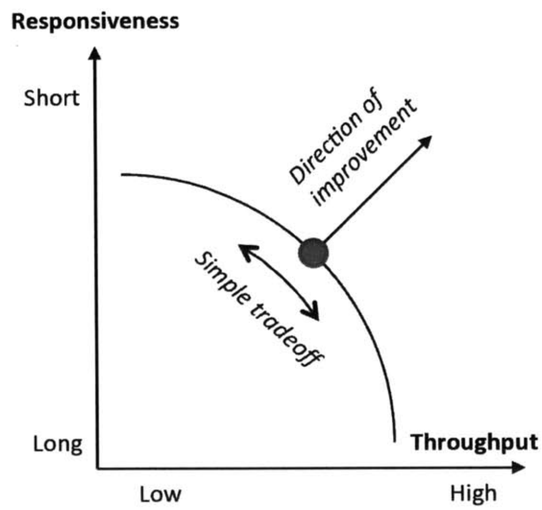

Figure 1-1: The current supply chain allows throughput and responsiveness to be traded off, but without any net improvement

equipment manufacturers that use its products. This, in turn, lowers demand per product and disaggregates it, resulting in higher variability.

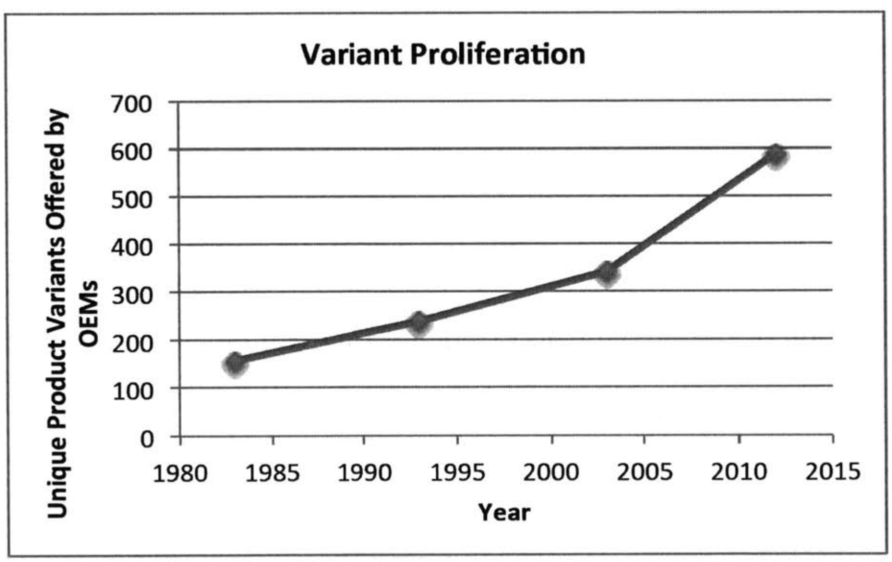

Figure 1-2: The increase in product variants sold by original equipment manufacturers over the last several decades has stressed supply chains [1]

To complicate matters further, some of Company X's products with low demand are premium products and highly profitable. This makes these products important to the company's strategy of focusing on growing sales of premium products. However, this important segment of the market is not well served by the existing supply chain that has been optimized for large, steady flows of products. In some cases, service levels for products with the new demand patterns are low, which leads to customer dissatisfaction and lost sales.

This research examines opportunities for improvement of Company X's supply chain in order to improve on the challenges identified above.

1.3 Objective

The primary objective of this study is to investigate supply chain strategies by which Company X can improve customer service, as measured by fill rate and responsiveness, while maintaining or reducing total landed cost. The current supply chain is designed primarily for low unit cost and high throughput. However, some stakeholders in Company X realize that the supply chain can be used to increase revenue in addition to lowering costs. A balanced, holistic approach needs to be developed that considers both factors in detail, and this new approach to supply chain strategy needs to be constructed into a coherent message for all stakeholders.

An additional objective is to justify and support new supply chain strategies with quantitative models. The models show changes in costs, inventory levels, and other relevant factors, as well as the sensitivity of these metrics to various types of uncertainty. The models used for this study are built to show important changes and design trade-offs, rather than to produce an exact, detailed model of the future state. The former are deemed more important and and useful at this stage of the project.

1.4 Hypothesis

The hypothesis of this study is that segmenting a supply chain improves its responsiveness, which, in turn, improves customer service and reduces cost. A segmented supply chain is one that uses different network designs, flow paths, and facilities for different products segmented by their demand characteristics. Each supply chain segment is optimized for its assigned products. This allows each supply chain segment to better serve the products assigned to it, as compared to a 'one-size-fits-all' supply chain.

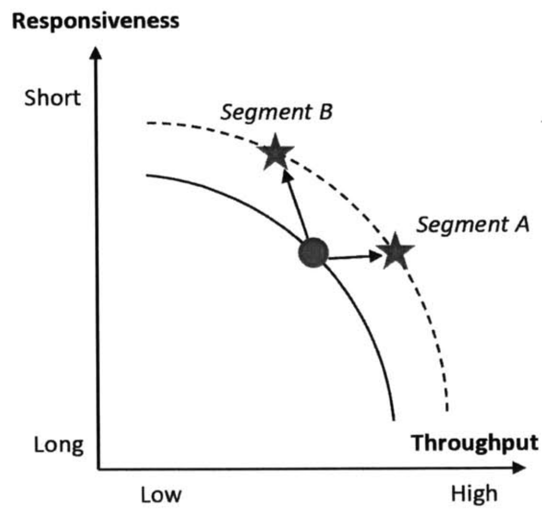

Figure 1-3: Using a supply chain allows both responsiveness and efficiency to improve for a net total improvement

Furthermore, lean supply chain concepts can be used to design each segment of the supply chain to achieve the desired future state. Lean supply chain concepts focus on eliminating waste, and they ideally target a supply chain design where product moves continuously from sourcing or production to the end customer.

1.5 Methodology & Approach

This study proceeded in multiple phases. First, stakeholder discussions, data analysis, and direct observation of the supply chain were used to understand its current state. As with all lean transformations, a good understanding of the current state is vital to designing the future state of a system.

Next, a set of initial future state concepts was developed to spur a discussion with key stakeholders and decision makers. These qualitative models covered a range of possibilities for the future state, from small modifications to completely new supply chain models that replaced the current model. Using feedback from the targeted audience, these concepts were refined through several iterations until a future state concept was chosen for further analysis.

Further analysis consisted of building quantitative supply chain models to compare the current and future states in terms of common metrics, such as expected service level, holding cost, transportation cost, supply chain length, and sensitivity to supply and demand variations.

Throughout the study, new developments were presented to key stakeholders for feedback, model improvement, building stakeholder engagement, and overcoming cultural barriers to change.

1.6 Literature Review

This study is a follow-on to the supply chain network design study performed by Noday [11]. The focus of that study is on strategic network design and optimization, formulated as a facility location problem. The primary decision variables in the optimization are the locations of supply chain facilities, and the objective function is total landed cost of products flowing through this supply chain. The scope of that study includes raw materials suppliers, production facilities, and the first echelon in Company X's distribution network. The design of the distribution supply chain is considered fixed.

Network design, as addressed by Noday, is the first 'layer' of supply chain management (SCM) [12]. The second layer of SCM is supply chain master planning, which this study addresses.

The scope of this study is shifted downstream in the supply chain. We assume that production facilities are located according to the method proposed by Noday, but distribution flow paths, production schedules, allocations of products to sourcing facilities, and inventory levels are in scope. This study is also focused on understanding and communicating (to Company X stakeholders) master planning design trade-offs and sensitivities, not simply developing an optimization model.

1.6.1 Segmented Supply Chain Framework

Simchi-Levi provides a framework for designing segmented supply chains based on product and customer characteristics [13]. Products can be categorized as functional versus innovative, with the former requiring an efficiency focus, and the latter a responsiveness focus. Furthermore, similar kinds of products may be characterized differently in this framework, depending on their demand characteristics and their targeted market niche.

Simchi-Levi et al. discuss a specific case study of a segmented supply chain at Dell [14]. In that study, they recommended four supply chain segments based on customer segments:

- Online/Low-Volume Configurations
- Retails
- Online/Popular Configurations
- Corporate Clients

Each supply chain segment varies in product portfolio, batch size, production strategy, inventory, lead time, and planning horizon.

One framework for demand analysis in the context of supply chain segmentation is DWV^3 [5]. In this framework, the classification variables are:

- *Duration* of life cycle
- Time *window* for delivery
- *Volume*
- *Variety*
- *Variability*

Godsell et al. use this framework on a SKU by SKU basis for a case study with a fast moving consumer goods company, and find only two of the five variables (volume and variability) to be relevant [7]. Life cycle was considered out of scope, time windows were rigid, and variety was irrelevant because demand characteristics were being analyzed at an item level of detail. Furthermore, a large number of SKUs were found to have a high variability in demand, which could lead to "demand hostility" where the supply chain sees unstable changes in demand. The authors make several recommendations for the supply chain of their subject company, including stabilizing the demand patterns of the highly volatile products and then dividing products between an agile and lean supply chain. High volume, low variability products are assigned to a lean supply chain while high variability, low-volume products are assigned to an agile supply chain.

Childerhouse et al. performed a case study on a lighting company to show the usefulness of the DWV^3 framework in designing 'focused supply chains' [5]. The subject company was able to transform their traditional supply chain into a market-focused one.

1.6.2 Lean and Agile Supply Chains

Two relevant supply chain concepts for this thesis are 'lean' and 'agile'. The value and application of each has been debated, as well the combination of the two concepts.

Lean, at its core, is the maximization of customer value through the elimination of waste. With lean, a process is analyzed to find instances of waste, and structured problem solving techniques are then used to find ways to eliminate them.

Underlying lean are several principles, one of which is 'pull', which means that a process step operates only in response to a direct demand signal from its successor step. For an entire supply chain, this direct demand signal is consumer demand for a product, and the same principle applies between steps within supply chain or manufacturing processes. A related lean principle is 'leveling' of demand, through which each process step is given a demand signal that is as smooth as possible to promote maximum efficiency. In the case of a supply chain, this might mean isolating manufacturing process steps from variable consumer demand through inventory, for example. Hines et al. provide a survey of recent academic literature on lean [8], and the Lean Enterprise Institute has a wealth of resources [9].

Agile systems, on the other hand, design in robustness to demand volatility, rather than striving to eliminate it, as lean does. The origin of 'agile' is in flexible manufacturing [2]. Several authors discuss the application of agile to supply chains, including Christopher [6] and Yusuf et al. [16].

It is important to note that lean and agile do not have to exist independently of each other. In some cases, the upstream parts, such as manufacturing, can focus on lean while downstream parts closer to the end consumer and volatile demand focus on agile. Naylor et al. use the term 'leagility' for the combination of these two concepts [10]. In the middle of a 'leagile' supply chain there is a decoupling point where the lean part is isolated from the volatility experienced by the agile part.

1.7 Thesis Overview

This thesis is divided into several chapters, as described below:

Chapter 1 sets up the problem being solved, including high-level context, and proposes a hypothesis. It also discusses the work of previous authors on the problem laid out in this study, including a directly-related predecessor study on network design [11].

Chapter 2 explains the current state of Company X, as observed and analyzed during this study, with a primary focus on the supply chain and demand characteristics.

Chapter 3 gives a recommendation for a future state of Company X, again with a focus on its supply chain.

Chapter 4 examines issues at the boundary of the supply chain, such as the interplay with manufacturing and product offerings. Specifically, it examines how these other considerations affect and complement the supply chain.

Chapter 5 concludes the thesis, summarizes the study, and provides recommendations for future developments and areas of study.

Chapter 2

Current State of Company X

In recent years, Company X has seen increasing profitability but decreasing net sales and units sold. Reversing the negative trends while maintaining profitability is a top priority for the company, and it is believed that supply chain improvements leading to better customer service are one strategy for achieving this goal.

These trends can be attributed to a number of factors, both within the company and externally. One set of factors relates to the supply chain, which the remainder of the thesis examines. These include:

- adverse demand characteristics
- a supply chain mismatched with corporate strategy of targeting premium products
- unbalanced and misallocated inventory levels
- lack of adequate processes to match supply and demand
- production limitations.

Demand characteristics are the starting point for analyzing the supply chain because they are at the core of the supply chain's design and performance. After all, the supply chain's ultimate goal is to satisfy demand.

2.1 Variable Characteristics of Demand

Company X's customer demand has large ranges in volume and variability from SKU to SKU, which makes it difficult to provide a high service level across all products using one supply chain model. Figure 2-1 plots the demand characteristics for each SKU in one of the company's operating regions. This pattern matches the one described by Simchi-Levi [13].

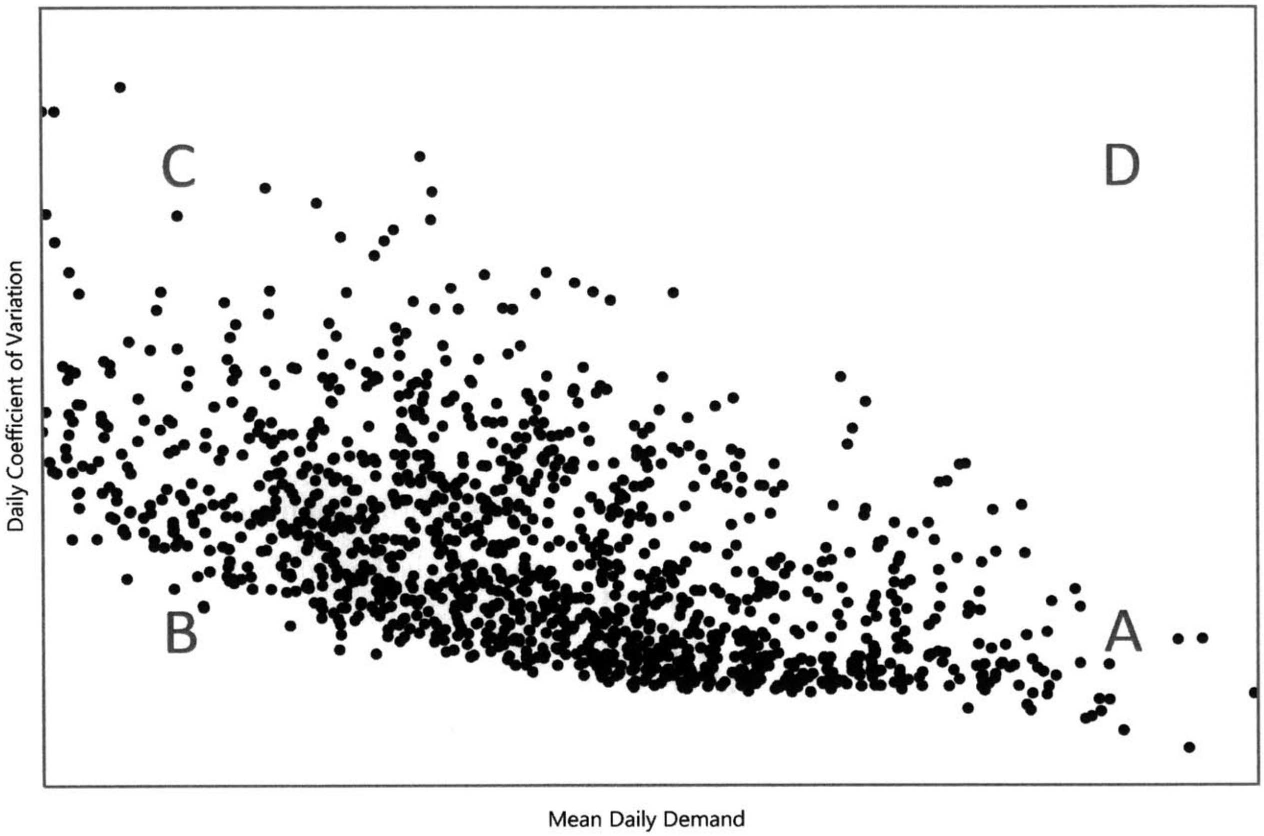

Figure 2-1: Company X's item-level demand characteristics, shown on a log-log scale

SKUs in quadrant A have high-volume, low-variability demand. These SKUs represent the largest volume segment (approx. 2/3), but a low number of unique SKUs (approx. 1/3). They also consist of primarily commodity products with resultant low profit margins. Because the demand of this segment is large and stable, supply chain processes can generally forecast it relatively accurately, and Company X's processes are optimized for this segment of demand.

In contrast, SKUs in quadrants B and C have low-volume, and a range of variability. Sales and profit margins also vary widely, but high sales and profit margin SKUs are found among this group, as shown in Figure 2-2. The SKUs in quadrant B represent approximately 1/3 of the volume, but 2/3 of the SKUs. Forecasting demand is relatively more difficult because of the increasing fragmentation of demand and relatively low volumes. Service levels are correspondingly lower than in quadrant A, and below company targets.

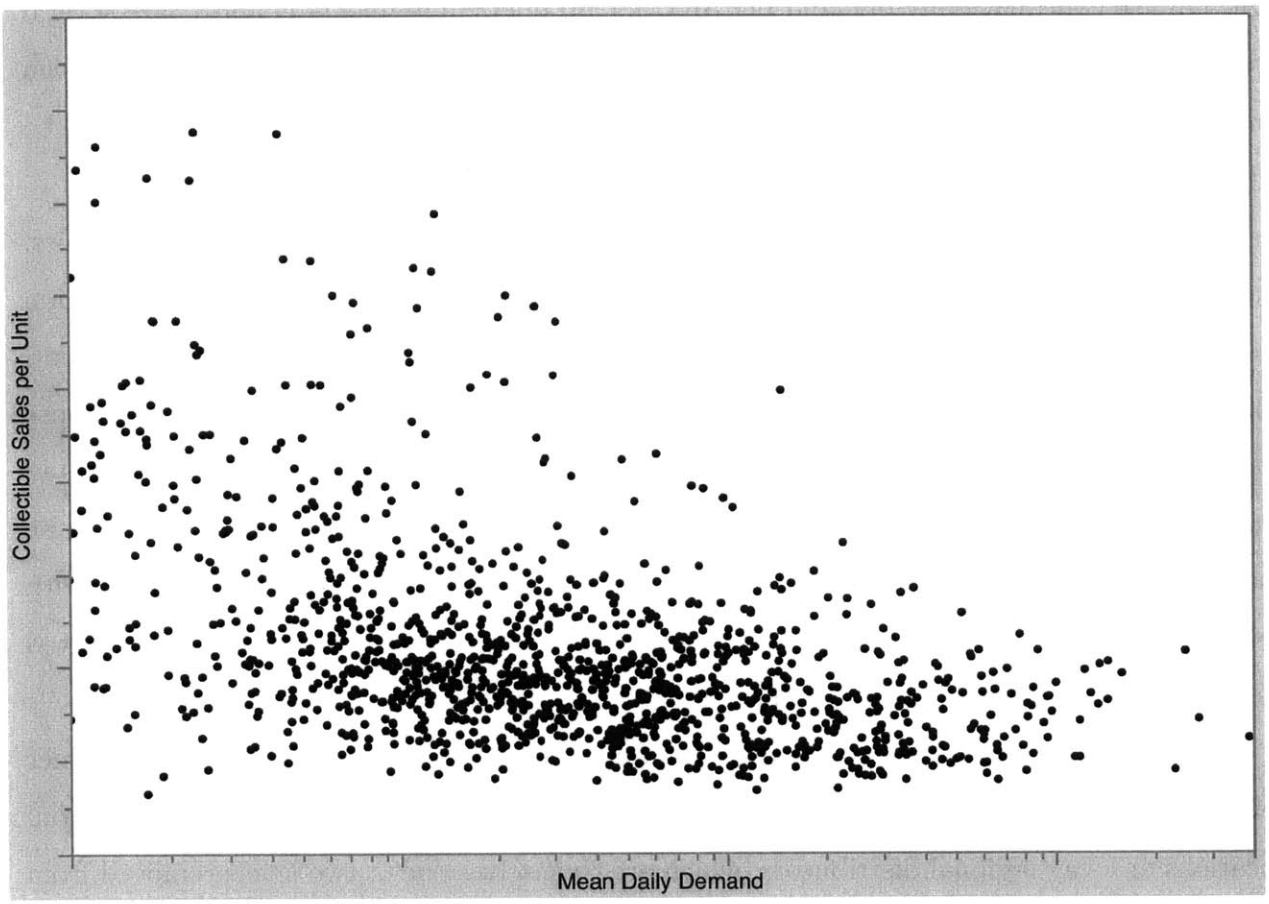

Figure 2-2: Company X's Per-Unit Sales Versus Mean Demand, shown per SKU

2.2 Supply Chain Processes

The current supply chain is well adapted for SKUs in quadrant A, but does not provide as good service of SKUs in quadrants B and C, as evidenced by data on on-time delivery. These latter quadrants have the highest proportion of past-due orders and the lowest on-time delivery rate. The supply chain processes that work well for segment A as not as effective for segments B and C, highlighting a key challenge that Company X must overcome.

For example, the current supply chain has several manufacturing plants that are optimized to produce large numbers of products at low unit cost. They work with preferred lot sizes of thousands of units. These traditional supply sources are matched to the demand in segment A, where daily demand per SKU is within an order of magnitude of the preferred lot size. On the contrary, daily demand per SKU for products in segments B and C are several orders of magnitude below the current preferred lot size. This results in a long time between production starts, which directly reduces the frequency with which product volumes can be adjusted, and which makes the supply chain less responsive.

Forecasting and planning are similarly setup to operate on the scale of thousands of units. Each production lot is allocated to one of several distribution centers (DCs) in the region (see Section 2.3) based on forecast demand at each DC. When production starts are frequent, this allocation occurs frequently, allowing local inventory levels to be adjusted in response to demand. However, when production starts are infrequent (as in the case of products in segments B and C), then allocations are also infrequent. This forces local forecasts to be made on a long timeline, thus exacerbating the already inaccurate forecasts associated with low-volume, high-variability demand. The ultimate result of this is product being directed to one DC when it is needed at another.

It is also important to note that planning and forecasting is performed at the customer level, rather than the consumer level, which distorts the true demand. Customers are retail locations or local/regional distributors, which are themselves one or two levels removed from the actual product consumer.

2.3 Network Structure

Company X uses a multi-echelon distribution supply chain, as shown in Figure 2-3. Company X owns elements at each level of the supply chain but also works with third party distributors and retailers. Transportation between nodes is primarily done by the truckload with other methods used exceptionally. This transportation choice minimizes unit logistics cost and is optimized for high-demand products.

For the final distribution step to retailers, multiple deliveries are combined into truckload milk runs. Each retailer's order is loaded onto a truck at the DC together with other orders. The truck then makes stops at each retailer receiving a shipment. A regular schedule is used with each retail location receiving a shipment once per week. This transportation option is used to minimize unit transportation cost and to provide predictability to retailers.

Inventory is used as the primary method to level demand. Short-term fluctuations in customer and consumer demand are absorbed through inventory, while long-term fluctuations trigger changes in the production schedule.

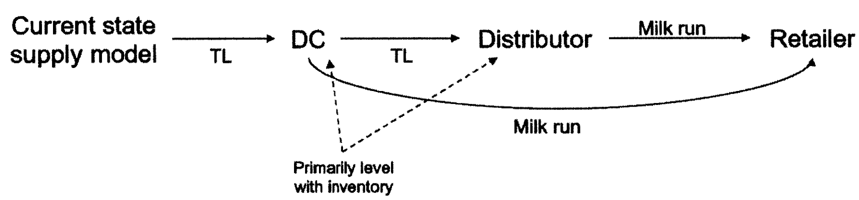

Figure 2-3: Product primarily follows one flow path in a uniform network structure

2.4 Lot Size Limitations

A final supply chain limitation is tied directly to the capabilities of the manufacturing system. Manufacturing Company X's products is a two-stage process. In the first stage, components are assembled together in a machine, and in the second stage, the assembly is processed in specialized tooling. The cycle time of a machine in the first stage is several times greater than in the second stage, which is why one first-stage machine feeds several second-stage machines, as shown in Figure 2-4.

The manufacturing system has setup and tooling costs that make it inefficient to make products with demand of less than several thousand units per year. Even low demand products that nominally require only one set of tooling (in the second stage) effectively use at least four sets to match the output rates of the first and second stages, incurring excessive tooling costs for new product introductions. As a result of these limitations, there is a lower bound on the predicted market size of new product introductions. This, in turn, makes it expensive for Company X to capture demand in niche, high-margin product segments.

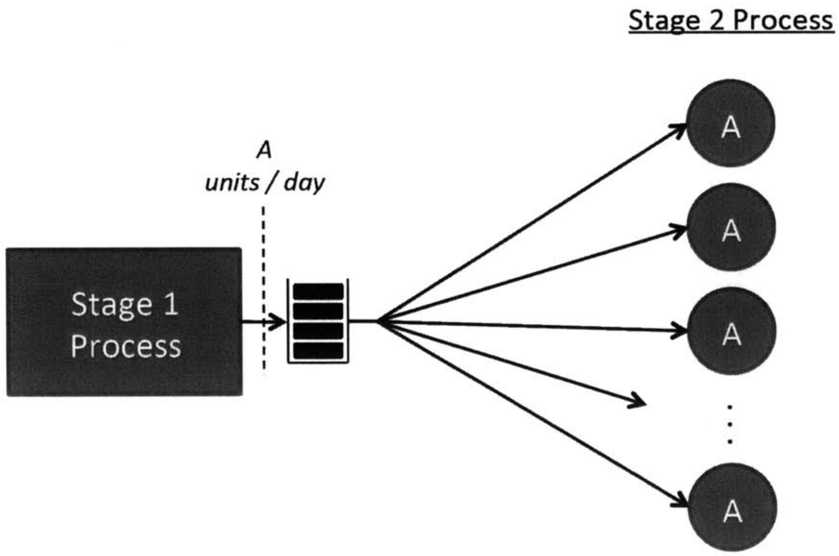

Figure 2-4: Products are manufactured in a two-stage process

2.5 Summary

The current state of Company X is such that its supply chain is optimized for a certain segment of products (those with high volume and low variability), but its corporate strategy has shifted to focus on a different segment (to premium products, which are often low volume). There is a mismatch between the supply chain and the strategy that the company is working to realign.

The mismatch can be seen in the design of several aspects of supply chain operations, as described above. Performance metrics also reflect the mismatch. The current state is one that is optimized for high throughput and low cost at high throughput, rather than for agility in supplying volatile and low demand products. The next chapters will make recommendations for how to achieve alignment between operations and strategy.

Chapter 3

Future State of Company X

Many of the challenges that the current supply chain faces can be mitigated with a more agile supply source. A supply source with smaller lot sizes and the ability to adjust production schedules more frequently is better matched to the demand characteristics of low-volume products than traditional supply sources are. However, traditional supply sources still match well with high-volume products. In short, an agile supply source enables a segmented supply chain where different segments of products are each served by (partially) different supply chains, each of which is tuned to the corresponding demand characteristics; an agile supply source supplies low-demand products and a high-throughput supply source supplies high-demand products.

3.0.1 A Note on Metrics

Several different metrics are used to measure supply chain performance when demand is uncertain. Inventory-based metrics generally calculate how well demand is met from inventory in a given time period. However, even among inventory-based metrics, there are several common ones.

A common metric, which this thesis uses, is service level (SL). SL is the probability that, in any given time period, the entire demand is supplied. If inventory is at 1000 units, the service level is the probability that the demand will not exceed 1000 units in a period. This can be thought of as the average across periods of a series of binary values. If in a given period the demand is 1000 units or less, the value for that period would be 1. If, instead, the demand is 1001 or greater, the value would be 0. Then, if in 100 periods five 0's and 95 1's are expected, the service level would be 95%. More mathematically, SL is calculated by integrating the cumulative distribution function (cdf) of demand over the range $[S + \frac{1}{2}, \infty)$, where S is the inventory level.

The concept of SL is shown graphically in Figure 3-1. In the case shown, in two out of ten periods, demand exceeds the inventory level. Thus, the average service level across the ten periods shown in 80%.

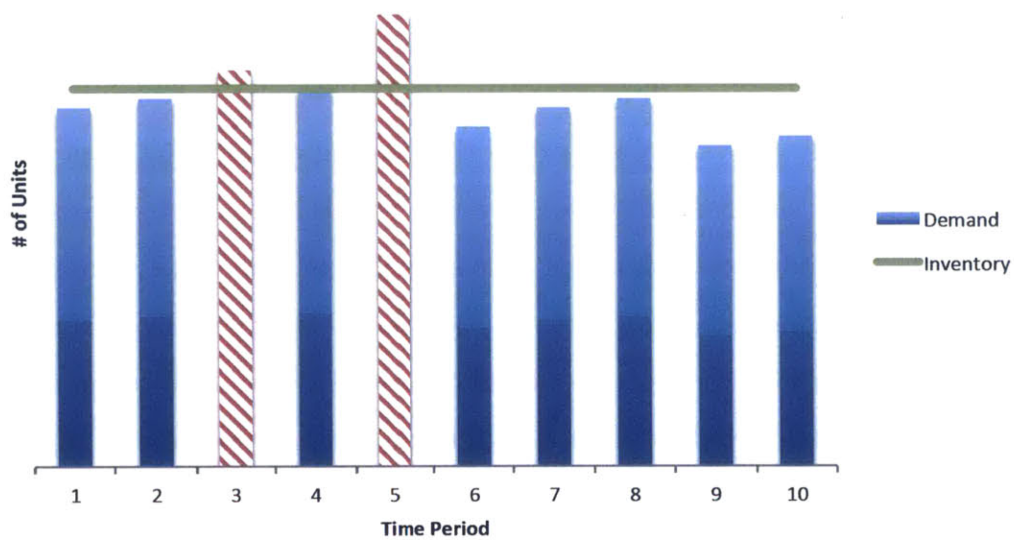

Figure 3-1: If demand exceeds inventory in two periods out of ten, the SL is 80%

This is a fairly strict metric, and other metrics are sometimes used instead. For example, item fill rate (IFR), is the expected value of the fraction of demand that is met in a given period [15]. In this case, if 1000 units are in inventory and the demand is 999 units, the IFR is 100%. If, instead, the demand is 1001 units, the IFR is 99.9% $(= \frac{1000}{1001})$. IFR is calculated using the loss function of the demand distribution, and this metric is typically higher than SL for the same situation.

The concept of IFR is shown in Figure 3-2. In this case, each period, except for periods 3 and 5, have an IFR of 1, while periods 3 and 5 have IFRs of 95.2% and 83.3%, respectively.

Thus, the average IFR across the ten periods is 97.9%, significantly higher than under the SL metric.

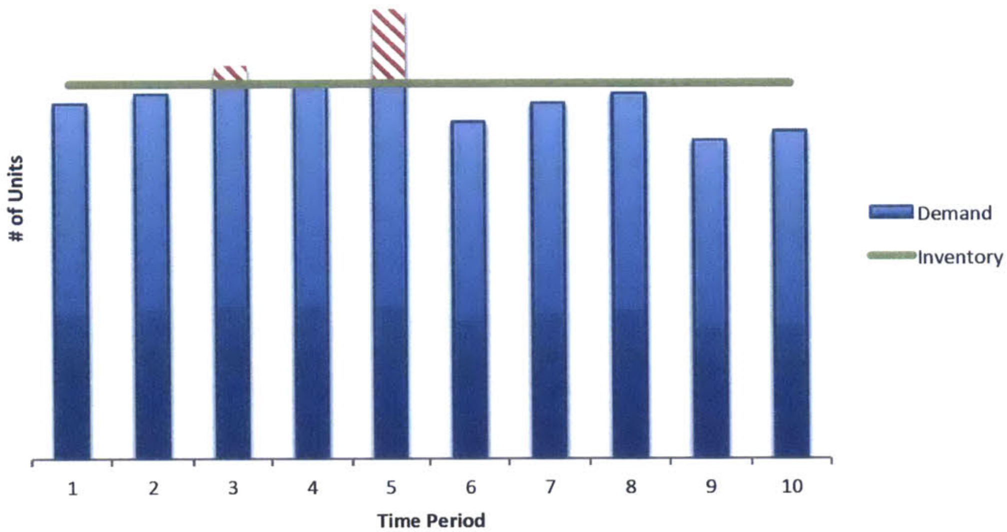

Figure 3-2: In the demand profile shown, the IFR is calculated from the fraction of demand that exceeds the inventory level, resulting in a metric value of 97.9% in this case

3.1 Enabling a segmented supply chain

A segmented supply chain is one that is optimized for multiple demand patterns at once. In Company X's case, this means that part of the supply chain is optimized for high-volume, low-variability products, while another part is optimized for low-volume products.

This is possible because not all products follow the same path in a segmented supply chain. One segment starts in the current state, traditional supply source and follows the current state path to the consumer. Another segment starts in an agile supply source and partially follows a different path to the consumer. In the near term, the two paths join at a DC, which is the first echelon of Company X's distribution network. However, with time, the path that each segment of product follows will be optimized further.

The main characteristic of an agile supply source is the increased production frequency (production starts) and a corresponding decrease in minimum lot size. This directly leads to a multitude of benefits:

- more opportunities to adjust production volume,
- shorter or no demand forecast horizon,
- smoother production flow and a reduction of peak output,
- reduced cycle stock,
- reduced safety stock[1].

Additionally, the agile supply source should not be tied to a strict cyclical production schedule and should easily adapt to demand. These advantages are especially relevant to low-demand products, and each is discussed in more detail in the following sections.

3.2 Network Structure

Figure 2-3 shows how Company X's distribution network looks now, and Figure 3-3 shows how the network could be augmented to create a segmented supply chain. As mentioned earlier, a segmented supply chain may overlap in some of its parts, as is the case here.

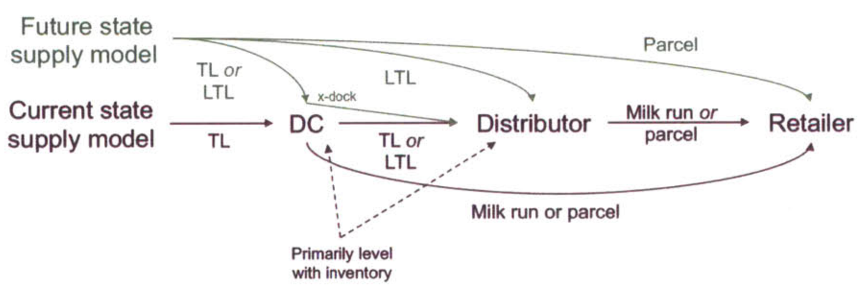

Figure 3-3: Several new flow paths in the distribution network were considered for the future state

The main difference in the segmented supply chain is the addition of a second type of supply source/model that is more agile. The other difference is the path a product follows in the network to eventually reach the same destination, the retailer. Several alternatives were

[1]excess inventory held to meet demand greater than forecast

considered, ranging from integrating with the current state supply chain at a DC to direct shipment from a new supply source to the retailer.

For initial implementation, the more conservative option, integrating at the DC is recommended. This allows Company X to focus on creating and integrating a new supply source into its business and supply chain without simultaneously changing the distribution supply chain.

Seen another way, the existing supply chain is a push system, where production plans and inventory allocations are made based on forecasts and central plans. The proposed new supply chain segment would be a pull system, where production is triggered by a demand signal from the next downstream inventory location. Inventory is held in nearly the same locations in both segments, but the agile segment would have different replenishment policies. This concept is shown in Figure 3-4.

Furthermore, because of the smaller quantities, transportation of product occurs in smaller quantities in the agile segment, as discussed in more detail below. In practice however, transportation flows may be mixed to gain cost efficiency.

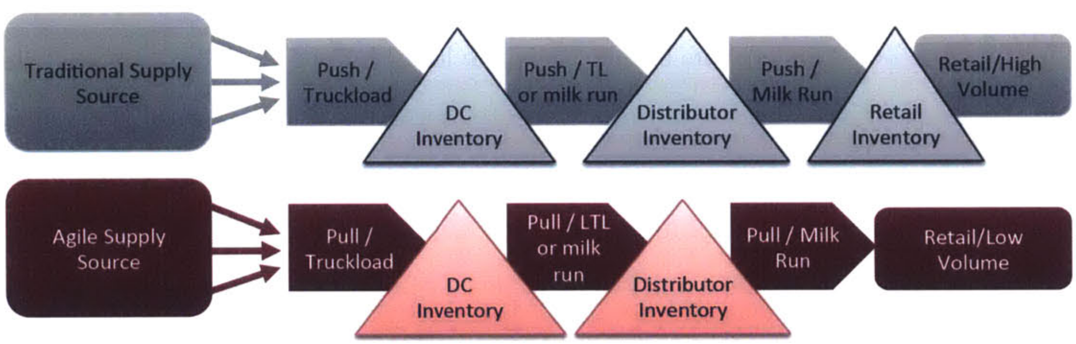

Figure 3-4: Push-Pull Division of Supply Chain

3.3 Increased Responsiveness to Variability

Given the uncertainties of supply and demand, production schedules need to be adjusted from time to time in order to keep supply and demand matched. The more frequently production is adjusted, the better supply and demand will be matched, and this concept is all the more important with high variability SKUs.

Furthermore, with typical batch sizes in traditional supply sources, high volume products can be produced continuously or weekly, whereas low volume products might be on a nominal production period of several weeks to several months. In the former case, there are already many opportunities to adjust production volumes, but in the latter case a more agile supply source with a minimum efficient batch size one to two orders of magnitude smaller would be needed to achieve the same production period. This would mean, for example, that products with low yearly demand would still be produced daily instead of monthly (or even farther apart).

A comparison of cycle stock shows this concept clearly. Cycle stock is the inventory needed to meet mean demand. Ideally, cycle stock follows the saw tooth pattern shown in Figure 3-5, where stock is replenished up to the production lot size at regular intervals, and then depletes at the forecast demand rate, reaching zero just as the next replenishment arrives. Lot size and time between replenishment are related by:

$$T_r = L/D_f \tag{3.1}$$

where T_r is the time between replenishment, L is the lot size, and D_f is the forecast demand rate.

Each replenishment represents an opportunity to adjust supply to match demand. For comparison, Figure 3-6 shows the same pattern but with a product that has a lower forecast demand. In this situation, opportunities to adjust supply are farther apart, making the supply chain less responsive for this lower demand product.

An intuitive countermeasure to this problem is to reduce the lot size, which proportionally reduces time between replenishment. The proposed agile supply source would produce in smaller lot sizes that make the supply chain more responsive. The same cycle stock pattern with a low demand (same demand is in Figure 3-6) and with a smaller lot size is shown in Figure 3-7.

However, cycle stock does not, by itself, paint a complete picture of how reduced lot size increases supply chain responsiveness. Cycle stock only shows how the supply chain operates under ideal, average conditions.

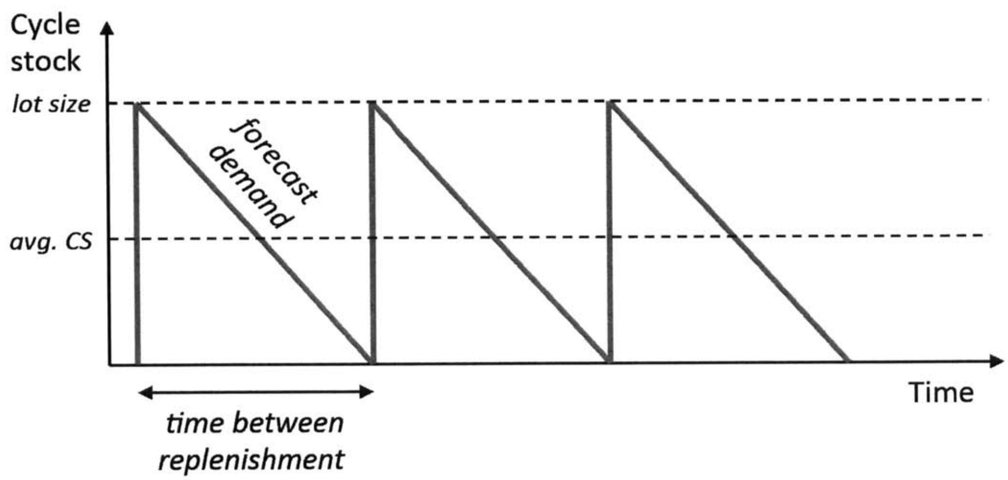

Figure 3-5: Lot size, forecast demand, and replenishment period have a linear relationship

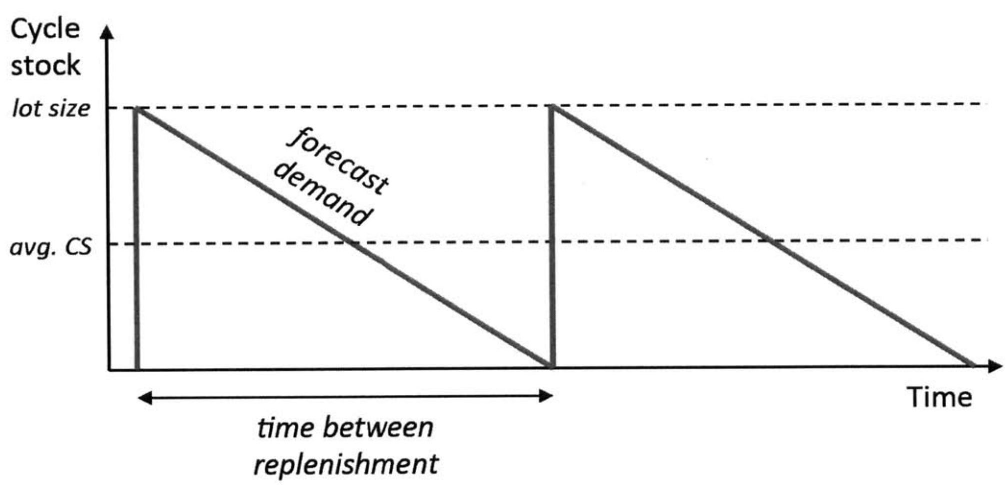

Figure 3-6: Lower demand results in longer time between replenishment (lower responsiveness)

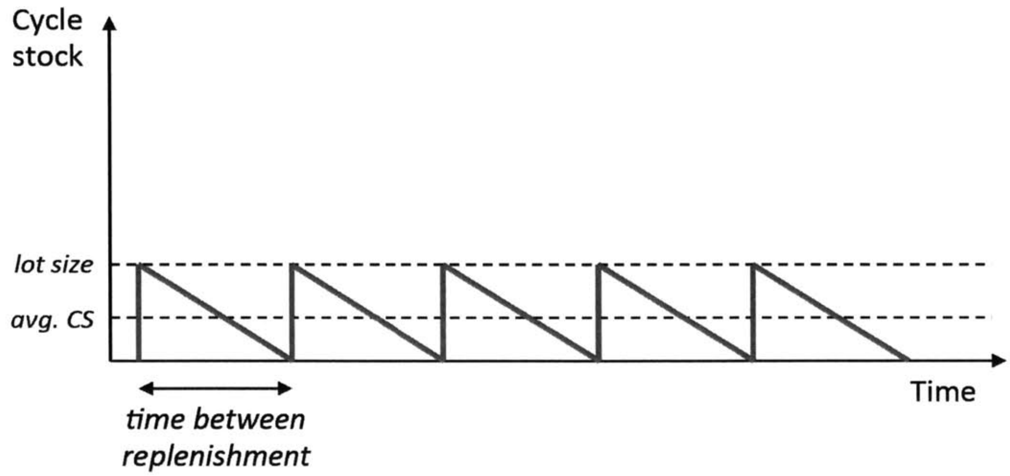

Figure 3-7: Reducing lot size reduces time between replenishment (more responsive)

To complete the picture of how a smaller lot size makes the supply chain more responsive, variability in supply and demand also needs to be considered. Actual demand will not follow forecast demand, and actual supply may not manifest itself in the planned quantity at the planned time. Instead, both supply and demand will vary from time period to time period. The variability needs to be compensated for with safety stock (excess stock held to meet demand greater than forecast), excess supply capacity, and flexible delivery time to the customer.

To understand the effects of variability on SL, we examine two manifestations of variability. One manifestation of supply variability is a delay in production (Figure 3-8), which is especially prevalent in the traditional supply source with low demand SKUs. Another manifestation of demand variability is a bias in realized demand that diverges from forecast demand (Figure 3-9). These sources of variability are examined further using inventory models.

3.4 Sensitivity Analysis

The following subsections analyze the sensitivity of supply chain performance to uncertainty using general inventory models. The intent of these models is to show general trends rather than the specific conditions present at Company X. Any numbers used are altered from their

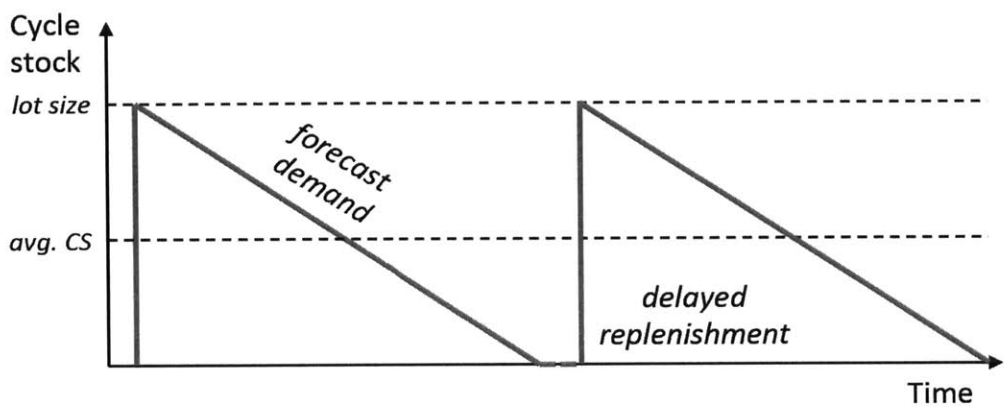

Figure 3-8: Production delays create supply variation

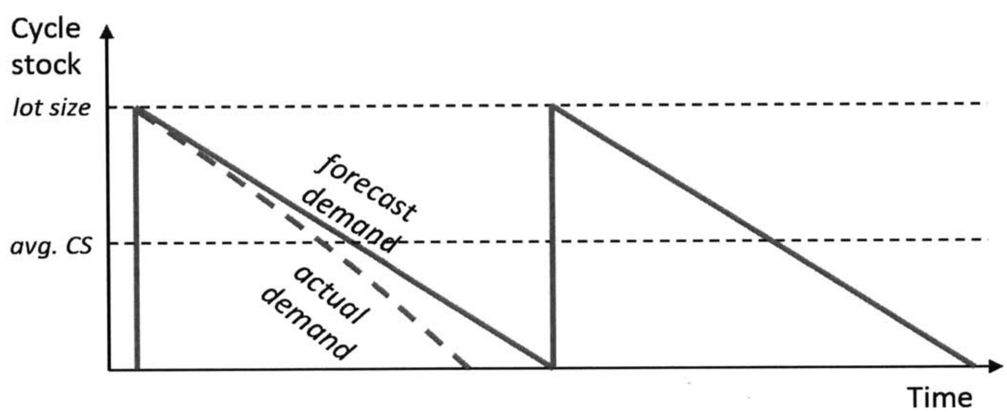

Figure 3-9: Changes in realized demand creates demand bias

true values, but the conclusions reached are nonetheless valid.

3.4.1 General Model Parameters

The two comparative models below use the following parameters shown in Table 3.1:

Table 3.1: General Model Parameters

Parameter	Units	Trad. Source	New Source
Target SL (SL_{target})	-	95%	
Mean demand ($D_{nom}(1)$)	[units / day]	50	
Daily standard deviation ($\sigma_{nom}(1)$)	[units / day]	50	
Replenishment period (T_{nom})	[days]	7	60
Order lead time (T_{lead})	[days]	$0.2T_{nom}$	

3.4.2 Service Level Sensitivity to Demand Bias

Model

The first model used is a classic single-echelon inventory model with normally distributed demand. Inventory levels are set based on the target SL (95%) and forecast demand. The sensitivity metric chosen is effective service level (ESL), which is calculated as the actual probability that all demand for a period is filled under the perturbed model parameters.

The equations below use subscripts to denote meaning rather than an index. The subscript *nom* is used to denote a parameter of the nominal model, while the subscript *per* is used to denote a parameter of the perturbed model.

For demand bias, the model parameter that is perturbed is the mean daily demand, and it is perturbed by a percentage (p) of the nominal mean daily demand, as follows:

$$D_{per}(T) = p \cdot D_{nom}(T) \tag{3.2}$$

The metric is calculated for a range of perturbations and replenishment periods (T_{nom}).

ESL is calculated as follows:

$$ESL = F(S_{nom}(T_{nom}); D_{per}(T_{nom}), \sigma_{per}(T_{nom})) \tag{3.3}$$

$$F(x;\mu,\sigma) = \frac{1}{2}\left[1 + \text{erf}\left(\frac{x-\mu}{\sigma\sqrt{2}}\right)\right] \tag{3.4}$$

where $F(\cdot)$ is the normal cdf function, $S_{nom}(T_{nom})$ is the optimal inventory level calculated using nominal model parameters, $D_{per}(T_{nom})$ is the mean total demand for the period under perturbed model parameters, and $\sigma_{per}(T_{nom})$ is the total standard deviation of demand under perturbed model parameters and nominal replenishment time period T_{nom}.

Standard deviation of demand varies with the time period over which demand is considered. Since this time period is varied in the model, it is left as a parameter in the above equations. Instead, daily standard deviation is specified as a base model parameter (see Table 3.1). Additionally, ordering lead time is included in the model through the total standard deviation value. Ordering lead time increases uncertainty about demand because a replenishment order needs to be placed a time T_{lead} earlier than it is needed. In this model, lead time is specified as a percentage of the replenishment period because it best reflects the capabilities of an agile supply source versus a traditional supply source. The former can adjust production more quickly in response to an order than the latter can. Thus, total standard deviation is calculated as follows:

$$\sigma_{per}(1) = p \cdot \sigma_{nom}(1) \tag{3.5}$$

$$\sigma_x(T_{nom}) = \sqrt{(T_{nom} + T_{lead}) \cdot {\sigma_x}^2(1)} \tag{3.6}$$

where $x \in \{nom, per\}$.

S_{nom} is the sum of two components, cycle stock (CS) and safety stock (SS). CS is set to the mean forecast demand for the period, and SS is calculated as follows:

$$CS = D_{nom}(T_{nom}) \tag{3.7}$$

$$SS = k \cdot \sigma_{nom}(T_{nom}) \tag{3.8}$$

$$k = F^{-1}(SL_{target}; 0, 1) \tag{3.9}$$

where $\sigma_{nom}(T_{nom})$ is the total standard deviation under nominal model parameters and time period T_{nom}, $F^{-1}(\cdot)$ is the inverse normal cdf.

Analysis

When demand increases from the planned level, the ESL drops for any length of replenishment period. However, the sensitivity of the ESL change depends on the supply period (days between replenishment). As expected, the sensitivity to demand bias is greater with longer supply periods as shown in Figure 3-10. For example, if demand increases 10% over the planned demand, the ESL drops from 95% (the target ESL) to 90% in the case of a 7-day period, but to 80% in the case of a 60-day period. This observation supports the argument that a shorter replenishment period has a positive effect on the observed service level of the supply chain.

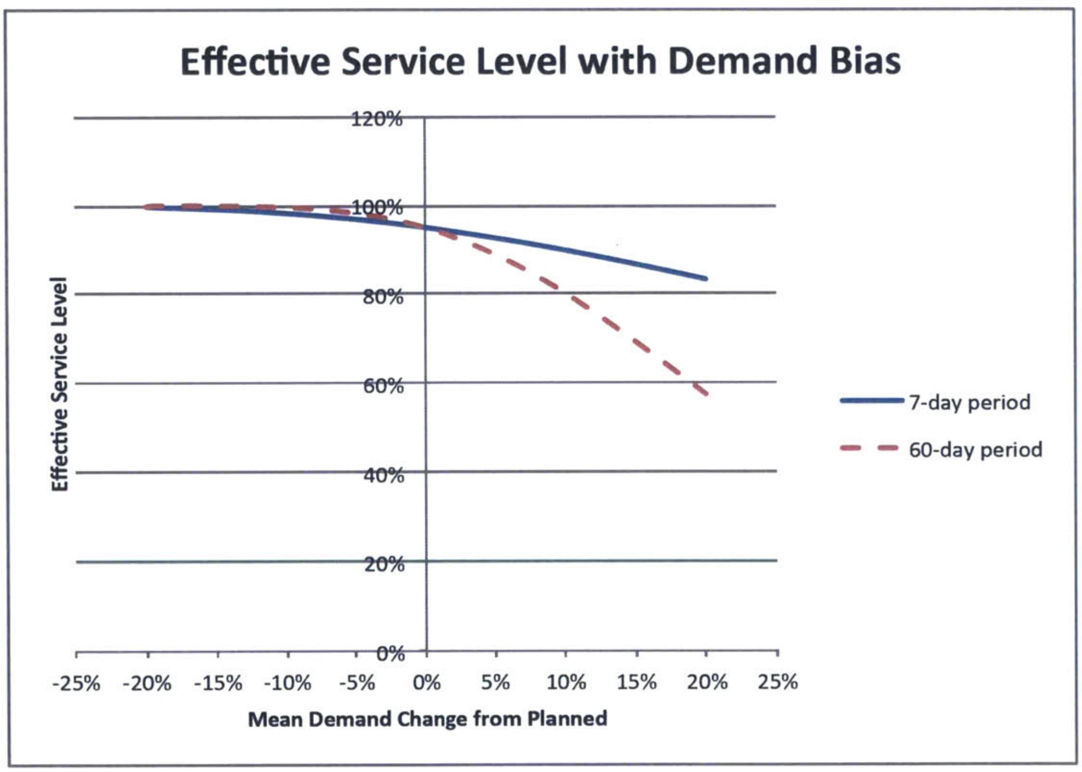

Figure 3-10: Sensitivity of Service Level to Demand Bias

Figure 3-11 shows the sensitivity profile on a different axis. In this figure, the effect of the period length on ESL is shown for two specified changes in demand (10% and 20%

increase). We again see that with greater period length sensitivity increases, especially for large demand biases, which might be typical of low-demand products.

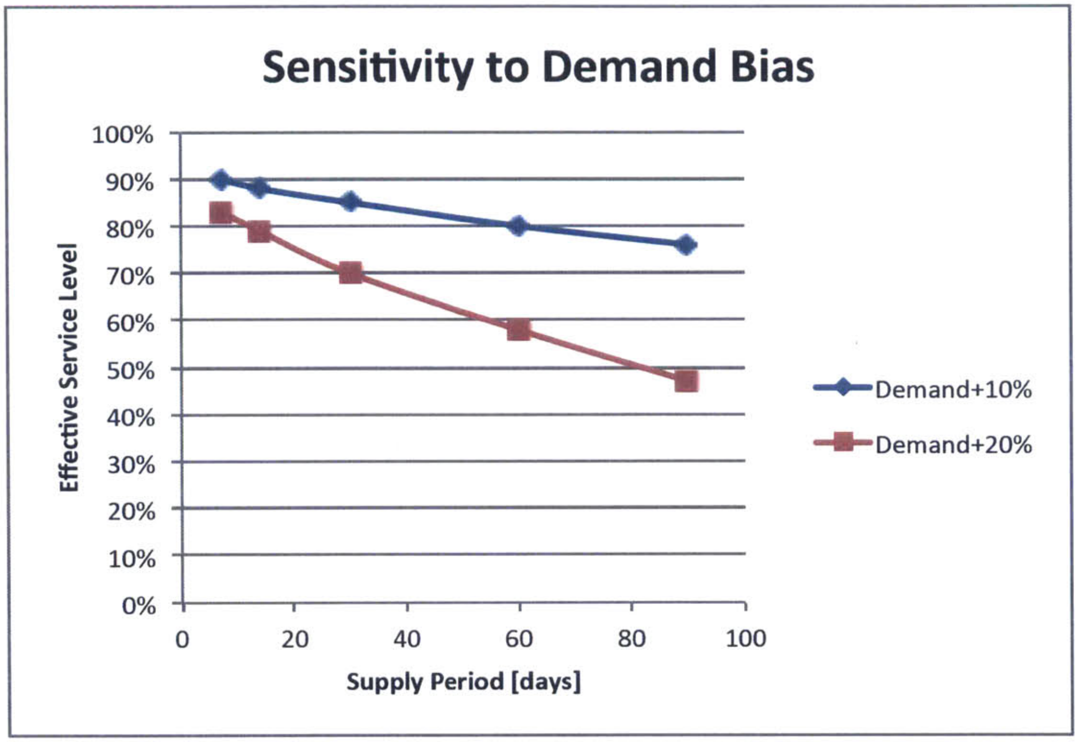

Figure 3-11: Longer supply periods lead to greater sensitivity to biases in demand

Furthermore, there is a larger decrease in ESL for increases in demand than there is an increase in ESL for corresponding decreases in demand. Because of this asymmetric property, equal but opposite variations in demand of different SKUs in a given period do not offset each other when it comes to supply chain performance. Such variations across multiple products would still decrease the overall supply chain performance.

3.4.3 Service Level Sensitivity to Supply Variation

Model

Supply variation can take many forms, one of which is variable delay in starting production. With a delay in production, inventory becomes more likely to be depleted before it can be replenished. Furthermore, the model assumes that delays are best characterized as a percentage of the nominal supply period. This assumption again models an agile supply source differently from a traditional one, in terms of responsiveness.

For the supply variation model, ESL is calculated as follows:

$$
\begin{aligned}
ESL &= F(S_{nom}(T_{nom}); D_{per}(T_{per}), \sigma_{per}(T_{per})) && (3.10)\\
F(x;\mu,\sigma) &= \frac{1}{2}\left[1 + \operatorname{erf}\left(\frac{x-\mu}{\sigma\sqrt{2}}\right)\right] && (3.11)\\
\sigma_{per}(T_{per}) &= \sqrt{\sigma^2_{nom}(T_{per}) + (D_{nom})^2 \cdot \sigma^2(T_{per} - T_{nom})} && (3.12)
\end{aligned}
$$

where $F(\cdot)$ is the normal cdf function, $S_{nom}(T_{nom})$ is the optimal inventory level calculated using nominal model parameters, $D_{per}(T_{per})$ is the total demand for the delayed replenishment period, $\sigma_{per}(T_{per})$ is the total standard deviation of demand under perturbed model parameters and delayed replenishment time period T_{per}, $\sigma_{nom}(T_{per})$ is the nominal standard deviation over a time of T_{per} (including the lead time, T_{lead}, as calculated above), D_{nom} is the demand during the nominal replenishment period, and T_{nom} is the nominal replenishment period. Equation 3.12 is the Hadley-Whitin equation, used to calculate the standard deviation of the random sum of random variables [4]. This equation is needed because both demand and the replenishment period are random.

For the model presented here, the assumption was made that half the time there is no production delay, and half the time the production delay is $2(T_{per} - T_{nom})$. Thus, the mean production delay is $T_{per} - T_{nom}$ and the variance is $(T_{per} - T_{nom})^2$. Using these values, we get:

$$\sigma_{per}(T_{per}) = \sqrt{{\sigma_{nom}}^2(T_{per}) + (D_{nom})^2(T_{per} - T_{nom})^2} \qquad (3.13)$$

S_n is the sum of two components, cycle stock (CS) and safety stock (SS). CS is set to the mean forecast demand for the period, and SS is calculated as follows:

$$
\begin{aligned}
CS &= D_{nom}(T_{nom}) && (3.14)\\
SS &= k \cdot \sigma_{nom}(T_{nom}) && (3.15)\\
k &= F^{-1}(SL_{target}; 0, 1) && (3.16)
\end{aligned}
$$

where $F^{-1}(\cdot)$ is the inverse normal cdf, and SL_{target} is the target SL.

Analysis

When supply is delayed beyond the planned replenishment period, the ESL drops for any length of replenishment period. However, the sensitivity of the ESL change depends on the supply period (days between replenishment). As expected, the sensitivity to supply variation is greater with longer supply periods as shown in Figure 3-12. For example, if the replenishment period increases 10% over the planned period, the ESL drops from 95% (the target ESL) to 92% in the case of a 7-day period, but to 82% in the case of a 60-day period. This observation supports the argument that a shorter replenishment period has a positive effect on the observed service level of the supply chain, as is also the case with demand variability.

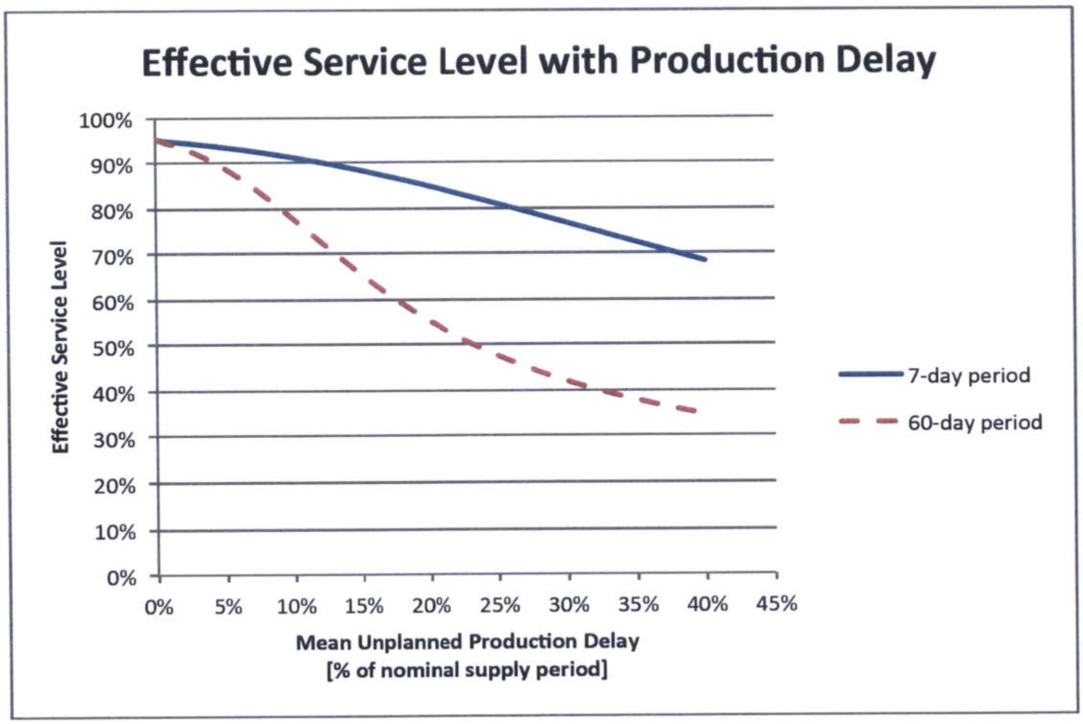

Figure 3-12: Sensitivity of Service Level to Production Delay

Figure 3-13 shows the sensitivity profile on a different axis. In this figure, the effect of the period length on ESL is shown for two specified delays in replenishment (10% and 20% increase). We again see that with greater nominal period length sensitivity increases, especially for large supply delays, which might be typical of low-demand products.

Even this simple single-echelon model shows the importance of reducing the nominal

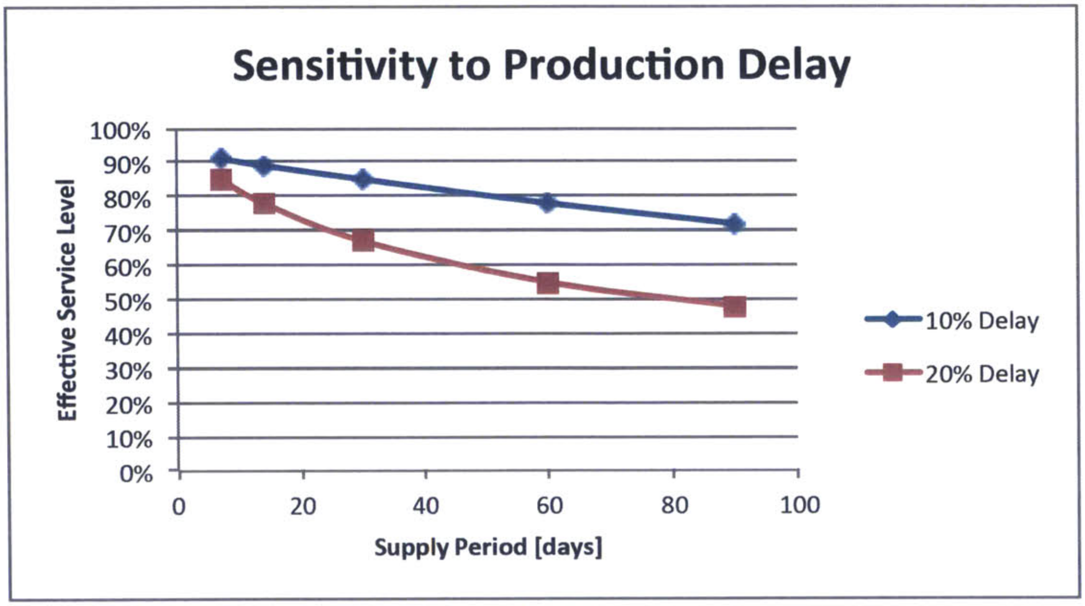

Figure 3-13: Longer supply periods lead to greater sensitivity to production delay

replenishment period for high-variability products, which the segmented supply chain is doing.

3.4.4 Sensitivity Under Alternative Metrics

As was discussed in section 3.0.1, one alternative metric to measure supply chain performance is IFR. This metric often has a higher value than SL for the same model and inventory level. Seen in another way, the same value can be achieved with lower inventory levels. The downside of using IFR is that it is 'lenient' about small stock-outs, which may provide the wrong incentives to managers in certain situations. Nevertheless, IFR is compared to SL below.

As a reminder, IFR can be calculated using the loss function of the demand distribution. The metric is the fraction of units short convoluted with the probability of that many units short. In other words, it's $\frac{1}{D} \cdot P(US = 1) + \frac{2}{D} \cdot P(US = 2) + ...$, where $P(US = x)$ is the probability that the supply chain supplies x units less than the demand, D, in a period. Written completely, this calculation is:

$$IFR = 1 - \frac{\sigma_L G[k]}{Q} \tag{3.17}$$

where σ_L is the standard deviation of demand over the lead time, $G[k]$ is the unit loss function, $k\sigma_L$ is the safety stock, and Q is the reorder quantity (typically the cycle stock) [3].

When effective IFR is calculated for the model presented earlier in this chapter, and with the inventory levels set to achieve a specified SL, the values are much higher. This comparison is shown in Figure 3-14 for the demand variability model analyzed previously.

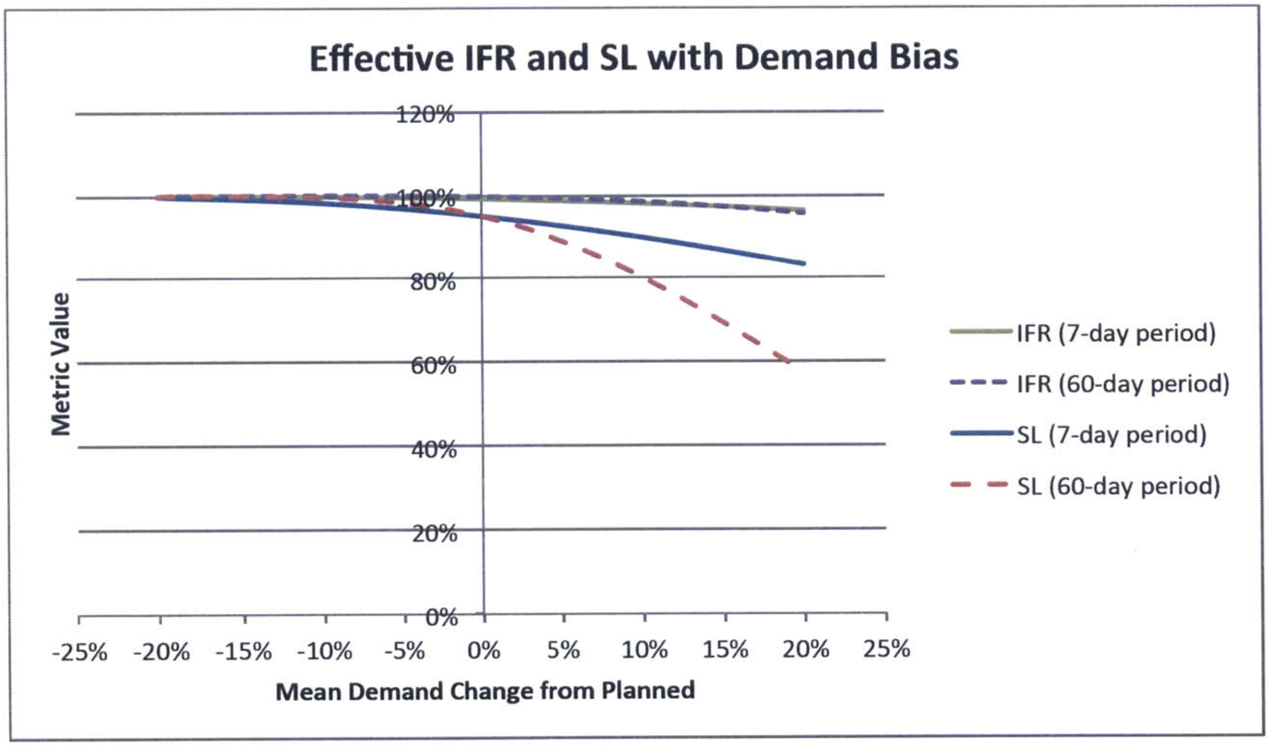

Figure 3-14: The Item Fill Rate metric achieves higher values, as compared to the Service Level metric, for the same scenario

When inventory levels are set to achieve a 95% IFR, the performance loss with increased demand is not as strong. This comparison is shown in Figure 3-15. Again, this is because IFR is not as strict of a metric as SL, and does not penalize small shortages as strongly.

Furthermore, it is important to note that inventory levels set according to IFR are much lower than inventory levels set according to SL. For example, in the demand variability model, safety stock was reduced by 95% for the 60-day replenishment period and by 52% for the 7-day replenishment period.

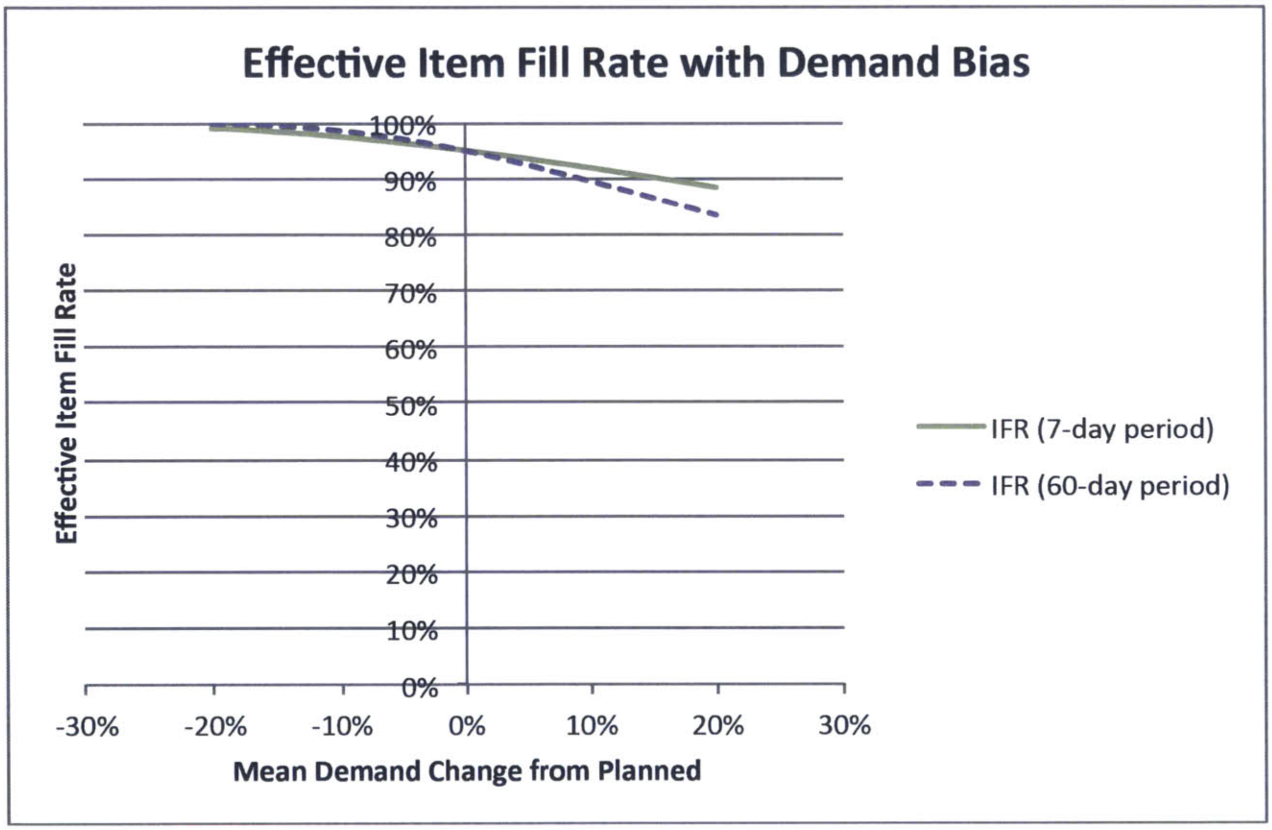

Figure 3-15: Item Fill Rate is less sensitive to changes in the replenishment period

3.5 Inventory Level Reduction

Inventory ties up capital and requires distribution centers, both of which incur recurring cost. Thus, reducing inventory is a direct way to reduce total landed cost. Inventory can generally be broken down into several components:

- pipeline stock,
- cycle stock,
- safety stock.

Pipeline stock is the inventory that is traveling from one location to another (e.g. production site to DC). This inventory is primarily reduced by shortening the length (measured with time) of transportation links in the logistics network, and reducing length variability. This component is a design trade-off that is discussed in a later section.

Cycle stock is the inventory needed to satisfy average demand between production periods. The amount of cycle stock is linearly proportional to the period between replenishment, so if an inventory location is replenished every 7 days instead of every 70 days (10 times more inventory turns), that location needs 10 times less cycle stock. Cycle stock was discussed in the previous section in the context of supply chain responsiveness.

Finally, safety stock is the inventory needed to absorb variability in supply and demand. The amount of safety stock needed increases with greater time between replenishment, variability, and target SL. However, the exact relationship depends on a number of factors and increases sub-linearly.

The cost of holding inventory consists of both cost of capital tied up in the inventory and allocated cost of operating the DCs. The value is expressed as a rate, such as $Y per product per year. Average cycle stock is generally calculated as half of the demand between replenishment periods, assuming no out-of-stock conditions. Because the replenishment period is linearly related to the production lot size, a smaller lot size linearly reduces the cost of holding cycle stock.

3.5.1 Illustrative example of inventory savings

To demonstrate the possible inventory savings, this example shows a calculation of approximate savings gained from switching to a smaller lot size. All values are masked to protect proprietary information. Take, for example a product with the following demand characteristics:

Table 3.2: Example SKU Parameters

Yearly demand	5000 units
Daily CV (variation as % of demand)	50%
Target service level	95%

If this product is produced with the traditional sourcing model and with a minimum production lot size of 2500 units, the replenishment period is 180 days, requiring an average of 1250 units of cycle stock, for a yearly cost of $\$\,(1250 \cdot Y)$. Using an agile supply source that shortens the replenishment period to approximately 11 days with a lot size of 150 units requires a cycle stock of approximately 76 units for a cost of $\$\,(76 \cdot Y)$. The cycle stock savings are 1174 units, for a cost of $\$\left(\frac{1174}{5000} \cdot Y\right)$ per unit of throughput, which consist of the greatest component of inventory savings.

Safety stock is also reduced, but to a lesser extent. Effective variability is lessened with a longer replenishment period because demand is aggregated, which minimizes the effect of safety stock savings. Specifically, safety stock grows in the square root of the demand aggregation period, as shown in Figure 3-16.

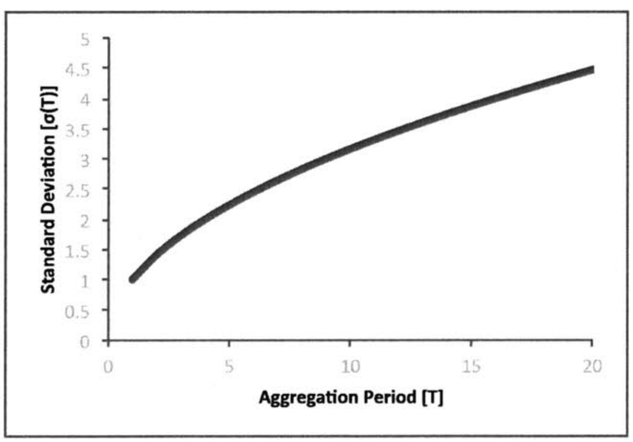

Figure 3-16: Safety stock grows with the square root of the demand aggregation period

Additionally, safety stock savings also depend on network structure. Safety stock can be aggregated in a single location, or it can be spread across multiple DCs. A model with completely separate inventory would stand to benefit more in terms of safety stock savings, but the model used here makes the conservative assumption of one virtual inventory pool.

A summary of the model is shown in Table 3.3 below.

Table 3.3: Supply model comparison

	Current State	Future State	Savings
Lot size	2500 units	150 units	
Replenishment period	180 days	11 days	
Cycle stock	1250 units	76 units	1174 units
Cycle stock cost per year	$\$(1250 \cdot Y)$	$\$(76 \cdot Y)$	$\$(1174 \cdot Y)$ / year
Cycle stock cost per unit	$\$\left(\frac{1250}{5000} \cdot Y\right)$	$\$\left(\frac{76}{5000} \cdot Y\right)$	$\$\left(\frac{1174}{5000} \cdot Y\right)$ / unit
Safety stock	153 units	38 units	115 units
Safety stock cost per year	$\$(153 \cdot Y)$	$\$(38 \cdot Y)$	$\$(115 \cdot Y)$ / year
Safety stock cost per unit	$\$\left(\frac{153}{5000} \cdot Y\right)$	$\$\left(\frac{38}{5000} \cdot Y\right)$	$\$\left(\frac{115}{5000} \cdot Y\right)$ / unit

Chapter 4

Boundary Considerations

The previous chapter analyzed and discussed Company X's supply chain specifically. However, the another important aspect of redesigning the supply chain is how it interfaces at its boundary with other parts of Company X's operations. Thus, this chapter discusses the interplay between the supply chain, manufacturing, and product offerings. These interactions are part of the entire design of the operating system.

At a high level, one parameter that affects the performance and operating cost of the system, and is key to the subsequent subsections, is the demand aggregation period. Even if Company X's supply chain can adapt over very short time periods, there may be a case for aggregating demand over a longer time period, thereby smoothing the variable demand from customers.

There are four costs that vary with the demand aggregation period, two which increase with the period, and two which decrease:

- Cycle stock (increasing)
- Safety stock (increasing)
- Peak tooling capacity (decreasing)
- Excess capacity (decreasing)

These costs are plotted notionally in Figure 4-1.

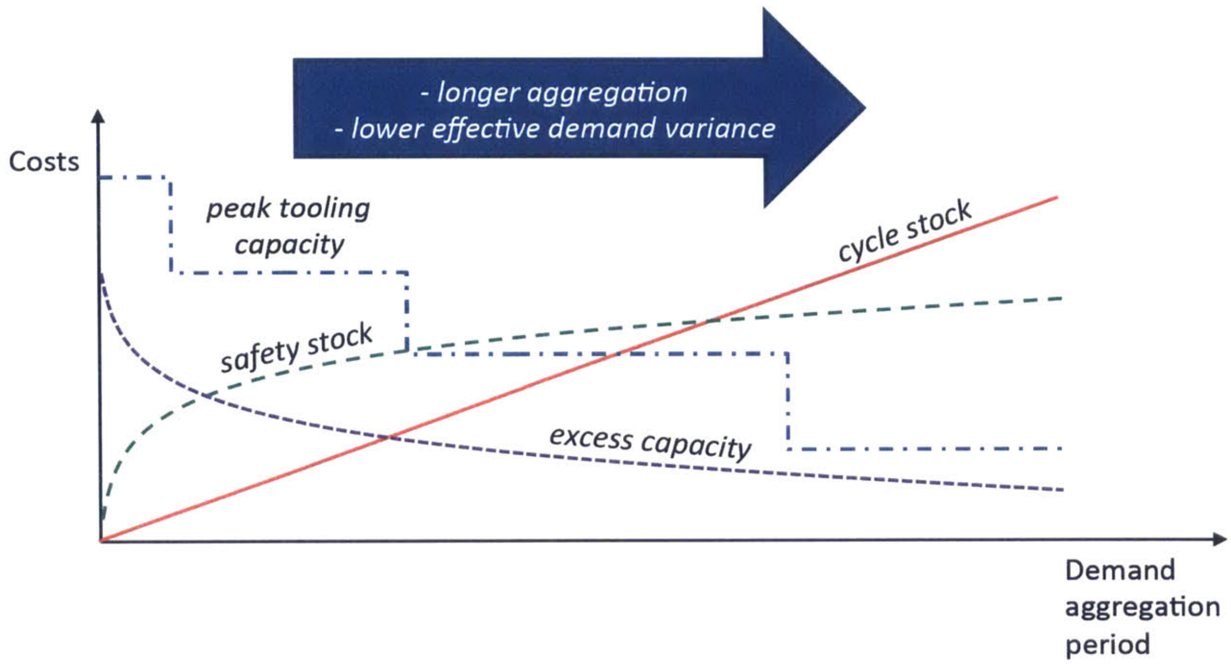

Figure 4-1: Designing Company X's operating system consists of cost trade-offs as a function of the demand aggregation period

The trade-off between these costs represent different ways of leveling demand, a key principle behind lean operations. With a short demand aggregation period, variable demand is absorbed directly by the supply system through excess capacity. On average the system needs to operate below peak capacity so that there is 'headroom' to meet demand when it exceeds the mean. This headroom is essentially an opportunity cost. Additionally, excess tooling is needed to meet peak demand.

On the other hand, if demand is aggregated over time, the demand signal is smoothed out (benefiting the supply system), but the supply chain also becomes less responsive. Demand variability is absorbed through inventory. As can be seen in Figure 4-1, this reduces tooling costs and excess capacity opportunity cost, but incurs inventory costs.

The optimal demand aggregation period minimizes the sum of these four costs, and the optimal period lies somewhere between the extremes. Tooling and excess capacity costs are reduced the most from a small aggregation period, and experience diminishing returns as the aggregation period increases. The inventory costs increase with the demand aggregation period. Cycle stock increases linearly, and safety stock increases by the square root of the demand period.

The following sections discuss these trade-offs and other system design considerations in more detail.

4.1 The Interplay Between Manufacturing and Supply Chain

4.1.1 Agile source reduces peak tooling requirements

A new agile source can reduce the tooling needed to supply a low-volume and/or high-variability SKU, as compared to the traditional manufacturing process. This enables lower cost new product introductions, the ability to pursue very low volume markets, and distributed production.

As illustrated in Figure 4-2, the first processing stage assembles products at such a throughput rate that four or more sets of tooling (along with an intermediate product buffer) are required to achieve equivalent throughput rate in the second stage. In this manufacturing system, all intermediate products in a batch are the same, which means all finished products will be the same.

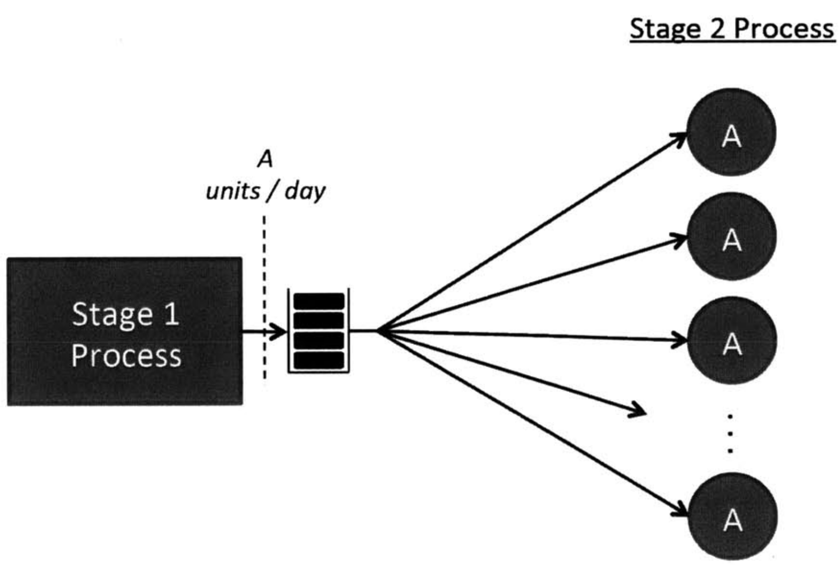

Figure 4-2: The traditional manufacturing process has a large minimum tooling requirement

To alleviate this constraint, it is recommended that a new, agile source be developed that directly matches the output of the two manufacturing stages, as shown in Figure 4-3. In other words, the agile system should assemble a different product in Stage 1 for each set of second-stage tooling, and assemble each of those intermediate products at the same throughput rate at which each set of second-stage tooling can process a product. The implication is that a product can be built at a lower rate and with just one set of second-stage tooling. This reduces cost and smooths production flow.

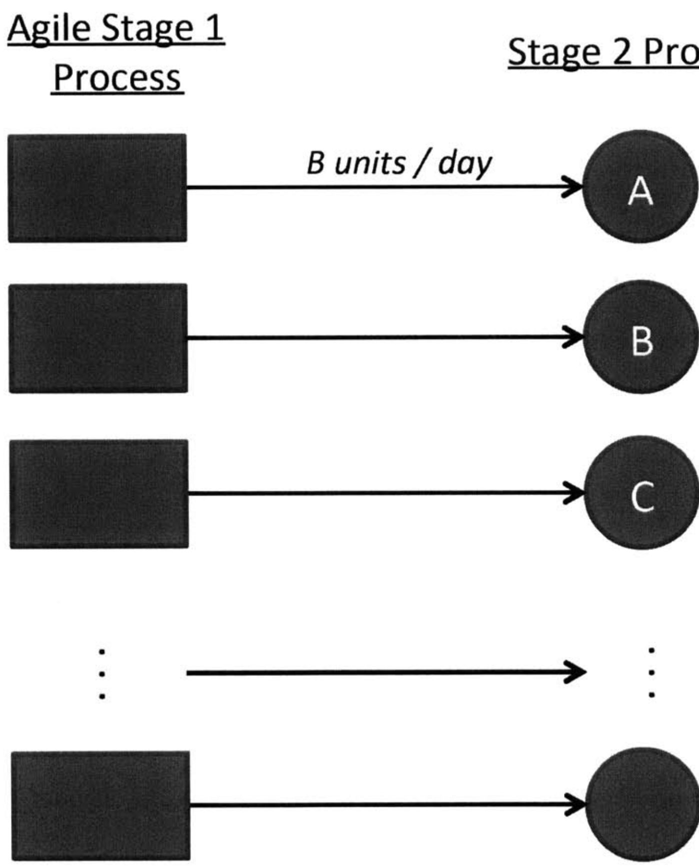

Figure 4-3: Flexibility enables the first and second stages of manufacturing to match throughput rates

Using a supply source that reduces the peak tooling requirement (even without considering reductions from demand aggregation), tooling costs are lower for new product introductions. Similarly, the minimum volume for a new product introduction is reduced because initial fixed costs are recouped sooner, allowing new markets to be pursued more easily.

Finally, this capability would also enable a distributed production model. High-volume products can be produced in several geographically distributed manufacturing sites with the same number of second-stage tooling sets as would normally be aggregated in one production facility. This would improve supply chain responsiveness due to market proximity, reduce transportation cost, and reduce pipeline inventory cost.

4.2 The Interplay Between Product Offerings and Supply Chain

4.2.1 Product Portfolio

The final aspect of the operations and supply chain strategy that is discussed in this report is the structure of the product portfolio that would be produced by the new, agile supply source. A portfolio of products can be segmented by its demand into several segments ranging from high- and low-volume SKUs, often labeled A, B, C, D, etc. The cumulative distribution of demand by SKU for the entire product portfolio is shown notionally in the upper part of Figure 4-4. The important characteristic to note is that the majority of the volume is concentrated in a minority of the SKUs.

Although an agile supply source should focus on producing low-volume SKUs, this subset can be further subdivided into a relative portfolio of A, B, C, and D items. Even when this subset of SKUs is subdivided, it continues to follow the pattern where the majority of the volume come from a minority of the SKUs. This is again shown notionally in Figure 4-4.

This characteristic provides a supply source with production schedule stability because A and B items form a baseline volume with (relatively) low variability. Meanwhile, flexibility to manufacture the very low demand C and D items is still retained. The supply chain similarly benefits from the stability of having a large volume produced on a daily basis.

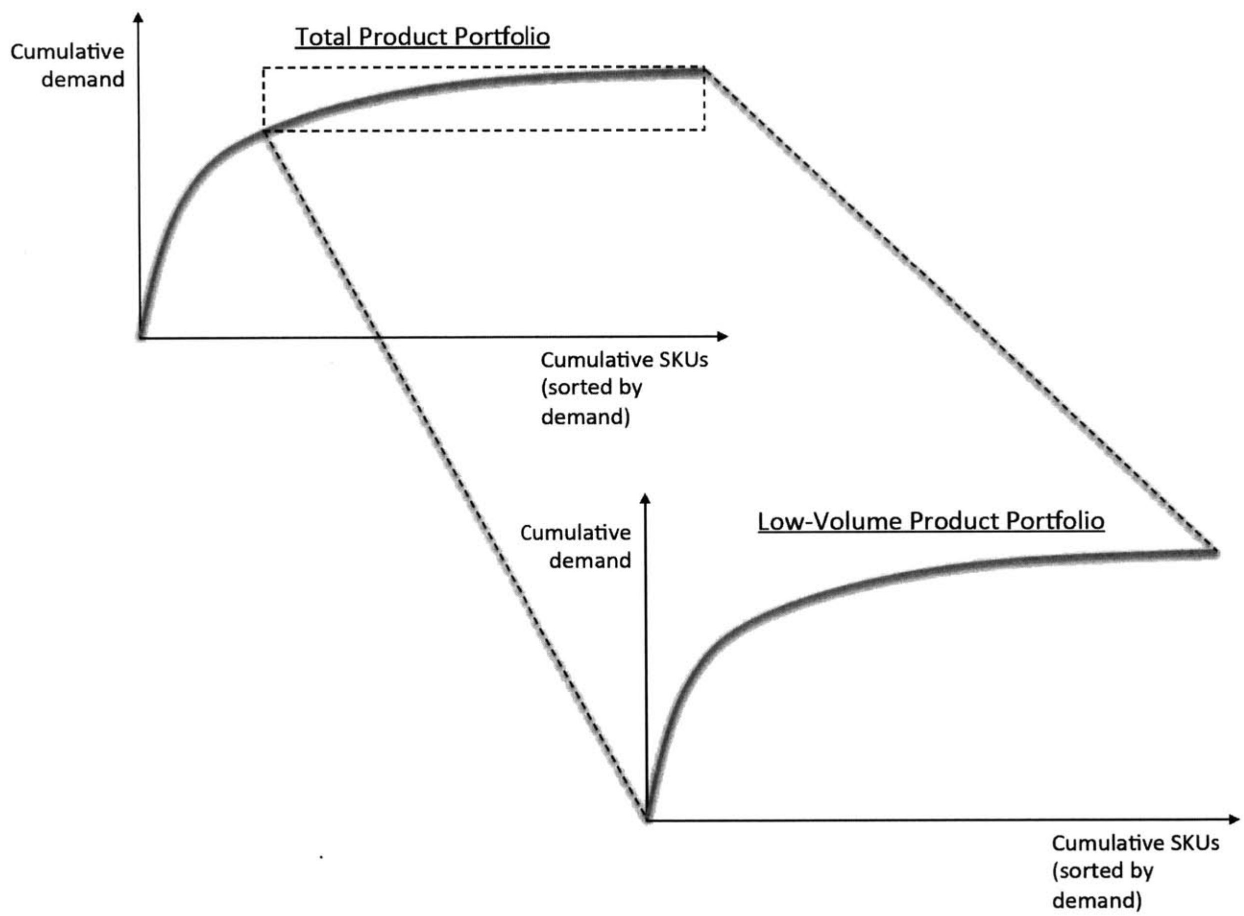

Figure 4-4: The demand distribution follows a typical pattern of a mixture of high and low volume SKUs

Chapter 5

Conclusions and Recommendations

5.1 Summary

This thesis investigated the implementation of a future segmented supply chain as a way for Company X to provide better customer service through improved service levels, while at the same time realizing cost reductions. In this study, a segmented supply chain is implemented by segmenting products by their demand characteristics and assigning each segment to a different source and flow path through the supply chain. In this way, products with high, steady demand are supplied from a supply source and through a supply chain flow path that is optimized for low unit cost and steady flow. This segment represents the only supply chain in the current state. Conversely, products with low and/or variable demand are recommended to be supplied from a new supply source and through a new supply chain flow path that is optimized for responsiveness and agility. This is needed to react to changing market demands and improve service levels on these products.

The central benefit of an agile supply source for Company X is that it reduces sensitivity to changes in supply and demand. In the current, unsegmented state of the supply chain, products that would be assigned to the new segment are underserved. For these products, the manufacturing and supply lead time is long, resulting in sharp reductions in the effective service level when demand increases or there is a supply delay. Employing a new, agile supply source can reduce the lead time and with it the sensitivity to variation.

5.2 Choice of Supply Chain Performance Metric

An important choice in the design of the segmented supply chain is the metric used to measure performance. Two metrics were considered, SL and IFR. For Company X, SL is the better metric for two reasons:

1. It sets a higher standard and pushes the company to improve more, relative to its current state, than IFR does,

2. It helps drive the company's position as a quality and service leader.

The company chooses not to compete on cost, so it needs to compete on other dimensions. If IFR is used, shortages will be more commonplace than if SL is used, which could create an image problem for the company. Even in the current state, orders are only partially met. Maintaining a high SL means orders are fully fulfilled with a high probability, rather than just partially fulfilled.

5.3 Future Work

Several avenues of research can be pursued to continue the work started here. The first would be to implement the segmented supply chain described in this thesis. The analysis presented is based on theoretical models of the supply chain, but a full implementation would certainly encounter new obstacles. An analysis and comparison of actual versus modeled performance could be conducted.

A second avenue would be to investigate other segmentation dimensions than volume and variability, such as by sales channel. Different sales channels support different business models and thus may need the support of different supply chains. For example, online retailers typically sell a large variety of products and ship these products to the consumer. On the other hand, a brick-and-mortar retailer has a smaller product variety but needs to have products available on the shelf to avoid lost sales. Thus, a supply chain for the former channel needs to be able to handle a large variety of products and could be integrated directly with the final shipment to the consumer. A supply chain for a brick-and-mortar channel instead has lower complexity regarding product variety but a greater need to keep products in stock at a specific location.

Glossary

cdf cumulative distribution function. 23, 33, 36

DC distribution center. 20, 25, 26, 27, 41, 42

ESL effective service level. 32, 34, 35, 36, 37

IFR item fill rate. 24, 25, 38, 39, 50, 51

SCM supply chain management. 13

SKU a unique product. 6, 8, 14, 17, 18, 19, 27, 30, 35, 42, 46, 48

SL the probability that all demand for a given planning time period is met. 23, 24, 30, 32, 36, 38, 39, 41, 50, 51

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