Supply Chain Design in the Volatile Semiconductor Capital Equipment Industry

By
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B.E., Mechanical Engineering, Thayer School of Engineering, 1995
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Submitted to the Sloan School of Management
and the Department of Mechanical Engineering
in Partial Fulfillment of the Requirements for the Degrees of

Master of Science in Management
and
Master of Science in Mechanical Engineering

In Conjunction with the Leaders for Manufacturing Program at the
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ABSTRACT

As companies outsource more manufacturing and design responsibilities to external vendors and therefore become less vertically integrated, the role of supply chain management becomes increasingly complex. Its role is particularly difficult when product generation follows a serial process flow, with the supply chain function residing at the end and where it inherits poorly defined supplier relationships. A more integrated approach that seeks to proactively design the supply chain during product generation is required. Central to this integrated approach is the timely exchange of information both within the company, between R&D and procurement, and external to the company, between procurement and its suppliers. The timing of the information flow is crucial. It needs to occur before the company is locked into a single supplier and when its bargaining power is the highest. It also needs to occur in a manner that does not slow down the product development process. In practice, that means that specific information needs to be exchanged and committed to prior to supplier selection. Ultimately, the information exchange described in this thesis leads to improved supplier relations that enable the company to shift its procurement practices from the tactical approach of buying materials to the strategic approach of buying supply services.

The research for this thesis was conducted at a partner company of the Leaders for Manufacturing (LFM) program. The company manufactures test equipment used in the semiconductor industry. Due to the highly cyclical and unpredictable nature of this industry, supply chains that can guarantee responsiveness and availability are desirable.

The supply chain design recommendations proposed in this thesis are based on an analysis of a recent product generation program at the company. By continuing to implement these recommendations, the company should benefit from shorter product development cycle times, smoother production ramps, improved customer service levels and lower sourcing costs.

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CHAPTER 1: INTRODUCTION AND OVERVIEW

1.1. Project Description

The role of supply chain management is becoming increasingly complex as companies become less vertically integrated by outsourcing design and manufacturing responsibilities to external vendors. Outsourcing typically increases the number of entities in the supply chain and therefore the number of transactions required to develop and produce a product. Additional transactions result in additional coordination of material, information and cash flow and therefore can be a source of variability and inefficiency. These inefficiencies can negatively impact a firm's profitability, revenue and/or market share, particularly in a volatile demand market. The supply chain needs to be proactively designed to mitigate these inefficiencies.

This thesis is based upon research conducted at a partner company of the Leaders for Manufacturing (LFM) program. Due to the confidential nature of the research project, the partner company will be referred to as "the Company" throughout this thesis. The project, which lasted approximately seven months, took place at a division of the Company's semiconductor test equipment group, which will be referred to as "the Division."

Prior to the internship, the Division recognized that its product generation process needed to better address supply chain design. Unfortunately, the Division had difficulty determining what that really meant for its business in terms of roles and responsibilities, guidelines, tools and processes. Part of the problem was that it did not fully understand the issues, decisions or constraints that led to various supply chain outcomes, both good and bad, on previous product generation efforts. The general belief was that a number of supply chain costs and risks could have been avoided had internally and externally available supply chain information been integrated into the product generation process in a more timely and effective manner. However, confirming evidence of this disconnect had never been gathered together in a format that would lend itself to analyzing the underlying organizational or process factors and to driving change in terms of how the supply chain organization engages with and supports the product generation effort.

1.2. Approach and Methodology

The research was divided into three sequential phases: Investigation, Causal and Solution. The Investigation Phase focused on gaining a clear understanding of the Division's current supplier and part selection process. It also identified areas of high risk in the Division's supply chain. The analysis was based on a semiconductor tester launched prior to the start of the internship. This tester was chosen because it represented a major recent product development effort. It will be referred to throughout the thesis as "the Product." Case reports were written about a number of the Product's high supply chain risk subassemblies and components. These reports developed a cause and effect relationship between the specific supplier and part selection processes and their supply chain outcomes. The Investigation Phase required approximately three months and included formal and informal interviews with individuals from R&D, Procurement, Marketing and Finance.

Based on the results of the Investigation Phase and a literature review, recommendations were made to the Division's Product Lifecycle (PLC) process during the Causal Phase. The recommendations included activities and metrics to improve future supply chain performance in a resource-constrained environment. The Causal Phase required approximately two months and concluded with a presentation to the Company's semiconductor test equipment R&D management.

The Solution Phase focused on developing and implementing the processes and management tools that complimented the recommendations made during the Causal Phase. These solutions were piloted on a new product development project within the Division. The Solution Phase required approximately two months and lasted through the end of the internship.

1.3. Project Goals and Measurement

By implementing the ideas discussed in this thesis, the Division's supply chain should experience:

- Improved delivery responsiveness[1] from critical suppliers
- Improved levels of availability[2] from critical suppliers

In addition, the Division's product development process should benefit through:

- Reduced time-to-market through shorter product generation cycles
- Reduced time-to-profit through smoother production launch ramps

Due to the long timeframe of the Division's product development projects, it was impossible to calculate the value of these benefits during the internship. Given that product development is such a complex and scenario dependent process, it would have been challenging to quantify the benefits even if time had not been a factor. Nevertheless, many of the Division and Company managers stated that the recommendations make good business sense and they would continue to institutionalize the ideas across the Division and the Company.

The main goal of this thesis is to communicate the recommendations for improved supply chain design. They should be useful to other capital equipment manufacturers that face volatile market demand. An ancillary goal of this thesis is to document the process taken to develop the recommendations. The supply chain risk analysis and case report investigation were effective methodologies for identifying the process and organizational gaps that existed in the product generation process at the Division. The approach may be appropriate for future students with similar project objectives.

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[1] Delivery responsiveness is defined here as a guaranteed order lead times with guaranteed available quantities.
[2] Availability is defined here as a specified quantity of material guaranteed within the leadtime.

CHAPTER 2: PROJECT SETTING AND BACKGROUND

2.1. Company Background

The Company is a leading provider of test equipment solutions for the semiconductor and electronics industries. The test equipment business of the Company is divided into several operating divisions, each responsible for a number of product lines. The scope of this research project was limited to the Division that designs, manufactures, markets and sells semiconductor test products to manufacturers worldwide. It dominates its market segment with a high percentage market share.

As is the case throughout the Company, the Division is a technology driven organization that competes primarily on innovation. Its technical prowess is a source of pride for most employees. Not surprisingly, the Division is an engineering driven organization. As will be seen throughout this thesis, the dominance of the engineering function during the early phases of the Division's product development process results in specific supply chain design challenges. These challenges are amplified by the geographic separation of the Division's R&D, Manufacturing and Supply Chain functions. Manufacturing and Supply Chain are collocated and removed from R&D through time zones and distance.

2.2. Supply Chain Management Challenges

As a capital equipment manufacturer for the high-tech industry, the Division faces large swings in demand due to its position in the value chain. The Division faces demand "volatility amplification" or the "bullwhip effect"[3] by residing far upstream of the ultimate semiconductor consumer. The bullwhip effect is especially pronounced for the Division because the consumer semiconductor market is itself highly cyclical. Finally, the Division's concentrated customer base results in additional cyclical demand amplification. Only a handful of manufacturers make up the majority of the Division's semiconductor market segment. The manufacturers' demand for this type of test equipment is also highly correlated with each other. Because direct material cost accounts for a very high percentage of its products' total cost, the Division's financial health

[3] Fine, C.H., Clockspeed, Perseus Books, 1998; pp. 89-94.

depends on an extremely responsive supply chain to minimize the number of lost sales during market upturns and to minimize the amount of excess inventory during market downturns.

Due in part to the integral product architecture[4] of its products, the Division's supply chain is not responsive enough. The technical requirements of testing semiconductors with decreasing feature size, at faster speeds and with equipment that consumes a minimum of the expensive manufacturing floor space of semiconductor fabs, require that the Division design its products with an integral product architecture. As a result of their architecture, the Division's products contain many long lead time, sole source and low manufacturing yield parts. Even in the instances where modular parts are designed into the products, the Division often faces capacity constraints at its suppliers. Its demand for these off-the-shelf parts tends to be tightly correlated with the demand from the overall semiconductor and electronics manufacturing industry, causing the Division to compete for its supplier's manufacturing capacity. The unresponsive nature of the Division's supply chain is largely responsible for the current stockpile of expensive excess inventory sitting in its warehouse during the recent dramatic market downturn. In some cases, the Division possesses over three years of supply of unique parts that cannot be resold on the open market.

Finally, the Division's outsourcing strategy will increase its dependence on its suppliers. The Division's goal is to outsource 100% of its manufacturing. Currently it performs the final assembly and test of its products in-house. All of its products' major subassemblies are manufactured, and in some cases, developed by its suppliers. The Division intends on following the lead of one of its sister divisions, which has completely outsourced the manufacture, assembly and test of a core product. The outsourcing strategy is motivated by a desire for improved asset utilization, lower labor rates and tax incentives.

[4] Defined in Section 3.1.

CHAPTER 3: LITERATURE REVIEW

This chapter reviews published information from three primary sources that are relevant to developing the appropriate supply chain design recommendations for the Division. The first source, Clockspeed by Charles H. Fine, provides a framework for understanding the challenges that the Division faces in terms of product generation and supply chain management. The second source, "Developmental Processes of Cooperative Interorganizational Relationships" by Peter S. Ring and Andrew H. van de Ven, presents a process for developing stronger supplier relationships. Finally, "Quantity Flexibility Contracts and Supply Chain Performance" by Andrew A. Tsay and William S. Lovejoy describes a specific technique for improving supply chain performance in a volatile demand environment. The ideas discussed in all three works will be intertwined and customized in this thesis and are the basis for the set of supply chain design recommendations submitted to the Division.

3.1. Three-Dimensional Concurrent Engineering

Fine coined the term "Three-Dimensional Concurrent Engineering" (3-DCE) in his book Clockspeed. 3-DCE adds supply chain design as a crucial third component to the traditional concurrent engineering framework of coordinated product and manufacturing process development. 3-DCE explains how the architectures of a product's design, manufacturing process and supply chain are interrelated and why their concurrent development is of strategic importance. Strengthening the Division's linkage between its product and supply chain architectures is crucial for improved supply chain design.

Fine divides product architecture into two categories, integral and modular. Technical or performance based products are typically characterized by an integral architecture. Components of an integral product architecture can be characterized as:

- performing multiple functions
- existing in close proximity or close spatial relationship in the product
- being tightly synchronized with other components or subsystems

Modular product architectures are typically pursued when business issues such as cost and time to market are of primary concern. Components of a modular architecture can be characterized as:

- being easy to interchange and upgrade individually
- containing interfaces that are standardized
- localizing system failures[5]

As discussed in Section 2.2, the Division's products appropriately exhibit a largely integral product architecture.

Fine also divides supply chain architecture into integral and modular. Integral supply chain architecture is defined as demonstrating "proximity" across four dimensions: geographic, organizational, cultural and electronic.[6] According to this definition, the Division's existing supply chain architecture is clearly modular. With the exception of its machined and sheet metal parts, which are sourced locally, the Division's suppliers are dispersed around the globe. Likewise, the Division exhibits low organizational proximity as it does not have any ownership stake in its suppliers and can enact only limited managerial control. Its cultural proximity, in terms of shared business practices and company values, is equally low. Finally, the Division's electronic proximity is limited to the basics (e-mail, fax, electronic data interchange) for the industry.

Fine provides convincing evidence that an integral product and modular supply chain architecture combination results in sub-optimal business performance. The integral product architecture makes it difficult to substitute one supplier for another. There is a high degree of dependency between the suppliers and the company, requiring that the processes of individual suppliers be well aligned with the rest of the supply chain.[7] As depicted by the shaded areas in Figure 1, integral products are best developed and built by integral supply chains, and modular products are best designed and built by modular supply chains. Due to the performance requirements of its products and the volatility of their market demand, the Division needs to develop a more integral supply chain architecture. In particular, the supply chain design

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[5] Fine, C.H., Clockspeed, Perseus Books, 1998; pp. 133-136.
[6] Ibid; pp. 136-140.

recommendations presented in this thesis will be focused on increasing the Division's organizational proximity.

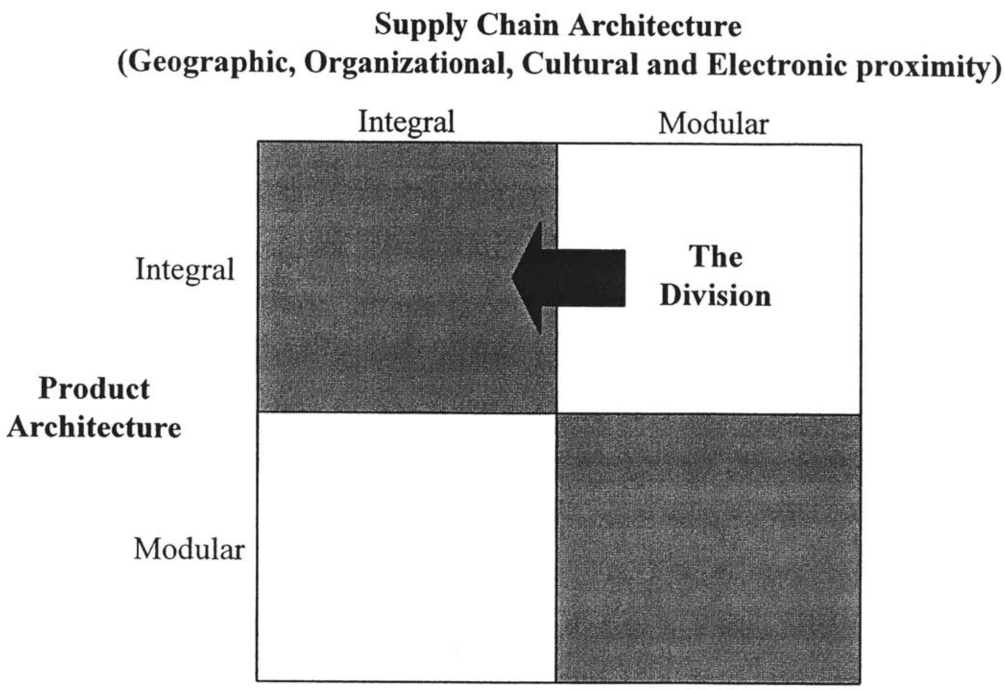


Figure 1: Interaction Effects between Product and Supply Chain[8]

In the Division's current modular supply chain, suppliers arrive at the their own optimal decisions based on local information. In an integral supply chain, decisions are based on global information. Amiya K. Chakravarty, in his book Market Driven Enterprise, points out why it is advantageous for products with an integral product architecture to be designed with a integral supply chain architecture.

> The total system profit in an integral supply chain, Π(I), tends to exceed the profit in a modular supply chain, Π(M). A contract, in this context, is a means for bringing Π(M) closer to Π(I), not just by coordination but by creating appropriate incentives for the entities involved.[9]

[7] Chakravarty, A.K., Market Driven Enterprise, John Wiley & Sons, 2001; pp. 307.
[8] Fine, C.H., Clockspeed, Perseus Books, 1998; pp. 142.
[9] Chakravarty, A.K., Market Driven Enterprise, John Wiley & Sons, 2001; pp. 437.

Section 3.2 describes a process for developing the relationships required for negotiating and managing such contracts. Section 3.3 describes the type of contract that is appropriate for coordinating the Division's supply chain.

3.2. Cooperative Interorganizational Relationships Process Framework

Because of its overall outsourcing strategy, the Division is generally unwilling to increase the organizational proximity to its supplier base through ownership stakes. A less drastic and more appropriate approach for improving organizational alignment is for the Division to develop strong Interorganizational Relationships (IORs) through contract deployment.

Given the integral product architecture of its products, the Division essentially locks in its supply chain design as it develops its products. That means that many of the critical suppliers that the Division will be dependent upon for many years, and often multiple product generations, are selected during the product generation process. Ideally, the process of developing its IORs across its supply base needs to begin prior to the development of a new product. In their paper, "Developmental Processes of Cooperative Interorganizational Relationships,"[10] Peter S. Ring and Andrew H. van de Ven present a conceptual framework that describes how IORs are developed and managed effectively. They point out that the process by which an IOR is developed greatly influences its subsequent performance. The ways in which companies negotiate, execute and modify the terms of the IOR impacts the degree to which it is judged to be equitable and efficient by both parties. Based on their research and as depicted in Figure 2, the Ring and van de Ven's process framework is based on a repetitive sequence of negotiation, commitment and execution stages.

[10] Ring, P.S., van de Ven, A.H., "Developmental Processes of Cooperative Interorganizational Relationships," *Academy of Management Review*, Vol. 19, No. 1, 1994; pp. 90-118.

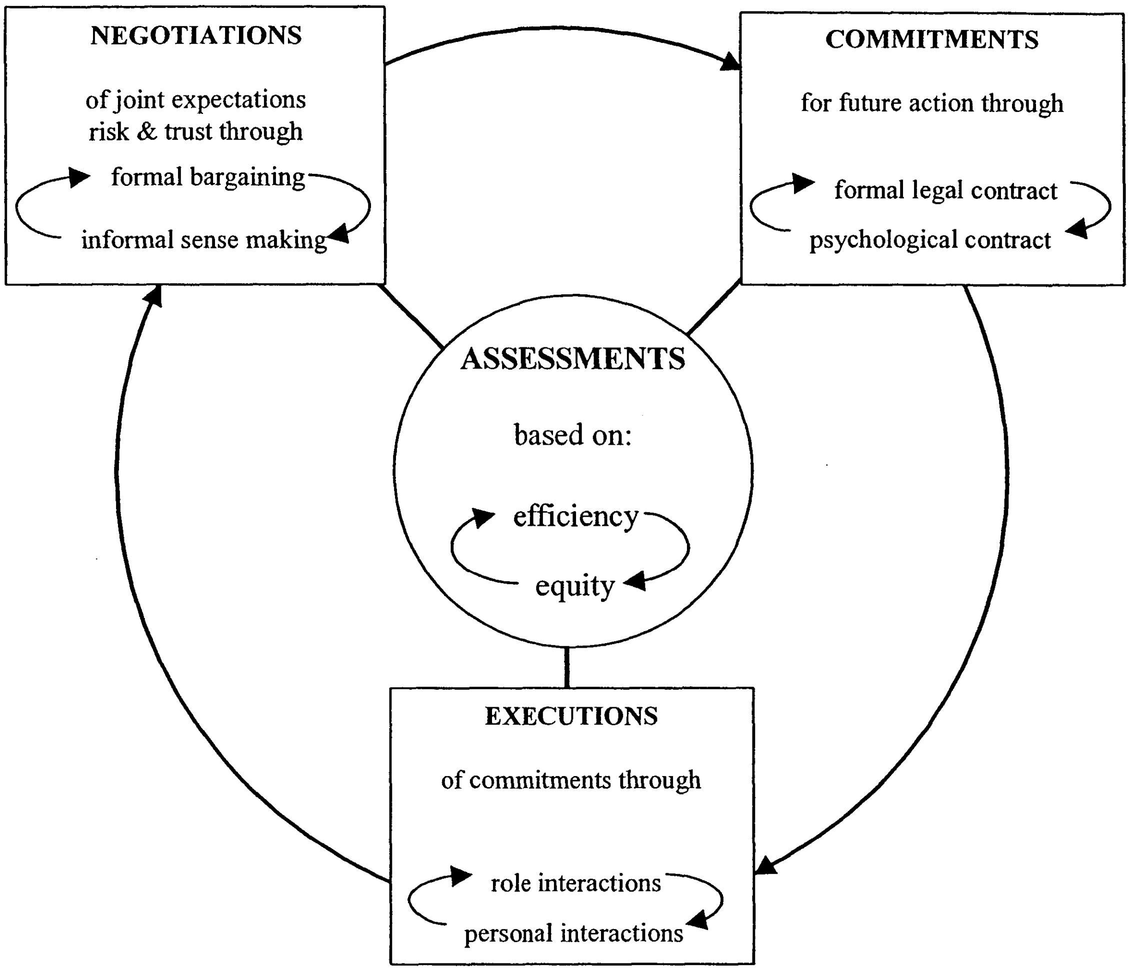


Figure 2: Process Framework of the Development of Cooperative IORs[11]

The process starts in the negotiations stage, during which joint expectations regarding motivations, possible investments and potential uncertainties are explored. Multiple prospective parties are often approached. Determining the trustworthiness of each potential participant plays an important role during the negotiations stage. The buyer's purchasing power with each of the prospective sellers also factors into their respective attractiveness. Formal bargaining that may include persuading, arguing and haggling over possible terms and procedures of a potential relationship helps determine which party is best suited for the desired IOR.

[11] Ring, P.S., van de Ven, A.H., "Developmental Processes of Cooperative Interorganizational Relationships," *Academy of Management Review*, Vol. 19, No. 1, 1994; pp. 97.

During the commitments stage, when the selected parties reach an agreement on the obligations and rules for future action in the relationship, the "wills of the parties meet."[12] At this point, the terms and governance structure of the relationship are established. The agreement can either be recorded in a formal contract, or simply understood through an informal verbal agreement. Informal agreements are appropriate if the degree of business risk is low and the level of mutual trust is adequately high. Otherwise, a formal and legal contract is more desirable. Written contracts may provide the added benefit of removing ambiguity around any of the terms of the agreement.

Finally, in the executions stage, the agreement is carried out. In a supply chain context, orders are placed, components are manufactured and delivered, and payment is made. Mutual trust is fostered the more closely the actions reflect the terms of the agreement, ultimately strengthening the bonds of the IOR. As is also the case in the previous two stages, both parties are continuously assessing the IOR in terms of its efficiency and equity.

As business conditions change, or as misunderstandings develop, the terms of the relationship are revisited. These inevitable situations result in the repetitive nature of the IOR development and management process. If individual terms are under contention, they are re-negotiated and the IOR is preserved. At some point the overall environment will change sufficiently to cause the entire agreement to be terminated, thereby breaking the cycle and dissolving the relationship.

Although the Ring and van de Ven framework appears to be relatively intuitive, it is not always adhered to in practice. Based on the case reports, the Division does a thorough job negotiating and committing suppliers to a part's technical specifications. It is much less rigorous when it comes to locking in supply chain requirements. The Division rarely negotiates and commits suppliers to specific performance metrics, leaving it susceptible to supply chain responsiveness and availability risks. These risks emerge and impact the financial performance of the Division when the supplier relationship is stressed. Unfortunately, this situation typically coincides with the product's production launch or its first market upturn, when the Division's resources are

[12] Ring, P.S., van de Ven, A.H. "Developmental Processes of Cooperative Interorganizational Relationships." *Academy of Management Review*, Vol. 19, No. 1, 1994; pp. 98.

already stretched. As the case reports indicate, negotiating the service agreements at this point can be challenging. Improving the delivery performance on the spot may be impossible or costly due to existing capacity constraints at the supplier. The very high switching costs associated with bringing a new supplier onboard also may lower the Division's bargaining power to renegotiate for better long-term service agreements. The bottom line is that the right IOR should be developed with a new supplier from the beginning. This conclusion means that the relationship building process should be initiated prior to a new product generation effort. The associated steps are mapped onto the Division's product development process in Section 5.1.

3.3. Flexibility Contracts

Due to the volatile nature of the Division's market demand, one of the greatest challenges to managing and coordinating the supply chain is ensuring that sufficient flexibility is built into the system. More specifically, that means that suppliers provide sufficient and predictable levels of responsiveness and availability during market upturns and that the material liability that they pass on to the Division is manageable during the downturns. The Flexibility Contracts that Andrew A. Tsay and William S. Lovejoy describe in their paper "Quantity Flexibility Contracts and Supply Chain Performance" are designed to help align the supply chain accordingly. These contracts, in a modified form, will be the cornerstone of the IORs the Division will develop with its critical suppliers in the future.

The Flexibility Contracts that Tsay and Lovejoy describe specifically target the supply chain inefficiencies that result from the mutual deception that commonly occurs between buyers and sellers regarding demand forecasts. Forecasts are a standard method used in supply chain management to help upstream suppliers plan their materials and resources based on the expected demand of their downstream partners. Forecasts typically provide month-by-month demand data over a specified planning horizon. In Tsay and Lovejoy's experience, these forecasts are intended for informational purposes only and do not oblige the buyer to actually purchase the indicated quantity of goods. This lack of obligation causes the buyer to artificially inflate the forecast to provide upside protection against unexpected demand. Suppliers eventually recognize the tendency for the forecast to exceed actual demand and deflate the forecast for their planning purposes. In the end, each party optimizes locally at the expense of increasing the overall cost and uncertainty in the system.[13] In the process, the coordination goal of the forecast becomes compromised.

The Division is not immune to this phenomenon of mutual deception. The incentive structure of the Division's individual buyers reinforces the misalignment. Although it is not literally true, buyers relate from experience that "the organization slaps you on the wrist for excess inventory, but fires you for material shortages." Buyers naturally forecast and order more material than expected demand warrants. In addition, the highly volatile nature of the Division's demand environment can further amplify the effects of the mutual deception around the forecast. For instance, at the trough of a market cycle, suppliers have been conditioned to be especially wary of the Division's forecast because they have experienced multiple periods of declining demand and readjusted forecasts. The declining trend causes them to recalibrate the forecast downward for their planning purposes by ever-greater percentages. By the time the market picks up, the suppliers are ill prepared to meet the Division's actual demand. The inverse is also true as the market demand peaks. In these situations, suppliers are often caught with too much material, which results in inventory and liability issues.

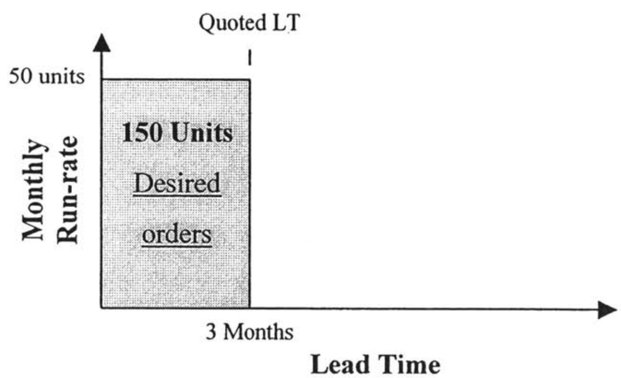
Flexibility Contracts address this problem by making the forecast more credible through the exchange of mutually beneficial commitments. The supplier provides the buyer with a formal guarantee to provide a specified level of upside protection against unexpected demand. The buyer agrees to a minimum purchase agreement through specified limits on order reduction. A mathematical illustration of how Flexibility Contracts coordinate the supply chain is provided in Appendix 2.

In essence, the contract improves communication and enables risk sharing. Tsay and Lovejoy list a diverse set of companies that have adopted Flexibility Contracts to help them manage their supply chain, such as Sun Microsystems, Nippon Otis and Solectron.

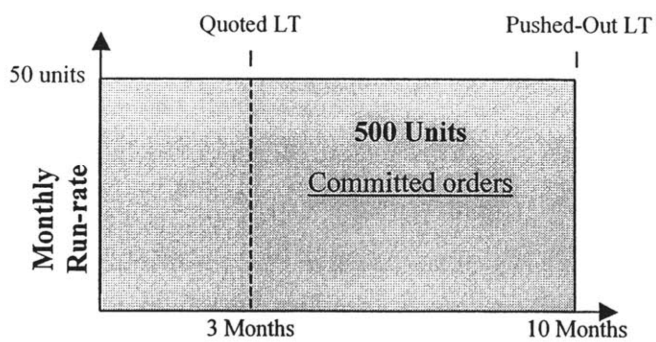
[13] Tsay, A.A., Lovejoy, W.S., "Quantity Flexibility Contracts and Supply Chain Performance", *Manufacturing & Service Operations Management*, Vol. 1, No. 2, 1999; pp. 89-90.

A major benefit of Flexibility Contracts that Tsay and Lovejoy do not focus on in their paper, is the ability of the agreements to address capacity constraints and the associated exploding lead times that plague the Division's supply chain performance. The market demand cycles that the Division experiences are highly correlated with the cycles that its suppliers experience. Many cannot keep up with demand when the overall semiconductor and electronics market heats up. In response, lead times get pushed out. The impact that these exploding lead times have on the Division's liability is best described graphically as shown in Figure 3.

1. During a market upturn, the Division drives a high plan to support demand. It orders enough parts from its supplier to cover a monthly run-rate of 50 units.



2. Capacity constraints and the lack of secured availability pushes out lead time to 10 months. The Division has to commit orders over extreme lead times.



3. In the end, actual demand comes in much lower than planned as the market cools abruptly and the Division is left with a glut of excess inventory/liability.

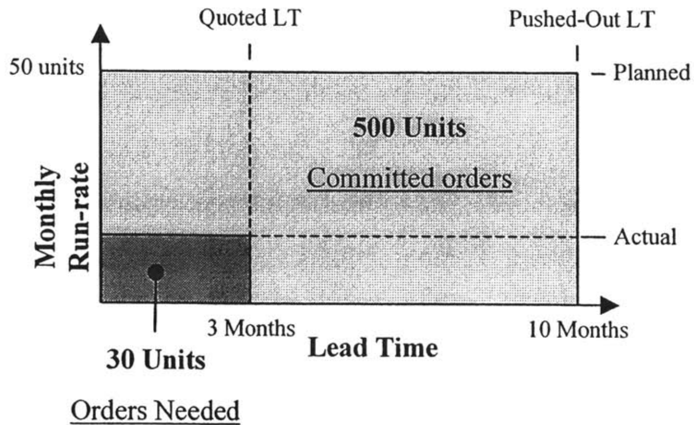


Figure 3: Effects of Exploding Lead Times

The quantities used in Figure 3 are representative of what the Division has experienced recently. As the figure illustrates, not having guaranteed levels of responsiveness with its suppliers can expose the Division to serious business risk. The Expected Months of Supply calculation below conveys how such scenarios impact the asset utilization of the Division.

Expected Months of Supply = Committed Orders / Actual Run Rate
= 500 / 10
= 50 months

The next market upturn usually occurs before the 50 month (4.2 year) time period elapses, but the Division has to carry the majority of the inventory through the cash-constrained months of the market trough. The material could also become obsolete during that time, resulting in an additional business risk.

One major difference between the buyer/seller relationship that Tsay and Lovejoy describe and the relationship that exists between the Division and its suppliers worth mentioning is that the Division is liable for at least a portion of its forecast in most cases. For instance, in its relationships with contract manufacturers, the Division is currently liable for all unique lower-level material with lead times that exceed the forecasted lead time of the subassembly. Unique parts represent a high percentage of the Division's direct material cost and can turn into significant liabilities. Figure 3 illustrates that these liabilities can fluctuate and are difficult to track and manage. Not surprisingly, the Division was caught off guard by the sheer magnitude of the liabilities it inherited during the past market downturn.

Although the Flexibility Contracts that Tsay and Lovejoy describe address many of the order fulfillment challenges that the Division faces, they can be difficult to administer in practice. The Division is in the process of adopting a different type of flexibility contract. For the purposes of this thesis, this contract will be referred to as a "Structured Contract." It is presented and discussed in detail in Section 5.4.

CHAPTER 4: CASE REPORT ANALYSIS

Six case reports were written on specific sub-assemblies and components of the Product. These cases established a cause and effect relationship between specific supplier and part selection processes and their supply chain outcomes. The cases were instrumental in identifying the primary gaps in organizational effectiveness in connection with supply chain related decisions made during product generation. The cases also helped build credibility throughout the internship by demonstrating a solid understanding of the actual issues, decisions and constraints that determined the path of the Product's actual development process. Together with the literature review, the case reports guided the development of the supply chain design recommendations presented in this thesis.

The case reports were all written with a consistent format. Each starts with general data about the sub-assembly/component, including its cost, lead time and associated supply chain risks. The part's technical function is explained. A chronology of the milestones in the part's development, supplier selection and procurement history is described next. Each report concludes with an analysis of the part's overall supplier selection process, identifying what went right and what could have gone better.

This chapter describes the methodology used to select the particular sub-assemblies and components and explains how the data for the case reports was gathered. It concludes by presenting the key takeaways of the case reports in terms of improved supply chain design.

4.1. Case Topic Selection Methodology

The cases were intended to highlight the greatest opportunities for improved supply chain design. For that reason, a methodology was developed to identify the Product's sub-assemblies and components that posed the greatest risk to the Division's supply chain performance.

First, a portion of the Product's supply chain was mapped. A fully loaded version of the Product contains well over 50,000 parts. Due to time and resource constraints, data on the entire supply chain could not be collected. The map included all first-tier suppliers and sub-assemblies.

Specific second-tier suppliers and their associated components that caused known supply chain challenges were also incorporated. Finally, a handful of critical third- and fourth-tier components were added. In all, approximately 7,800 of the Product's parts were captured. Basic information such as supplier name, unit cost and extended cost was documented for each part. Since the actual order lead time of many of the parts varied throughout the market cycles, the longest lead time that occurred during the past 12 months was used in order to reflect the worst case scenario.

The following list of risk categories and consequences is based on discussions with procurement managers and buyers.

1) **Capacity Constrained**
   Definition: The supplier cannot support the peak product forecast quantity.
   Possible Consequences: During a market upturn, material unavailability, lead-time push out and/or price escalation.
2) **Sole Source**
   Definition: Only one supplier can make the part.
   Possible Consequences: Low bargaining power for improved supply chain service. The Division is susceptible to price escalations.
3) **Single Source**
   Definition: Although multiple suppliers are capable of making the part, the Division has only one established relationship.
   Possible Consequence: Switching costs will be incurred if a second source is brought on line.
4) **Low Yield**
   Definition: The part manufacturing process is unstable.
   Possible Consequences: Unpredictable delivery, quality and/or responsiveness.
5) **Obsolescence**
   Definition: The lifecycle of the component has historically been shorter than the lifecycle of the Division's products.

Possible Consequences: Unanticipated permanent material unavailability. Forced lifetime-buy or forced redesign and incurred switching costs for bringing a replacement source on line.

6) **Poor Supplier Performance**

Definition: The supplier does not adequately support the Division's procurement requirements. This risk is based on the buyer's subjective judgment.

Possible Consequences: Unpredictable delivery, quality and/or responsiveness, customer alienation.

7) **Design Evolution**

Definition: The part experiences numerous design changes, which makes it difficult to procure efficiently. Either the Division or the supplier can initiate the design changes.

Possible Consequences: Scrapping costs, supplier alienation and/or procurement resource strain.

Each of the mapped sub-assemblies and components were evaluated against these seven risk categories. The evaluation process was conducted through one-on-one discussions with the buyers and material engineers responsible for each part. For simplicity and consistency, each risk category was applied to the part in a binary fashion. For instance, it was only determined whether or not a particular part was Capacity Constrained. The degree to which the part was Capacity Constrained was not taken into consideration. Next, each risk category was weighted according to its relative severity. Finally, a "Supply Chain Risk Score" was calculated for each sub-assembly and component based the weighted sum of its risk categories.

The "Supply Chain Risk Score" was used to examine the sub-assemblies and components from three perspectives. First, all of the parts were sorted according to their raw score. This perspective highlighted the items that posed the overall highest supply chain risk. In the second perspective, the score was multiplied by the part's extended unit cost in order to draw attention to the parts that would likely present the greatest inventory liability concerns. In the third perspective, the score was multiplied by the part's lead time to focus on the parts that could result in the highest response time issues.

The highest scoring parts from each perspective were presented to the R&D and Procurement management to guide the case topic selection process. The chosen sub-assemblies and components were all among the top 10 scoring parts in at least one of the three perspectives. Management made a conscious effort to select a variety of parts to provide a representative cross-section of the entire product. In the end, the six case topics spanned the gamut from a custom designed electro-mechanical sub-assembly that costs over $100,000 to a standard off-the-shelf connector that costs less than $5.

The supply chain risk analysis methodology also provided the Company with some ancillary benefits. The Division used the results to target specific suppliers and parts for continuous improvement efforts. A sister division adopted the methodology to help one of its contract manufacturers identify potential problem areas in its supply chain.

4.2. Information Gathering Process

The case reports had to be accurate and complete in order to be useful. A minimum of five individuals, including the R&D Engineer, Materials Engineer and Strategic Buyer responsible for the part, were interviewed for each report. The interviews started with a formal questionnaire about specific events relevant to the supplier selection and the supplier's subsequent performance. The interviews ended with a set of open-ended questions that helped uncover any unique circumstances that impacted the sourcing decision. The cases reports evolved through multiple iterations. Each version was edited by all of the contributors to the report.

4.3. Case Report Key Takeaways

Each of the six cases describes a unique set of circumstances and challenges that drove the selection of various parts and suppliers. Nevertheless, when analyzed as a group, the cases point to a consistent set of opportunities for improved supply chain design within the Division. This section will describe the overarching themes. The actual case reports are not included in this thesis for confidentiality reasons. However, they remain available at the Division for its reference.

In all of the case reports, the part and supplier selection processes were almost exclusively determined by technological and time-to-market factors. This prioritization makes sense. The Company as a whole competes primarily on innovation. The success of this specific Product stemmed from its advanced technology, which enabled it to achieve short semiconductor test times in a compact design.

Unfortunately the product's success in the marketplace came at the expense of some significant supply chain risks. The cases help make a very important distinction about how these risks were designed into the Product. The cases demonstrate that the biggest contributing factor was not which specific suppliers were selected, rather how they were selected. That means that the risks were largely attributable to the development process. For instance, four of the six part and supplier selections investigated in the cases were completed with little or no involvement by procurement. Consequently, procurement inherited these parts and suppliers with poorly defined and difficult to improve relationships and order fulfillment agreements.

One consequence of this lack of supply chain involvement was that no general 'terms and conditions' contracts were in place with any of these suppliers at product launch. In most cases, this also meant that no agreement was signed over three years after the original supplier selection occurred. In one extreme case, a supplier whose components contribute over 15% of the Product's total material costs, rejects the Division's rudimentary terms and conditions that accompany every purchase order. The supplier responds with its own set of terms and conditions with its order acceptance. This means that the Division cannot depend on the supplier for basic services, such as committing to fix and return defective material in an agreed upon timeframe. Unfortunately, this supplier produces a lot of defective material. Even more concerning is that the Division is locked into this supplier for many years and probably numerous product generations due to intellectual property and development time reasons.

Another consequence of the product development process was that no agreements for delivery responsiveness were defined with critical suppliers. One of the cases illustrate how a $20 off-the-shelf, but unique, chip could have cost the Division severe late delivery penalties if the previous market upturn had lasted a couple months longer. The case paints a representative picture of the organizational gaps that exist in the Division's current product development process. First, almost a yearlong delay existed between the supplier selection by R&D and procurement being informed of the decision. Second, once procurement was notified of the decision, it did not have the appropriate processes and tools in place to secure delivery responsiveness. Multiple Divisions within the Company use the selected supplier for other parts. All of the other Divisions had been experiencing severe leadtime push outs due to the supplier's current capacity constraints. Retrospectively, it seems like the delivery challenges that the Division encountered during the Product's production ramp should have been predictable and obvious. This leads to the third consequence of the limited supply chain involvement during product development. The Division did not a have a process in place to track, diagnose and manage the Product's supply chain from a system level. Therefore, the Division was not in a position to identify and proactively focus its limited resources on the subassemblies and components that posed the greatest risk to responsive supply chain performance.

The two cases in which supply chain was involved from the beginning provide noteworthy lessons for future supply chain design improvement. The first case describes the approach and outcome of a major electro-mechanical subsystem sourcing decision. Unlike all of the other supplier decisions, this one followed a structured selection process that required multi-functional participation. The manager responsible for this subsystem followed a process from his previous employer. Although R&D and Procurement disagreed on the final vendor selection, Procurement's early involvement enabled it to address supply chain concerns appropriately. Of the six suppliers investigated, this supplier was the only one that has signed a comprehensive terms and conditions contract. It is also the only supplier that was willing and prepared to provide leadtime and availability guarantees. From an organizational perspective, the structured selection process that was followed provides the Division with a mechanism for evaluation and continuous improvement.

The other case in which Procurement was involved during the supplier selection process involved a machined cooling plate assembly. Relative to the other cases, this situation is an anomaly because it identifies engineering design issues as the primary cause of procurement's difficulties, rather than the supplier selection process. Due to the 'low-tech' nature of the assembly, the Division was able to select a local machine shop as the supplier. Even though the part went through numerous major design iterations, the supplier consistently provided good quality and responsive service. The "geographic proximity" of this supplier has undoubtedly contributed to its superior performance. Unfortunately, due to the technical nature of most of its other subassemblies and components, the Division is not able to leverage this integral supply chain architecture dimension further across its supply base.

Finally, the reports indicate that effective supply chain involvement needs to take the form of active inter-personal collaboration. One case, in particular, illustrates how manuals intended to guide strategic[14] supplier selection are easily disregarded. The R&D engineer responsible for the chip design of a critical and expensive ASIC chose a supplier that was clearly "Not Recommended" in the company's "Technology Reference Book." The engineer based his decision on the word-of-mouth recommendations from another R&D group. Unfortunately, selection guides for strategic suppliers are too easily disregarded or overlooked. They also constantly face the risk of being out-dated. Finally, simply choosing a "Recommended" supplier does not ensure that the proper part-specific agreements are committed to.

[14] Refer to the Chapter 5 Introduction for the definition of a strategic supplier.

CHAPTER 5: RESULTS AND RECOMMENDATIONS

A full day case report discussion forum was conducted with the Division's R&D, Procurement and Manufacturing management. The results from the case discussion forum, together with the literature review, led to the set of supply chain design recommendations described in this chapter. The first section introduces the individual recommendations, the next section shows how the recommendations can be integrated into the Division's product development process and the remaining sections provide more detailed information about each recommendation. Although these recommendations were formulated to specifically address the Division's supply chain design challenges, they can apply to other companies that desire greater organizational proximity in terms of order fulfillment.

It should be noted that these recommendations are geared towards helping the Division improve its supply chain design with respect to "strategic" suppliers. As defined by the Division, "Strategic" suppliers typically exhibit all of the following attributes. They

- require a significant level of joint investment
- provide a source of business competitive advantage
- contribute a critical technical capability
- deliver value-added supply chain management services

These are the suppliers that the Division is most dependent upon from an order fulfillment perspective. The cases and the risk analysis also indicate that effective processes that guide lower level commodity component (i.e. non-strategic) selection already exist. R&D engineers use the corporate commodity selection guide religiously. A dedicated group of Materials Engineers maintains and improves the valuable resource for the Company. It should be noted that this process will soon need to be revisited, as the Division continues down the path of 100% outsourcing. It will have to adopt the approved component lists of its contract manufacturers and develop a method for collaborating with them during product development soon.

5.1. Summary of Recommendations

The supply chain design recommendations for the Division can be summarized in three points.

Recommendation #1: De-couple the strategic supplier "part-independent[15]" contract deployment from the product generation critical path.

The first recommendation is aligned with the need for reduced product development cycle times. Historically, the process for aligning the basic terms and conditions of conducting business with a new strategic supplier has either been incorporated into the product development process or indefinitely postponed. In the former case, the alignment process extends the product development process and increases the Division's time to market. In the latter case, the supplier relationship remains ambiguous and is stressed during the peaks and valleys of the Division's business cycles.

One of the cases describes a frustrating situation in which the alignment process both extended the product development time and failed to result in a signed agreement. The ASIC that this particular supplier provides required the longest development time of any of the Product's components. It inherently resided on the project's critical path. The Division spent over six months bringing the supplier online, effectively extending the Product's overall development process by the same amount of time. In the end, the Division locked itself into an unresponsive, sole-source supplier and still does not have a signed contract. The expensive chip has a six-month lead time and can easily cause the Division to miss system deliveries during market upturns and lose money through inventory liabilities during downturns. Unfortunately, there are no good alternatives to this chip. It enables the Product to test semiconductors up to 200% faster than the competitions' best offering.

Evaluating whether the Division's core set of strategic suppliers are aligned with its business practices and supply chain philosophies needs to be taken off of the critical path of product development. Partnering up with the right supplier is too critical to the Division's overall business objectives to allow the process to be postponed to a point in time when tremendous schedule pressure exists.

This business alignment process can be done prior to product generation. Terms and conditions governing warranties, non-compliance, confidentiality, intellectual property, etc. govern the basic relationship. They can be agreed to without complete knowledge of the technical specifications of the final procured part(s). Ultimately, the Division will have a set of strategic suppliers with a strong track record from past product development programs that already have existing general terms and conditions contracts in place. At that point, the supply chain organization will just need to evaluate the performance of current suppliers and pursue new suppliers, as technology advances require. The Division has recently started to cultivate this strategic supplier base. It has initiated terms and conditions contract negotiations with current suppliers that will hopefully turn into long-term strategic partners.

Recommendation #2: Prior to supplier selection, define the order fulfillment requirements for parts that have a high impact on supply chain responsiveness. Take advantage of the Division's increased bargaining power prior to awarding the business to lock in the required services in the form of a "structured contract."

The second and third recommendations are aligned with the need for smooth production ramps and reduced time to profitability. The second recommendation requires a change of mindset in terms of supplier management. Rather than buying materials from suppliers, structured contracts enable the Division to buy services. Structured contracts are a "real option" service agreement between the Division and a supplier that establishes credible guarantees to:

- The level of availability that the supplier will be prepared to provide to the Division at a fixed order lead time over the life of the agreement, and
- The level of material liability risk that the Division will assume.

[15] A "Part-independent" contract includes those terms and conditions that can be agreed to without complete knowledge of the technical specifications of the final procured part(s). This concept is further elaborated in the

These contracts benefit both the Division and its suppliers. Suppliers benefit by having unambiguous requirements that can be planned around, with prices that are determined by commitments, rather than on the basis of a variable forecast. The Division benefits from Structured Contracts because they provide clearly defined guarantees. The contracts also cap the Division's liability. They protect against the financial repercussions of the exploding lead times illustrated in Figure 3.

A key learning from the recently completed structured contracting pilot project that was conducted in parallel to this internship is that Structured Contracts should be negotiated prior to awarding new business to a supplier for two reasons. First, the Division needs to determine whether a supplier would even be willing to provide the type of guaranteed services that the contracts describe. These types of agreements are not yet common in the electronics industry. They require that the supplier possess excellent order fulfillment capabilities. They also require that the supplier's management appreciates and is prepared to act on the benefits that the contracts offer. During the structured contracting pilot project, the Division encountered resistance from existing suppliers that were fundamentally unprepared and unwilling to guarantee order fulfillment services to the Division. In the future, they should be weeded out early in the product generation effort. Ideally, they should be disqualified prior to the product development process, when the part-independent contract is deployed as described in Recommendation #1. The second reason for agreeing to the Structured Contracts prior to supplier selection is for the Division to take advantage of its increased bargaining power. The Division should use the supplier's desire for more business to lock in favorable service guarantees. Due to the high switching costs associated with most of the Division's critical sub-assemblies and components, its suppliers possess significantly higher bargaining power immediately after they have been selected. Both of these reasons mean that structured contracting needs to be incorporated into the product generation process.

In essence, the Division should engage with its suppliers in the same manner that some of its customers engage with it. Its customers often fully constrain the Division's product and

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following paragraphs.

business requirements, in terms of technical capabilities and delivery service. The Division eagerly signs up to the customers' terms because of the associated profit and revenue potential.

In some cases, a supplier may not find the Division's prospective business lucrative enough to warrant agreement to the terms of the Structured Contract. Using specialized supply chain analysis software[16], the Division can quantify the value of the Structured Contract service guarantees. The software uses dynamic programming methods to generate a range of scenarios that fit with the Division's historical and projected demand parameters. It projects the terms of the contract, together with procurement decision rules, onto the generated scenarios to predict the likely financial savings of the agreement. This information can help determine the pricing the Division should be willing to pay for the services. Based on the Division's experience, the pricing schedule, the order commitments and the exchange of information has generally provided suppliers with sufficient incentive to sign a Structured Contract. In the cases that it does not provide sufficient incentive, the exercise of attempting to deploy the contract is still valuable. The Division should be prompted to pursue a different supplier. If this is not an option, it should acknowledge the inherent supply chain risks it is accepting and initiate the appropriate risk mitigation strategy.

Recommendation #3: Align supply chain roles, responsibilities, resources and deliverables earlier in the product generation process and monitor adherence to these goals continuously.

The third recommendation revolves around setting the appropriate goals around the previous two recommendations throughout the product generation process. Ideally, the Division would have general terms and conditions and structured contracts in place with all of its suppliers. Realistically, the Division has limited resources and time, and needs to make prudent trade-off decisions about which key suppliers to focus its attention on. As the case studies indicate, the supply chain organization was barely involved during the early stages of past product development projects. The Division has allocated a strategic buyer to a recent project, but is still struggling to define how that person should engage with the R&D organization and what should be concentrated on.

[16] The software was developed by Vivecon, a supply chain software company based in Mountain View, California.

A "Supply Chain Design Dashboard" was developed and piloted towards the end of the internship. The dashboard is a "rich" bill of material that is intended to serve as a management tool. Its purpose is threefold. First, it helps set product-level supply chain design goals at the beginning of the project. Second, it prioritizes the product's subassemblies in terms of their greatest potential to influence the overall supply chain performance. Finally, it gives management quick feedback about potential supply chain risks throughout the product generation effort. Since supply chain design occurs concurrently with product development, the faster these risks can be identified, the better the chances that they can be eliminated.

The dashboard needs to be simple and straightforward in order for it to be used and maintained. It is designed to capture at least 80% of the total system material cost at the subassembly level. Consequently, it captures almost all of a product's subassemblies while not becoming unwieldy with thousands of lower-level components. The dashboard contains a target direct material cost goal and compares it to actual performance. Surprisingly, this basic metric has not been tracked diligently in the past, resulting in significant product cost overruns and margin shortfalls. The dashboard also contains a measurement of the overall product supply chain flexibility through a "Dollar Weighted Supply Chain Length" ($WASCL) metric. This metric guides decision-making at both the product and subassembly level and is discussed in detail in Section 5.6 and 5.7. Finally, it uses a risk analysis methodology similar to the one described in Section 4.1 to diagnose supply chain risks in a forward-looking manner. An example of a supply chain dashboard is included in Appendix 4.

The dashboard is not a perfect tool. However, its simplicity is its greatest strength. It provides the Division with a common framework and language to guide and evaluate supply chain design. This is especially valuable given the geographically dispersed and process resistant nature of the organization.

5.2. Integration of the Recommendations into the Product Development Process

Mapping the three recommendations described in Section 5.1 onto a product development process helps makes them more actionable. A generic version of the early stages of the

Division's Product Lifecycle (PLC) is depicted in Figure 4. The gray box in the center contains the basic existing activities in the PLC through supplier selection. The shaded boxes with the arrows represent the supply chain design enabling activities that, based on the case reports, are missing from the Division's product development process.

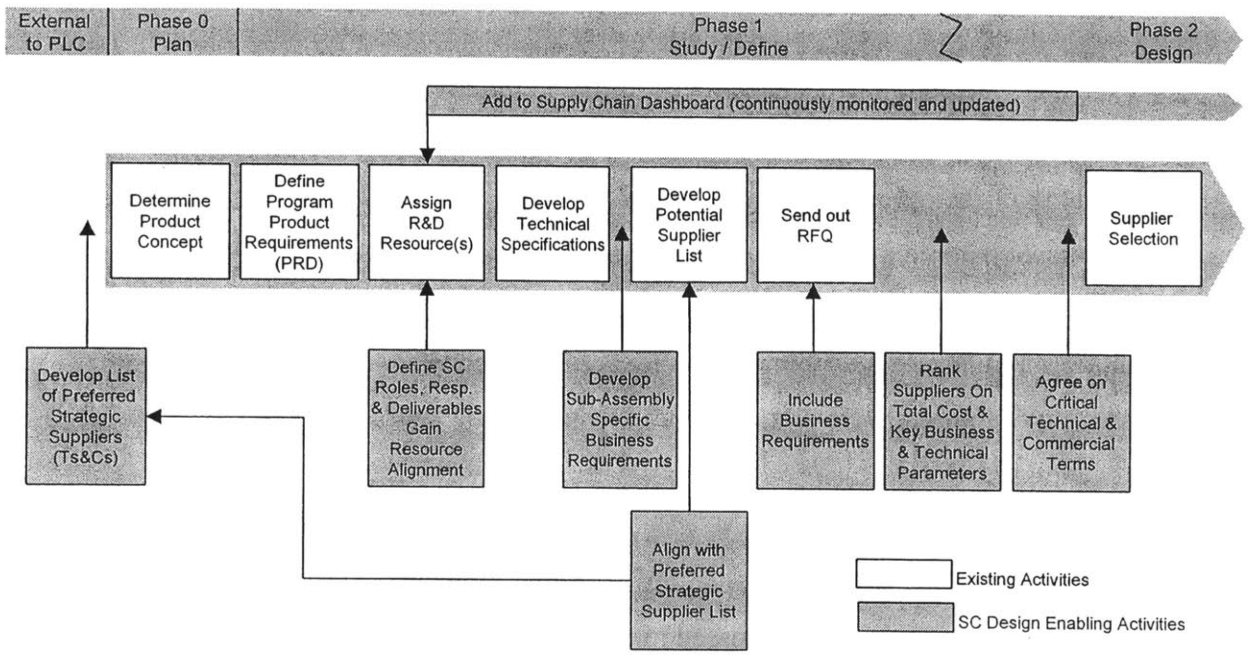

Figure 4: Supply Chain Design Activities through Supplier Selection

The three recommendations are captured in this process as follows. First, the list of preferred strategic suppliers is created external to the PLC. This is shown by the shaded box all the way to the left and is described in Recommendation #1. The list of preferred strategic suppliers is dynamic. Suppliers are added when they are technologically and commercially aligned with the Division's requirements and removed when they are not. The commercial requirement hurdle for a new supplier could be signing the corporate purchase agreement.

The latest point in the PLC that supply chain roles, responsibilities and deliverables need to be defined at is when the new product is broken down into "bite-size" chunks and individual R&D resources are assigned to specific subassemblies. These supply chain deliverables should be monitored using some kind of supply chain performance and risk tracking tool, such as the supply chain design dashboard described in Recommendation #3.

Finally, the Division should engage with its strategic suppliers in a manner that facilitates agreement to a Structured Contract, as discussed in Recommendation #2. The subassembly specific order fulfillment requirements should be developed as soon as the technical specifications have been completed. The order fulfillment requirements should be included in the request for quotation (RFQ) to notify the supplier that the Division is not just evaluating them on their technology or their piece part price, but on their total sourcing cost[17]. The RFQ would clearly communicate that the quoted levels of responsiveness and availability need to be services that the supplier can guarantee. Based on the replies to the RFQ, the Division should move forward with the supplier most capable of meeting both the technical and order fulfillment requirements. At minimum, a verbal agreement to a Structured Contract should be achieved prior to final supplier selection.

The sequence of the supply chain design enabling activities deviates slightly from the Ring and Van de Ven IOR process framework discussed in Section 3.2. Based on the approach described above, new suppliers work through two rounds of negotiations and commitments before entering the execution stage. The new suppliers should first negotiate and commit to the Division's general terms and conditions contract and then negotiate and commit to the part specific structured contract before starting to deliver any parts. Although this approach may appear cumbersome, it is necessary for setting the appropriate expectations. It is also certainly better than the current situation in which new suppliers are selected and effectively guaranteed business without making any credible order fulfillment commitments. For existing suppliers being considered for new business, the sequence of the supply chain design enabling activities mirrors the IOR process framework exactly. The existing supplier simply negotiates and commits to the Structured Contract for the new part and then moves back into the execution stage. This streamlined sequence will become more prevalent as the Division continues to cultivate its strategic supplier base.

[17] Total Sourcing Costs is defined in Section 5.6.

5.3. Early Supplier Business Alignment

The Division needs to develop two capabilities in order to enable the benefits of Recommendation #1. The first capability is technology forecasting. Decoupling the strategic supplier alignment process from product generation can only occur if the Division is able to accurately predict the technologies that are required in future products. David McCutcheon and F. Ian Stuart echo this conclusion in their paper, "Issues in the Choice of Supplier Alliance Partners." Their research in technology and supply chain management indicates that long-term supplier relationships need to be reconciled with the increased speed of technology obsolescence. They therefore "foresee a growing need for firms to connect technological forecasting with supplier management, as is already the practice in successful high-technology firms." R&D and procurement need to partner up to make sure that the Division is working towards the same technology forecast. Ideally, the Division will dedicate cross-functional resources to determine what new technologies will be required in the future and initiate strategic relationships that address the Division's technological and order fulfillment requirements jointly.

The second new capability involves developing a clear understanding of the costs and benefits of the individual terms and conditions in their current corporate purchase agreement. This understanding is important because the longer and more biased the contract is in favor of the Division, the higher the cost, in terms of time and money, of the associated negotiations. The Division has recently improved its contract template by strengthening its language and adding new terms and conditions. Reaching agreement to the earlier version required approximately six months in the past. Changing priorities and limited resources often precluded completing the negotiations. This new version may take even longer to sign and therefore may make it more difficult to separate strategic supplier development from product generation. The contract certainly needs to be complete. However, a streamlined version that is tough on specific terms and conditions most relevant to the Division's business requirements, but is otherwise written in a more evenhanded manner may provide the Division with more overall value. To expedite the negotiations, the language of the contract needs to be commensurate to the market power of the Division and its parent Company. This approach may also foster greater supplier trust.

5.4. Structured Contracts

Structured Contracts help provide the Division with the supply chain flexibility it needs to react to cyclical market demand. Perhaps the best way to describe the benefits of a structured contract is first to describe the uncertainties that exist when the Division procures materials without such agreements in place. The "un-structured" agreements that currently prevail in the electronics industry, fail to secure flexibility because they do not establish clear, manageable limits or credible guarantees. Figure 5 illustrates the order fulfillment ambiguity that results.

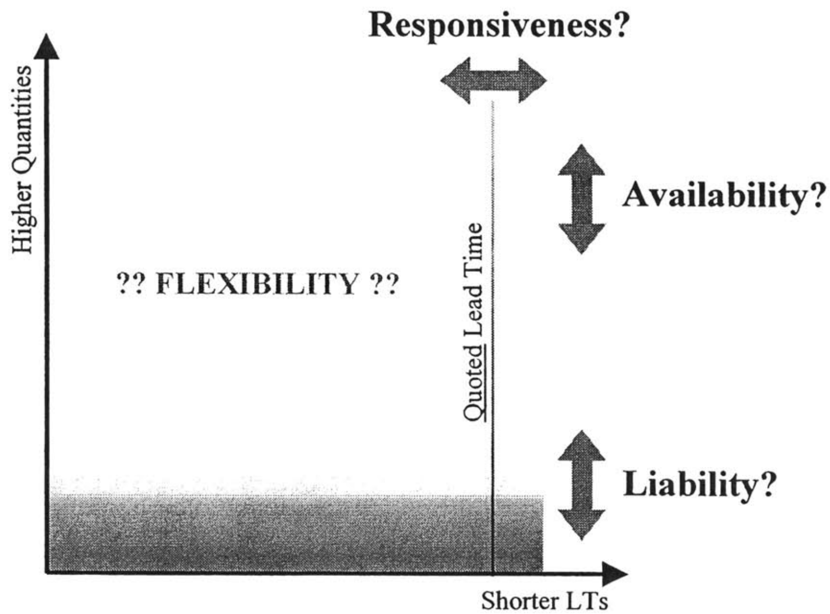

Figure 5: Order Fulfillment Ambiguity Associated with an "Unstructured" Agreement

Without a Structured Contract, the three most critical order fulfillment parameters are left undefined. Without such an agreement, responsiveness can vary based on the market conditions of the overall electronics industry and the capacity constraints at individual suppliers. Quoted lead times cannot be planned around because they fluctuate and are only guaranteed on a "best effort" basis. Quoted lead times also lose meaning when they are not tied to defined levels of availability. A lead time cannot be guaranteed against infinite availability. In this industry, lead times that are not guaranteed get pushed out when the overall semiconductor and electronics market heats up. These exploding lead times result in volatile and uncapped liability exposure as described earlier in Figure 3. In the end, there is little to no flexibility in the Division's supply chain if the material outputs are only loosely connected to the order inputs.

Structured Contracts enable greater supply chain flexibility by unambiguously answering the following five questions in any demand scenario.

1) **How much can the Division buy?** i.e. What level of availability will be guaranteed within leadtime?

2) **When can the Division buy it?** i.e. At what fixed lead time will guaranteed quantities be available?

3) **What happens if the guarantees are not met?** i.e. What corrective action or penalty will be required to make the guarantees credible?

4) **What is the Division's risk or commitment?** i.e. What is the Division liable for if demand expectations are not met?

5) **What will it cost?** i.e. What is the pre-determined price for these services?

A generic version of a Structured Contract is illustrated in Appendix 3. The Structured Contract becomes an addendum to the larger terms and conditions contract that should have already been negotiated based on Recommendation #1.

In contrast to Figure 5, Figure 6 describes how a Structured Contract secures flexibility by establishing guaranteed levels of availability and responsiveness and clearly established liability limits.

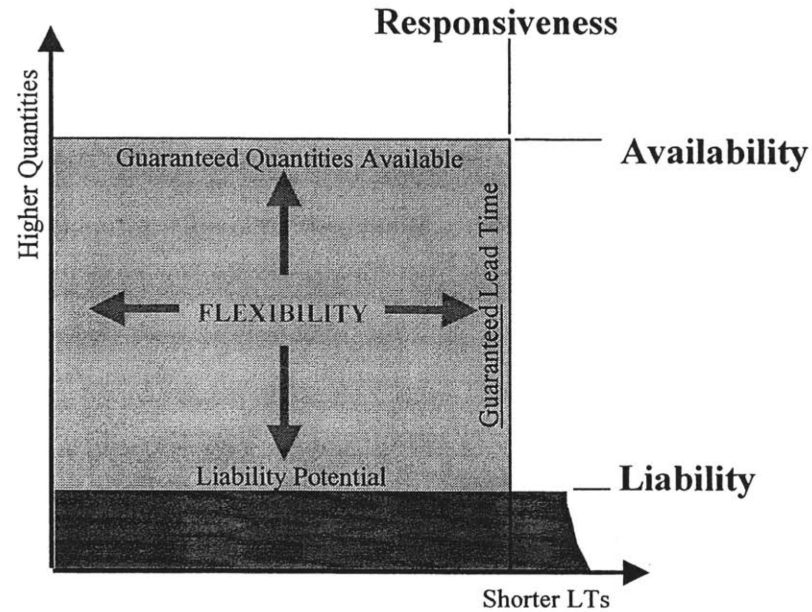

Figure 6: Order Fulfillment Clarity Associated with a Structured Contract[18]

Liabilities remain stable and capped based on the number of committed orders. The flexibility of the order fulfillment agreement increases as the guaranteed lead times decrease and the difference between the guaranteed quantities available and the number of committed orders increase. Greater levels of flexibility normally translate into higher service premiums. There are logical upper limits to how much flexibility the Division should try to establish in its supply chain. For instance, the Division should not need more availability in its supply chain than it can process in its final assembly. As discussed in Section 5.1, the Division can value flexibility using it's specialized supply chain software analysis tool. Of course, if market demand exceeds the guaranteed levels of availability, the supplier is still free to deliver additional material on a "best effort" basis.

It is important to recognize that an extremely high demand scenario in the future can breakdown the flexibility agreements within the Division's supply chain, regardless of the best intentions of its suppliers to honor the agreements and regardless of how well the agreements have been structured. For instance, capacity constraints at lower tier suppliers can holdup first-tier

[18] Lead times decrease on the x-axis in order to associate greater flexibility with more area on the graph. For consistency, the x-axis of Figure 5 also shows decreasing lead times.

suppliers from making deliveries when market demand remains very high for an extended period of time across the semiconductor and electronics industries. The penalties written into the Structured Contracts that are associated with not delivering the agreed upon services cannot compensate the Division for the lost sales that it may incur. In any case, the intention of the penalties is only to make the commitments credible, not to cover potential losses.

The recent economic boom may be representative of such an extreme demand event. Many seasoned managers within the Division refer to it as a "100 year flood." It probably does not make sense for the Division to prepare for such an extreme occurrence. Given the time and resources required to deploy Structured Contracts, the Division needs to make prudent trade-off decisions in terms of how broadly and deeply to formalize such agreements across its supply base. One challenge that remains is determining whether the recent economic cycle was truly an outlier or whether it could occur again in the next 10 years.

5.5. Structured versus Flexibility Contracts

The Flexibility Contracts that were introduced in Section 3.3 and the Structured Contracts that the Division is beginning to adopt both improve supply chain performance through guarantees and limits. Although they are very similar in theory, Structured Contracts tend to be more manageable in practice.

Flexibility Contracts are usually more difficult to administer. For example, the flexibility bounds on the forecast could be specified as follows:

	α (upside)	ω (downside)
+ 1 month	30%	30%
+ 2 month	60%	30%
+ 3 month	100%	50%

Figure 7: Flexibility Bounds Relative to Forecast

These bounds are open to interpretation. It is not clear how soon the "baseline" gets reset after adjusting the plan by one or more "upside" or "downside" percentages. Can the plan continuously increase 30, 60, 100% month after month? What ultimate availability can be counted on? There has to be a limit, because it cannot be "infinity". Given the Division's dramatic business cycles, what happens if a steep demand ramp is forecasted? Is it realistic for the Division to expect that the upside availability percentages still apply? These open questions make the Flexibility Contract hard to score and less enforceable. Of course, the contract document could explicitly address all of these questions. Unfortunately, that would make the agreement appear more complex, while not guaranteeing that it is well understood by all of the parties that have to execute to it.

Materials and production planning is also more straightforward for suppliers under a Structured Contract. The availability limits for a given month remain constant. Forecasts are still provided and are based on the best available market demand information and help set consistent expectations across the entire supply chain. Flexibility Contracts, on the other hand, compromise the neutrality of the forecast. The forecast turns into a business decision that determines the supplier's availability commitment and the Division's liability exposure.

Unfortunately, the benefits of Structured Contracts come at a price. They require more upfront preparation and ongoing maintenance. Long-term scenario forecasting is required to appropriately size the availability and responsiveness requirements. These requirements need to be updated periodically as the contracts approach the end of their duration. The Division still needs to develop a robust internal process for creating long-term scenario forecasts. In comparison, Flexibility Contracts leverage the existing forecast and remain "evergreen." Assuming the flexibility bounds are appropriately sized, they never have to be refreshed.

5.6. Dollar Weighted Average Supply Chain Length ($WASCL)

Dollar Weighted Average Supply Chain Length ($WASCL) is a metric that started to be adopted by other divisions in the Company at the beginning of the internship. They were using it to drive continuous improvement efforts in terms of supply chain performance after product launch. The metric combines the price and lead time of directly purchased materials to create a dollar weighted average product lead time. $WASCL is calculated as follows:

$$\$WASCL = \frac{\sum (\textbf{Part Cost}_n \textbf{ x Supply Chain Lead Time}_n)}{\textbf{Total Product Cost}}$$

For simplicity, the $WASCL calculation only includes parts that are directly purchased by the Division. This includes consigned parts. An explanation about how to determine the "Supply Chain Lead Time" of a part is included in Appendix 4. Price and lead time are used in this metric because they both directly impact the total sourcing cost of a part.

Total Sourcing Cost = Materials Cost + Shortage Cost + Inventory Cost

Price is an obvious component of total sourcing cost because it equals the materials cost. Lead time is more subtle. Demand uncertainty increases with time. Therefore, lead time directly influences shortage and inventory cost. The longer the lead time of a part is, the greater the chance of demand exceeding the procurement plan and resulting in shortages. The cost of a shortage can be estimated to equal the gross margin of a lost sale. Likewise, the longer the lead time is, the greater the chance of a demand shortfall, resulting in excess inventory. Inventory costs are determined by the cost of capital and storage costs. Obsolescence can also affect inventory cost, especially in the high-tech industry. It is impossible to calculate the exact relationship between lead time and shortage and inventory costs, because the relationships are scenario dependent. For instance, shortage costs are typically higher than inventory costs during a market upturn. The opposite is true during a market downturn. The Division is starting to try to approximate the relative value of each of the total sourcing cost factors for its business and for various demand scenarios.

Also note that this total sourcing cost equation is simplified. Certainly, quality is an additional factor. For simplicity, quality is assumed to be perfect. Expedite charges also play a role. They increase with longer part lead times.

$WASCL is useful for identifying the highest leverage parts from a total sourcing cost perspective. This ability can be best demonstrated through an example. Figure 8 contains the bill of material for a fictitious product made up of four parts.

Part	Direct Material Cost	Percent Bill of Material	Supply Chain Lead Time (days)	Percent $WASCL
A	$20,800	37%	85	37%
B	$15,200	27%	25	8%
C	$14,000	25%	135	40%
D	$6,500	12%	110	15%

Total Material Costs: $56,500 **$WASCL (days): 84**

Figure 8: Bill of Material of a Fictitious Product

The parts have been sorted in descending order in terms of direct material cost. By setting continuous improvement goals to achieve a lower product $WASCL, the company can create the right incentives for its buyers to negotiate lower lead times and lower costs on the parts that most influence a product's total sourcing cost. Rather than targeting Part A, because it has the highest direct material cost, the buyer is now more likely to first focus on Part C, because it is the greatest $WASCL contributor. Likewise, Part D is more deserving of attention than Part B, even though it costs less than half as much. Percent $WASCL serves as an excellent and simple triage tool for focusing and motivating the limited procurement resources on the highest leverage total sourcing cost parts.

Due to the way that Supply Chain Lead Time is calculated, buyers are encouraged to develop creative approaches for reducing $WASCL. Beyond the traditional procurement focus of negotiating lower costs, $WASCL motivates:

- working with suppliers and internal process centers to lower manufacturing cycle times
- developing strategies with suppliers for sizing lower-level material buffers to shorten the lead time of the purchased part
- collaborating with engineering to architect the product such that expensive parts can be postponed, or delayed to process centers that are closest to the customer

Like all metrics, $WASCL is not perfect. Nevertheless, it promotes directionally correct behavior. All of these activities ultimately increase the Division's responsiveness to its customers, while reducing costs.

5.7. $WASCL during Product Generation

The Supply Chain Design Dashboard that is discussed in Recommendation #3 enables the Division to use $WASCL during product development. The metric is even more valuable during this stage of a product's life. It promotes the same type of behavior as described in the previous section, but does so at a point in time when the organization and its suppliers have greater flexibility to make significant improvements to the product design.

The metric provides two additional benefits during product generation. First, $WASCL can be used at the beginning of the product development process to set system-level supply chain design goals. One of the major deliverables during Phase 0 of the Division's PLC is evaluating the new product's market feasibility. Part of that assessment is determining what the market will accept in terms of the product selling price and customer lead time[19]. Combining this data with the margin that the Division expects to earn indicates how responsive a supply chain the product will need to have. For instance, if the Division can only earn a small margin and the market will require a short customer lead time, then the product's supply chain should be highly responsive. If the supply chain is not responsive enough, a substantial amount of the margin will be consumed through the total sourcing costs.

Using its knowledge of the required technology and available supply base, the Division can put together a supply chain dashboard with target cost and lead time values and calculate an expected $WASCL early during Phase 1. The appropriate $WASCL goal needs to be set at this time to ensure that the product's supply chain is responsive enough relative to the required product architecture, customer lead time and pricing strategy. This concept is best explained through the following visual example.

[19] Customer lead time is defined here to equal the lead time of the product from the Division to its customer.

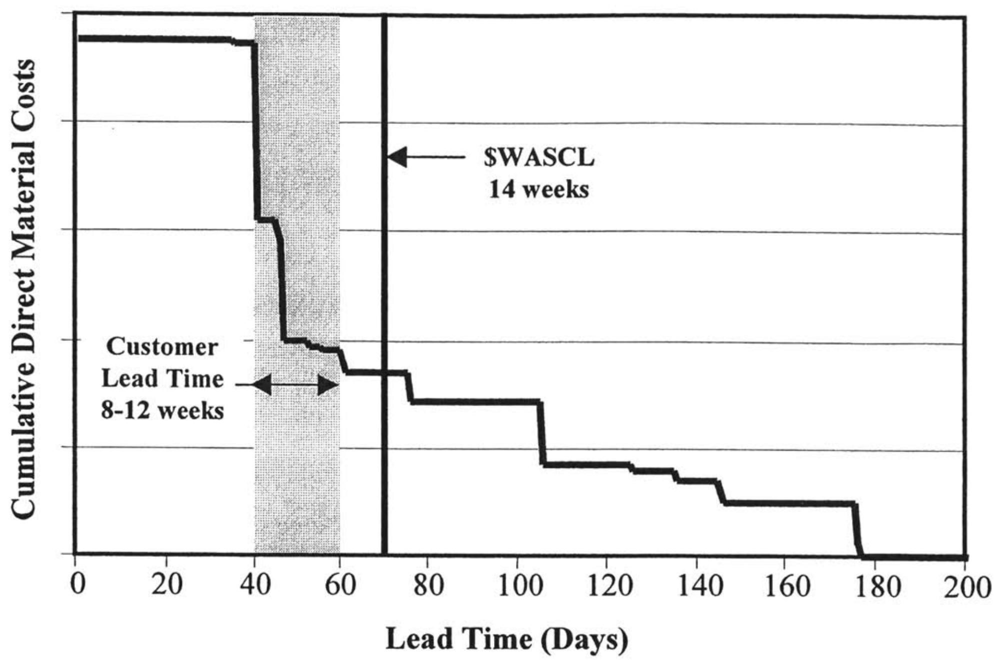

Figure 9: Product Lead Time Profile

Figure 9 shows the lead time profile of one of the Division's products. The graph shows how far in advance of the product's delivery to a customer materials need to be purchased based on quoted lead times. $WASCL consolidates this profile into a single number, which in this example is 14 weeks. The customer lead time can vary between 8 and 12 weeks, depending on the customer and the total number of units that have been purchased. Most customers expect shorter lead times as the Division progresses down the manufacturing learning curve. The gap between customer lead time and $WASCL is an indicator of the cost of responsiveness. In this case, a significant amount of material has to be purchased outside of firm demand, resulting in inventory liabilities during market downturns. The product's profit margin needs to be able to support these additional costs. If the profit margin is too small, the product should have been designed with a shorter $WASCL.

Note that both the lead time profile and $WASCL in Figure 9 are conservative. They are based on quoted lead times and therefore do not account for the effect of "exploding" lead times. This observation leads to the second additional benefit of using $WASCL during product development.

Recommendation #2 suggests that the Division guarantee order fulfillment services through Structured Contracts prior to supplier selection. Just like other Divisions are using percent $WASCL contribution as a continuous improvement tool to target parts with the highest total sourcing costs, percent $WASCL contribution can also be used as a triage tool for contract deployment during product development. Using the target cost and lead time values from the supply chain dashboard, the Division can calculate the expected percent $WASCL contribution of each of its major subassemblies. It can use this information, together with the supply chain risk categories introduced in Section 4.1, to prioritize the parts in terms of potential supply chain performance impact. The parts with the highest percent $WASCL contribution and the most associated supply chain risk categories are the most deserving candidates for Structured Contract deployment.

CHAPTER 6: IMPLEMENTATION AND FUTURE RESEARCH

Although the above recommendations seem appropriate and straightforward, they can be challenging to implement. Much of the internship was spent working with managers and functional groups to explain and illustrate these concepts. The Division's consensus based decision-making culture means that organizational change process takes time. Nevertheless, the recommendations have taken root and are gaining momentum.

6.1. Steps to Driving Organizational Change

Implementing the supply chain design approach presented in this thesis is particularly challenging because the benefits of the improved process will not be recognized until after a new product is launched. Since the product development cycle times of the Division typically span multiple years, the organization may be wary to expend additional energy so far in advance of any reward. The key to institutionalizing the new process is to foster an environment where it will occur naturally. Although this is not easy, it can be accomplished through modifications to the organizational structure of the Division. The following three steps will help bring about the appropriate transformation.

<u>Step A: Develop integrated product development teams with dedicated resources.</u>

The supply chain design recommendations require that R&D and Supply Chain work closely together and collaborate during the early stages of product development. One of the factors that contributed to the disconnect that still existed between the two groups by the end of the internship was that Supply Chain did not have any dedicated resources allocated to the current product development project. All of its strategic buyers were focused on maintaining products that had already been launched. Therefore, the buyers did not have the bandwidth to push forward with the same sense of urgency as R&D on the new product development effort. Management acknowledges that it has historically understaffed its Supply Chain group. Once the business climate starts to recover, the Division should consider hiring and dedicating new procurement resources in order to create integrated product development teams.

The Division could also benefit from following the example of Toyota and other lean manufacturers in terms of timing when resources are devoted to an integrated product development team. Lean manufacturers tend to achieve the highest staffing levels at the beginning of a project. All applicable functions are well represented. This forces the group to confront and tackle all of the difficult trade-off decisions upfront. Their staffing levels decrease as the development project progresses and as certain functions and specialties are no longer needed. This approach has been shown to require much fewer people over the course of the project because problems are solved from the outset.[20] This approach also mirrors the underlying philosophy of the supply chain design recommendations presented in this thesis. That is, that the order fulfillment objectives of a new product with an integral product and supply chain architecture are best achieved if they are set and proactively designed to from the outset of the development project.

Step B: Co-locate the integrated product development teams.

Communication delays associated with the geographic separation of working groups has been well documented. The lines of communication that exist between R&D and Supply Chain at the Division are impeded by distance, time zones and inconvenience. The physical separation has certainly contributed to the frustrations that the two groups have with one another. R&D continues to list time delays and miscommunication as reasons for initiating the supply chain design process on its own. For instance, R&D still sends out RFQs on occasion without the knowledge of Supply Chain. This situation is less likely to occur if the two groups were sitting next to one another. Trust between R&D and Supply Chain can also be cultivated more readily through daily face-to-face interaction. Co-location does not necessitate moving one of the two functional groups completely. A much less disruptive possibility could be to move a couple seasoned strategic buyers to the R&D location. They would retain their ties to the Supply Chain group, but report to the product development project leader for the duration of the product development program.

[20] Womack, J.P., Jones, D.T., Roos, D., The Machine That Changed The World, Harper Collins Publishers, 1990; pp. 115-116.

Step C: Develop product development contributors with cross-functional expertise.

Getting the two groups to work together seamlessly requires that each team member appreciate the needs of the other functional group's members. One of the best approaches for imparting this understanding is by providing each individual contributor with the opportunity to develop a set of cross-functional experiences. A R&D engineer who has spent nine months as a strategic buyer is more likely to appreciate the importance and difficulties of developing the appropriate relationships and commitments between the Division and its suppliers. When he returns to his original role, he will approach his work from a different perspective and will be better prepared to facilitate proactive supply chain design. Unfortunately, the specialized training that engineers require generally precludes sending a strategic buyer from working in R&D for a short period of time. Nevertheless, due to the engineering dominated nature of the Division, the unidirectional transfer of experience from procurement to R&D is still highly valuable and worth pursuing. Developing cross-functional experience within the workforce has the added benefit of boosting morale. One way for management to encourage cross-functional development is by making it a rotational program for high potential employees in the Division and across the Company.

As a side note, this cross-functional development should certainly not be limited to the R&D and Supply Chain functions. For instance, developing a strong linkage between R&D and Manufacturing can dramatically improve the quality of the Division's new products. This linkage would help the Division strengthen its "design for manufacturability" competence, which is of special importance considering its outsourced manufacturing strategy.

Finally, in order to make sure that the above mentioned organizational modifications produce the desired effect, Management should consider measuring the Division's supply chain design performance with activity-based metrics. Such metrics encourage process adherence and help drive continuous improvement. They also signal Management's commitment to making supply chain design a priority. Results-based metrics are less appropriate because actual supply chain performance can only be measured after product launch. The delay between the required process inputs and the final output is too long to motivate the correct supply chain design behavior.

6.2. Challenges to the Acceptance of Structured Contracts

The supply chain design recommendations presented in this thesis cannot be fully implemented without the acceptance of Structured Contracts. These contracts represent a radical change in procurement practices and therefore continue to face resistance within the Division and from its suppliers. The Structured Contracting pilot project highlighted a source of internal resistance. In one particular case, management rejected a contract that a supplier was prepared to sign, although the contract promised significant long-term cost savings for the Division. Management objected because the contract committed the Division to up-front material purchases that conflicted with a corporate mandate to minimize current procurement expenditures. Even though Structured Contracts reduce long-term total sourcing costs, they may increase short-term expenses. Management needs to promote the actions that are in its long-term interest.

Structured Contracts face similar resistance at the Division's suppliers. The contracts provide the supplier with improved planning information and, in some cases, purchase commitments. In exchange, suppliers may need to maintain higher inventory levels to meet their availability and responsiveness guarantees. The suppliers may be reluctant to accept the inventory costs, even though they can benefit from more efficient production down the road. Tsay and Lovejoy observed that Flexibility Contracts suffered similar conflicts of interest when they were first introduced.[21]

6.3. Future Research Topic

This thesis is focused on the order fulfillment side of supply chain design. It assumes that the Division needs to procure strategic sub-assemblies and components and focuses on how to optimize the delivery performance of its suppliers. There is another, potentially more important, side to supply chain design. It asks the question, "Which parts of the product does the Division want to design and manufacture in-house and which parts does it want to outsource?" This question is commonly referred to as the make/buy decision and has been the subject of a great deal of research.

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[21] Tsay, A.A., Lovejoy, W.S., "Quantity Flexibility Contracts and Supply Chain Performance", *Manufacturing & Service Operations Management*, Vol. 1, No. 2, 1999; pp. 107.

A cursory application of the "Strategic Value Assessment"[22] model developed by Charles Fine, Roger Vardan, Robert Pethick and Jamal El-Hout, shows that ASICs are a supply chain component of high strategic value. Accordingly, the Division should consider designing its ASICs internally through one of its sister divisions. The Division may benefit from developing a formal make/buy decision process that is appropriate for its business and that would further enhance its supply chain design capabilities.

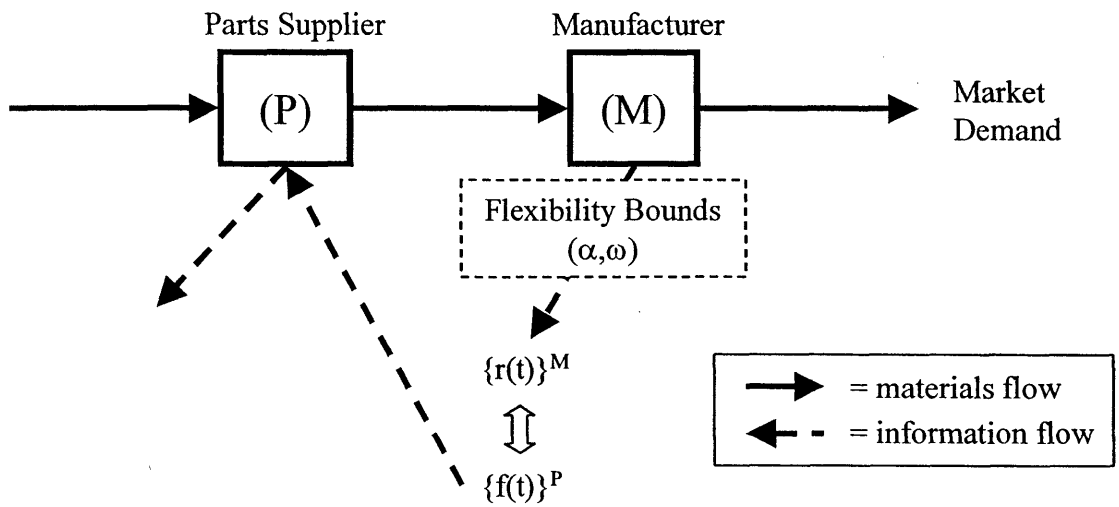
6.4. Conclusion

The most important realization for the Division needs to be that supply chain design occurs concurrently with product development. If the right actions are not taken at the right points in time, the supply chain performance of the product will suffer. Given the Division's volatile market demand, it will continue to be saddled with the financial burden of an unresponsive supply chain. Due to the integral nature of its products' architectures, it is difficult, time consuming and expensive for the Division to improve a product's supply chain after the suppliers have been selected. Proactive collaboration between the R&D and Supply Chain functions is necessary during the early stages of the product generation process to enable effective and efficient supply chain design.

[22] Fine, C. H., Vardan, R., Pethick, R., El-Hout, J., "Rapid-Response Capability in Value-Chain Design", *MIT Sloan Management Review*, Vol. 43, No. 2, 2002; pp. 69-75.

APPENDICES

Appendix 1: Supply Chain Coordination using Flexibility Contracts[23]



The manufacturer uses its knowledge of market demand to coordinate its supply chain. The manufacturer provides the parts supplier with a replenishment schedule vector $\{r(t)\}^M = [r_0(t), r_1(t), t_2(t),\ldots\}^M$, where

> $r_0(t)$ = actual purchase made in period t
>
> $r_j(t)$ = estimate of purchase to be made in period (t + j), for each j ≥ 1.

This becomes the part supplier's release schedule vector, denoted by $[f(t)\}^M = [f_0(t), f_1(t), f_2(t),\ldots]^M$, where

> $f_0(t)$ = quantity sold in period t
>
> $f_i(t)$ = estimate of quantity to be sold in period (t + j), for each j ≥ 1.

[23] Tsay, A.A., Lovejoy, W.S., "Quantity Flexibility Contracts and Supply Chain Performance", *Manufacturing & Service Operations Management*, Vol. 1, No. 2, 1999; pp. 89-92.

The manufacturer-parts supplier flexibility contract is parameterized by (α,ω), where $\alpha = [\alpha_1, \alpha_2,\ldots]$ and $\omega = [\omega_1, \omega_2, \ldots]$. This places bounds on how the manufacturer may revise $\{r(t)\}^M$ going forward in time. Specifically, for each t and $j \geq 1$:

$$[1 - \omega_j]\ r_j(t) \leq r_j\text{-}1(t+1) \leq [1 + \alpha_j]\ r_j(t)$$

That is, the estimate for future period (t + j) cannot be revise upward by a fraction of more than α_j or downward by more than ω_j. Contingent on this, the contract stipulates that the manufacturer's eventual orders will be filled with certainty.

Appendix 2: Generic Version of a Structured Contract

AVAILABILITY AND RESPONSIVENESS		PRICE
Quantities guaranteed available w/ X month LT ②		$P1 per unit ⑤
Q1'02	Y units per month	
Q2'02 ①	Y units per month	
Q3'02	Y units per month	
Q4'02	Y units per month	

LIABILITY (COMMITMENT)		PRICE
Quantities Division commits to buy		$P2 per unit
Q1'02	Z units per month	
Q2'02 ④	Z units per month	
Q3'02	Z units per month	
Q4'02	Z units per month	

NON-PERFORMANCE

Example: % discount for units delivered late ③

① **How much can the Division buy?**

② **When can the Division buy it?**

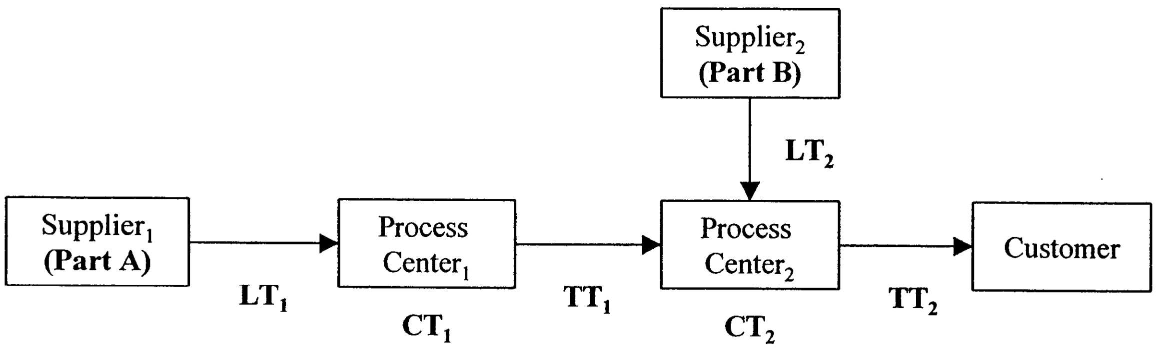
③ **What happens if the guarantees are not met?**

④ **What is the Division's risk or commitment?**

⑤ **What will it cost?**

Appendix 3: Supply Chain Lead Time Definition

Supply Chain Lead Time equals the sum of all of the lead times, internal cycle times and transit times that are required to receive a purchased part from a supplier, assemble it into a product and ship it to a customer. The diagram below provides a couple of examples.



- LT1 and LT2 are the lead times from Supplier1 and Supplier2 for Part A and Part B, respectively
- CT1 and CT2 are the cycle times for the internal company Process Centers for Part A and Part B, respectively
- TT1 is the transit time between Process Center1 and Process Center2 for Part A
- TT2 is the transit time between Process Center2 and the Customer for Part A and Part B (transit time is assumed to be equal because Part A and Part B are assembled into the same product)

SCLT (Part A) = LT1 + CT1 + TT1 + CT2 + TT2

SCLT (Part B) = LT2 + CT2 + TT2

The Supply Chain Lead Time can include the lead time of more than one supplier if the company consigns a lower-level part to a supplier.

Appendix 4: Supply Chain Dashboard Example

General Bill of Material Data					Metrics	Supply Chain Risks						Contract Requirements	
Part	Supplier	Part Cost	Extended Cost	Supply Chain Lead Time	Percent $WASCL	Peak Monthly Capacity Req'd	Max Supplier Capacity Available	Sole Source	Single Source	Yield	Obsolescence	General Terms & Conditions Contract	Structured Contract
A													
B													
C													
.													
.													
.													

Total Actual:	
Total Goal:	

$WASCL Actual:	
$WASCL Goal:	

Capacity Constrained

The Division should prioritize the deployment of its contracts based the parts with:

- the highest percent $WASCL contribution
- the most supply chain riks

The Division should also track their performance against direct material cost and $WASCL goals throughout the product development process.

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