Supply Chain Architecture in a High Demand Variability Environment

by

Varun Parmar

B.S. Electronics and Telecommunications (1999)
University of Pune, India

M.B.A. Marketing (2001)
The George Washington University, USA

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Signature of Author

Varun Parmar
System Design and Management Program
June 2005

Certified by

David Simchi-Levi
Thesis Supervisor
Professor of Engineering Systems
Co-Director, LFM/SDM

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Chapter 1: Industry and Company Background

1.1 Communications Equipment Industry [1]

The communications equipment industry provides the electronic products from hand-held telephones to large-scale computer and telephone network infrastructure that people use daily to communicate. These products may operate with a wired or wireless connection to the public communications network. The electronic signals that they receive and transmit may be either analog or digital in kind. The primary drivers of the industry are corporate information technology spending and telecommunications capital expenditures. Products sold to the telecommunications market, or the public carriers, are classified as telecom equipment. Products sold to enterprise customers (such as large corporations, government agencies, and educational institutions) to help connect computer information systems are usually classified as networking equipment. With the increasing convergence of communications and computing, most equipment is commonly able to serve both markets. At present, voice traffic is currently the main source of revenues for communications media. However, data traffic transmitted via the Internet and via intranets is an important driver of future growth. For the equipment industry, this means a significant opportunity for those manufacturers able to help their customers make the transition to data-enabled networks. Wireline service providers employ a variety of media, including copper, fiber-optic, and coaxial cables, to carry data and voice traffic. The equipment employed to send and receive this traffic is critical to the process. Customers for network equipment, public or private network operators, typically purchase their equipment in large quantities under long-term contracts with producers. As a result of the complexity of communications systems and the high cost of developing and maintaining in-house expertise, today's network operators are demanding integrated turnkey installations.

1.2 Transmission Media [2]

There are three basic types of wireline media- copper, fiber, and coaxial. Each of these transmission media has distinguishing characteristics that warrant further discussions as below:

- **Copper Wire**: Conventional copper wire transmits signals as electrical pulses; a standard three-inch copper cable can transmit about 14,400 phone calls at once. While copper is the most cost-effective of the mediums, it also has the greatest limitations: signals weaken the further they travel down a copper wire, and commonly encounter interference.

- **Fiber-optic Cable**: This medium transmits signals as light pulses; just like digital technology, the signals are binary in nature. A single fiber-optic strand constructed of very pure glass and no thicker than a human hair, can transmit a thousand times more information than all of today's radio frequencies combined. A typical half-inch fiber-optic cable contains approximately 72 pairs of fibers that together have a capacity of up to 3.5 million phone calls. Fiber-optic lines are immune to interference and are able to handle longer distances better than copper. However, fiber is also more expensive than copper, for which reason it is used primarily for long-distance networks rather than in local networks.

- **Coaxial**: Coaxial cable consists of a single strand of copper wire surrounded by a sheath or shielding made of foam. Over this sheath is yet another layer of insulation. The different layers of the cable help to prevent signals, like television transmissions, from leaking out. In general, coaxial has higher capacity than copper wire but lower than fiber-optic cable. Within many cable operators' networks, coaxial cable is tied together with fiber-optic cable, creating a hybrid fiber-coax (HFC) network. The coaxial portion is used to deliver cable signals directly to the home, while fiber forms the backbone of the network.

1.3 The Switch [2]

The heart of the wireline communications or computer network is typically a piece of equipment known as a switch. Switches are devices that complete connections between callers and route information from one network user to another. At present, circuit switched networks are used for the majority of voice traffic. Circuit switches can be inefficient: one phone conversation ties up an entire circuit until the call is disconnected. Consequently, any dead time that may occur during the call is not used efficiently. For this reason, circuit switching is poorly suited for the unpredictable nature of data traffic. Packet-based networks offer more efficient means of transport by breaking data into small "packets" for transmission. Originally designed to manage the flow of data in a computer network, they are increasingly being used to handle voice traffic. Packet-switching technology utilizes bandwidth more efficiently by supporting both voice and data simultaneously and by not consuming the network resources when no information is being sent. Perhaps the most important attribute of packet switching is its ability to offer new multimedia services to the mature telephony market. Yet despite its advantages, the transition to packet switching will likely occur gradually.

1.4 Communication Transmission Systems [2]

The distances between different central offices, as well as between a central office and a local telco office or end office, are served by wireline transmission equipment. The major transmission equipment suppliers include Cisco, Alcatel, Ciena, Fujitsu, Lucent, and Nortel. Transmission systems use multiplexing techniques to send voice, data, image, and video communications over fiber-optic cables. Multiplexing means that numerous signals are sent simultaneously on the same transmission path. The two main methods are time division multiplexing (TDM) and dense wavelength division multiplexing (DWDM).

- **TDM**: Time division multiplexing is the most common multiplexing technique. This technology separates a voice conversation into pieces, which it then weaves, along with pieces of other conversations, onto a broadband circuit for transport to various destinations. TDM works by assigning portions of bandwidth (slots) to devices like telephones or computers. If the speakers pause during the course of a phone conversation, the slot remains dedicated to their call, which wastes available bandwidth. Similarly, if a personal computer is logged onto the Internet but not actively requesting information, a slot that could normally be used by another device remains idle. The dominant types of TDM equipment in North America are synchronous optical network (SONET), and in other markets, synchronous digital hierarchy (SDH). SONET/SDH equipment and software transports traffic over fiber-optic cables at very high speeds, ranging from 52 megabits to multiple gigabits per second (called optical carrier, or OC, speeds). It provides carriers with standard framing size, network survivability, and equipment compatibility. The downside to this equipment category is that it employs the TDM technology as designed for predictable voice traffic. It does not scale to support data traffic and is tailored for specific speeds. If a carrier wishes to upgrade a network to a higher speed, a "forklift" upgrade is necessary: all the old equipment must be replaced with expensive new equipment.

- **DWDM**: Dense wavelength division multiplexing systems provide a more robust form of multiplexing than TDM systems. DWDM uses lasers to divide light (data traffic) into eight or more separate wavelengths before sending them through fiber-optic networks. Some of the most advanced DWDM systems can split traffic into 160 wavelengths over a single strand of fiber. By contrast, SONET equipment employs the use of only one wavelength. DWDM systems allow service providers to add capacity without installing new fiber-optic cable.

1.5 About Cisco's Optical Networking Group (ONG) [3]

ONG is home to Cisco's comprehensive family of optical transport solutions (refer to figure 1). With its complete time division multiplexing (TDM), data and storage support, extensive topology (linear, mesh, rings) capability and integrated element management, the Cisco optical solution portfolio focuses on many key segments such as service provider and enterprise customers. The goal of ONG is to help these segments evolve to a service transparent architecture - a network architecture that is not dependent upon nor limited to the types of services delivered on it. The idea is to make the optical network not only a carrier of traditional TDM traffic, but also a provider of various IP services, including voice over IP, video on demand, video conferencing, storage and security. The two main product platforms are enlisted below:

- **Multi-service Provisioning Platform (MSPP):**

  The Cisco ONS 15454 SDH Multi-service Platform is a key building block in today's optical networks, through its ability to offer next generation transport performance and economics for the international market. It offers supercharged transport capability by combining the best of traditional SDH TDM and statistical multiplexing in a single platform. The Cisco ONS 15454 SDH MSP can aggregate traditional services such as E1, E3, DS3, E4, STM-1, STM-4, STM-16 and STM-64 including multi-wavelength dense wavelength division multiplexing (DWDM) optics, but is also designed to support data interfaces such as Ethernet/IP. This enables drastically improved efficiencies in the transport layer and breakthrough cost savings for initial and life-cycle deployment. Due to its unprecedented bandwidth density, its numerous applications and its very compact size, the Cisco ONS 15454 SDH MSP features the solution expected by the service providers to revolutionize the traditional voice-centric transport networks.

- **Multi-service Transport Platform (MSTP):**

  The MSTP strategy brings enhanced photonics capabilities directly into the service platform, extends geographical coverage, ensures flexible topology support, and delivers on the requirements of today's multi-service environment. Platform such as the ONS 15454 integrates DWDM into MSPPs thereby providing operational savings and letting the platform be tailored for MSPP architectures. With the MSTP strategy, customers can use a single solution to meet metro reach requirements ranging from campus through to long-haul applications, with significantly more flexibility in the DWDM layer than traditional long-haul solutions.

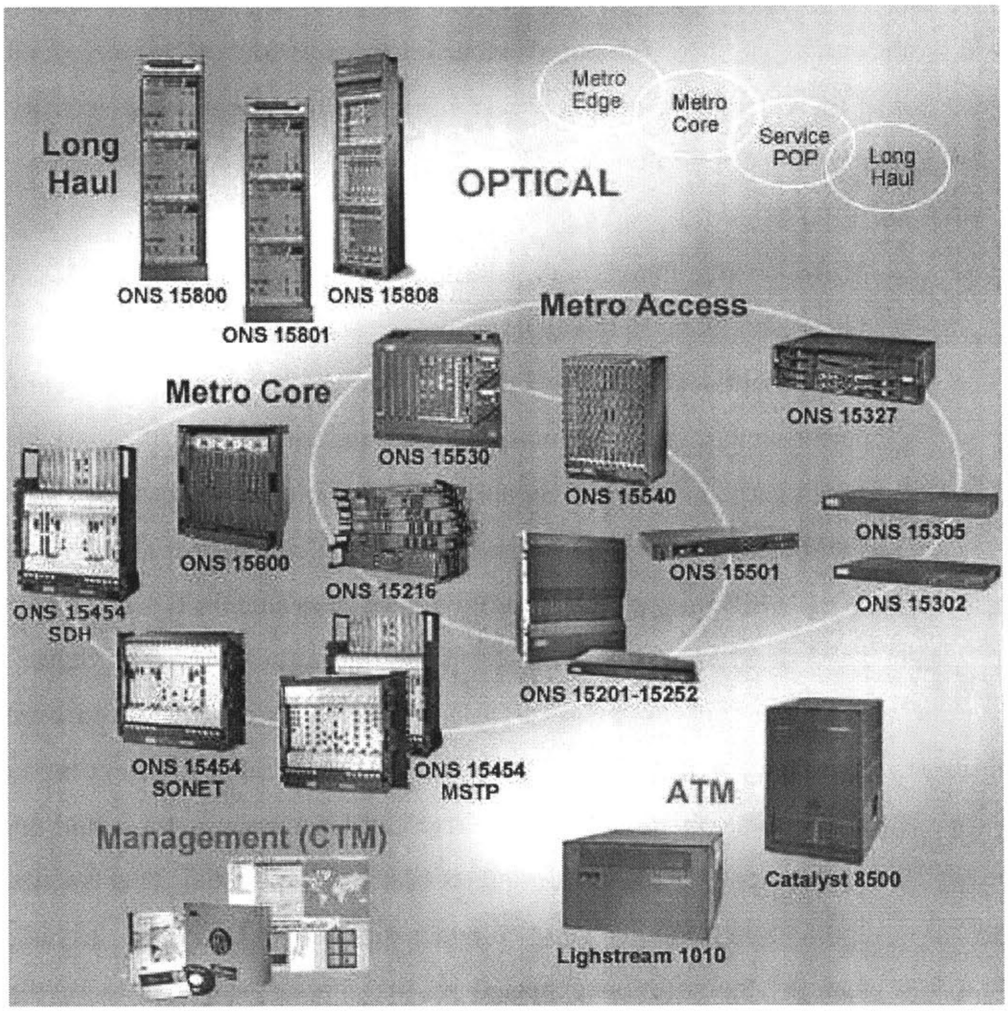


Figure 1: Cisco's ONG Product line [3]

1.6 Cisco's Optical Technology Supply Chain

Unlike the well-known and conventional Cisco business model characterized by high volume and low mix, ONG group has a dramatically different model characterized by low volume and high mix. The reason for this nature is embedded in the customer segment that ONG sells its product into which is primarily service providers, including ILECs, CLECs, and ISPs. In addition, internal divisions of Cisco are customers of ONG and use the equipment for demonstrations, warranty and repair, etc. A total of 7 customers represent 80% of the division's sales. The annual run rate for ONG division is approximately $400M. From a platform viewpoint, sales are split up between MSTP and MSPP in the ratio of approximately 3:7. MSPP portion of the business primarily targets the enterprise customer market whereas MSTP portion targets service providers. Unlike MSPP, which is already well entrenched in the market and demonstrates fairly stable demand, MSTP is ridden by uncertainty in demand. Furthermore, a sales history of about a year renders trend-based forecast analysis ineffective for MSTP. Notwithstanding above, the MSTP portion of the business continues to demonstrate higher growth rates and hence is expected to become the dominant revenue contributor.

There is a large lead time associated with parts that make up ONG equipment. Typically, on most components, lead times can vary anywhere from 10 to 14 weeks and in case of some specialty components such as lasers, lead times can shoot up to anywhere from 12 to 16 weeks. However, ONG is challenged to ship over 90% of the orders in 15 days or less. Due to this dynamic, ONG group maintains a manufacturing strategy of *'build to stock and ship to order.'* Furthermore, globally there exist only a limited number of suppliers that have the technology and production capabilities to supply the required components to Cisco.

The 4 major technologies contributing the highest revenues for the division are optical (OC 192, etc), control (TCC, XC, AIC, etc), DWDM, and electrical. Overall, ONG maintains a roster of 882 orderable SKUs out of which forecast is available for only 446 SKUs. These SKUs are spread across various technologies and demonstrate variability anywhere from currently 392 SKUs for DWDM to 33 for optical technology. Revenue per SKU per technology also varies with control technology generating ~$800K, optical generating ~$780K, and electrical

~$300K. Similar to most other companies, forecasting is owned by marketing department, allowing limited influence/ inputs from manufacturing.

Cisco outsources manufacturing to Celestica, a contract manufacturer that maintains a manufacturing facility in Salem, New Hampshire and the other in Thailand. Currently, ONG division is co-located in the same campus as Celestica -New Hampshire which leads to face-to-face communication and prompt issue resolution. New Hampshire campus offers lower lead times due to proximity to North American customers. On the other hand, with ever increasing pressures on margins, Celestica-Thailand allows Cisco the ability to competitively price its products. This, however, comes at the cost of increased lead times-approximately a week in transit.

The overall vision of ONG Group is to become a recognized leader in the field of new product introduction (NPI) and virtual supply chain management. Additionally, ONG wishes to provide a leveraged, superior, global manufacturing and order-fulfillment capability that delivers a strong and sustainable advantage to Cisco. The performance metrics of ONG division are listed below:

- Lead time of **15 days for 90% of the orders**
- On-time shipment (OTS) at **97% or higher**
- Quality Metrics:
  - Dead on Arrival (DOA) rate of **1,400 DPPM**
  - Return Merchandize Authorization (RMA) rate of **900 PPM**

Chapter 2: Project Description and Approach

2.1 Overall Project Objective

The objective of the project was to help Cisco fundamentally change its supply chain architecture to reduce inventory levels across the entire enterprise, including Celestica, while maintaining service levels. Cisco's ONG supply chain architecture was causing large excess and obsolescence inventory (E&O) expenses in the range of about $13 M annually. In addition, due to the large uncertainty in customer demand coupled with a huge demand forecast error, customer orders were being delayed leading to lower performance on metrics such as on-time shipment. All this while inventory levels were soaring! Consequently, inventory turns were unimpressive and Cisco's ONG group was becoming inefficient in satisfying customer demand while maintaining optimal inventory levels.

Marketing department generated sales forecast and the project explored opportunities to reduce forecast error so as to reduce inventory levels and E&O expenses. During the analysis, it was found that in some cases forecast error exceeded 1,000% and Cisco operations had started to generate their own forecasts after scrubbing the forecast provided by Cisco marketing. However, the current architecture of the supply chain and a focus on functional silos provided little opportunity to influence the marketing department. Due diligence was also performed to investigate and document buffers in the cycle times at Celestica. The goal was to reduce Celestica's cycle times to the lowest possible so as to reduce inventory levels. Furthermore, lead times of components were investigated and various programs such as Vendor Managed Inventory (VMI) were explored to further reduce component-level inventory held at Celestica and Cisco.

Lastly, product architecture was evaluated to investigate savings that may be derived by modifying product architecture to fit with the supply chain architecture so as to reduce inventory levels further.

2.2 Customer Demand and Forecasting

Customer demand exhibits large variability and uncertainty. One of the reasons for this variability is that the primary customers, i.e., service providers are on the verge of recovery after a long recession and hence are cautiously placing new orders. Uncertainty arises because service providers are not the end-consumers. In other words, service providers place an order with Cisco only when enterprise customers place an order with them. Traditionally, Cisco and other equipment manufacturers have not had visibility into the customer preferences of service providers. Clearly, uncertainty exists and actual demand variability is large as shown in figure 2. As seen below, actual sales for Rockwell boards, MSTP product, over an 11 month period are plotted. For example, product 800-23020-01 has seen demand of less than 12 units for all but 1 month. During December, 2003 the product saw more than 6 times increase in sales. It sold about 78 units demonstrating the point that actual demand exhibits huge variability. For almost all other products, similar trends exist.

Please Note: Data has been normalized to honor confidentiality agreement

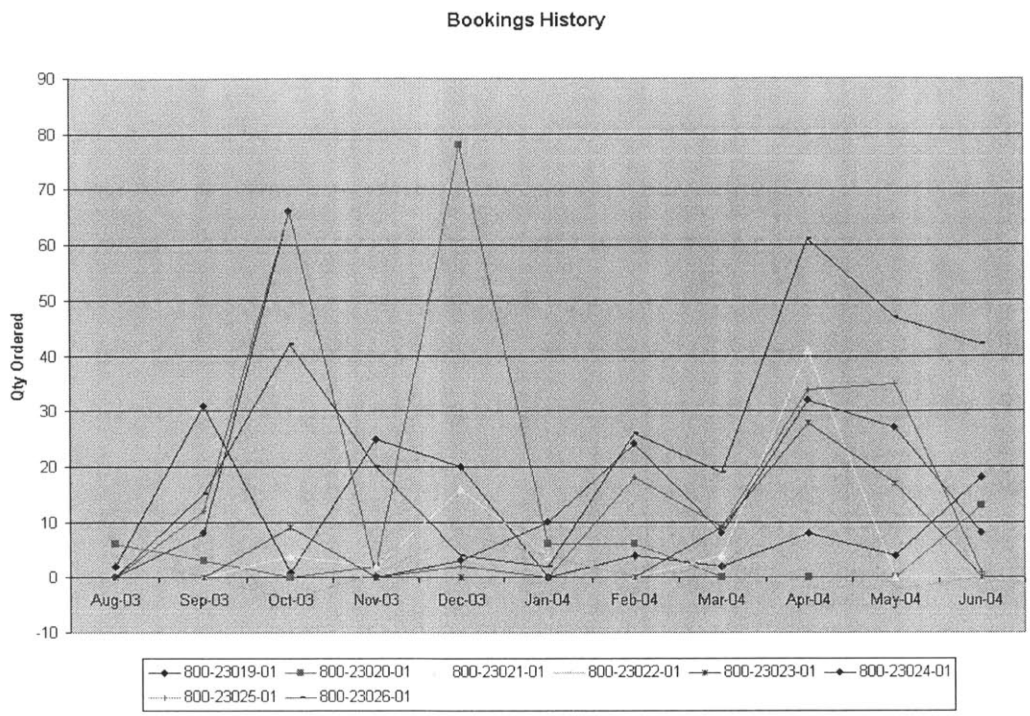


Figure 2: Rockwell Board Actual Demand

Rockwell boards, a product category that contains a total of 16 orderable stock keeping units (SKUs) was considered for analysis. The 16 SKUs were categorized into two platforms- protected and unprotected. Hence, 8 SKUs were part of the protected platform and the remaining 8 SKUs were part of the unprotected platform. Furthermore, each of the 8 SKUs represented 8 unique wavelengths. Wavelengths correspond to the type of optic used in the product. Figure 2 represents demand exhibited by unprotected product where as the following figure 3 represents demand exhibited by protected products. Again, as mentioned earlier, large uncertainty exists in actual demand, which is reiterated in the figure below. For example, for one of the wavelengths, 800-223227-01, over the 11 month time frame witnessed only one order which was placed for about 9 units. This is not to say that orders will only be booked once every 11 months. All depends upon the end-customer, i.e., enterprises and their business needs.

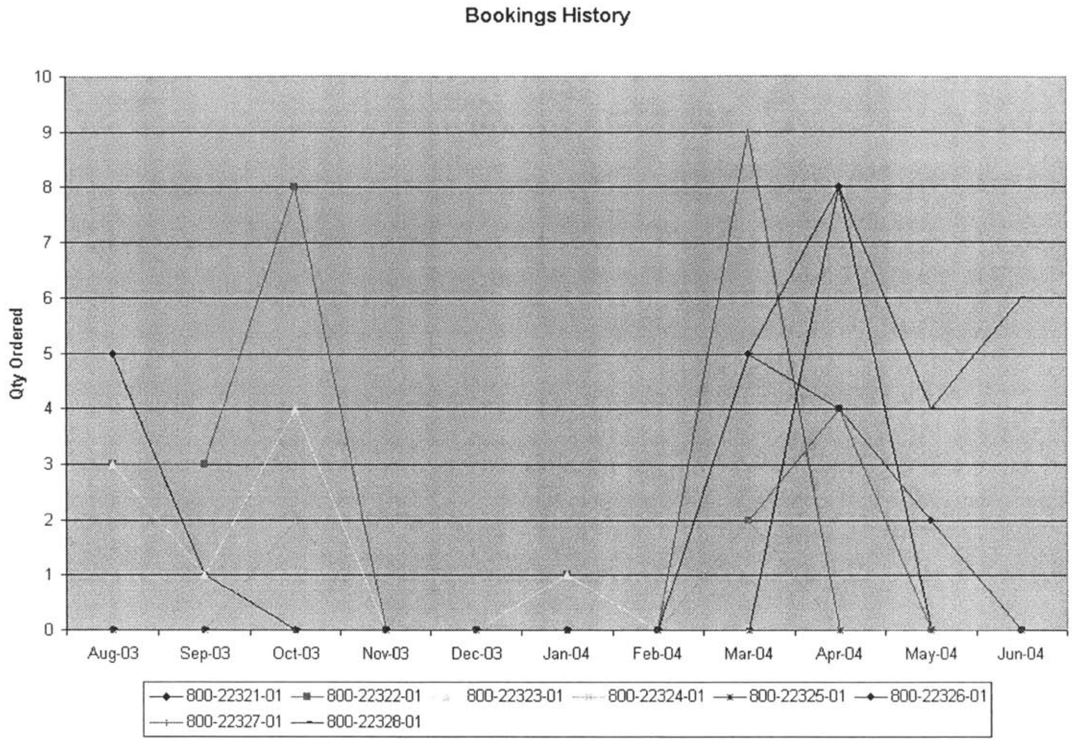


Figure 3: Unprotected Rockwell Board Actual Demand

Furthermore, variability in actual demand is quantified using coefficient of variance (CV), which is essentially the ratio of standard deviation of demand to the average demand. Table 1 represents the CVs of 8 SKUs for unprotected products whereas table 2 represents CVs of 8 SKUs for protected products. As seen below, for unprotected products, only 1 out of 8 (12.5%) has CV below 1.0 (or 100%). For protected products, only 2 out of 8 products (25%) have CV below 1.0. Those boards that have CVs below 1.0 are marked with a red star as shown in the tables below.

	μ(old)	σ(old)	CV(old)
800-23019-01	10.45	11.01	**1.05**
800-23020-01	10.36	22.79	**2.20**
800-23021-01	6.45	12.37	**1.92**
800-23022-01	2.73	5.73	**2.10**
800-23023-01	5.73	9.35	**1.63**
800-23024-01	16.91	19.60	**1.16**
800-23025-01	16.09	21.08	**1.31**
800-23026-01	25.27	20.28	✦ **0.80**

Table 1: CV of Unprotected Rockwell Boards

	μ(old)	σ(old)	CV(old)
800-22321-01	3.63	2.33	✦ **0.64**
800-22322-01	7.13	6.42	✦ **0.90**
800-22323-01	1.38	1.92	**1.40**
800-22324-01	0.25	0.71	**2.83**
800-22325-01	0.75	1.04	**1.38**
800-22326-01	1.00	1.51	**1.51**
800-22327-01	0.25	0.71	**2.83**
800-22328-01	0.25	0.71	**2.83**

Table 2: CV of Protected Rockwell Boards

✦ CV<1

2.3 Value Stream Map of ONG Group

Figure 4 represents the existing value stream map of Cisco's ONG group. It maps the flow of information and product, including cycle times and lead times from the component supplier to customers. The process starts with the product line managers (PLM), who is part of the marketing group, generating a monthly forecast for the next 65 weeks. This forecast is sent to manufacturing, specifically the demand planning manager (DPM), once every month. The forecast is generated by employing both objective and subjective forecasting methods. A moving average of 3 or 6 months is calculated, depending upon the business environment and a forecast is generated based on intelligence gathered by field sales.

Value Stream Map of Cisco's ONG Group

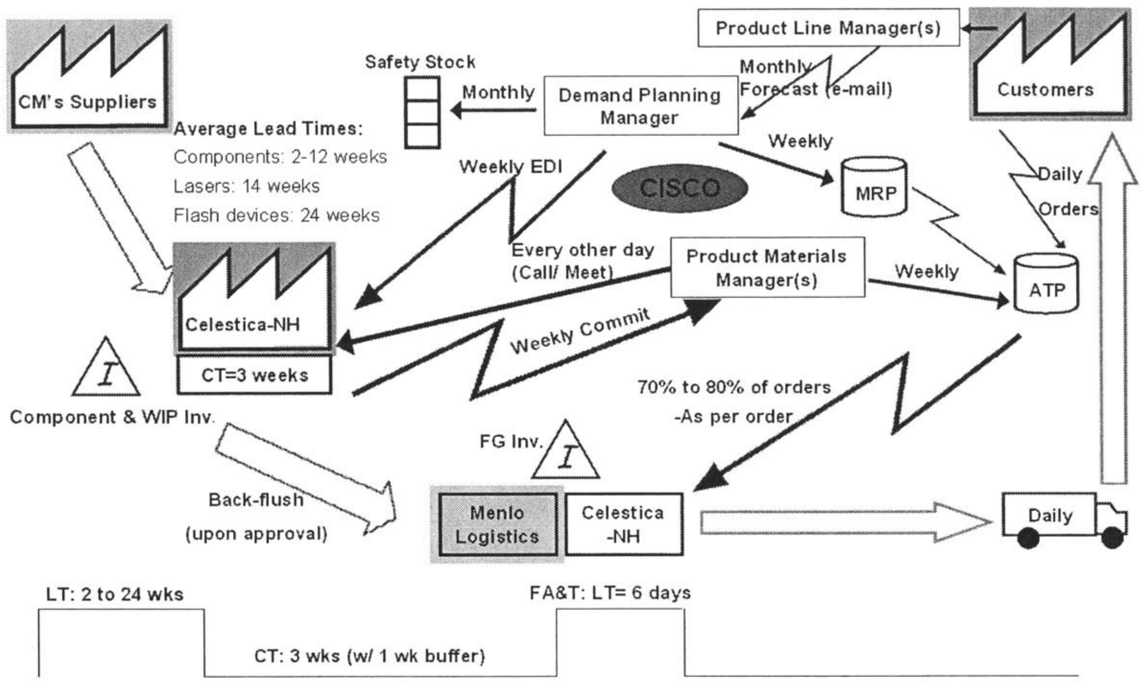


Figure 4: Value Stream Map of Cisco's ONG Group

The DPM is responsible for Rockwell inventory and inventory of all other ONG products. Depending upon the monthly forecast generated by marketing department and current component lead times, DPM sets the safety stock level. The forecast is modified if the DPM 'feels' that it doesn't accurately represent actual demand. In addition, any product that is currently in inventory is automatically scheduled for customer shipment by using the available-to-promise (ATP) system.

Any product that is currently not in inventory is scheduled for production. The forecast is fed into the material resource planning (MRP) system to explode bill-of-material (BOM) for the products on forecast. Next, MRP build is electronically transferred to Celestica via electronic data interchange (EDI). Based on the EDI, which acts as a sales order for Celestica, manufacturing is scheduled and components are purchased as per BOM. The EDI is sent weekly by DPM to Celestica and any new sales information gathered by marketing after the issue of monthly forecast is accommodated into the weekly EDI. EDI is sent Friday of every week and Celestica sends a supply commit to Cisco by Thursday of the following week. Supply commit essentially informs Cisco of Celestica's transformation times and ability to meet EDI requirements. Sometimes Celestica cannot commit to 100% of EDI due to various reasons, including shortage of components, yield issues, and extended component lead times.

The lead times on components range anywhere from 2 to 24 weeks. All passive components are cheap and hence are stocked at Celestica. Typically, lead times for passive components is about 2 weeks or less, however, the lead times for active components, including optics, flash memory, and ASIC can range anywhere from 14 to 24 weeks. Component suppliers are geographically spread-out with some located inside North America and other internationally. Currently no VMI program exists at Celestica and hence every time EDI is issued by Cisco, a component purchase order is issued.

It takes approximately 3 weeks for Celestica to transform various components into a product. The 3 week cycle time contains a 1 week buffer as a cushion against EDI churn rate, which is the change in EDI caused by Cisco. After the product is manufactured it is held at Celestica until such time that Cisco sends an approval to move the product to Menlo Logistics, a 3PL provider. The signal to move inventory to Menlo Logistics is called 'backflush.' The ATP system mentioned above schedules orders through Menlo Logistics. Typically, 70% to 80% of the orders are automatically scheduled by ATP. The product materials managers (PMM) constitute a very crucial link in the overall supply chain. They are responsible for ensuring that components, as and when required, are available at Celestica. Due to the nature of the products, all active components can only be purchased from vendors approved by Cisco. Hence, Celestica is only allowed to purchase active components from Cisco's approved vendors and this relationship is handled by PMMs.

Finally, FedEx ships products from 3PL to customer premises as per the factory commit date. Before products are shipped to customer, final analysis and testing is performed, which typically takes up to 6 days. Once the product has been shipped from 3PL, Cisco's customer service and sales department interacts with the customer to address any issues.

3.1 Inventory Management Policies (base stock and safety stock) [4]

Figure 5 represents inventory level with respect to time. As customer demand is satisfied, inventory is shipped that leads to reduction in inventory level. There are various inventory management policies that recommend 'optimal' inventory levels while avoiding stock out occurrences. Before proceeding any further, a few symbols are defined below:

μ: Average monthly demand faced by manufacturer

σ: Standard deviation of demand faced by manufacturer

L: Lead time of replenishment from supplier to manufacturer (includes transportation lead time)

α: Service level (expressed as a percentage) of manufacturer to customer

z: Safety factor (statistically determined by ensuring probability of stock out during lead time is 1- α)

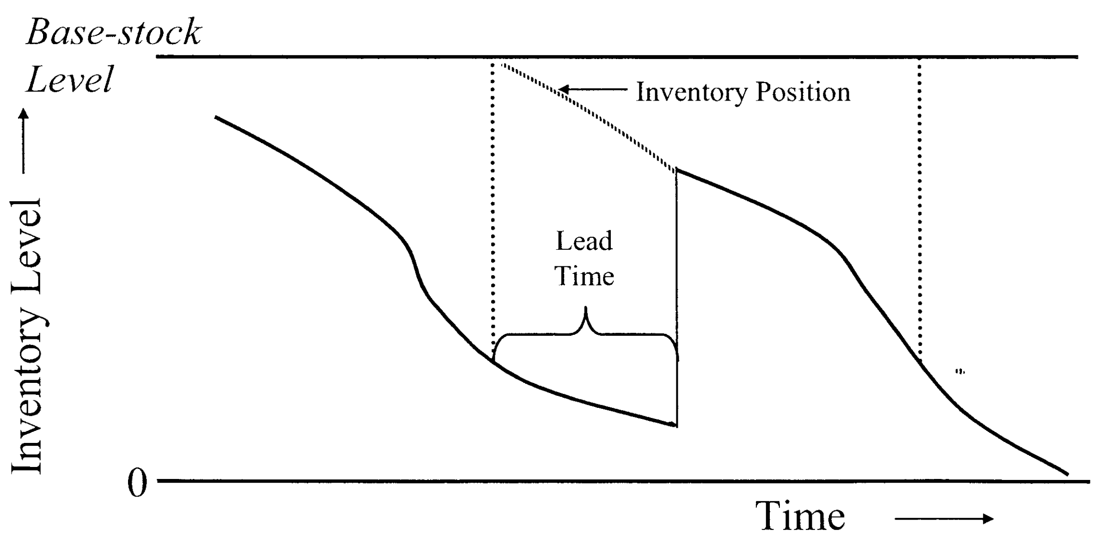


Figure 5: Inventory Level with Time (Adapted from [4])

Typically, inventory is reviewed periodically. The length of the period is determined by a number of factors, including the nature of business and fixed costs incurred in reviewing inventory. At any given point of time, the true measure of 'enterprise-wide' inventory is represented as inventory position. Inventory position is defined as the actual inventory at a given point of time in the warehouse plus inventory in transit plus inventory on order with supplier minus the current sales backlog.

Base-stock Policy, also popularly known as (s,S) policy, suggests an optimal value of reorder point and order-up-to level. Here s refers to the reorder point and S refers to order-up-to level. The difference between order-up-to level and reorder point is caused by fixed costs associated with ordering inventory. Since it takes time 'L' to receive inventory from suppliers, the reorder level contains average inventory during lead time. This is represented as follows:

Average inventory during lead time = $L*\mu$

However, as defined above, average demand faced by manufacturer has a standard deviation and the manufacturer needs to satisfy deviations in average demand, which is represented as follows:

Inventory required to satisfy deviation in average demand= $\sigma * \sqrt{L}$

Customers are guaranteed service levels by manufacturer and hence only part of the deviation in average monthly demand needs to be satisfied, which is represented as follows:

Inventory required to satisfy deviation in average demand based on service levels= $z * \sigma * \sqrt{L}$

Therefore, $s = L * \mu + z * \sigma * \sqrt{L}$

For normally distributed demand, safety factor is determined by calculating the area under the normal curve as shown in figure 6.

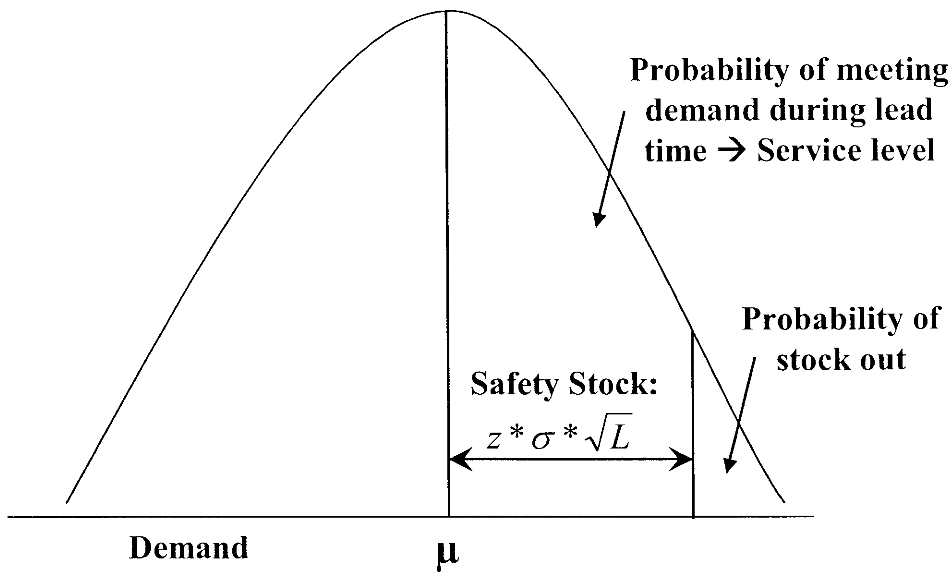


Figure 6: Safety Stock in Normally Distributed Demand

As seen above the reorder level must satisfy the following:

$$\text{Probability [Demand during lead time} \geq L * \mu + z * \sigma * \sqrt{L}] = 1 - \alpha$$

To determine order-up-to level, economic order quantity (EOQ) model needs to be employed. First, we define the following:

k: Fixed costs associated with every order

h: Cost of holding one unit of inventory per unit time at manufacturer

Economic Order Quantity, $Q = \sqrt{\frac{2 * k * \mu}{h}}$

Therefore,

$$S = Q + s$$

3.2 Risk Pooling/ Demand Aggregation [5]

Risk pooling refers to the decrease of relative variation in multi-level inventory systems in which risk is pooled at demand points. Risks may be pooled based on demand across products, geographic region, or time. The risk pooling effect is a consequence of the fact that independent random variables, variances rather than standard deviations, are additive. There are two main factors that impact risk pooling. These are as follows:

1. **Coefficient of variance (CV)**: Defined as the ratio of standard deviation to average demand. Essentially, it represents variation in demand around the mean demand.

2. **Demand Correlation**: Demand can either be positively or negatively correlated. Positive correlation refers to similar behavior whereas negative correlation refers to dissimilar or opposite behavior.

Demand aggregation concept leads to decrease in safety stock and therefore reduction in average inventory. The effects of demand aggregation are significantly increased if the product exhibits high CV and negatively correlated demand.

3.3 Definition and Application of 'Push-based' Supply Chain [6]

In a push-based supply chain, manufacturing decisions are made based on a forecast of customer demand. Push-based supply chains are pro-active as they are built on anticipated customer demand. At a periodic time interval, production occurs based on forecast. It therefore takes push-based supply chains much longer to react to any changes in customer demand or marketplace dynamics. Additionally, there are product obsolescence risks if there are frequent changes in the architecture of the product. Specifically, in an industry where product lifecycles are short, a push-based supply chain can lead to significant excess and obsolescent expenses. A forecast typically has some error and the magnitude of the error increases with the forecast time horizon. Due to the forecast error, large inventory levels need to be maintained to ensure committed customer service levels. In case where manufacturer sells multiple products, push-based supply chains exhibit larger and more variable production batches.

3.4 Definition and Application of 'Pull-based' Supply Chain [6]

In a pull-based supply chain, manufacturing decisions are made based on actual customer demand, as opposed to a forecast in a push-based supply chain. In other words, pull-based supply chains are reactive and hence don't hold any inventory. Due to the reliance of such a supply chain on customer orders, strong tightly integrated information systems are required to communicate customer order to production line. The average inventory at the manufacturer reduces dramatically as production occurs only when a customer order drops in. Furthermore, inventory obsolescence expenses are reduced dramatically and in short-lifecycle product industries pull-based supply chains provide the opportunity to further reduce excess and obsolescence costs. Pull-based supply chains are very responsive and can immediately change to any changes in either customer demand or external environment.

However, pull-based supply chains are difficult to implement as their design is influenced by component lead times. In industries where service level time-frames are shorter than the combined lead times and manufacturing cycle times, inventory needs to be maintained to avoid stock-outs. Additionally, in pull-based supply chains it is often difficult to take advantage of economies of scales in either transportation, component purchasing, or manufacturing batch sizes.

3.5 'Push-Pull' Supply Chain [6]

Leveraging the advantages of both push- and pull-based supply chains, a hybrid supply chain design has emerged. Part of the supply chain is architected to respond to customer order and the other part is proactive- based on customer demand forecast. Although, push-pull supply chains have inventories levels higher than pure pull-based supply chains, they have significantly reduced inventories when compared to push-based supply chains. The amount of inventories is determined by the lead times associated with various components that constitute of the final product. In addition, push-pull supply chains take advantage of concepts such as risk pooling/ demand aggregation, which were discussed earlier in this section. Typically, aggregate forecasts are more accurate than individual product forecasts. Furthermore, demand for a component is an aggregation of demand for all products that use the component and since aggregate forecast of all products is more accurate than forecast of each product, uncertainty and variability at the component level is less than that at product level. The portion of the supply chain that is proactive and employs demand aggregation based on risk pooling at the component level is push-based and the other part of the supply chain that is reactive and responds to actual customer demand is pull-based.

3.6 Selecting Appropriate Supply Chain Strategies [6]

As discussed above, industries that face high demand variability and uncertainty should model their supply chains as pull. However, the model of supply chain also depends upon the lead times of components and cycle time of manufacturing. If the cycle time associated with component transformation into products is higher than the service level time then the supply chain needs to be partly push-based. In addition, another metric to consider while designing supply chain architecture is economies of scale. Economies of scale related to various reasons such as volume purchasing discounts, batch production discounts, and bulk transportation discounts can also influence supply chain architecture. Clearly, as economies of scale increase there is incentive to move towards a manufacturing system based on long-term forecasts. This means supply chain architecture moves closer to a push-based supply chain. Conversely, the supply chain architecture is pull-based if there are low economies of scale. Using a matrix, potential supply chain architectures can be identified as show below in figure 7.

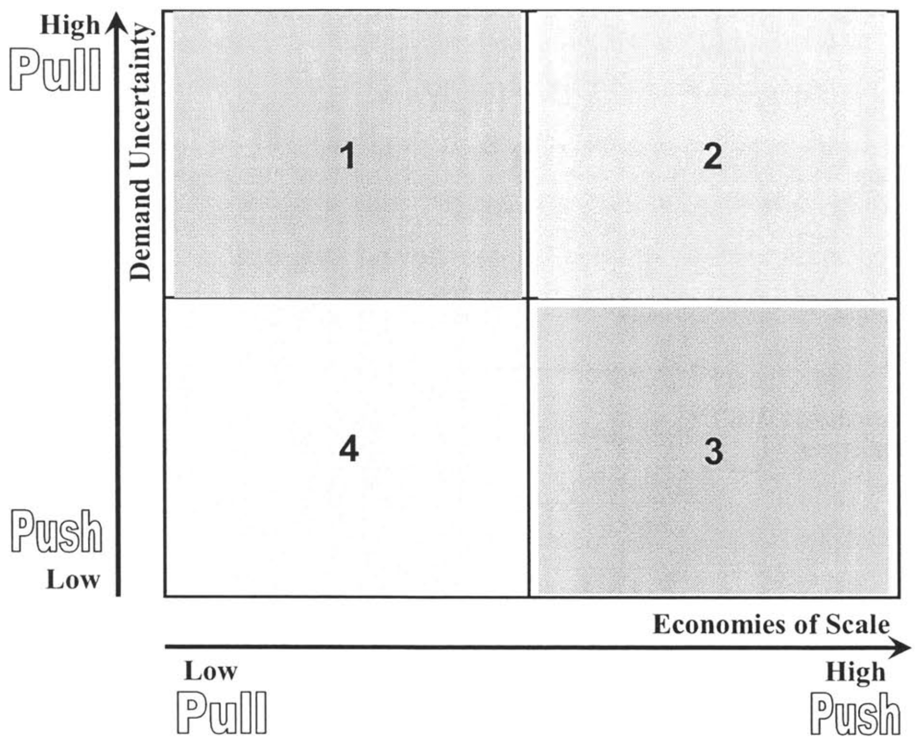


Figure 7: Supply Chain Architecture Selection Matrix (Adapted from [7])

As shown above, industries that fall in quadrant 1 and 3 can easily decide upon the appropriate architecture of their supply chains. For quadrant 1, the best supply chain architecture is pull-based as it represents high demand uncertainty and high economies of scale. On the other hand, for quadrant 3, the best supply chain architecture is push-based as it represents low demand uncertainty and high economies of scale. Quadrants 2 and 4 have conflicting architectures based on demand uncertainty and economies of scale. A more careful analysis is required, since both push strategies and pull strategies may be appropriate, depending on the specific costs and uncertainties. Furthermore, depending upon the industry and advantages that may be derived, both these quadrants are candidates for hybrid architectures- push-pull supply chain architectures.

3.7 Supply Chain with De-centralized and Centralized Information Sharing

3.7.1 Bullwhip Effect [8]

In a multi-echelon supply chain there is an increase in variability further up the supply chain and this phenomenon is called the Bullwhip effect. Consider the following four stage supply chain as shown in figure 8.

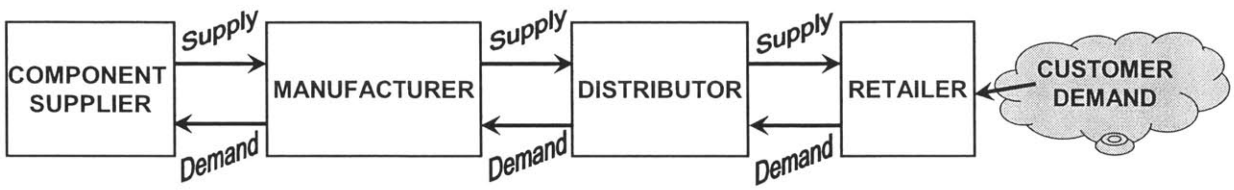


Figure 8: Multi-echelon Supply Chain

Retailer experiences customer demand and request distributor to satisfy demand by supplying products desired by customers. The distributor forecasts retailer demand and expects manufacturer to supply requested products. Similarly, manufacturer requests component supplier to supply requested components so that products requested by distributor may be manufactured. Lastly, component supplier ship components as per manufacturer order.

Distributor needs to satisfy retailer orders. If the distributor doesn't have visibility into customer demand then the distributor needs to forecast retailer demand based on historical sales. To satisfy retailer demand as per service levels, distributors holds extra inventory. Due to changes in customer demand the retailer order to distributor varies but the distributor experience higher variability in demand as compared to demand variability seen by retailer. Subsequent echelons of the supply chain experiences even higher variability with the component supplier experiencing the worst fluctuations in demand. There are many reasons that contribute to demand variability, thereby contributing to bullwhip effect. These are as follows:

- **Forecast**: Demand is forecasted by each echelon of the supply chain. The forecast is based on historical demand patterns. Depending upon the forecast method employed, optimal inventory level may vary. For example, in min-max inventory policy, safety stock and order-up-to levels are determined based on average demand and standard deviation of demand. With time as more historical customer demand is available, average and standard deviation of demand is modified that directly impacts the inventory levels. This increases variability in the supply chains.

- **Lead Time**: Inventory levels are proportional to lead times for products. If lead times are high, higher inventory needs to be maintained to satisfy demand. A small change in estimate of customer demand can lead to large change in inventories when lead times are high. Hence, variability is affected by lead times.

- **Product Price**: Product prices can lead to large variability. When price discounts are introduced then 'stock up' can occur. Subsequent echelons of the supply chain will order more than what is their current demand. They hope to increase profitability by buying low and then trying to sell high. Clearly, this leads to higher variability across the supply chain.

- **Batch Orders**: Any time min-max inventory policy is employed then order-up-to level is ordered every review period. Suppliers experience orders equal to order-up-to level and then no orders are received during the review period. Additionally, incase there are transportation discounts entities will order in batch to take advantage of the cost savings. Such an erratic ordering pattern increases variability in the supply chain.

- **Inflated Orders**: Whenever retailers and distributors suspect that a specific product will be in short supply then they order inflated amounts to satisfy demand during the time when products are in short supply timeframe. When supply is restored then retailers and distributors revert to normal ordering pattern. This fluctuation in order leads to variability.

3.7.2 Quantifying Bullwhip Effect [8]

Using the min-max inventory policy described in earlier section, we obtain the following:

$s = L * \mu + z * \sigma * \sqrt{L}$, where s is the reorder point

Now let's assume that orders are placed at time 't' and orders arrive after 't+L' lead time. The new reorder point is represented as follows:

$$y_t = L * \hat{\mu}_t + z * \sigma_t * \sqrt{L}$$

where y_t is reorder point at time t

$\hat{\mu}_t$ is estimated average demand

σ_t is standard deviation of demand at time t

Now, let's further assume that the retailer uses 'Moving Average' as the demand forecasting method with the average of 'p' periods representing as the demand forecast. Also, D_i represents customer demand in period i. Then we can define, estimate of average demand and standard deviation of demand as follows:

$$\hat{\mu}_t = \frac{\sum_{i=t-p}^{t-1} D_i}{p}$$

$$\sigma_t^2 = \frac{\sum_{i=t-p}^{t-1} (D_i - \hat{\mu}_t)^2}{p-1}$$

It is further assumed that every period retailer calculates a new mean and standard deviation based on the most recent p observations of actual customer demand.

Now, let's assume that the variability experienced by distributor is represented as Var(D) and the variability experienced by retailer is Var(Q) then the bullwhip effect is expressed as follows:

$$\frac{Var(Q)}{Var(D)} \geq 1 + \frac{2 * L}{p} + \frac{2 * L^2}{p^2}$$

3.7.3 Impact of Information Sharing on Bullwhip Effect [8]

To reduce variability across various echelons of the supply chain, information on customer demand should be shared. In other words, if the distributor, manufacturer, and component supplier all get access to the actual customer demand as seen by the retailer then the bullwhip effect can be reduced. One effective way of sharing the customer demand is by centralizing the information flow and giving access to all constituents of the supply chain to view customer demand and then plan their production and manufacturing decisions based on this information.

In case of **centralized demand information**, all the echelons of the supply chain use one estimate of average demand and standard deviation. This estimation is the actual demand forecast generated by retailer, which is closest to the end-consumer. It can be shown that if the variance of the orders placed by the k^th^ stage of the supply chain is $Var(Q^k)$ and the variance of customer demand is $Var(D)$ then the overall variance seen by the k^th^ stage relative to customer demand is as follows:

$$\frac{Var(Q^k)}{Var(D)} \geq 1 + \frac{2\sum_{i=1}^{k} L_i}{p} + \frac{2\left(\sum_{i=1}^{k} L_i\right)^2}{p^2}$$

In case of **decentralized demand information**, the retailer's forecast of customer demand is not made available to other echelons of the supply chain. Hence, each of the echelons- the distributor, manufacturer, and component supplier generate their own forecasts based on historical demand they have seen. Clearly, lack of current customer demand trends increases the variability and can be represented as follows:

$$\frac{Var(Q^{k})}{Var(D)} \geq \prod_{i=1}^{k}\left[1+\frac{2*L_i}{p}+\frac{2*L_i^2}{p^2}\right]$$

Note that for decentralized demand information supply chains, variability is multiplicative as opposed to additive in case of centralized demand information supply chains.

3.8 Forecasting Methods

3.8.1 Characteristics of Forecasts [9]

Forecasts exhibit the following five characteristics:

1. **Usually Wrong**: Forecasts are usually inaccurate and cannot predict actual customer demand. Due to this reason, production decisions need to be adaptive and flexibility needs to be built into the processes to accommodate unexpected customer demands.

2. **Longer the time horizon, the less accurate the forecast**: The accuracy of forecast is inversely proportional to the time horizon of forecast. Sales forecast for the next week is more accurate than the forecast for the next month.

3. **Good forecast is more than a single number**: Given the fact that forecast is usually inaccurate; forecast should include, besides an average demand, a range for anticipated customer demand. This range can either be expressed as forecast error or variance (or standard deviation) of forecasted demand.

4. **Aggregate forecast is more accurate**: The error made in forecasting demand for an entire product line is generally less than the error made in

forecasting demand for an individual product. This is due to the fact the variance of sample mean is smaller than the population variance. Additionally, the variance of the average of a collection of independent identically distributed random variables is lower than the variance of each of the random variables.

5. **Value of forecast increases with inclusion of other known information**: Objective forecasts are generated by analyzing historical demand patterns. However, known information needs to be factored into the forecast to increase accuracy and relevance. For example, if price promotions are introduced then manually objective forecast based on historical demand need to be altered. In addition, if the competition dramatically lowers the prices of its products then manual adjustments need to be made to forecast.

3.8.2 Subjective Forecasting Methods [9]

Subjective forecasting methods are those that formally don't employ analytics or statistics in determining a forecast. Subjective forecasting methods should be used complementary to objective forecast method in order to reduce forecast inaccuracy. Some of the popular subjective forecasting methods are as follows:

1. **Delphi Method**: Delphi method requires a group of experts to express their opinions about customer demand by responding to surveys conduced individually. The results of the individual surveys are then compiled and a summary is circulated to all experts so that they can review the results of other experts. In case there are discrepancies or large inconsistencies in the results then all the experts are requested to reconsider their results. This process is iterated until overall group consensus is reached. Intentionally, no group interaction is allowed to restrict one expert influencing the entire group. Therefore, it is critical that the survey questions be extremely clear, concise, and easy to comprehend so as to ensure an accurate forecast.

2. **Customer Surveys**: Customer surveys method is an effective way of collecting customer preferences. Surveys need to be designed with caution to ensure questions are clear, comprehensive, and easily understandable by customers. Furthermore, sampling plan needs to be carefully designed to ensure resulting data is unbiased and is representative of entire customer base.

3. **Sales Force Composites**: Sales force of a company is closest to customers and constantly obtains information regarding customer preferences. Sales force composite method leverages the proximity of sales force to customers to generate demand forecasts. Sales force generates forecast of products they are tasked to sell for a given time frame- week, month, or quarter. The individual forecast of each salesman is then aggregated to arrive at the total sales forecast for the product during the timeframe. One important observation regarding sales force composites is that 'you get what you measure.' In other words, if sales force incentive mechanisms are misaligned then the sales force has incentive to over- or under-estimate customer demand.

3.8.3 Objective Forecasting Methods

Measure of Forecast Error [9]

The forecast error in period 't' is defined as e_t , which is represented as the difference between the forecasted value of demand and the actual demand during the same period. Forecast error is represented as follows:

$$e_t = F_t - D_t$$

where, F_t is the forecasted demand in period t

D_t is the actual demand in period t

There are three common measures of determining forecast accuracy that are explained below:

- **Mean Absolute Deviation (MAD)**:

  MAD is one of more preferred methods of calculating forecast error since it doesn't require squaring of forecast errors as in the case of MSE. It is calculated as the mean of absolute values of forecast errors and represented as follows:

  $$MAD = (1/n)\sum_{i=1}^{n}|e_i|$$

  When the forecast errors are assumed to be normally distributed then the estimate of standard deviation of forecast error, σ_e is represented as follows:

  $$\sigma_e = 1.25 * MAD$$

- **Mean Squared Error (MSE)**:

  MSE is similar to variance of a random sample. It is calculated as the mean of squared forecast errors and represented as follows:

  $$MSE = (1/n)\sum_{i=1}^{n}e_i^2$$

- **Mean Absolute Percentage Error (MAPE)**:

  Unlike MAD and MSE, MAPE is independent of the magnitude of the values of demand. It is calculated as the mean of the ratio of forecast error to the demand and expressed as follows as a percentage:

  $$MAPE = \left[(1/n)\sum_{i=1}^{n}\left|\frac{e_i}{D_i}\right|\right] * 100$$

Forecasting Methods for Stationary Series [9]

Stationary series is one in which each observation can be represented by a constant plus a random fluctuation. Although there are many forecasting methods for stationary series, only the following three methods relevant to this paper are discussed.

1. **Moving Average (MA)**: A very popular method for forecasting, MA is based on calculating demand forecast based on a simple arithmetic mean of the most recent 'N' observations of actual demand. Such a method is also known as one-step-ahead or simple moving average method. Therefore, demand forecast for period 't', F_t , is represented as follows:

   $$F_t = \left(\frac{1}{n}\right)\sum_{i=t-N}^{t-1} D_i$$

   In other words, forecast for period 't' is the mean of actual demand for N periods. This is also represented as MA(N) for N period moving average. All forecasts for future periods are the same for one-step-ahead moving average. For example, a moving average for 3 months performed in month 6 will yield a forecast for month 7 and this is the forecast for all subsequent months. Therefore, one-step-ahead moving average needs to be computed every period.

   An important observation for moving average is that forecast lags behind the trend. Furthermore, moving average forecast is dependent on the value of N periods selected for forecast. A forecast based on a higher N will lag more behind the trend. Clearly, simple moving average is not recommended in industries where there is a trend in sales.

2. **Exponential Smoothing**: In exponential smoothing method, demand forecast is the weighted average of the last forecast and the current value

of demand. Relative weights are assigned to last forecast and current demand to obtain the next forecast. This is represented as follows:

New forecast= α (Current observation of demand)+ (1- α)(Last forecast)

or

$$F_t = \alpha * D_{t-1} + (1-\alpha) * F_{t-1}, \text{ where } 0 < \alpha \le 1$$

α is the smoothing constant

By rearranging terms, demand forecast in time ‘t’ is represented as follows:

$$F_t = F_{t-1} - \alpha * e_{t-1}, \text{ where the forecast error, } e_t = F_{t-1} - D_{t-1}$$

Further, we can rearrange terms as follows:

$$F_{t-1} = \alpha * D_{t-2} + (1-\alpha) * F_{t-2}$$

$$\Rightarrow F_t = \alpha * D_{t-1} + \alpha * (1-\alpha) * D_{t-2} + (1-\alpha)^2 * F_{t-2}$$

Continuing in the same way, we can obtain infinite expansion for F_t,

$$\Rightarrow F_t = \sum_{i=0}^{\infty} \alpha * (1-\alpha)^i * D_{t-i-1}$$

Therefore, exponential smoothing assigns declining weights to all past data. The role of smoothing constant in exponential smoothing is extremely important. If α is large, more weight is assigned on current observation of demand and less weight on past observations, which results in forecasts that will react quickly to demand changes but will exhibit larger variations from period to period. On the other hand, if α is small, then more weight is assigned on past observations and hence the forecast is more stable.

3. **Double Exponential Smoothing Using Holt’s Method**: Double exponential smoothing using Holt’s method is used to generate demand

forecast for time series with linear trend. The method requires the use of two smoothing constants, α and β as per the following equation:

$$S_t = \alpha * D_t + (1-\alpha) * (S_{t-1} + G_{t-1})$$

$$\Rightarrow G_t = \beta * (S_t - S_{t-1}) + (1-\beta) * G_{t-1}$$

where, S_t represents the value of intercept of the regression line (Demand vs. Time) at time 't' and G_t is the value of the slope at time 't.'

When the most current observation of demand, D_t, becomes available, it is averaged with the prior forecast of the current demand, which is the previous intercept, S_{t-1}, plus 1 times the previous slope, G_{t-1}. Further, the new estimate of intercept, S_t, causes a revision to estimate of slope to $S_t - S_{t-1}$. The smoothing constants may be the same; however, more stability is given to the slope estimate implying $\beta \le \alpha$.

Chapter 4: Approach and Model Development

4.1 Approach

To explore potential savings by re-engineering ONG supply chain, a pilot analysis was performed on 'Rockwell board'. As mentioned earlier, service level for Cisco's ONG group is 3 weeks for 90% of the orders. However, internal divisions of Cisco are also customers of Cisco's ONG group. The internal orders are not forecasted and hence the service level is higher and currently stands at 6 weeks. Historically, ONG has not analyzing past internal demand to generate a forecast of future internal demand. Obviously, opportunities exist to plan for future demand and also to explore any correlation between internal and external demand. For example, typically, if sales of a specific product go up then customer service will follow soon after to purchase the same product so as to honor product performance guarantee and warranty agreements. To leverage any synergies in buying pattern, demand was divided into two parts- internal and external. For modeling inventory, internal and external demand was considered as two separate customers with two different lead times. Next, the cost of goods sold (COGS) of the end- product was obtained. Additionally, costs of components and work-in-progress inventory were calculated based on extrapolation of available data. The goal of determining costs was to obtain the total value of inventory position across the entire enterprise, including Celestica. Table 3 contains normalized information on costs of Rockwell boards, WIP inventory, and optics.

	MR: 800-230XX-01	MRP: 800-2232X-01	MR: 73-8267-07	MRP: 73-8266-07	MR: Optic (10-X)	MRP: Optic (10-X)
Cost	$5,000	$5,950	$1,800	$3,126	$1,253	$1,108
Delta	~$900		~$900			
Percentage			36%	53%	25%	19%

Table 3: Rockwell Board Cost Information

As discussed earlier, Rockwell boards are sold as two variants- protected and unprotected. All 8 SKUs for protected platform use the same 73-level board and the remaining 8 SKUs for unprotected platform use another 73-level board. In other words, there are only 2 types of 73-level boards, each of which corresponds to either protected or unprotected platform. The difference between the cost of protected board and unprotected board is approximately $900. As a percentage of the total costs, platform for the protected board is 53% whereas the platform for unprotected board is 36%. Each Rockwell board has a unique optic, which corresponds to a wavelength ordered by the customer. Optics for both protected and unprotected board are the same, however, due to the difference in the cost of the platform as a percentage of the total cost, optics for protected board constitute 19% of the cost whereas optics for unprotected board constitute 25% of the cost. There are two important observations to be made from the table above:

1. Given the cost structure, intuitively, one should hold less number of 73-level boards, i.e. WIP-level inventory, compared to optics.

2. Since there are two types of 73-level boards that are used across all 16 SKUs, demand aggregation can be applied at the 73-level.

For the same service level, we can reduce safety stock and average inventory by performing demand aggregation. Typically, high CV and negatively correlated demand leads to reduction in required safety stock. 73-level is where demand aggregation may be applied. Hence, all the demand for unprotected boards was added on a monthly basis to obtain total unprotected board monthly demand. Similarly, total protected board monthly board was computed. As discussed earlier, demand from internal divisions is different from demand from customers. Hence, as shown in table 4 for each of protected products (MRP) and unprotected products (MR), actual demand was aggregated for internal and external customers.

	μ(old)	σ(old)	CV(old)
MR TOTAL	94.00	65.38	✦ 0.70

Unprotected Boards Demand- External Customers

	μ(old)	σ(old)	CV(old)
MRP TOTAL	14.63	8.05	✦ 0.55

Protected Boards Demand- External Customers

	μ(old)	σ(old)	CV(old)
MR TOTAL	27.38	22.47	✦ 0.82

Unprotected Boards Demand- Internal Customers

	μ(old)	σ(old)	CV(old)
MRP TOTAL	8.27	8.78	1.06

Protected Boards Demand- Internal Customers

✦ CV<1

Table 4: Rockwell Board Aggregate Demand

As seen above, for all but one, CV is reduced to less than 100%. In fact, CV is about 55% for external customer demand of protected boards, which is dramatically lower to CV of individual products. However, there are additional opportunities available to further reduce CV. For example, if demand is analyzed as a combination of 'stable' and 'peak' demand then CV can be further reduced. Clearly, as discussed earlier, there is large variability in demand and this variability is driven by orders received by Cisco's customers. In other words, whenever there is a large order received by Cisco's customer, Cisco experiences huge demand surge. At all other times, customer orders are at a steady state. The challenge here is how to separate peak demand from stable demand. Since only 11 months of sales data was available for Rockwell boards, hence it was relatively easy to determine a threshold for stable demand. Any demand that exceeded twice the average demand for 11 months was considered as peak demand.

Next, average for stable demand was computed by removing the peak demand. Similarly, peak demand was computed by subtracting the average demand for peaks only by stable demand. As seen in table 5, CV of stable and peak demand was computed. For peak demand, the average and standard deviation of demand was computed and the average of stable demand is subtracted from that. This is done because when peak demand occurs there will be no stable demand and conversely when stable demand occurs then peak demand will not occur. Clearly as seen below for both internal and external demand and for protected and unprotected boards, CV is brought down considerably and for all 4 scenarios the CV is less than 100%.

	μ(old)	σ(old)	✦ CV(old)
MR TOTAL (Stable)	34.09	19.07	0.56

↓ μ(peak)= μ(calc.)- μ(old)

	μ(peak)	σ(peak)	✦ CV(peak)
MR TOTAL(Peaks)	86.60	54.72	0.63

Unprotected Boards Demand- External Customers

	μ(old)	σ(old)	✦ CV(old)
MRP TOTAL (Stable)	6.00	5.60	0.93

↓ μ(peak)= μ(calc.)- μ(old)

	μ(peak)	σ(peak)	✦ CV(peak)
MRP TOTAL (Peaks)	2.33	0.58	0.25

Protected Boards Demand- External Customers

✦ CV<1

	μ(old)	σ(old)	✦CV(old)
MR TOTAL (Stable)	11.50	7.56	0.66

↓ μ(peak)= μ(calc.)- μ(old)

	μ(peak)	σ(peak)	✦CV(peak)
MR TOTAL (Peaks)	26.33	25.79	0.98

Unprotected Boards Demand- Internal Customers

	μ(old)	σ(old)	✦CV(old)
MRP TOTAL (Stable)	12.13	6.20	0.51

↓ μ(peak)= μ(calc.)- μ(old)

	μ(peak)	σ(peak)	✦CV(peak)
MRP TOTAL (Peaks)	9.50	2.12	0.22

Protected Boards Demand- Internal Customers

✦ CV<1

Table 5: Aggregate Demand (Peak and Stable) of Rockwell Boards

4.2 Optimization Software (Logic-Tools)

Inventory Analyst is an inventory optimization software solution that helps businesses improve their profitability by strategically positioning inventory across the supply chain. It leverages non-linear optimization techniques to free up working capital tied up in inventory. Additionally, Inventory Analyst helps reduce obsolete inventory, improve service levels while maintaining or even reducing inventory, manage demand fluctuations, and recommends optimal location of inventory across the supply chain. The key strength of Inventory Analyst, unlike other commercial software packages, is that it considers inventory across the complete supply chain instead of a single facility, which enables Inventory Analyst to perform global optimization, instead of local optimization.

For more information about Inventory Analyst, please visit http://www.logic-tools.com/solutions/inventory_analyst.html.

4.3 Model Inputs

To optimize inventory various inputs are required. A snapshot of all inputs is presented below. Following data is only for Rockwell boards and has been normalized to protect confidential information. Table 6 explodes the BOM of two SKUs, 800-22321-01 and 800-22322-01, to the first level and lists what quantity of each component constitutes the SKU. Please note that some of the components listed below are in fact WIP-level inventory and can further be broken down. For simplicity, only first-level BOM explosion is shown here.

Assembly Product	Assembly Product ID	Component Product	Component Product ID	Quantity
800-22321-01	1	05-1048-01	100	1
800-22321-01	1	10-1753-01	101	2
800-22321-01	1	10-1756-02	102	1
800-22321-01	1	47-15591-01	119	1
800-22321-01	1	471-00019-01	110	1
800-22321-01	1	501-00155-04	127	1
800-22321-01	1	69-0983-04	128	1
800-22321-01	1	73-8266-07	130	1
800-22321-01	1	800-22154-06	132	1
800-22322-01	2	05-1048-01	100	1
800-22322-01	2	10-1753-01	101	2
800-22322-01	2	10-1757-02	103	1
800-22322-01	2	47-15592-01	120	1
800-22322-01	2	471-00019-01	110	1
800-22322-01	2	501-00155-04	127	1
800-22322-01	2	69-0983-04	128	1
800-22322-01	2	73-8266-07	130	1
800-22322-01	2	800-22154-06	132	1

Table 6: First-level BOM of 2 Rockwell SKUs

To forecast inventory levels, the model requires information on various customers. In the model, as mentioned earlier, we assume only two customers. First, external customers were modeled which included enterprise customers and service providers such as IBM, Verizon, and SBC Datacomm. All of these external customers are modeled with the same service level of 3 weeks. The second customer group is internal customers and they were modeled with a 6 week service level. Table 7 lists all major customers and table 8 lists service levels and Cisco's maximum committed service levels. It is important here to note that internal customers are categorized as non-revenue as Cisco manufacturing cannot count sales towards internal orders as part of their revenue targets. Further, as shown in table 8, it is assumed that there is unlimited storage capacity available at the customer's warehouse and also at Cisco's warehouse.

ID	Name	Group	Location
1	Cisco Internal	Non-Revenue	Various
2	IBM	Revenue	Various
3	Verizon	Revenue	Various
4	KDL Inc	Revenue	Various
5	Road Runner	Revenue	Various
6	SBC DATACOMM	Revenue	Various
7	Sprint	Revenue	Various
8	Others	Revenue	Various

Table 7: List of Major Customers

Customer	Product	Service Level (%)	Max Committed Service Time	Storage Capacity
Cisco Internal	800-23021-01	90	42	999999999
Cisco Internal	800-23022-01	90	42	999999999
Cisco Internal	800-23023-01	90	42	999999999
Cisco Internal	800-23024-01	90	42	999999999
Cisco Internal	800-23025-01	90	42	999999999
Cisco Internal	800-23026-01	90	42	999999999
IBM	800-22321-01	90	21	999999999
IBM	800-22322-01	90	21	999999999
Verizon	800-22325-01	90	21	999999999
Verizon	800-22326-01	90	21	999999999
Verizon	800-22327-01	90	21	999999999
Verizon	800-22328-01	90	21	999999999
KDL Inc	800-22328-01	90	21	999999999
KDL Inc	800-23019-01	90	21	999999999
KDL Inc	800-23020-01	90	21	999999999
KDL Inc	800-23021-01	90	21	999999999
Road Runner	800-23022-01	90	21	999999999
Road Runner	800-23023-01	90	21	999999999
Road Runner	800-23024-01	90	21	999999999
Road Runner	800-23025-01	90	21	999999999
Road Runner	800-23026-01	90	21	999999999
SBC DATACOMM	800-22321-01	90	21	999999999
SBC DATACOMM	800-22322-01	90	21	999999999
SBC DATACOMM	800-22323-01	90	21	999999999
Sprint	800-23019-01	90	21	999999999
Sprint	800-23020-01	90	21	999999999
Sprint	800-23021-01	90	21	999999999
Sprint	800-23022-01	90	21	999999999
Sprint	800-23023-01	90	21	999999999
Sprint	800-23024-01	90	21	999999999
Sprint	800-23025-01	90	21	999999999
Sprint	800-23026-01	90	21	999999999
Others	800-22321-01	90	21	999999999
Others	800-22322-01	90	21	999999999
Others	800-22323-01	90	21	999999999
Others	800-22324-01	90	21	999999999

Table 8: Customer Service Levels

Further, weekly customer demand per SKU is represented below in table 9. Customer demand is characterized as average and standard deviation of weekly demand. Please note that all external customers are grouped into the 'Customer' category and all internal customers are grouped into the 'Cisco Internal' category.

Customer	Product ID	Product	Time Period ID	Time Period	Demand	Demand Std Dev
Customers	1	800-22321-01	1	Weekly Period	1.00	2.83
Customers	2	800-22322-01	1	Weekly Period	0.88	1.46
Customers	3	800-22323-01	1	Weekly Period	0.13	0.35
Customers	4	800-22324-01	1	Weekly Period	0.25	0.71
Customers	5	800-22325-01	1	Weekly Period	0.00	0.00
Customers	6	800-22326-01	1	Weekly Period	1.38	2.07
Customers	7	800-22327-01	1	Weekly Period	1.13	3.18
Customers	8	800-22328-01	1	Weekly Period	2.38	3.02
Customers	9	800-23019-01	1	Weekly Period	12.38	13.07
Cisco Internal	9	800-23019-01	1	Weekly Period	9.63	10.01
Cisco Internal	10	800-23020-01	1	Weekly Period	0.50	0.93
Cisco Internal	11	800-23021-01	1	Weekly Period	5.63	6.93
Cisco Internal	12	800-23022-01	1	Weekly Period	5.13	6.45
Cisco Internal	13	800-23023-01	1	Weekly Period	1.75	3.81
Cisco Internal	14	800-23024-01	1	Weekly Period	0.63	1.19
Cisco Internal	15	800-23025-01	1	Weekly Period	1.75	2.66
Cisco Internal	16	800-23026-01	1	Weekly Period	2.25	3.24

Table 9: Internal and External Customer Demand

Network visualization of the model created for Rockwell boards is as shown in figure 9. As seen below, all the component suppliers were grouped into one component supplier with different lead times on components and different service levels were assigned to each component. Components are supplied to contract manufacturer, Celestica, where manufacturing and final assembly occurs. The 3PL is considered part of Cisco and demand was modeled based on two customers- internal and external.

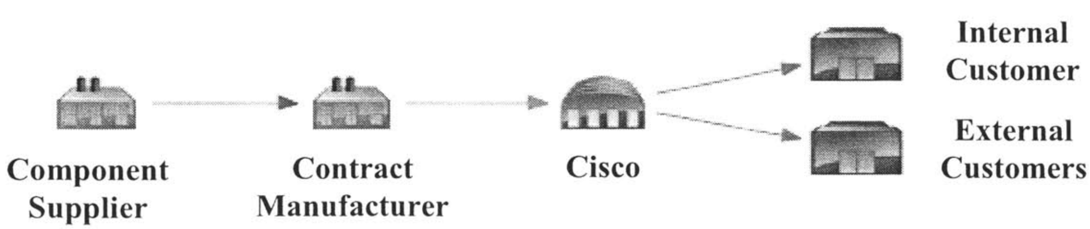


Figure 9: Network Visualization of Supply Chain

As seen in table 10 below, NHM refers to Celestica located in Salem, New Hampshire. The products listed below are first-level components that constitute finished product (SKU). Celestica does not hold first-level inventory; in fact, on a monthly basis, depending upon the EDI received from Cisco a purchase order is issued to component suppliers. Hence, as a model input, no information was entered for inventory of components.

Plant ID	Plant	Product	Current Base Stock Level	Current Total Inventory	Current Safety Stock
1	NHM	05-1048-01	0	0	0
1	NHM	10-1753-01	0	0	0
1	NHM	10-1756-02	0	0	0
1	NHM	47-15591-01	0	0	0
1	NHM	471-00019-01	0	0	0
1	NHM	501-00155-04	0	0	0
1	NHM	62-10895-01	0	0	0
1	NHM	69-0983-04	0	0	0
1	NHM	73-8266-07	0	0	0
1	NHM	800-22154-06	0	0	0
1	NHM	93-1744-01	0	0	0
1	NHM	93-1745-01	0	0	0
1	NHM	93-1746-01	0	0	0
1	NHM	93-1749-01	0	0	0

Table 10: Inbound Product Inventory at Celestica

Component suppliers, referred herein as 'Supplier', provide components to NHM based upon a pre-agreed transit time. The service level information for components was entered as an input in the model. All times are expressed in weeks. Table 11 lists transit times of all major components.

Source Plant	Destination Plant	Product	Transit Time	Transit Time Std Dev	Max Committed Service Time
Supplier	NHM	05-1048-01	0.03	0.14	1
Supplier	NHM	10-1753-01	0.03	0.14	2
Supplier	NHM	10-1756-02	0.03	0.14	1
Supplier	NHM	10-1757-02	0.03	0.14	1
Supplier	NHM	10-1758-02	0.03	0.14	1
Supplier	NHM	10-1759-02	0.03	0.14	1
Supplier	NHM	10-1760-02	0.03	0.14	1
Supplier	NHM	10-1761-02	0.03	0.14	1
Supplier	NHM	10-1762-02	0.03	0.14	1
Supplier	NHM	10-1763-02	0.03	0.14	1
Supplier	NHM	471-00019-01	0.03	0.14	0.72
Supplier	NHM	47-15583-01	0.03	0.14	0.72
Supplier	NHM	47-15584-01	0.03	0.14	0.72
Supplier	NHM	47-15585-01	0.03	0.14	0.72
Supplier	NHM	47-15586-01	0.03	0.14	0.72
Supplier	NHM	47-15587-01	0.03	0.14	0.72
Supplier	NHM	47-15588-01	0.03	0.14	0.72
Supplier	NHM	47-15589-01	0.03	0.14	0.72
Supplier	NHM	47-15590-01	0.03	0.14	0.72
Supplier	NHM	47-15591-01	0.03	0.14	0.72
Supplier	NHM	47-15592-01	0.03	0.14	0.72
Supplier	NHM	47-15593-01	0.03	0.14	0.72
Supplier	NHM	47-15594-01	0.03	0.14	0.72
Supplier	NHM	47-15595-01	0.03	0.14	0.72
Supplier	NHM	47-15596-01	0.03	0.14	0.72
Supplier	NHM	47-15597-01	0.03	0.14	0.72
Supplier	NHM	47-15598-01	0.03	0.14	0.72
Supplier	NHM	501-00155-04	0.03	0.14	0.36
Supplier	NHM	69-0983-04	0.03	0.14	0
Supplier	NHM	69-1025-04	0.03	0.14	0
Supplier	NHM	73-8266-07	0.03	0.14	0.75
Supplier	NHM	73-8267-07	0.03	0.14	0.75
Supplier	NHM	800-22154-06	0.03	0.14	0
Supplier	NHM	800-22155-06	0.03	0.14	1.25

Table 11: Transit Times of All Major Components

Menlo Logistics, the 3PL provider, is considered part of Cisco and it holds inventory on behalf of Cisco. Contract manufacturer and 3PL is collated within the same campus in New Hampshire and hence the transit time is in hours, which is listed in table 12. Here Menlo Logistics is referred to as NHM-STKPCB. It is important to note that only finished goods inventory is held at Menlo and any

WIP-level and component-level inventory is held at Celestica- NHM. As seen below finished products, i.e. Rockwell SKUs, are shipped from NHM to NHMSTKPCB.

Source Plant	Destination Warehouse	Product	Transit Time	Transit Time Std Dev	Min Committed Service Time	Max Committed Service Time
NHM	NHM-STKPCB	800-22321-01	0.01	0	0.01	2
NHM	NHM-STKPCB	800-22322-01	0.01	0	0.01	2
NHM	NHM-STKPCB	800-22323-01	0.01	0	0.01	2
NHM	NHM-STKPCB	800-22324-01	0.01	0	0.01	2
NHM	NHM-STKPCB	800-22325-01	0.01	0	0.01	2
NHM	NHM-STKPCB	800-22326-01	0.01	0	0.01	2
NHM	NHM-STKPCB	800-22327-01	0.01	0	0.01	2
NHM	NHM-STKPCB	800-22328-01	0.01	0	0.01	2
NHM	NHM-STKPCB	800-23019-01	0.01	0	0.01	2

Table 12: Plant to Warehouse Transit Time

For both external and internal customers, Cisco is bound by service levels committed in sales contracts. Part of the service levels is the transit times, which are listed below in table 13. Please note that the transit times are the same for internal and external customers.

Source Warehouse	Destination Customer	Product	Transit Time	Transit Time Std Dev	Min Committed Service Time	Max Committed Service Time
NHM-STKPCB	Customers	800-22321-01	0.57	0.3	0.15	1
NHM-STKPCB	Customers	800-22322-01	0.57	0.3	0.15	1
NHM-STKPCB	Customers	800-22323-01	0.57	0.3	0.15	1
NHM-STKPCB	Customers	800-22324-01	0.57	0.3	0.15	1
NHM-STKPCB	Customers	800-22325-01	0.57	0.3	0.15	1
NHM-STKPCB	Customers	800-22326-01	0.57	0.3	0.15	1
NHM-STKPCB	Customers	800-22327-01	0.57	0.3	0.15	1
NHM-STKPCB	Customers	800-22328-01	0.57	0.3	0.15	1
NHM-STKPCB	Cisco Internal	800-23021-01	0.57	0.3	0.15	1
NHM-STKPCB	Cisco Internal	800-23022-01	0.57	0.3	0.15	1
NHM-STKPCB	Cisco Internal	800-23023-01	0.57	0.3	0.15	1
NHM-STKPCB	Cisco Internal	800-23024-01	0.57	0.3	0.15	1
NHM-STKPCB	Cisco Internal	800-23025-01	0.57	0.3	0.15	1
NHM-STKPCB	Cisco Internal	800-23026-01	0.57	0.3	0.15	1

Table 13: Warehouse to Customer Transit Time

A snapshot of inventory was taken to record product inventory at 3PL. As expected, it was observed that the inventory levels were directly proportional to the accuracy of demand forecast. As seen in table 14 some SKUs such as 800-23019-01 had 206 units available because an order was forecasted but it never materialized and hence inventory was stuck in the warehouse. On the other hand, SKU such as 800-22323-01 had just 7 units in inventory.

Warehouse	Product	Time Period	Current Average Inventory
NHM-STKPCB	800-22321-01	Weekly Period	21
NHM-STKPCB	800-22322-01	Weekly Period	14
NHM-STKPCB	800-22323-01	Weekly Period	7
NHM-STKPCB	800-22324-01	Weekly Period	13
NHM-STKPCB	800-22325-01	Weekly Period	19
NHM-STKPCB	800-22326-01	Weekly Period	10
NHM-STKPCB	800-22327-01	Weekly Period	12
NHM-STKPCB	800-22328-01	Weekly Period	17
NHM-STKPCB	800-23019-01	Weekly Period	226
NHM-STKPCB	800-23020-01	Weekly Period	70
NHM-STKPCB	800-23021-01	Weekly Period	102
NHM-STKPCB	800-23022-01	Weekly Period	66
NHM-STKPCB	800-23023-01	Weekly Period	89
NHM-STKPCB	800-23024-01	Weekly Period	68
NHM-STKPCB	800-23025-01	Weekly Period	84
NHM-STKPCB	800-23026-01	Weekly Period	55

Table 14: Warehouse Inventory

Service level includes processing time, which is the time it takes for the warehouse to process any customer orders. Table 15 lists the processing times of all Rockwell SKUs. As seen below, Cisco needs to maintain its service levels on 90% of the total orders. However, sometimes customer requests a delivery date which falls before the service level of Cisco. In this case, depending upon the importance of the customer to Cisco's business, Cisco tries to expedite the order. In our model it was assumed that early shipments are not allowed.

Warehouse	Product	Service Level (%)	Processing Cost	Processing Time	Processing Time Std Dev	Receipt Period	Reorder Period	Early Shipments Allowed
NHM-STKPCB	800-22321-01	90	30	0.57	0.3	1	1	FALSE
NHM-STKPCB	800-22322-01	90	30	0.57	0.3	1	1	FALSE
NHM-STKPCB	800-22323-01	90	30	0.57	0.3	1	1	FALSE
NHM-STKPCB	800-22324-01	90	30	0.57	0.3	1	1	FALSE
NHM-STKPCB	800-22325-01	90	30	0.57	0.3	1	1	FALSE
NHM-STKPCB	800-22326-01	90	30	0.57	0.3	1	1	FALSE
NHM-STKPCB	800-22327-01	90	30	0.57	0.3	1	1	FALSE
NHM-STKPCB	800-22328-01	90	30	0.57	0.3	1	1	FALSE
NHM-STKPCB	800-23019-01	90	30	0.57	0.3	1	1	FALSE
NHM-STKPCB	800-23020-01	90	30	0.57	0.3	1	1	FALSE
NHM-STKPCB	800-23021-01	90	30	0.57	0.3	1	1	FALSE
NHM-STKPCB	800-23022-01	90	30	0.57	0.3	1	1	FALSE
NHM-STKPCB	800-23023-01	90	30	0.57	0.3	1	1	FALSE
NHM-STKPCB	800-23024-01	90	30	0.57	0.3	1	1	FALSE
NHM-STKPCB	800-23025-01	90	30	0.57	0.3	1	1	FALSE
NHM-STKPCB	800-23026-01	90	30	0.57	0.3	1	1	FALSE

Table 15: Warehouse Processing Time

4.4 Model Assumptions

In order to perform inventory optimization, assumptions were made to translate Cisco's supply chain, and business paradigm, into a mathematical model. The following is a list of these assumptions:

- All component suppliers were grouped together into one category to simplify the inputs of the model. However, lead times of all components were maintained to keep authenticity and validity of results.

- Internal customers, i.e. divisions of Cisco, are shipped products at current lead times, instead of the 6 weeks assumed in the model. In some cases if there is no external customer backlog then the turnaround time is much less than 6 weeks. On the other hand if there is a large external customer backlog then internal customers need to wait for more than 6 weeks. In order to model the supply chain, after discussion with manufacturing manager, a mean service level of 6 week was assumed for optimization.

- Some of the component costs were computed based on extrapolation of cost information available on similar components. Due to restricted visibility of component costs some cost assumptions were made. However, all assumptions were validated with management so as to ensure realistic results.

- Service level for external customers was assumed to be 3 weeks. In reality, depending upon the backlog, sometimes this service level may be increased at the time of signing of a sales contract. Conversely, some customers are assured less than 3 week lead time due to their special relationship with Cisco. Some of these special customers are large customers, in terms of revenue, of Cisco.

- The manufacturing and transformation cycle times at Celestica are accurate and based on interviews conducted at Celestica and Cisco. However, these cycle times have buffer built in them and hence are not the average cycle times but are higher than the average. Celestica has built in time buffers because they are sometimes required to react to customer demand that it outside the monthly forecast and such buffers help them to execute on these special requests.

- It is assumed that the demand forecast generated by marketing and sales department is directly sent to Celestica as an EDI order to build. In reality, the DPM, based on his experience, modifies the forecast. There is was no methodology in which DPM scrubs the forecast, other than looking at past demand and normalizing any peaks, and hence it was assumed that the sales forecast is directly sent to Celestica.

4.5 Model Development

Based on the inputs mentioned earlier, Inventory Analyst was run to optimize inventory across the enterprise, including Celestica. Demand aggregation was performed by aggregating sales at the WIP-level inventory, i.e. 73-level. Since there are two types of 73-level inventory, each of which corresponds to 8 SKUs of

Rockwell boards considerable inventory reduction can be achieved by performing risk pooling at the 73-level. However, optics are unique and there are a total of 8 different wavelengths that customers can order from. Hence, risk pooling advantages will not benefit optics inventory. However, given the fact, 11 months actual sales data is available, a forecast of optics can be generated for the next 6 months. The goal is to establish a push-type inventory bucket of all 8 wavelengths and analyze the existence of any trends in the sales of any specific optics. To generate forecast of optics and analyze seasonality/ trend, Crystal Ball Predictor software tool was used. A forecast for the next 6 months was generated by analyzing the historical data of 11 months. A regression line was fit to project future sales. Among the various forecasting methods, the following were considered by the software tool:

Non trend-based Analysis

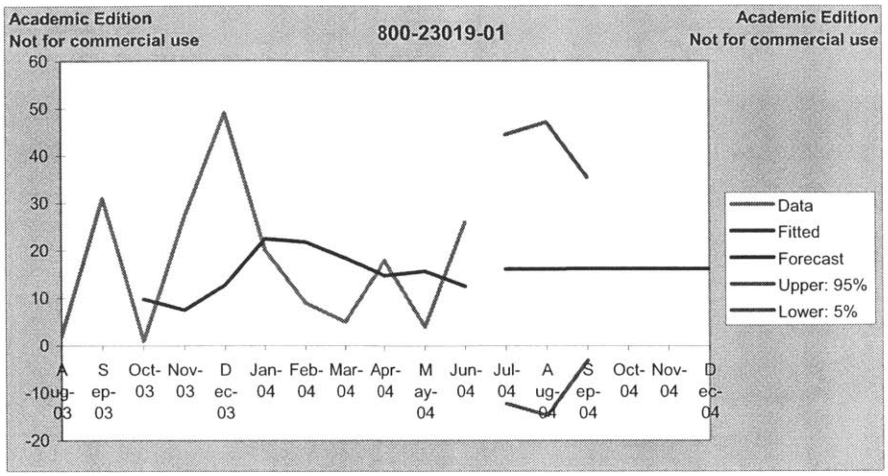
- Single Moving Average
- Single Exponential Smoothing

Trend-based Analysis

- Double Moving Average
- Double Exponential Smoothing
- Holt-Winter's Additive

The following plots represent forecasts for next 6 months based on a **5% and 95% confidence interval**. Additionally, our analysis demonstrates the performance of different forecasting methods on various metrics such as RMSE, MAD, and MAPE. Crystal ball predictor software recommends the best forecasting method for each wavelength based on analysis of historical demand. Figure 10 summarizes the best forecasting method for each optic and also lists the forecast error for each of the top 3 forecasting methods.

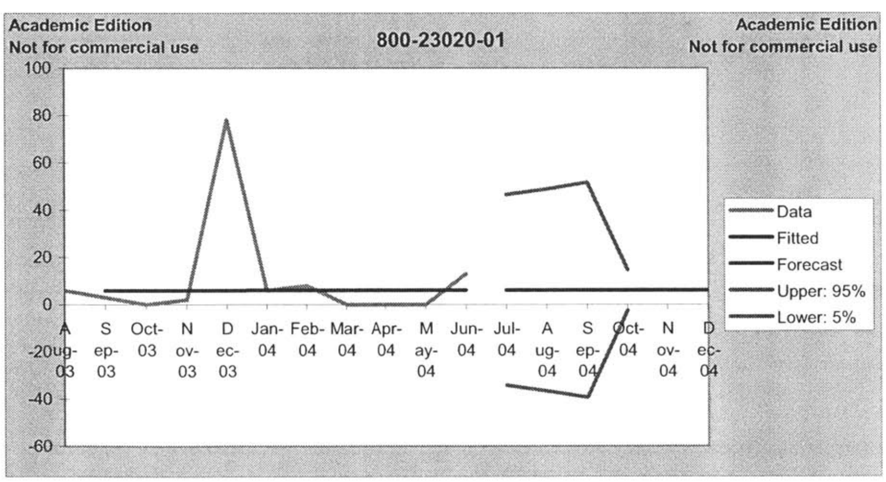
Product: 800-23019-01



	Method	RMSE	MAD	MAPE
Best:	Double Exponential Smoothing	16.516	13.517	201.12%
2nd:	Single Moving Average	17.628	15.625	136.36%
3rd:	Single Exponential Smoothing	18.153	15.071	190.43%

Recommended Forecasting Method: **Double Exponential Smoothing**

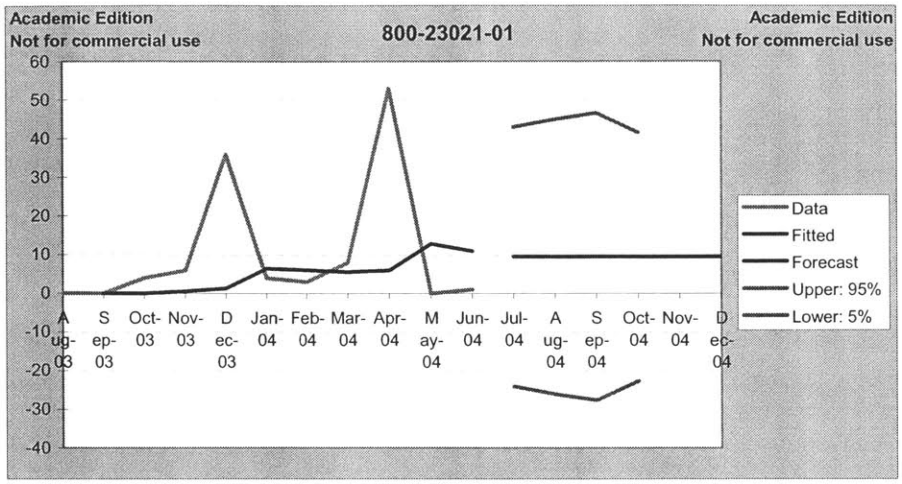
Product: 800-23020-01



	Method	RMSE	MAD	MAPE
Best:	Single Exponential Smoothing	23.257	11.212	78.44%
2nd:	Double Exponential Smoothing	24.495	12.125	74.13%
3rd:	Single Moving Average	30.724	19.333	243.08%

Recommended Forecasting Method: **Single Exponential Smoothing**

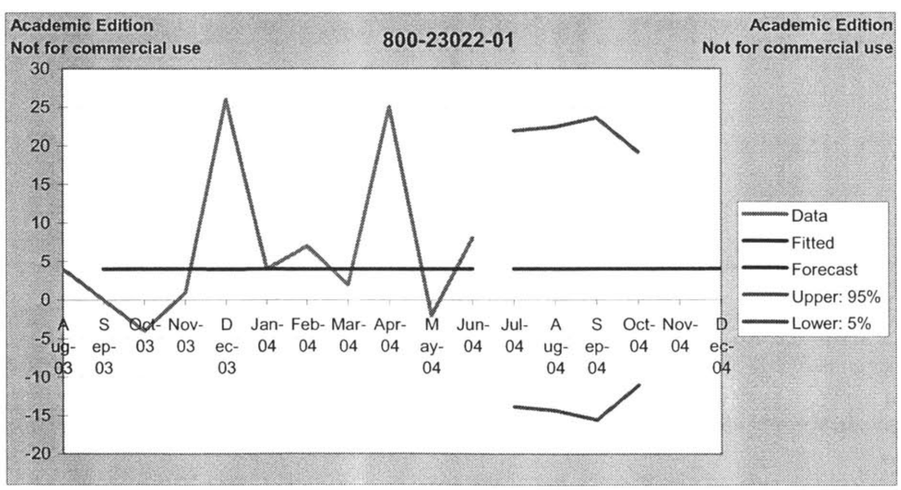
Product: 800-23021-01



	Method	RMSE	MAD	MAPE
Best:	Single Exponential Smoothing	19.341	12.179	195.81%
2nd:	Double Exponential Smoothing	20.164	13.539	252.77%
3rd:	Single Moving Average	22.106	18.143	371.05%

Recommended Forecasting Method: **Single Exponential Smoothing**

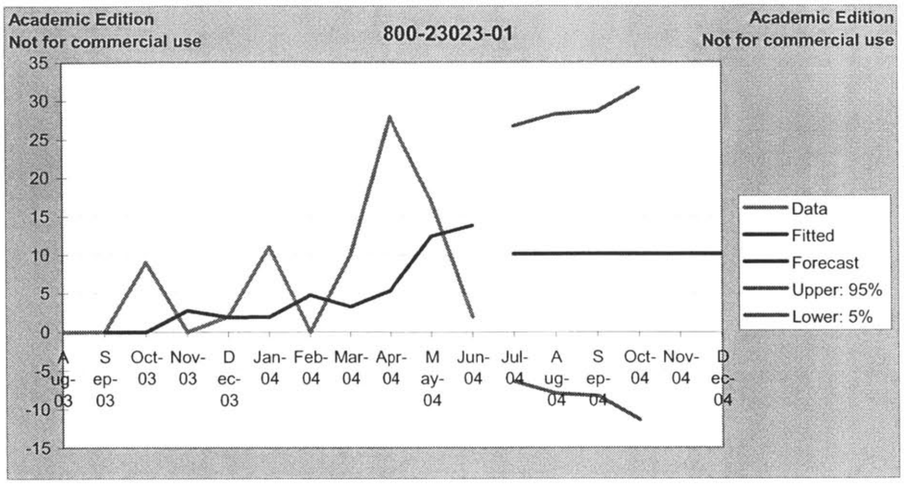
Product: 800-23022-01



	Method	RMSE	MAD	MAPE
Best:	Single Exponential Smoothing	10.389	7.3007	129.10%
2nd:	Double Exponential Smoothing	10.87	7.6674	129.10%
3rd:	Single Moving Average	12.463	8.8571	165.34%

Recommended Forecasting Method: **Single Exponential Smoothing**

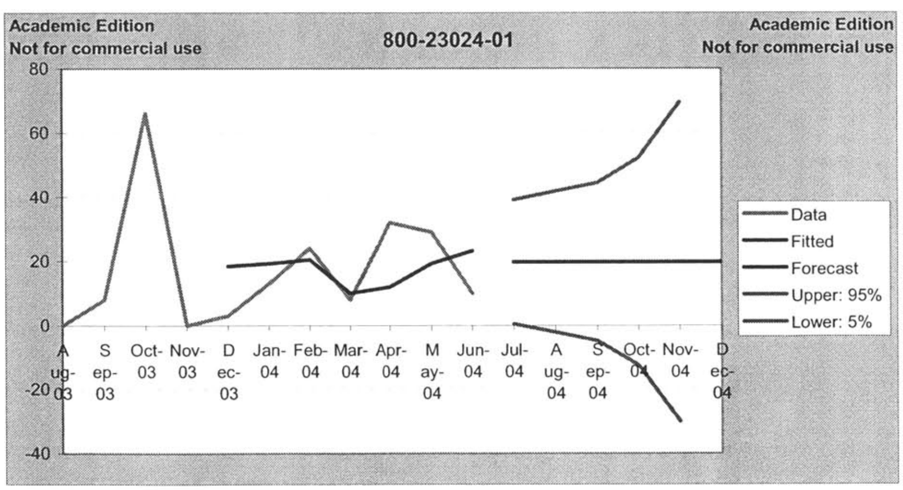
Product: 800-23023-01



	Method	RMSE	MAD	MAPE
Best:	Single Exponential Smoothing	9.5486	7.1457	136.11%
2nd:	Double Exponential Smoothing	9.7631	7.5952	147.20%
3rd:	Single Moving Average	10.254	7.875	181.75%

Recommended Forecasting Method: **Single Exponential Smoothing**

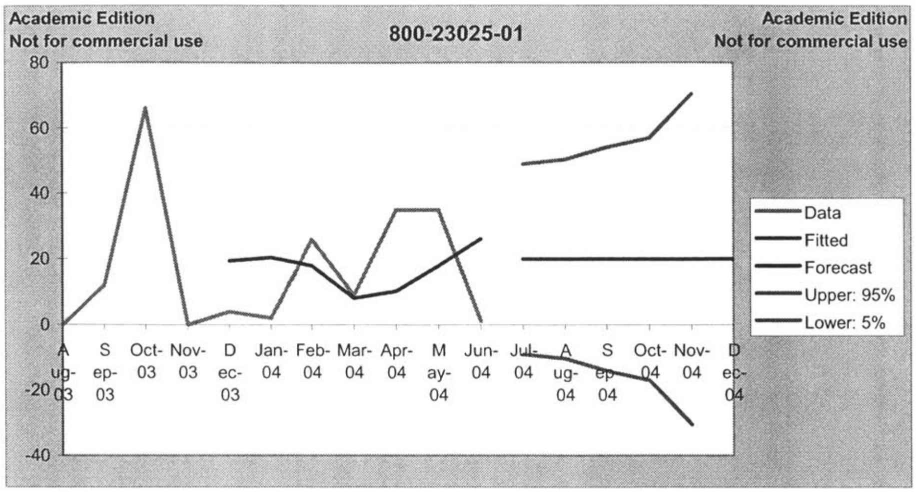
Product: 800-23024-01



	Method	RMSE	MAD	MAPE
Best:	Single Moving Average	11.748	10.036	118.99%
2nd:	Single Exponential Smoothing	23.126	15.821	90.02%
3rd:	Double Exponential Smoothing	23.591	14.949	86.11%

Recommended Forecasting Method: **Single Exponential Smoothing**

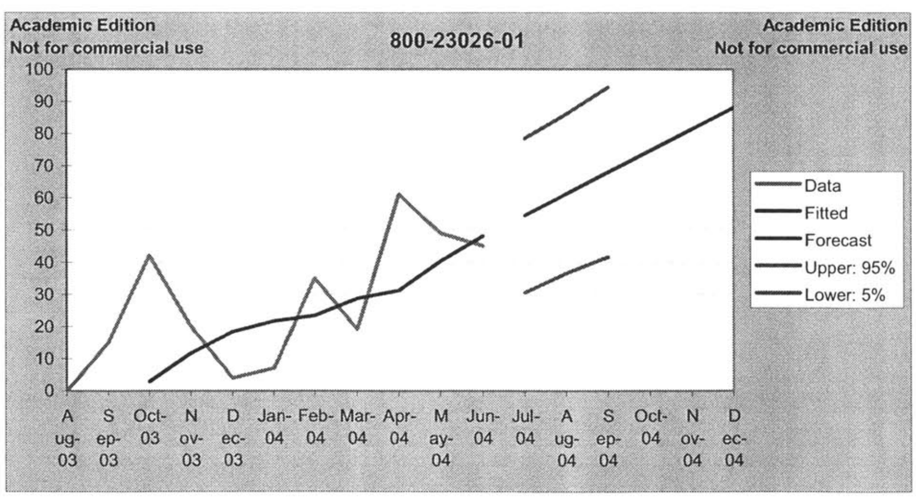
Product: 800-23025-01



	Method	RMSE	MAD	MAPE
Best:	Single Moving Average	11.748	10.036	118.99%
2nd:	Single Exponential Smoothing	23.126	15.821	90.02%
3rd:	Double Exponential Smoothing	23.591	14.949	86.11%

Recommended Forecasting Method: **Single Exponential Smoothing**

Product: 800-23026-01



	Method	RMSE	MAD	MAPE
Best:	Double Exponential Smoothing	18.941	15.498	95.61%
2nd:	Single Moving Average	19.65	14.917	117.95%
3rd:	Single Exponential Smoothing	20.267	15.824	95.59%

Recommended Forecasting Method: **Double Exponential Smoothing**

Figure 10: Optics Forecasting Method Recommendations

As seen above, in all of the 8 wavelengths the software either recommended use of single or double exponential smoothing. Therefore, the existing moving average forecasting method is yielding higher forecast errors and there is significant room for improvement by moving to a forecasting method mentioned above.

4.6 Model Recommendations (Base stock and Safety stock)

Based on inventory optimization performed at 73-level WIP inventory and forecast of optics, optimal inventory quantities were determined for the entire supply chain. Min-max policy was used to determine inventory quantities and the following is a summary of model recommendations:

Aggregate Demand (Risk Pooling)

After applying demand aggregation, the base stock and safety stock was determined for the two 73-level boards as shown in table 16.

Warehouse	Product	Demand	Forecast Error	Service Level	Base Stock Level	Safety Stock Level
NHM-STKPCB	800-2232X-01	23	12	90%	19	11
NHM-STKPCB	800-230XX-01	121	69	90%	156	77

Table 16: Base Stock and Safety Stock of 73-level Boards (Aggregate Demand)

Stable Demand

After applying demand aggregation to only stable demand of 73-level boards, base stock and safety stock was determined as shown in table 17.

Warehouse	Product	Demand	Forecast Error	Service Level	Base Stock Level	Safety Stock Level
NHM-STKPCB	800-2232X-01	18	8	90%	13	7
NHM-STKPCB	800-230XX-01	46	21	90%	51	23

Table 17: Base Stock and Safety Stock of 73-level Boards (Stable Demand)

Peak Demand

After applying demand aggregation to peak demand of 73-level boards, base stock and safety stock was determined as shown in table 18.

Warehouse	Product	Demand	Forecast Error	Service Level	Base Stock Level	Safety Stock Level
NHM-STKPCB	800-2232X-01	12	2	90%	4	1
NHM-STKPCB	800-230XX-01	113	60	90%	138	65

Table 18: Base Stock and Safety Stock of 73-level Boards (Peak Demand)

Optics

After generating forecast for all 8 wavelengths of optics, base stock and safety stock of optics was determined for each of the 8 wavelengths. The min-max inventory levels for optics are summarized in table 19.

	Base Stock Level	Safety Sotck Level
Optic 1	56	36
Optic 2	28	18
Optic 3	30	19
Optic 4	11	7
Optic 5	33	22
Optic 6	67	43
Optic 7	65	42
Optic 8	337	235

Table 19: Base Stock and Safety Stock of Optics

5.1 Strategic Shift from Build-to-Stock to Build-to-Order

Based on the optimization results, the architecture of Cisco's supply chain was modified from a pure push-based to push-pull with the push-pull boundary located at the merge level where 73-level WIP is merged with the optics. The value stream map of the new supply chain architecture is shown in figure 11.

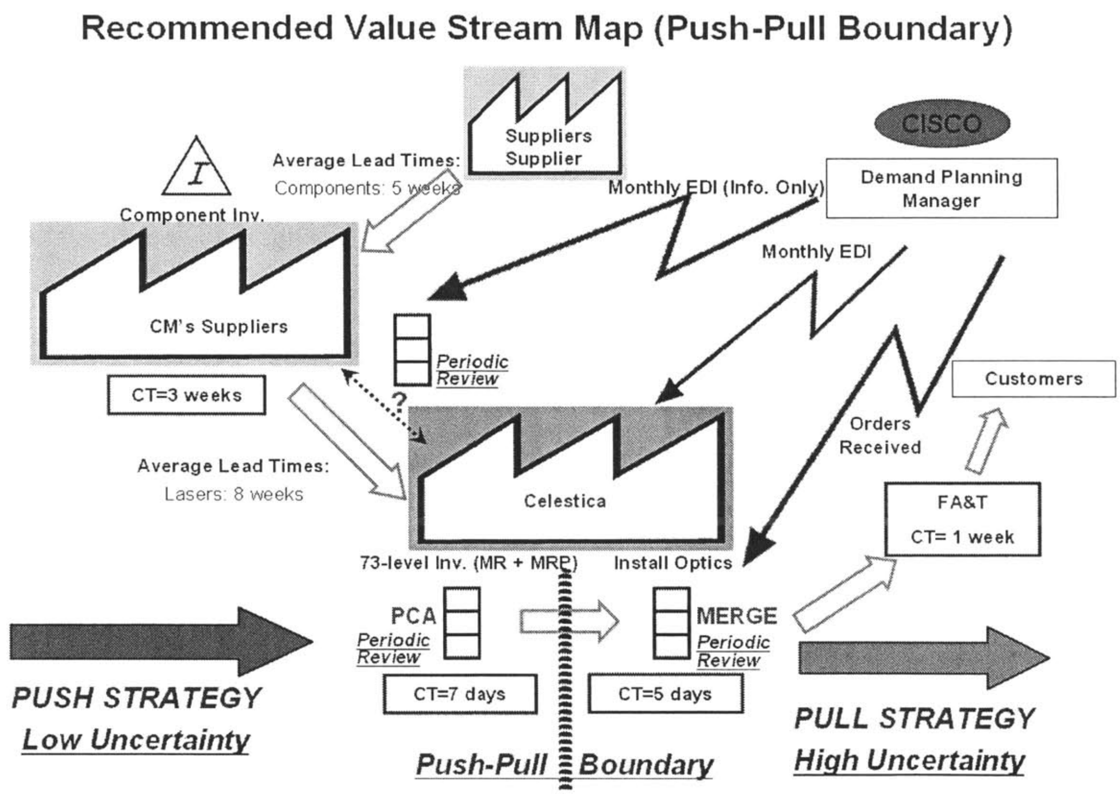


Figure 11: New Value Stream Map

As seen above, there has been a dramatic change in the overall design of the supply chain. The first change is in the design of the fulfillment process which now leverages postponement strategy. All components that exhibit high uncertainty in demand are part of the pull strategy whereas all components that exhibit low uncertainty are part of the push strategy. The push-pull boundary is based at the merge process where optics are installed on 73-level WIP. An important change is that now Cisco has the option of not holding any finished goods inventory, i.e. 800-level SKUs. In fact now, only when the customer signs a sales contract will the actual merge process occur. As seen from figure 11, as and when customer orders are received, DPM will issue a merge signal to Celestica to produce the 800-level product. The 73-level boards are built as per a push strategy. Safety stock inventory and order-up-to level inventory for 73-level boards is maintained at Celestica based on the optimization results discussed earlier. Every time the inventory for 73-level board falls below the safety stock, a production run will occur to replenish the inventory to order-up-to level. Obviously, the order-up-to level recommended by the optimization model is only a suggested inventory quantity. If there are any economies of scale or batch size discounts then the order-up-to level may be moderately modified to gain additional savings. Furthermore, DPM will send a modified monthly EDI to Celestica. The modified monthly EDI should contain recommended safety stock and order-up-to levels of both 73-level boards and optics. The purpose of this EDI is to incorporate any changes in actual demand based upon inputs from sales and marketing department at Cisco.

The optics inventory is based on a forecast of past 11 months of demand. Based on the previous analysis, inventory of all 8 wavelengths need to be maintained. Depending upon the actual demand for optics, inventories will need to be replenished on a periodic basis. A suggested way of replenishing optics inventory is by partnering with the optics supplier to run a VMI program at Celestica. A VMI program will ensure that at all times proper levels of optics inventory is available to Celestica. Another advantage of VMI program is that optics inventory is owned by the supplier and only at time of transformation is the inventory owned by Celestica. Again, inventory of optics needs to be held based on the calculations of optics safety stock and order-up-to level done in the previous chapter.

So far suppliers have obtained demand information from Celestica, instead of directly receiving it from Cisco. Celestica promptly forwards the EDI received from Cisco to all suppliers. However, the new supply chain architecture introduces another signal from Cisco to suppliers. As seen in figure 11, DPM sends EDI directly to the suppliers. The EDI is for information purpose only and does not correspond to an order to buy components. The main purpose of the informational EDI is to reduce the Bullwhip effect. It is important to note that the new supply chain architecture maintains the service level but dramatically reduces total inventory in the entire enterprise.

5.2 Overall Savings Calculation

Total Demand (Non-Aggregate) Model

To determine savings of aggregate inventory model over non-aggregate (push-based) supply chain, first inventory for non-aggregate/ total demand model needs to be determined. A min-max calculation was performed for all 16 SKUs and inventory of 16 SKUs were added to determine that total units of inventory. Service level was assumed to be 90% and actual demand for past 11 months was used to generate average demand and standard deviation of demand. Table 20 summarized the total units of inventory to satisfy service levels for all 16 SKUs. As seen below 249 units of inventory are required for base stock level and 163 units are required for safety stock.

Warehouse	Product	Time Period	Demand	Forecast Error	Service Level	Base Stock Level	Safety Stock Level
NHM-STKPCB	800-22321-01	Monthly Period	5	4	90%	5	3
NHM-STKPCB	800-22322-01	Monthly Period	9	7	90%	6	4
NHM-STKPCB	800-22323-01	Monthly Period	2	2	90%	3	2
NHM-STKPCB	800-22324-01	Monthly Period	1	1	90%	1	1
NHM-STKPCB	800-22325-01	Monthly Period	1	1	90%	0	0
NHM-STKPCB	800-22326-01	Monthly Period	2	2	90%	3	2
NHM-STKPCB	800-22327-01	Monthly Period	1	3	90%	4	3
NHM-STKPCB	800-22328-01	Monthly Period	2	3	90%	5	4
					Sub Total	**27**	**19**
NHM-STKPCB	800-23019-01	Monthly Period	20	15	90%	23	13
NHM-STKPCB	800-23020-01	Monthly Period	11	23	90%	35	27
NHM-STKPCB	800-23021-01	Monthly Period	12	14	90%	20	15
NHM-STKPCB	800-23022-01	Monthly Period	8	9	90%	10	7
NHM-STKPCB	800-23023-01	Monthly Period	8	10	90%	16	11
NHM-STKPCB	800-23024-01	Monthly Period	18	20	90%	37	23
NHM-STKPCB	800-23025-01	Monthly Period	18	21	90%	38	25
NHM-STKPCB	800-23026-01	Monthly Period	28	21	90%	45	24
					Sub Total	**223**	**144**
					TOTAL	**249**	**163**

Table 20: Total Demand Inventory Level

However, as discussed above, Cisco doesn't use min-max inventory method to determine inventory levels. In fact, inventory is determined by comparing forecast to actual demand. Due to this approach, Cisco had considerably higher level of inventory than the total demand model. In fact, at the time of this analysis- July 2004, between Cisco owned inventory and inventory on-order at Celestica, Cisco ONG had a total of 873 units. As mentioned earlier, part of the reason of this large inventory is the large forecast error that has built up inventory of specific wavelengths whereas others remain in short supply. Table 21 summarized Cisco's actual inventory level.

SKU	Cisco OH	Cel-Salem OH or O/O
800-23019-01	66	160
800-23020-01	5	65
800-23021-01	6	96
800-23022-01	7	59
800-23023-01	20	69
800-23024-01	35	33
800-23025-01	35	49
800-23026-01	10	45
Sub Total	**184**	**576**
800-22321-01	21	0
800-22322-01	14	0
800-22323-01	7	0
800-22324-01	13	0
800-22325-01	19	0
800-22326-01	10	0
800-22327-01	12	0
800-22328-01	17	0
Sub Total	**113**	**0**
TOTAL	**297**	**576**
		873

Table 21: Actual Inventory Level at Cisco

In addition, after conducting interviews with Cisco managers, it was determined at any given point in time the total inventory at Cisco is about 7 weeks, which includes 2 weeks of return merchandize authorization (RMA) and dead on arrival (DOA) inventory. This inventory is listed in table 22. In other words, there are about 1,050 units of inventory at Cisco, which includes about 300 units of RMA/ DOA inventory.

FG Inventory	
Operating Inventory	2 wks
Demand Variability	3 wks
RMA/ DOA	2 wks
TOTAL	**7 wks**

Table 22: Weeks of Inventory at Cisco

Furthermore, inventory level at Celestica is as shown in table 23. As seen below there are about 8 weeks of inventory at Celestica.

Comp. Inventory	
Ideally	4 wks
Actual (Variability + Ord. Qty)	**8 wks**

Table 23: Weeks of Inventory at Celestica

After performing inventory savings calculation based on inventory units, we obtain an average savings of 36% for unprotected boards and 35% for protected boards. As seen in table 24 the savings for safety stock are much higher and stand at about 47% for unprotected boards and 42% for protected boards.

	Total Demand		Aggregate Demand		Reduction		Avg. Reduction
	Base Stock	Safety Stock	Base Stock	Safety Stock	Base Stock	Safety Stock	
800-230XX-01	223	144	156	77	**30%**	**47%**	**36%**
800-2232X-01	27	19	19	11	**30%**	**42%**	**35%**

Table 24: Inventory Savings

Translating savings from inventory units to working capital by using average price of a Rockwell board, we obtain that over the total demand model about **$420K** can be saved for Rockwell boards. However, over the actual inventory model that accounts for current inventory levels at Cisco, the new supply chain architecture can free up approximately **$1.25M**. The calculations for inventory savings are summarized in table 25. It is important to note that Rockwell is just one of the 20 boards that ONG manufactures. Also, Rockwell is a low volume board and many other boards present larger opportunities for inventory optimization. A modest estimate of 10 boards that demonstrate about $1M savings per board can lead to about **$10M** working capital being freed up from inventory.

	Price (Actual as of 7/7)	Price (Total Demand)	Price (Agg. Demand)	True Price (Agg. Demand)
800-230XX-01	$985,720	$477,296	$303,498	$109,278
800-2232X-01	$394,483	$80,293	$52,365	$27,510
TOTAL	$1,380,203	$557,589	$355,863	$136,788
Savings over total demand model			$201,726	$420,801
Savings over actual inventory position			$1,024,340	$1,243,415

Table 25: Dollar Savings for Rockwell Board

As discussed earlier, based on a forecast of wavelength demand, separate min-max inventory levels for optics need to be maintained. The setup of optics inventory will require additional working capital infusion. Part of the savings identified through demand aggregation may be employed towards working capital required to purchase extra optics. Obviously, the ideal scenario is one where the product architecture of optics may be change so that postponement or risk pooling strategy may be applied to optics.

5.3 Sensitivity Analysis and Effects of Information Sharing

To demonstrate the effects of forecast error reduction, sensitivity analysis was performed on forecast error. The goal of this analysis was to provide objective data to marketing and sales department so as to demonstrate the effects of inventory pill up due to large forecast error. The forecast error was reduced by 10% and its subsequent effect on inventory was analyzed. Interestingly, 10% reduction in forecast error leads to ~18% reduction in inventory for 800-2232X-01 and ~20% reduction in inventory for 800-230XX-01. Therefore, a **1x** reduction in inventory leads to **1.8x to 2x** reduction in inventory. Clearly, additional savings can be reaped if marketing can modify existing forecasting method.

Next the effects of information sharing were analyzed across the supply chain. Using lead times of component suppliers, Celestica, and Cisco bullwhip effect was quantified. As seen in figure 12, q^0 is the customer demand seen by Cisco. L_1 is the lead time of products manufactured by Celestica for Cisco and q^1 is the demand for these products as seen by Celestica. Similarly, L_2 and q^2 is the component lead times and demand seen by component supplier respectively. Now, two supply chain scenarios exist, one in which there is information sharing and the second where there is no information sharing.

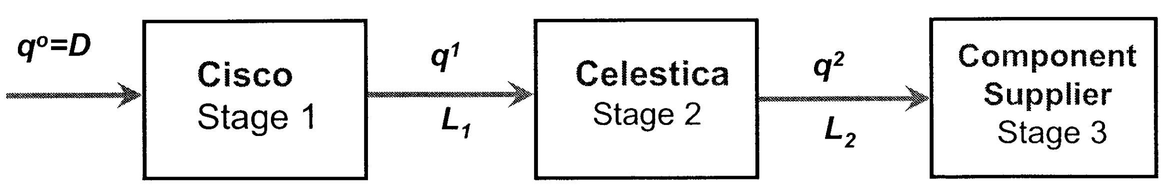


Figure 12: Effect of Information Sharing on Cisco's Supply Chain

As seen below, the supplier witnesses huge demand variance when no information is shared. In other words, if there is a decentralized demand information system then suppliers exhibit huge variances. However, if centralized demand information is available then demand variance is reduced drastically.

- Decentralized Demand Information:

Celestica	Supplier
220%	2200%

- Centralized Demand Information:

Celestica	Supplier
220%	1000%

5.4 Other Recommendation

Product Architecture (Modular vs. Integral) [10]

An important consideration in the design of supply chains is the effect of product architecture on overall performance and efficacy of the supply chain. Each Rockwell board uses one of the two 73-level boards and hence presents an excellent opportunity to perform demand aggregation. However, each board has a unique optic installed on it which corresponds to a specific wavelength. In other words, the design of optics is discrete. The supply chain design is not optimal until all potential cost savings can be identified and implemented. If optics architecture can be changed to modular from discrete, then additional savings can be reaped. Figure 13 presents the block diagram of Rockwell board and location of the optic.

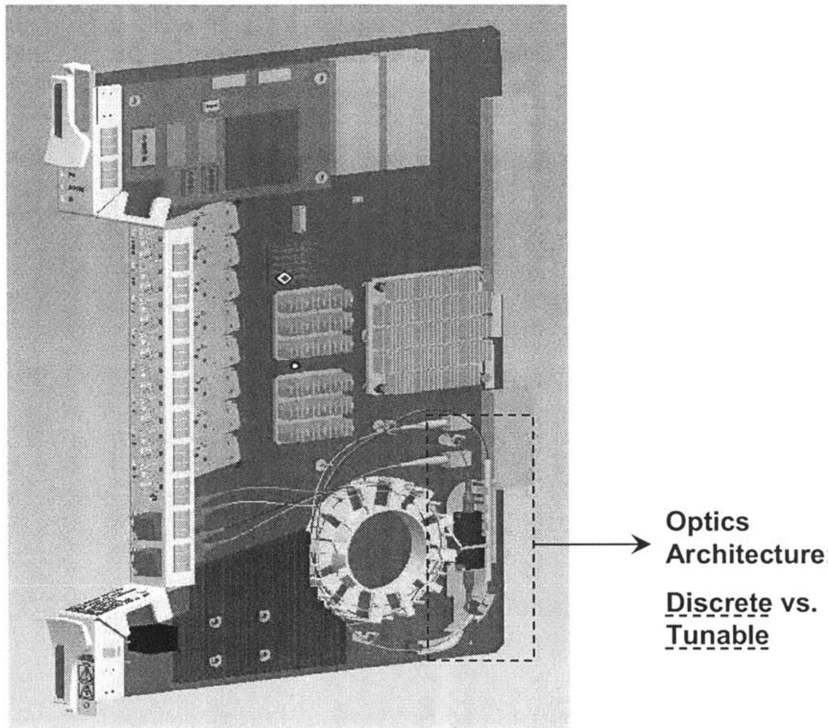


Figure 13: Rockwell Board Block Diagram

A modular architecture will lead to installation of just one component- tunable optic across all 16 SKUs. The tunable optic should be designed such that it is easy to program it to a specific wavelength. Tuning of the wavelength can occur either through a hardware or software modification. If the optics architecture can be modified into modular then postponement strategy can be implemented wherein a risk pooled inventory of modular optic can be held similar to 73-level boards. In such a case, only when a sales contract is signed will the optic be tuned to the wavelength ordered by the customer. Clearly, this will lead to further working capital savings.

Chapter 6: Implementation and Conclusions

6.1 Practical Considerations

Cisco Systems has embraced the new supply chain design with much enthusiasm. However, many bottlenecks exist from an implementation viewpoint. The first and, most obvious, is a move away from existing business processes. The workforce at Celestica and Cisco is very familiar with the 'build to forecast' business model and all physical and informational processes have been designed around this business model. Tools that support these processes such as EDI, backflush of inventory from Celestica to Cisco, and monthly marketing forecast, to name a few, need to be drastically changed so as to operate in the new business paradigm. Even if Cisco makes these changes, it will have to wait for Celestica and component suppliers to adapt to the new business environment. Most importantly training needs to be conducted at Cisco so that all involved parties such as DPM, PMM, Sales, and other manufacturing staff understand the advantages of the new model and their exact role within it. Training also needs to be conducted at Celestica and at component suppliers so as to ensure that all involved parties thoroughly understand the intricacies of the new business model. The fulfillment process will also change and hence Menlo Logistics will need to be trained to handle shipment orders differently.

Further, implementation roll-out needs to occur in a phased manner. During the first phase, Rockwell boards should be moved to the push-pull model and any implementation kinks need to be resolved. After all implementation issues have been resolved, other boards should be moved to the new business model. This means that during the initial implementation phase, some boards will be on the new business model whereas others will be on the old business model. Running both the business models smoothly will require much care and attention not only from the involved staff but also from Cisco executives.

6.2 Conclusion

A push-pull based supply chain presents tremendous advantages to Cisco such as freeing up working capital, reducing inventory levels, and increasing service levels. To reap these advantages Cisco needs to re-engineer its supply chain and perform demand aggregation/ risk pooling at the 73-level. In addition, further savings can be reaped if the product architecture of optics is changed to modular. This will lead to reduction in optics inventory. Below is a summary of the recommendations for Cisco's ONG group for Rockwell boards.

- To reduce variability, focus on 73-level inventory (WIP) instead of FG. 73-level inventory should be managed based on either 'Periodic Review Policy' or 'Min, Max.'

- Move from the existing pure 'Push'-based supply chain to a 'Push-Pull' system with the 'merge' process as the boundary of push-pull system. This will lead to reduction in working capital tied in Inventory and E&O.

- Forecasting is always wrong but our goal should be to strive for reduction in forecast error. Marketing should review existing forecast method (Moving Average- 3/6 months) and consider a change to exponential smoothing for better accuracy. The key issue here is how incentive mechanisms for marketing department are structured.

- Increase responsiveness by reducing supply chain lead times. Detailed evaluation of Celestica's cycle time, scheduling time, and offset is required. In other words, Cisco should identify and remove mudas!

- Engineering should consider modular product architecture (starting with pluggable optics) so as to come up with a 'common platform.' This will help in reducing aggregate demand uncertainty.

- Share demand information with all suppliers so as to reduce variance across multiple levels of the supply chain (bullwhip effect). This will help in smoothing out production process at each of the levels.

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