Strategy for Reducing the Length and Variability of Aircraft Lead Time

By

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Bachelor of Science in Mechanical Engineering, United States Naval Academy, 2002

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

Master of Business Administration

AND

Master of Science in Mechanical Engineering

In conjunction with the Leaders for Global Operations Program at the

Massachusetts Institute of Technology
June 2010

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Abstract

Helicopter manufacturers typically build each aircraft to order, and the lead time for make or buy parts and assemblies can be several months or more. The manufacturers generally have a backlog of orders at any given time, so customers in the helicopter market can expect to wait several months for delivery. However, due to the current economic conditions causing softened demand in the industry, some manufacturers have worked through most of their backlog and now have a finished goods inventory that allows for little or no wait for customer delivery, providing these companies a sales advantage. Between this effect of market conditions and recognition of the cost reduction benefits associated with shorter product lead times, successful helicopter companies with continued high demand and backlog, such as Sikorsky Aircraft Corporation, are seeking ways to deliver helicopters in a consistently shorter time frame.

In the past, Sikorsky has approached the issue through speculative ordering and parts production prior to customer point of order. This approach has had limited success due to higher than forecasted variability in demand. In order to provide a more optimal means for speculative ordering and parts fabrication, the cause of demand variability was explored and implementation of a parts supermarket of critical, high lead time parts was considered. The solution proposed would be used as a pilot to ensure a consistent, shortened lead time for the main gearbox assembly. This methodology could then be applied to other sections of the helicopter.

Analysis of the proposed supermarket reveals that by properly sizing the safety stock of 26 critical parts and using disciplined parts ordering, the objective lead time could be met. The calculated findings indicate large opportunities for cost savings in the implementation of this supermarket by offsetting original and spare parts demand to reduce variability, and by helping suppliers to establish reliable lead times through more consistent ordering patterns at Sikorsky.

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Proprietary Information

In order to protect potentially sensitive information and to ensure competitors do not gain competitive advantage from the information contained herein, sensitive or specific identifying information is not included. Most notably, the scale has been removed from a number of plots.

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1. Introduction

1.1 Overview

For most customers of helicopters, particularly those that are not government entities, the purchase represents a major allocation of capital. Since this allocation requires budgeting in advance of the purchase, the demand for helicopters tends to lag the financial performance of the customer, and thus the overall economy. Since the overall economy stopped declining several months ago, the rotary aircraft industry is now experiencing the low point of demand. Most helicopter manufacturers build to order and normally operate with a sizable backlog of greater than a year. However, with demand currently low, the backlog is decreasing. This effect is especially significant for the less successful players in the industry, that is, those helicopter manufacturers who have experienced greater than average decline in unit sales. The abnormally small backlog allows these companies to hold a greater inventory of finished goods, and to therefore deliver aircraft to the customer in a much shorter timeframe than normal, thereby providing a marketing advantage. In response, all the other players in the industry must also find ways to decrease the lead time to the customer. With relatively low sales volume compared to other industries, a high degree of product mix and customization, and long lead times for aerospace-grade parts from suppliers, the players in the rotary aircraft industry, and especially those who continue to be successful in the current market conditions, such as Sikorsky Aircraft Corporation, face a daunting challenge to decrease lead time to the customer.

1.2 Research Context & Objective

The objective of this thesis it to provide recommendations and a methodology to reduce the average lead time and its variability in the production of complex, low volume, products such as aircraft. The data and analysis shown in this thesis were collected and performed during a six and a half month internship in the Operations Planning group at Sikorsky Aircraft Corporation. The resulting recommendations were created to assist Sikorsky in meeting the evolving demands of the customer and implementing the most effective inventory control.

1.3 Outline

Chapter 2, Background, provides an overview of the helicopter industry and Sikorsky Aircraft Corporation. The chapter discusses aspects of aircraft lead time and the challenges in reducing that lead time. This chapter defines the problem statement.

Chapter 3, Approach & Methodology, discusses the approach and analysis required to develop a strategy to address the lead time issue in low volume, high mix product industries. The chapter introduces the concept of critical path analysis to identify those individual parts that drive overall lead time. The chapter also includes a discussion of current efforts in place to reduce the lead time of long lead parts and an alternative solution, a parts supermarket, to ensure reductions in overall lead time.

Chapter 4, Conclusions and Recommendations, summarizes the analysis and findings. The chapter offers specific recommendations for Sikorsky to reduce the lead time of the main gearbox.

2. Background

2.1 *Rotary Aircraft Industry*

The rotary aircraft industry has five major players: Sikorsky Aircraft Corporation, The Eurocopter Group, AgustaWestland, Bell Helicopter, and The Boeing Company. By estimated production value of helicopters in the years 2009 through 2013, the market share is divided as follows (Royce, 2009):

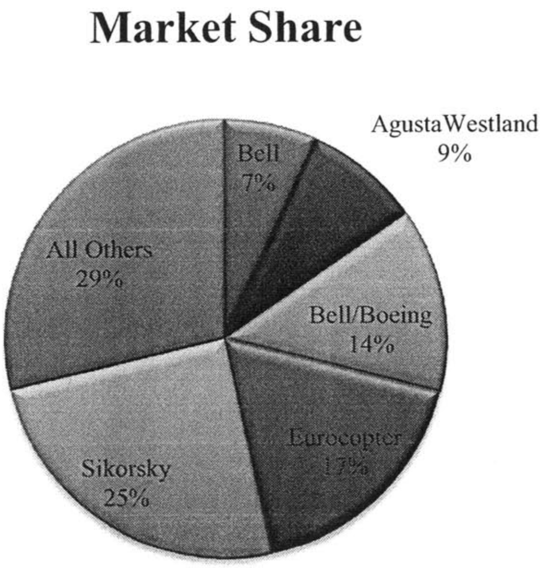

Figure 1: Market Share by Value of Production, 2009-2013 (Royce, 2009)

Although global economic conditions are affecting the rotary aircraft business, the major players typically operate with a substantial backlog of orders. Production is expected to maintain high levels through 2010 as companies work through backlogs, but a current decrease in demand will result in lowered production levels until the industry picks up again in the 2014 timeframe

(Royce, 2009). As commercial sales decline in the industry, government sales have remained relatively high, meaning that several of the players are now receiving a higher percentage of revenue from military aircraft than in the past.

In general, the traditional helicopter markets are maturing, forcing companies to expand globally, particularly to the BRIC (Brazil, Russia, India, and China) nations. To supplement decreased revenue expansion in traditional markets, companies such as Sikorsky and Eurocopter are focusing on increasing aftermarket parts and services.

2.2 Sikorsky Aircraft Corporation

Sikorsky Aircraft Corporation is a subsidiary of United Technologies Corporation (UTC), which is headquartered in Hartford, CT and had sales of $58.7 billion in 2008. United Technologies provides technological products in aerospace and building systems through its seven subsidiary companies which include, in order of decreasing revenue in 2008, Carrier, Pratt & Whitney, Otis, UTC Fire & Security, Hamilton-Sundstrand, Sikorsky, and UTC Power. Four of UTC's subsidiaries are involved in commercial business, and include Carrier (heating, ventilation, air conditioning, and refrigeration products), Otis (elevators, escalators, and moving walkways), UTC Fire & Security (electronic security and fire safety systems, software, and services), and UTC Power (fuel cell systems for onsite power applications and transportation). The remaining three subsidiaries are involved in both commercial and defense aerospace, and include Pratt & Whitney (engines for military and commercial aircraft), Hamilton-Sundstrand (electrical and flight control products for military and commercial aircraft), and Sikorsky (military and commercial helicopters, and light fixed wing aircraft).

Sikorsky is one of the worldwide market leaders in both military and commercial helicopter products and services. Major helicopter production programs include the UH-60M BLACK HAWK, HH-60M Medevac, S-70 BLACK HAWK, MH-60S and MH-60R NAVAL HAWK, S-76®, and S-92®. Additionally, Sikorsky is developing the CH-53K, CH-148, and X-2® Technology Demonstrator. Sikorsky is also involved with the helicopter aftermarket through spare parts sales, overhaul and repair services, logistical support, and maintenance contracts (United Technologies Corporation, 2008).

Sikorsky has been a leader in the helicopter industry since Igor Sikorsky invented the helicopter in the early twentieth century. The company remained relatively small until recent demand for the BLACK HAWK helicopter caused tremendous growth. Over the past five years, Sikorsky has experienced greater than 10% year-over-year revenue growth[1].

As UTC's fastest growing unit, Sikorsky has put much greater emphasis on long term planning than they had during their slower-growth years. In recent years, the Operations (Ops) Planning group was formed to analyze capacity at the enterprise level and to align proposed production schedules with the long term forecast, and to identify any inadequacies in production capacity over those five years.

Sikorsky's Stratford, CT facility has six product centers (which include, for instance, Precision Machining, Blade Shop, Final Assembly, etc.) that serve as each other's internal suppliers and customers. Coordination amongst the product centers is facilitated by the Ops Planning Group.

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[1] Source: UTC Annual Reports

2.3 – Aspects of Aircraft Lead Time

2.3.1 Lead Time in the Industry

Today, the major players in the helicopter industry have become less vertically integrated than they once were. The major helicopter companies generally produce those parts that they perceive or have determined to be their core competencies, while they often outsource other parts to external suppliers.

Those parts that are purchased from suppliers, referred to as "buy parts," range from simple and cheap fasteners to complex and expensive subassemblies. Many of the parts require certification of the design and production from the Federal Aviation Administration (FAA). Each time the helicopter manufacturer chooses to outsource a part, process, or assembly, it takes as long as two years to first certify the supplier to produce the part. The parts often require high precision and exotic materials, such as titanium and superalloy. The raw materials often have lead times greater than a year due to the time required to mine, process, and deliver to the supplier. Although some raw material is kept in inventory at the supplier, the rate of raw material replenishment lags behind the rate of change in demand for parts made from those raw materials. Furthermore, those precision parts often have applications outside of the aerospace market, so particularly for those parts with which rotary aircraft constitutes only a small percentage of overall demand, such as bearings, the lead time can be even longer.

The manufacturing of the parts by the suppliers often take months due to backlogs, low yield rates, and slow production processes needed to meet the precision required. Because of the intricacies and challenges of producing these parts, there tends to be only a handful of suppliers available to the helicopter manufacturers. Furthermore, regulations from the U.S. Department of Defense dictate that suppliers for American military helicopters be American companies, which further reduces the number of available suppliers for a given part. Although efforts by the helicopter manufacturers to reduce the lead time of buy parts from suppliers (e.g., sending consultants to streamline the production process, providing capital to increase capacity, certifying additional suppliers for a given part, buying a higher share of a given supplier's capacity, etc.) have been in place for the last several years, the reality is that certain parts have lead times that are far in excess of the customers' expectations of lead time for aircraft delivery. In other words, most purchases of helicopters require delivery time frames that are less than the lead times for certain parts and production processes; these parts and production process are referred to in this thesis as "critical."

Those parts produced by the helicopter manufacturers themselves, called "make parts," come with challenges that result in long lead times, as well. Like suppliers, the helicopter manufacturer must also produce parts to exacting precision after a lengthy certification process. Furthermore, production of helicopters is capital intensive, and much of the machinery used to create these high precision parts is sometimes decades old. Between the precision required and the age of the machinery, yield rates on make parts are relatively low compared to other industries. On top of the low yield rates, a high number of parts are required to undergo destructive testing and must then be scrapped. The overall effect is lengthy lead times for make parts. Adding to the challenge is the broad product mix that requires similar, but not exactly identical, parts among the various models. For instance, a military helicopter used for transportation to and from ships is subjected to different operating conditions (e.g., salt water) than a military helicopter used in a desert environment (heat, sand, etc.). Although both helicopters may be similar in design, there are subtle differences at the part level.

Whether a particular part is bought or made, a host of challenges exist that make it difficult to reduce lead time. With the current market condition, it is very difficult to satisfy the customers' desire for a short lead time to aircraft delivery while part lead times are as long as they are. Clearly, helicopter manufacturers face a complex challenge to deliver aircraft in an ever decreasing amount of time.

In order to reduce the total aircraft lead time, there is some amount of speculative parts ordering based on anticipated helicopter sales. Likewise, some production of parts and assemblies commences prior to the customer point order. This speculative ordering and production is based on forecasted helicopters sales and often does not take into account possible variability in demand. Although this speculative ordering helps to reduce the customer's perceived lead times when the forecast is accurate, there are long delays in lead time when actual demand is greater than forecasted demand. This can lead to a ripple effect as newly available make and buy parts intended for subsequent aircraft are instead redirected to the unanticipated customer orders. Overall, this leads to longer, and less consistent, average total aircraft lead times.

It is important to note that expected aircraft lead time for delivery varies drastically for each order. For instance, some military orders occur years before expected deliveries; highly customized orders for VIPs such as royalty and high net worth individuals, on the other hand, might be placed only several weeks before the expected delivery. Interestingly, final assembly of a "green aircraft," Sikorsky's terminology for a fully assembled helicopter that does not yet have any degree of customization, typically constitutes less than 10% of the overall lead time. The majority of the completion time consists of lead time for buy parts or make parts, and the subsequent assembly of subsections such as main landing gear, cabin, cockpit, tail-cone, tail pylon, QCA (quick change assembly; consists of the main rotor head mated to the main gear box), and blades. Figure 2 below provides a general overview of the production sequence involved in helicopter manufacturing.

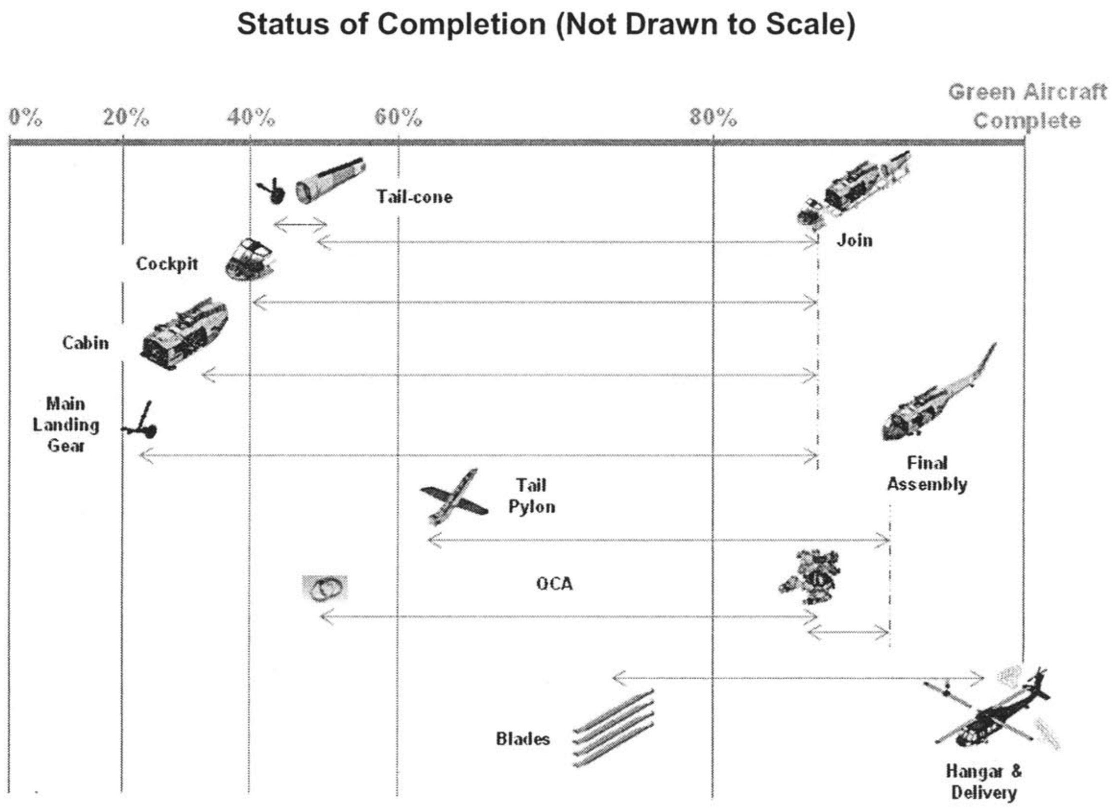

Figure 2: Overview of Helicopter Production

Other than satisfying customers in the current market condition, there are compelling reasons to reduce aircraft lead time. These reasons include reduced work in progress (WIP), smaller finished goods inventory of subassemblies, improved quality, reduced costs, improved forecasting, and increased manufacturing flexibility (Johnson, 2003). As an example, Airbus, another subsidiary of Eurocopter's parent company, EADS, launched an effort to reduce aircraft lead time by 60% as a means to reach an overall company goal of 2% year-over-year savings per aircraft program (Wall & Mecham, 2005). As of 2005, Airbus had reduced the customer's lead time for delivery of single-aisle aircraft from nine months to seven months.[2]

2.3.2 Lead Time at Sikorsky

Generally, ownership is transferred from Sikorsky to its customer at the time the green aircraft is complete. The next major production step is installation of standard options, which the Sales & Marketing group provides as options to the customer at the time of purchase. The aircraft is typically delivered upon installation of standard options. However, if the customer has requested further customizations, this work will be performed prior to final delivery. Figure 3 below illustrates the general time line of helicopter production at Sikorsky. The focus of this thesis is the lead time from Sikorsky's perspective, which starts with the order or fabrication of the longest lead part, and ends with the completion of the green aircraft. It should be noted that the length of time between order or fabrication of that first part and customer point of order is not pre-specified; rather it is unique to each individual aircraft based on the overall production schedule and accuracy of forecasting. This speculative ordering and fabrication does not directly

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[2] Source: 2005 EADS Annual Report

impact the customer; thus, the customer's perspective of lead time is different from Sikorsky's, as shown in figure 3.

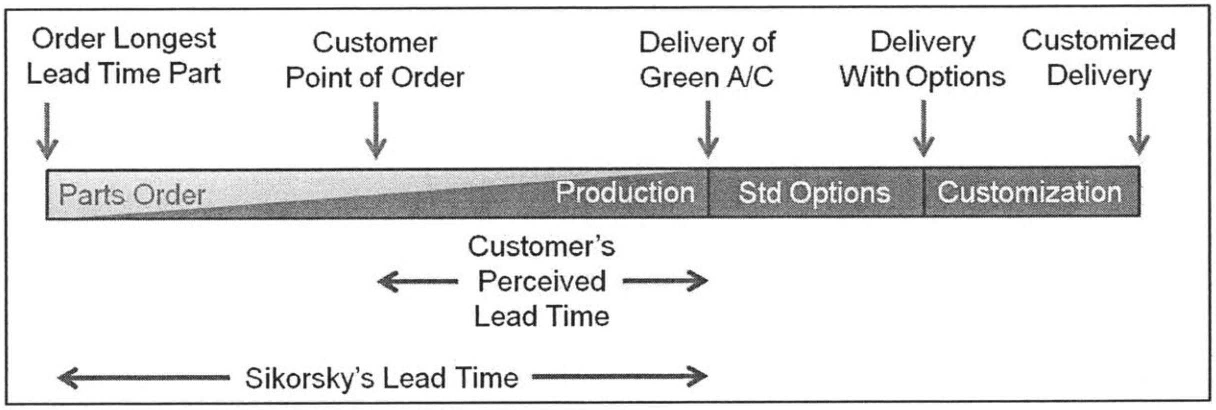

Figure 3: Generic Perceived Timeline of Production

For the suppliers, the perceived lead time is based on the type of part. Depending on the raw material required, the material lead time to the supplier can be months. Once the material is received or pulled from stock, fabrication begins. Some parts are common across the industry, and are therefore produced regularly and often held in finished goods inventory. For these parts, the supplier's lead time to Sikorsky consists primarily of administrative tasks. Other parts share common characteristics with parts made for other helicopter manufactures, and are therefore stocked as partially finished goods, with product differentiation achieved through a final production process once an order is received. These parts have a lead time to Sikorsky based on the throughput of the final production process at the supplier. Still other parts are custom fabricated to specification, and so are not held in inventory. Production of these parts does not commence until the supplier receives the order, resulting in a longer lead time to Sikorsky. Regardless of part type, the consistency in quantity and frequency of ordering, as well as visibility into overall demand at Sikorsky and other customers of the supplier, plays a major role in being able to accurately forecast and fabricate parts so as to minimize lead time to Sikorsky.

During the entire production of most helicopters, only a small portion of time is associated with actual assembly of the aircraft and its subassemblies. More specific data for the UH-60M BLACK HAWK, which is the focus of this thesis and has a production process typical to other Sikorsky models, are included in figure 4 below.

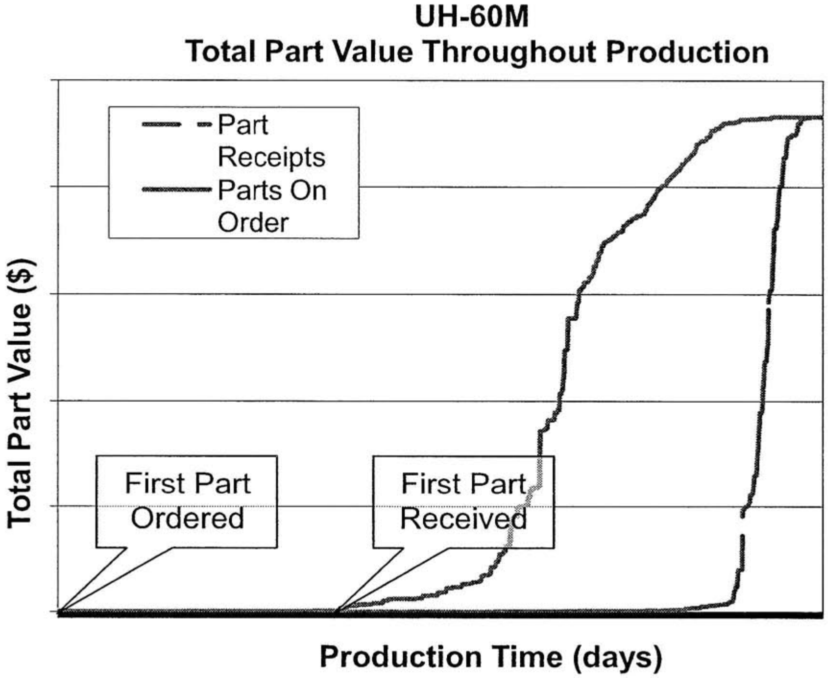

Figure 4: Aircraft Value Throughout Production (Source: Sikorsky)

The solid line represents the dollar value of parts on order throughout the production time of a specific, and typical, aircraft. The dashed line represents the dollar value of parts received during that production time. The horizontal separation of the lines presents, then, a rough graphical representation of the lead time of most buy parts. Of more significance, however, is the starting point for the solid and dashed lines. For roughly 40% of the overall production and assembly sequence, a small dollar amount of parts are on order (as shown by the beginning of the solid line), but have not yet been received (as depicted by the beginning of the dashed line, commencing approximately 40% through the production). Thus, roughly the first 40% of Sikorsky's lead time is comprised entirely of waiting for parts to arrive in order to commence assembly. Assembly cannot be completed, or sometimes even started, until receipt of all applicable parts; therefore, assembly is often delayed until much later after the arrival of the first of the applicable parts. These critical parts have long lead times from the supplier and although these parts have a small relative value (< 0.1% of total aircraft cost), they drive a large portion of the overall lead time.

The long lead times for these critical parts exacerbate the bullwhip[3] effect, lead to increased errors in forecasting, and introduce delivery date risks for both Sikorsky and its end customers. While planners try to use accurate forecasting and speculative ordering to deliver aircraft faster, decisions are often based more on the planners' best guess rather than on rigorous analysis. The critical parts are used for both assembly of original equipment and for spare parts; however, this speculative work does not fully take into account the variability of both original equipment and spare parts demand, which leads to stockouts of critical parts when the combined demand is higher than expected. This thesis provides a methodology for optimally stocking these critical parts so as to minimize the significant portion of overall aircraft lead time that is made up

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[3] The bullwhip effect refers to the amplification of demand variation from the end of the supply chain (the customer) to Sikorsky and its upstream suppliers (Beckman & Rosenfield, 2008)

entirely of waiting for parts to arrive. The solution presented would also assist suppliers in long term reduction of their own lead times by leveling Sikorsky's demand for parts over time.

As figure 4 shows, most of the parts have shorter lead times and are therefore non-critical and much less problematic. The receipts of the majority of the parts, in both value and quantity, are just prior to assembly, which reduces carrying costs associated with excessive inventory.

Meeting promised delivery dates is critical to Sikorsky. Military contracts usually involve multiple aircraft, which represent a large revenue opportunity for the company. Inability to deliver aircraft on time, then, can jeopardize future contracts. For military sales contracts, there are generally clearly defined production schedule for several years, which allows Sikorsky to appropriately acquire the necessary parts such that the delivery date is stable. However, some military contracts contain options that allow the customer to purchase additional aircraft in a given year without the advance notice that is typical in military sales. With these flexible contracts and commercial sales that are typically scheduled around an annual budget, Sikorsky is challenged with adequately forecasting demand to place accurate speculative orders of time-critical parts.

For commercial sales, the customer often requires specific delivery dates due to a variety of factors such as financing, hiring and training of pilots, and business needs. Therefore, late deliveries can lead to the cancellation of orders. In addition, some contracts, both military and commercial, contain penalties for late delivery. Finally, there is a possibility of lost sales if the customer decides that the quoted lead time is too long; this is particularly true for VIP sales in which the customer will often make a purchase decision based on which manufacturer can provide an adequate helicopter fastest.[4]

Further complicating the challenge of lead time is the issue of spare parts. Spare parts generally have higher margins than original equipment, so spare part orders are often given priority, especially if the order is for an inoperable helicopter. As a result, some of the speculative parts orders may not go to a planned production aircraft, but rather to a spare parts order. It is not uncommon for parts to be diverted from a planned aircraft to a spare parts order.

2.4 Problem Statement

Shortened lead times and accurate delivery dates are critical to the continued success of Sikorsky, particularly with the current market conditions in which some competitors can offer helicopters with little or no lead time. To this end, Sikorsky Aircraft Corporation has established an objective to substantially decrease average lead times, and has set a specific lead time goal. Achieving a reduced average aircraft lead time not only presents a stronger value proposition to the customer, but also allows the company to potentially reduce costs, increase revenue, and improve cash flow. However, tackling the issue of historically long lead times is a difficult task.

Sikorsky, like all of its competitors, faces challenges in reducing lead time of parts due to suppliers. Whether the critical part is bought or made, it often has a lead time that is greater than Sikorsky's objective goal for total aircraft lead time. The helicopter industry as a whole makes up a small proportion of the volume for most of the required raw material, which decreases

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[4] Source: Interview with a Sales & Marketing executive at Sikorsky

buying power and the ability to acquire the materials in a more timely and prioritized manner. Sikorsky currently approaches the problem through speculative buying and production prior to the customer point of order, but this speculative work does not necessarily involve the correct parts/assemblies or the optimal quantities and therefore creates unnecessary WIP.

This thesis offers a plan to achieve lead time reductions and consistency by optimizing this speculative approach to parts purchases. The project required integrating several separate, on-going efforts throughout the company, as well as identifying other opportunities to reduce aircraft lead time. Due to commonality in parts and processes among the various aircraft models, successful methods to reduce the lead time of one model can be applied to other models. Therefore, for the purposes of determining best practices and limiting the scope of the project within the given timeline, the analysis and recommendations pertain to one particular model line, the UH-60M BLACK HAWK.

3. Approach & Methodology

With reduced rotary aircraft demand, less successful companies have seen substantially decreased orders for their products, resulting in increasing inventories of finished goods. This inventory has allowed these less successful helicopter manufacturers to offer helicopters with significantly shortened lead time, and has forced the other helicopter manufacturers to reduce their own lead times to the customer in order to remain competitive from a marketing standpoint. For this reason, Sikorsky designated the reduction of overall aircraft lead time as a strategic objective for the company. Efforts have been in place for more than a year, yielding some incremental improvement. However, a new strategy is required to make the significant impact on lead time that is desired.

The six and a half month internship on which this thesis is based was used to explore options and present recommendations to meet Sikorsky's pre-determined lead time goal. Given the short time frame of the internship, it was determined that any new strategy be focused on just one aircraft model. Due to the prevalence and parts commonality with other models, the UH-60M BLACK HAWK helicopter was chosen as the targeted model for new strategies.

The first step of the internship involved gathering data and conducting interviews to determine the current state of efforts. It was clear that Sikorsky had made incremental improvements by working with suppliers to deliver critical parts faster. However, these improvements in lead times from the suppliers were caused primarily by the decrease in the suppliers' aggregate demand from all customers, and so Sikorsky saw diminishing returns as it continued working with its suppliers; subsequent improvements would require more resources. The success achieved was viewed as temporary in nature due to the market conditions that caused decreased parts demand from the industry as a whole. While several long term options, such as qualification of new suppliers and increased vertical integration, were explored, they typically involve significant monetary investments, long periods of time to implement, and introduction of new risks; these long term options are discussed more in section 3.2. Since it became clear that the long term options could not quickly meet the objective lead time without significant investment, a parts supermarket concept, as described in section 3.3, was explored to determine the viability of strategically stocking critical parts. This concept, once implemented, would replace the current system of speculative ordering based on error-prone forecasting of individual aircraft sales, and will continue to ensure consistent and reduced lead times as overall demand grows in the future.

The second step of the internship involved using critical path analysis, described in section 3.1, to identify long lead time parts and processes that currently prevent Sikorsky from achieving its lead time objective. With limited time available for the internship, it was decided that one particularly complex assembly would be addressed, with the idea that the findings and methodology could then be applied to other parts of the helicopter.

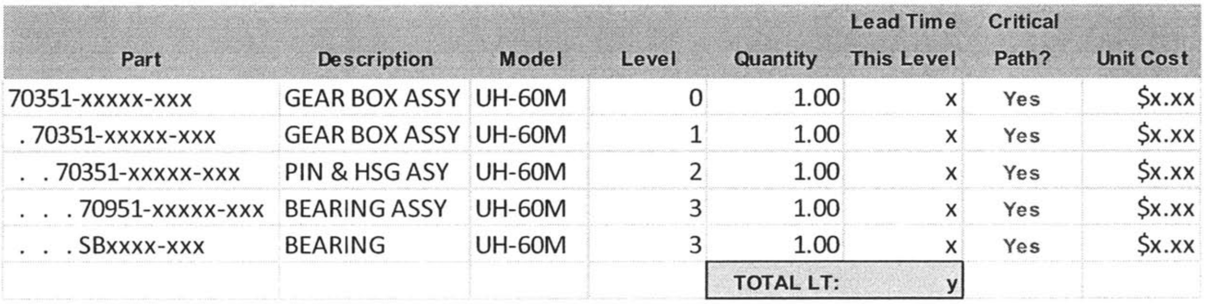
The main transmission gearbox was selected as the pilot assembly on which to focus analytical efforts. The gearbox is a complex assembly requiring many supply chain aspects, such as buy parts, make parts, kitting, and commodities. It is assembled by the Precision Assembly product center and delivered to the Final Assembly product center. The gearbox is also often cited as one of the limiting factors in terms of reducing aircraft lead time. Critical path analysis of the gearbox identified 26 parts that prevent the assembly from being completed within the objective lead time. Interestingly, all 26 parts are buy parts. Most of these parts have capital-intensive production processes, and therefore would be difficult for Sikorsky to start producing in-house.

With the critical lead time parts identified, the next step of the internship was to determine the proper size of the supermarket, as described in section 3.3.1. Analysis of the results revealed that certain factors, particularly variation in monthly part demand and variation in lead time from the suppliers, dictate a sizable required parts inventory for the supermarket. These findings helped create a consolidated list of recommendations for Sikorsky. These recommendations can be found in section 4.

3.1 Critical Path Analysis

In the context of this thesis, the critical path is the limiting sequential, dependent steps (e.g. lead time of a make or buy part, assembly process, etc.) that dictate the overall lead time of the aircraft from time of order of the longest lead part through the delivery of the aircraft to the customer. Identifying the critical path in the production of an aircraft allows for the selective targeting of lead time reduction efforts in the most efficacious manner. By reducing the overall length of the critical path, the overall aircraft lead time is reduced.

Sikorsky recently purchased software that allows for detailed critical path analysis. This software, Kinaxis RapidResonse™, works by taking a weekly snapshot of Material Requirements Planning (MRP) data from the SAP™ software. This data can then be manipulated to run hypothetical scenarios or to plan production without altering the data stored within SAP. One especially useful feature within RapidResponse is an indented bill of materials (BOM). Like a typical BOM, this feature shows all of the parts and assemblies required for each aircraft model, and also illustrates their interdependencies, and the sequence of production and assembly, by listing high level assemblies on the left margin and lower level parts and assemblies indented to the right, as shown in the example in figure 5. The software can also identify the critical path within the indented BOM. With this information, the lead time for the long lead part in the critical path can be reduced for simulation purposes to identify the secondary critical path. The process can then be repeated as many times as required to reach a final critical path iteration that provides an overall lead time that meets the objective aircraft lead time. By performing these simulations, every critical part that prevents the delivery of the aircraft within a specified time frame can be identified and addressed.



Part	Description	Model	Level	Quantity	Lead Time This Level	Critical Path?	Unit Cost
70351-xxxxx-xxx	GEAR BOX ASSY	UH-60M	0	1.00	x	Yes	$x.xx
. 70351-xxxxx-xxx	GEAR BOX ASSY	UH-60M	1	1.00	x	Yes	$x.xx
. . 70351-xxxxx-xxx	PIN & HSG ASY	UH-60M	2	1.00	x	Yes	$x.xx
. . . 70951-xxxxx-xxx	BEARING ASSY	UH-60M	3	1.00	x	Yes	$x.xx
. . . SBxxxx-xxx	BEARING	UH-60M	3	1.00	x	Yes	$x.xx
				TOTAL LT:	y		

Figure 5: Example Critical Path in Indented BOM Format

This methodology depends on accurate part lead times in SAP, but this assumption is not always valid and is discussed further in section 3.3.3. The software allows the user to easily simulate changes in the lead time of any given part, which helps to compensate for incorrect data or plan for uncertainties in lead time.

For this project, the primary critical path was identified for the main gearbox assembly. The output appeared similar to the example shown in figure 5, which allowed for easy identification of the long lead critical part for the critical path. The lead time of the critical path was then simulated to be zero days (that is, the part was assumed to be stocked in the proposed parts supermarket), and then the process was repeated to find the secondary critical path for the gearbox. This process was continued until a critical path was found that had a total lead time that was less than the previously established objective lead time. For some iterations of this process, parallel critical paths emerged (that is, the paths were of the same length) and therefore revealed more than one long lead time critical part for that particular iteration. After 21 iterations, a total of 26 long lead time critical parts were identified.

After the 26 critical parts were identified, further data were gathered on the parts. While the critical path analysis methodology is valid for both make and buy parts, all 26 parts identified were buy parts, indicating that in-house parts production is not currently preventing gearbox demand from being met within the objective lead time. The assigned buyers for each of the parts were contacted to ensure that the information in SAP (e.g., part lead time, part cost, etc.) was, indeed, correct. Most information was correct, but small changes needed to be made for some of the parts, and the affected critical paths were then analyzed again. For ease in the ongoing use of this methodology, accuracy of SAP data would need to be assured. This is especially important as part lead time changes with overall industry demand and part costs change with the cost of raw materials. The accuracy of data is most important for those long lead time parts that currently, or may in the future, make up the critical path. So while data maintenance is important, the most careful data maintenance should be applied to the longest lead time parts, such as those that have a lead time longer than a pre-determined threshold. The data accuracy in SAP is addressed further in section 3.2.

Finally, the commonality of the parts to other aircraft models was also examined to see if these parts caused long lead times for other models, as well; all but two of the parts were found to be used in other models.

The software proved to be a valuable tool in identifying the critical parts that need to be addressed. It also helped to ascertain the commonality of those critical parts across various helicopter models to determine how to most effectively implement solutions for lead time reduction.

Although the software proved to be useful, some of the challenges associated with its use should be noted. First, only a limited number of licenses were included with the purchase of the software, thus restricting its use to only a handful of individuals. Additionally, a substantial amount of time and training is needed to learn how to effectively use the software. Finally, the data in the software are held on remote servers. While most of the servers are located in the United States, some are located in Canada, which can present issues for American defense contractors such as Sikorsky.

3.2 Supplier Lead Time Reduction

Faced with a need to decrease overall aircraft lead time, Sikorsky initiated action prior to the efforts described in this thesis. The company developed solutions which can generally be categorized as: 1) longer term, capital intensive solutions and, 2) shorter term solutions that relied on suppliers to reduce part lead times. These two categories of solutions are described in greater detail below.

Initially, long term solutions were considered to solve the issue of long part lead times. The approach included assigning the appropriate commodity managers to work with suppliers to develop strategies for lead time reduction.

Many of the longest lead parts are those traditionally known throughout the industry as having long lead times (e.g., bearings), and therefore require significant changes in the supply chain to reduce the lead time. Some of the potential options open to Sikorsky included the following: purchase of parts through a distributor rather than directly from the supplier, although with a 15-20% price premium; sending a Lean consulting team from Sikorsky to the supplier to streamline production processes; qualifying new suppliers over a time period of several years; providing capital to the suppliers to increase capacity; purchasing a dedicated production cell at the supplier that would produce strictly for Sikorsky; leveraging overall UTC buying power to negotiate a larger percentage of supplier output; and outright acquisition of suppliers. Although these alternative solutions offer some long term means to ensure that critical parts arrive on time, they require significant monetary investments, take a prolonged period of time to achieve results, or introduce high levels of risk. Given Sikorsky's desire to find a timely solution to lead time reduction with the current market conditions, the company decided not to rely on these approaches to solve the current issue. However, consideration should be given to implementing these long term solutions in parallel to short term solutions so as to most effectively reduce overall aircraft lead time.

Recognizing that suppliers were also facing decreased demand for parts, Sikorsky saw an opportunity to work with its suppliers to reduce the lead times of certain parts, some of which were critical parts. In practice, this meant that commodity managers continually pushed suppliers to deliver parts faster. This proved somewhat effective initially due to the decreased demand seen by the suppliers, but the suppliers could only do so much due to the lead time of raw materials and fabrication.

This approach, while achieving some success, did not focus on the most critical parts. Rather than using critical path analysis, targeted parts were identified by sorting all parts in the BOM by longest lead time, and then addressing the longest lead parts. While this approach targeted many of the same parts that were identified with critical path analysis, it also led to some ineffective allocation of time and money as certain efforts targeted parts whose subsequent lead time reduction had no effect on the total aircraft lead time. These parts, although having long respective lead times, are not part of the critical path, and this previous approach did not take into account the point of part consumption. Still, the work did achieve some success; figure 6 shows how these efforts reduced overall aircraft lead time for the first nine months of 2009. Due to the fact that there was some overlap in the targeted parts between the previous effort and the critical path analysis, there was significant progress made in the reduction of overall aircraft lead time. This overall reduction was caused by the respective lead time reductions of those parts that are part of the critical path. For instance, efforts in 1Q09 focused on certain bearings, among other parts, which were part of the critical path and therefore yielded a small decrease in the total aircraft lead time. During 2Q09, efforts included lead time reductions of other parts in the critical path, such as other long lead bearings, bearing assemblies, and actuators, resulting in another reduction in overall lead time. The efforts in 3Q09 involved more parts, and included lead time reductions for manifolds and piston assemblies, both of which were part of the critical path, and thus resulted in another reduction in total aircraft lead time. By 4Q09, however, some of the previous success in total lead time reduction was reversed, and is described in more detail below.

The suppliers lacked the resources to meet reduced lead time demands on a long term basis, so they resorted to expediting by using the excess capacity that was temporarily available to them due to the current market conditions. Given the overall reduction in aerospace demand, the suppliers provided, and continue to provide, parts in a shortened time frame. However, this solution is temporary. In fact, evidence of a reversal in overall aircraft lead time reduction can be seen in the fourth quarter of 2009, as shown in figure 6. As the lead times of certain parts vary, the critical paths for assembly change, and therefore the parts that are deemed critical also change. For instance, if the lead time of a given part increases to a certain point, a new critical path emerges and that part becomes critical; this effect was evident in 2009. Despite decreases in the lead times of certain critical parts during 1Q09 through 3Q09 that led to subsequent decreases in the overall aircraft lead time, the overall lead time increased by 4Q09 due to increases in the lead times of other parts that became new critical parts.

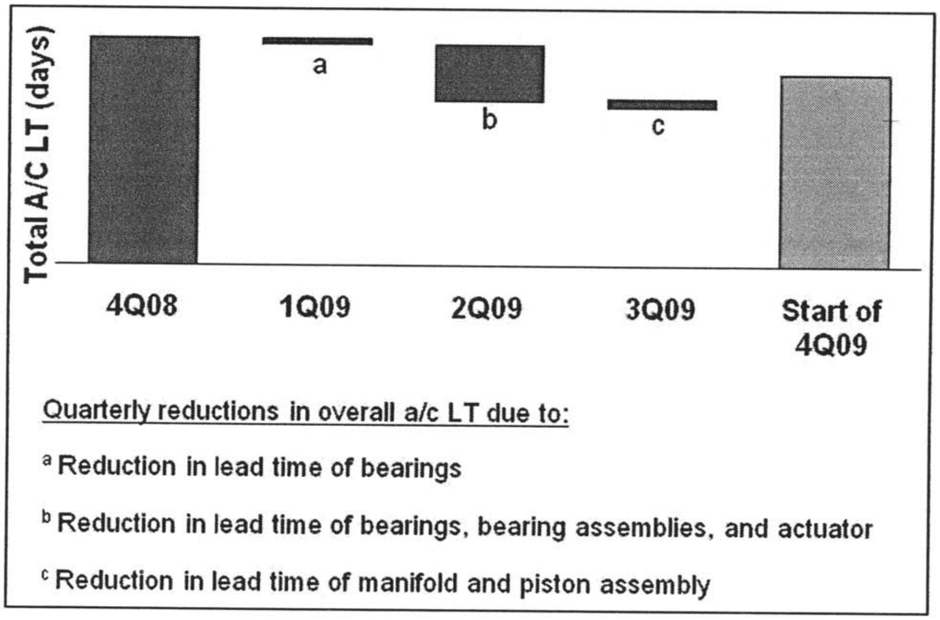


Figure 6: LT Reduction with Previous Efforts

In addition to the cost, time, and risk involved with the aforementioned solutions, there is a procedural issue of buyers that must be considered. The lead times of each part are tracked in SAP and updated by the buyer tasked with purchasing the given part. The purchasing group has established standard operating procedures that direct the buyers to update part lead time each time that part is purchased. However, after some investigating and interviewing of buyers, it became clear that SAP data was not fully maintained, as the lead times listed in SAP did not necessarily reflect reality. For instance, the administrative time period (that time allocated to paperwork, processing, etc.) included in the lead time ranged from 30 to 90 days for various parts, without any consistency in rationale. Also, some buyers were not aware of their responsibility to update part lead time, or admitted that they were too overburdened to take care of the task, and in some cases had not updated a given part's lead time in years. It was not uncommon to see the SAP default lead time of 270 days listed for parts. There was also a great deal of confusion regarding calendar days vs. manufacturing days. The policy at Sikorsky is to track lead time from the supplier in calendar days, the actual number of days to receive a part, while internal production lead time is measured in manufacturing days, the number of work days required to produce or assemble a piece. Many buyers were unaware or confused about the policy, however, and an audit of SAP part lead times revealed some lead time measurements in calendar days and others in manufacturing days. Finally, some buyers felt that the determination of part lead time from the supplier is more of an art than a science. Some suppliers consistently overstate or understate lead time; others quote round numbers rather than actual numbers for lead time (for instance, 30 days rather than 27 days). Some buyers took into account these supplier idiosyncrasies and knowledge of current market conditions to tweak the lead time as quoted by the supplier. Other buyers recognized the effect on planning schedules if they listed an incorrect lead time in the system, and would therefore choose not to increase or decrease the lead time in SAP.

So while efforts at Sikorsky have been somewhat effective in reducing overall aircraft lead time, these efforts are temporary in nature. The proposed parts supermarket presents a solution that can be more efficient at reducing total aircraft lead time and also more permanent in nature.

3.3 Parts Supermarket

Given the underlying issues that suppliers face in the production of long lead parts, it is difficult to achieve long term improvements without significant investments in resources. As an alternative to the previously discussed approaches, then, it is possible to strategically stock critical parts by optimizing the speculative ordering process that Sikorsky currently uses. Through identification of the critical parts and optimally sizing the inventory of those parts, the overall lead time can be assured to meet the objective while minimizing additional costs. While such a solution does incur associated carrying costs and ties up cash in inventory, the costs could be partially offset by the reduction of inventory of those parts not deemed critical. This solution mitigates risk during periods of unexpected increases in demand because Sikorsky would no longer need to delay production during the fabrication lead time of critical parts. A parts supermarket offers a means to mitigate the effects of long lead time parts until longer term solutions can be implemented to fix the underlying issues of the supply base.

The proposed parts supermarket would make use of kanban controls in the critical parts inventory. Kanban, a concept developed in the Toyota Production System, is a simple signaling system that prompts the producing work center to move inventory to the distributing work center based on actual need (i.e., depletion of input inventory at the producing work center). The objective of the kanban system is to reduce the amount of inventory held while still recognizing the need for some safety stock (Beckman & Rosenfield, 2008).

There are two prevalent kanban systems: withdrawal and production ordering (Nahmias, 1997). The kanban system would be applied to the supermarket for both parts ordering and parts withdrawal to control the flow of material from the suppliers to the Precision Assembly work center, which assembles the main gearbox using the critical parts previously discussed, in order to allow timely delivery of a completed main gearbox to the Final Assembly work center. A withdrawal kanban would be used to request parts or assemblies (i.e. critical parts) from the parts supermarket, and then to the Precision Assembly work center. A production ordering kanban would be used by the Final Assembly work center to signal a request for a gearbox to be assembled.

In a kanban system, the feeding work center provides the consuming work center only what is required; in this sense, the kanban system is a pull system. In an MRP system, such as that currently used in Precision Assembly and Final Assembly, material is provided based on a forecast, and is therefore a push system. With a push system, the feeding work center provides the consuming work center, whether or not the work center requires the parts or assemblies. This system could result in too few parts at Precision Assembly to complete a gearbox if the downstream demand for gearboxes at Final Assembly exceeds the MRP determined rate that parts are pushed to Precision Assembly. On the other extreme, Final Assembly might receive excessive main gearbox assemblies that it must then stock and pull from. This inventory of completed main gearbox assemblies is carried at a higher cost than the individual parts from which it is made. By implementing a parts supermarket with kanban controls, the push-pull boundary is moved upstream, resulting in the correct amount of critical parts at Precision Assembly and the correct amount of finished goods (gearboxes) at Final Assembly. Requirements for kanban controls include (Silver, Pyke, & Peterson, 1998):

- Employee motivation and trust between workers and management
- A multi-skilled workforce that can handle/provide schedule flexibility
- Good relationships with suppliers
- High quality production methods that will not be interrupted by instances of low quality
- Low setup times and small batch sizes

- High reliability equipment
- A stable master production schedule
- Repetitive manufacturing of a reasonable volume of parts or assemblies
- Some excess capacity to allow for variability in demand

The kanban system allows for a simple yet effective exchange of information both upstream and downstream from the production work center. Although not discussed in this thesis, a wealth of literature exists that provides in-depth discussion on the theory and implementation of a kanban system.

Any inventory control policy involves either continuous or periodic review of current inventory levels. Periodic review of inventory levels at regular intervals does not require as many resources as continuous review, and offers a reasonable prediction of inventory levels at any given time, provided that the consumption rate of the inventory is relatively steady. Continuous review of inventory, in contrast, requires more resources. Depending on quantities and consumption rates, sophisticated and costly inventory monitoring systems, such as scanners or radio-frequency identification (RFID), may be required. For products with few parts or inventory control systems that require continuous review of only certain critical parts, less extensive and expensive monitoring systems can be used (e.g., implementation of a smaller RFID system or use of kanban cards in a manual monitoring system). The primary advantage of continuous inventory review is less required safety stock for a given service level, which results in reduced inventory holding costs (Silver, Pyke, & Peterson, 1998). A continuous inventory review also helps avoid stockout costs, which in Sikorsky's case might be as high as the cost of an order for an aircraft.

Silver et al describe four types of inventory control systems that can be used in situations similar to the one described in this thesis. An order-point, order-quantity[5] (s, Q) system is a continuous review system that involves a set order quantity once inventory reaches a pre-specified level. This system, also known as a two bin system, takes into account the quantity of an incoming order not yet received (the second bin) in addition to the inventory that is physically held (the first bin). An order-point, order-up-to-level (s, S) system is also a continuous review system, but differs from the (s,Q) system in that the re-order quantity is variable in size to ensure that the physically held inventory is equal to S after arrival of the order. An order-up-to-level (R, S) is a periodic review system that involves variable re-order quantities every R units of time such that total inventory is equal to S. Finally, an (R, s, S) system is a periodic review system that involves a variable re-order size every R units of time, if current inventory is less than s, to bring total inventory levels to S. If current inventory levels are greater than s, nothing is done until the next periodic review (Silver, Pyke, & Peterson, 1998). Each of the systems offers different advantages and disadvantages.

At Sikorsky, the relatively small inventory size of critical parts and their reasonably low consumption rate allows continuous review of this specific inventory. Provided that Sikorsky can offset demand variability of original parts with spare parts and vice versa, as described in section 3.3.2, Sikorsky will be better able to forecast, resulting in parts orders that will be reliably placed at approximately equal intervals with equal quantities. In turn, this would

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[5] s = order point; Q = order quantity; S = order-up-to-level; R = units of time

provide Sikorsky's suppliers with the ability to better plan and anticipate orders, thereby increasing reliability of filling the orders in a timely and consistent manner. In this improved situation, a continuous review policy would work well.

With the small inventory quantity of each of the critical parts, a kanban system can easily be used for continuous review of inventory. As an example of this method in practice, a particular critical part might be stocked in low quantity at Precision Assembly. Each time the bin is emptied, a kanban signal is initiated. The empty bin would indicate a certain overall inventory of the part at Sikorsky, and provide a signal to request a new bin of parts from the supermarket, and for the supermarket to place a batch order from the supplier. For Sikorsky, the (s, Q) system is recommended due to its simplicity and ease of implementation. Note that for this particular supermarket of critical parts, the continuous review policy need not mean daily review of total parts quantity, but rather a review process in place in which the reorder point (which is based on inventory level) is always the same, and that the total inventory of the part is precisely known at that reorder point. From the suppliers' perspective, the quantity of each order will be constant and the interval between orders will be consistent provided that Sikorsky level loads production, as recommended and discussed later in this thesis. The more consistent that the orders are, in both quantity and frequency, the more it would help the supply base to establish a more consistent lead time for critical parts as the bullwhip effect is decreased.

A supermarket system requires analysis to determine the optimal amount of inventory to hold, which involves a tradeoff between the cost of stockouts from carrying too little inventory versus the cost of holding excessive inventory. While properly sizing inventory carries many advantages, many companies do not perform the appropriate analysis to determine the correct inventory size. As an example, one large US-based international consulting firm estimates that 80-90% of its clients use a simplistic inventory control system in which safety stock is set to the estimated demand over a set period of time (Silver, Pyke, & Peterson, 1998). For instance, the inventory is maintained by placing an order when the current inventory minus the forecasted lead time drops below a given threshold, such as two months. This approach does not take into account variability in demand, so it leads to stockouts of parts with volatile consumption rates. This simple system is currently in place at Sikorsky, which hampers efforts to assemble the main gearbox within the objective lead times due to a dearth of the required critical parts. In lieu of major changes to the supply base of critical parts, the supermarket system offers a shorter term means to ensure the right parts are on hand at the right time in the assembly process.

To discuss the analysis required for supermarket sizing, several concepts must first be introduced (Anupindi, Chopra, Deshmukh, Mieghem, & Zemel, 2005). Safety, or buffer, stock refers to the inventory of parts "maintained to insulate the process from unexpected supply disruptions or surges in demand." Cycle stock, or inventory, is variable inventory that is due to the depletion and reordering of parts.

The economic order quantity (EOQ) is the optimal order quantity that minimizes total fixed and variable costs if the replenishment lead time is constant and the demand is relatively stable. In such a case, then, the ideal replenishment size of the cycle stock is therefore the EOQ. In the situation described at Sikorsky, the lead time for some critical parts is variable and the demand, although relatively stable year-to-year, is much more variable month-to-month; however, recommendations given later in this thesis specifically address ways to help establish these two conditions. Some alternative approaches to EOQ are more useful in that they relax the assumptions of lead time consistency and demand stability, but these alternatives are often more complex to calculate and more difficult conceptually. Given that the EOQ presents a simple approach that can be easily understood and updated, it was used as the basis for determining reorder quantities at Sikorsky.

Ideally, EOQ should be calculated using the cost penalty associated with costs of overage (ordering too much) and underage (ordering too little), but these costs are often hard to quantify. For this reason, EOQ is more frequently calculated using a service level approach (Nahmias, 1997). During the internship, attempts were made to calculate the cost penalty of overages and underages using historical data, such as contract penalties for late delivery, scrap rates for obsolescent parts, etc., but it was difficult to quantify a precise value; ultimately, managers in the Operations Planning group decided that a service level approach was preferred.

The service level can be defined differently depending on the objective. Measures of service level include specified probability of no stockout per replenishment cycle (or more simply, cycle service level), specified fraction of demand to be satisfied routinely from the shelf (or more simply, fill rate), or specified fraction of time during which net stock is positive (or more simply, ready rate) (Silver, Pyke, & Peterson, 1998). In this thesis, the service level is the cycle service level and is used to protect inventory level of critical parts during replenishment lead time. The optimal safety stock at Sikorsky, then, is the minimum number of critical parts held to ensure that the demand for completed gearboxes can be met during a time period at a given service level. As the desired service level increases, the inventory required to be on hand also increases in order to compensate for larger variations in expected demand. As the desired service level decreases, the required inventory also decreases, but the chance of a part stockout increases. No changes are needed for the non-critical parts inventory as they are consistently available, regardless of variations in gearbox demand.

3.3.1 Sizing the Supermarket

With the critical parts identified, specific data on the parts were then collected. The vital information included the most recent part cost, the current inventory quantity for each part, the part lead time as listed in SAP, and the monthly demand for each part according to MRP.

Calculation of the optimal inventory size required making several assumptions. First, a fixed order cost was assumed because the actual cost data could not be obtained. Second, the order quantity for each part was assumed to be the EOQ, as determined by the calculations described below. Third, it was assumed that the supplier lead times were constant. Fourth, the forecast error was assumed to be normally distributed. Finally, it was assumed that the demand for critical parts in the supermarket could be leveled. A discussion of the validity of these assumptions is included toward the end of this section of the thesis.

To determine the size of the required safety stock, I_{safety}, the calculations below were utilized (Anupindi, Chopra, Deshmukh, Mieghem, & Zemel, 2005). These calculations assume a constant lead time from the supplier; this assumption is examined in section 3.3.3.

$I_{safety} = z \times \sigma_{LTD}$

$\sigma_{LTD} = \sigma_R \times \sqrt{L}$

where:

I_{safety} = safety stock (inventory)

z = safety factor = NORMSINV(service level)

σ = standard deviation of demand

R = monthly demand

L = lead time (months)

LTD = lead time demand = L x R

The EOQ is calculated using the following calculation (Anupindi, Chopra, Deshmukh, Mieghem, & Zemel, 2005):

$EOQ = \sqrt{[(2 \times S \times R) / H]}$

where:

EOQ = economic order quantity

S = fixed cost per order

R = annual outflow rate

H = unit holding cost per year

In this analysis, the fixed cost per order, S, is treated as a transaction cost to account for the resources required to place an order (e.g., buyer's time, use of the IT system, etc.), regardless of part value or quantity. The annual outflow rate, R, is the aggregate demand for main gearbox assemblies at the Final Assembly work center, as listed in SAP. As previously discussed, the information for the critical parts must be maintained diligently in SAP since the calculated value of EOQ relies on the accuracy of this demand data. The unit holding cost per year, H, is based on the overhead and period cost incurred while holding the parts. This value depends on many factors such as warehousing, handling, and obsolescence of parts, as well as taxes, theft, insurance, and most significant, although most difficult to quantify, the opportunity cost of the money invested (Silver, Pyke, & Peterson, 1998). The holding cost is regularly calculated at Sikorsky, and is expressed as a percentage of part cost. The facility cost is excluded from Sikorsky's holding cost since open floor space is available at the company, and so the costs associated with the facility is an ongoing cost whether or not the supermarket system is implemented.

The maximum inventory on hand, I_{max}, is simply $I_{max} = I_{safety} + EOQ$. The minimum inventory on hand is equal to I_{safety}. It follows, then, that the average inventory on hand, I_{avg}, is $I_{avg} = I_{safety} + EOQ/2$, assuming an approximately constant rate of part consumption. This assumption is valid if production is level loaded, as discussed later in this thesis.

Although the EOQ minimizes total costs associated with parts reordering, the applicable total costs are relatively insensitive to precise order quantity; this is especially true with order sizes that are greater than EOQ (Silver, Pyke, & Peterson, 1998). The implication of this insensitivity is that precise adherence to the EOQ is not important so long as it is approximately followed. The percentage cost penalty (PCP) from use of an order quantity other than EOQ can be calculated as follows, where p represents the difference in order size from EOQ in terms of percentage:

$$PCP = 50 \times \frac{p^2}{1+p}$$

As an example, an order size 40% less than the EOQ results in an increased total cost of only 13%. This sensitivity analysis is shown graphically in figure 7. The derivation of this percentage cost penalty can be found in the Appendix.

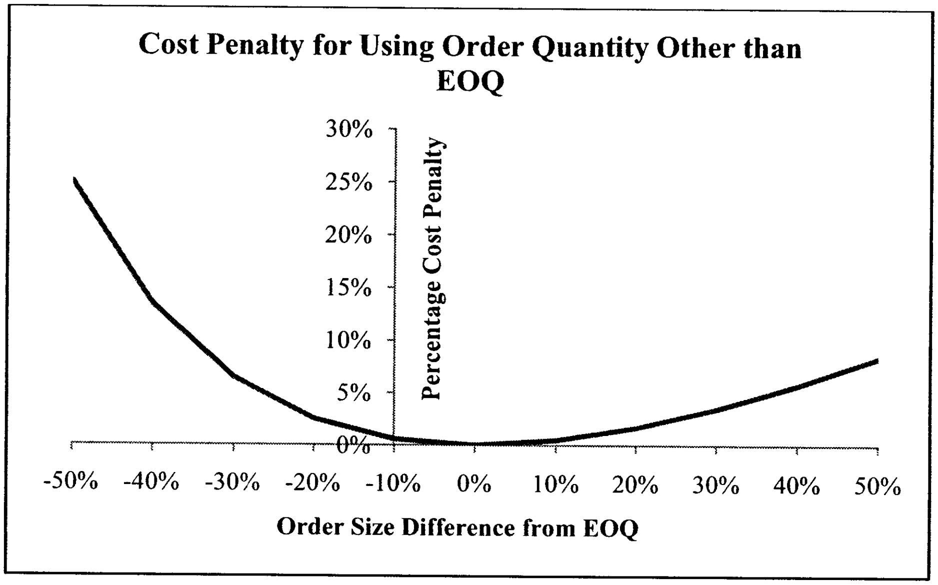

Figure 7: Cost Penalty for Using Order Quantity Other than EOQ

3.3.2 Results of Analysis

Using the above formulas and the individual part data, a Microsoft™ Excel model was built to allow for easy data entry and updating of inventory figures. The remaining information necessary to run the model was the desired service level. For purposes of comparison, the model was created to run five service levels at once. The levels used for the calculation of the gearbox supermarket were 99%, 95%, 90%, 75%, and 50%, although it should be noted that the lower service levels subject Sikorsky to increased risk of delayed delivery or the potential of losing customer orders. Figure 8 below shows the relative differences in required inventory size. The model is used to calculate the required inventory for each individual part; the data points in figure 8 represent the aggregate dollar value of all critical parts. Although the figure uses only three data points for each service level value (I_{max}, I_{avg}, and I_{min}), the data is presented as continuous because it more or less approximates the inventory values over time, assuming a constant demand rate. For example, I_{max}, represents the inventory level at the time the reorder quantity is received. The inventory is then depleted over time, albeit at a rate that is not exactly linear, until I_{min} is reached, thus triggering a reorder of parts. The current inventory is a single datum point, but is depicted as a line for comparison purposes with the required inventory quantities.

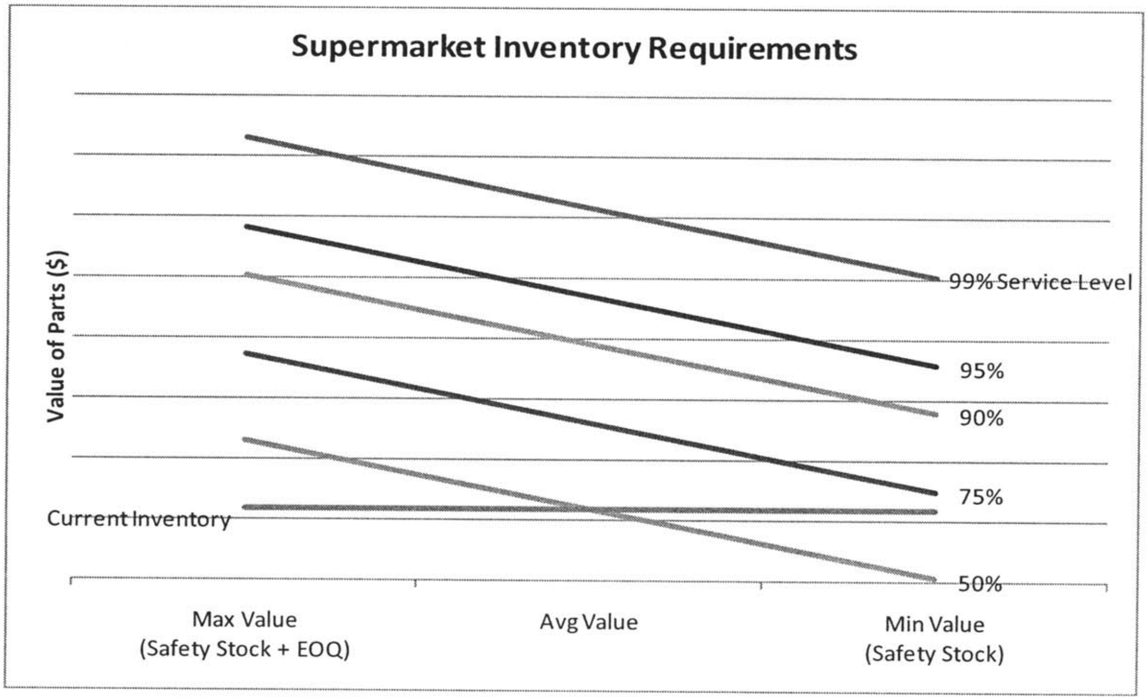

Figure 8: Supermarket Inventory Requirements

The results of the calculations revealed several interesting findings. First, the current inventory value of the critical parts is approximately equal to I_{avg} at the 50% service level; this implies that Sikorsky should be able to complete the main gearbox assembly within the objective lead time about half of the time. This, however, does not reflect reality.

Investigation of the matter revealed that part of the cause was inconsistent ordering practices. If production and assembly is level loaded, it is optimal for the EOQ to be used each time a part is reordered, and this order should take place once I_{safety} is reached for that particular part. In practice, however, buyers use their own knowledge to decide when and in what quantity a part should be reordered. A review of the buying patterns showed a great variation. In one particular case, an order was placed for a quantity of 24, followed two weeks later by another order of four;

no more orders were placed for the next two months. Examples such as this one probably reflect the buyers' attempt at compensating for variable part demand with variable ordering quantities and frequencies. So long as part demand can be made more predictable based on level loading, this finding reveals a key opportunity to save costs and increase the probability of having a given part on hand by training buyers on the concept of EOQ and making disciplined ordering part of standard work. From the suppliers' perspective, a consistent ordering practice at Sikorsky would help to better plan production to ensure that orders could be fulfilled to satisfy lead time requirements.

The investigation also revealed that although the aggregate dollar value of the critical parts approximately equaled the optimal aggregate dollar value at a 50% service level, the quantity of individual part numbers differed from the optimal. For instance, the inventory of a given part number was greater than optimal, while the inventory of a different part number was less than optimal. The overall effect was an aggregate inventory value that closely matched the optimal inventory value at a 50% service level, even though the proportion of each part number held was less than optimal. With less than optimal inventory of these certain parts, the required number of gearboxes could not be completed during those months when the demand was higher than average. As a result, the assembly of the gearboxes was delayed until the parts became available, thereby affecting the overall aircraft lead time.

Another finding involved the size of I_{safety}. A cursory examination of figure 8 reveals that I_{safety} is several times the size of EOQ, especially at the higher service levels. As discussed above, there are two major drivers in the determination of I_{safety}: service level and variability in lead time demand. The effect of service level is evident by comparing the various inventory requirements at different service levels, indicating that the relatively large size of I_{safety} is due to high variability in part demand. Each of the critical parts is used for both original equipment and for spare parts, so the demand for each part is made up of both original and spares. A brief audit of individual part demand revealed that part demand for original equipment was fairly consistent month-to-month since demand for helicopters was, and is, fairly consistent on a month-to-month basis. However, the spares demand was very inconsistent month-to-month despite the fact that demand for the same spare parts is consistent year to year. An example of the overall variability in the monthly demand of one of the critical parts is shown in figure 9. This data from MRP show the forecasted monthly demand, and therefore the planned monthly purchase of the part, for the following 12 months after the data were collected, rather than the actual demand for the previous 12 months. Since demand for original parts does not exhibit drastic fluctuations month-to-month and since aggregate annual demand for spare parts is steady, then forecasted demand should be fairly level given the ability to offset variability in original equipment demand with spare parts demand. The actual demand will likely have increased variability due to last minute demand for spare parts, but months with increased demand will be offset by months with decreased demand. The variability in actual month-to-month demand for a given critical part is difficult to forecast due to spares demand, but leveling the planned monthly purchases for the part allows aggregate demand to be met while also decreasing the resultant safety stock of the part at a given service level.

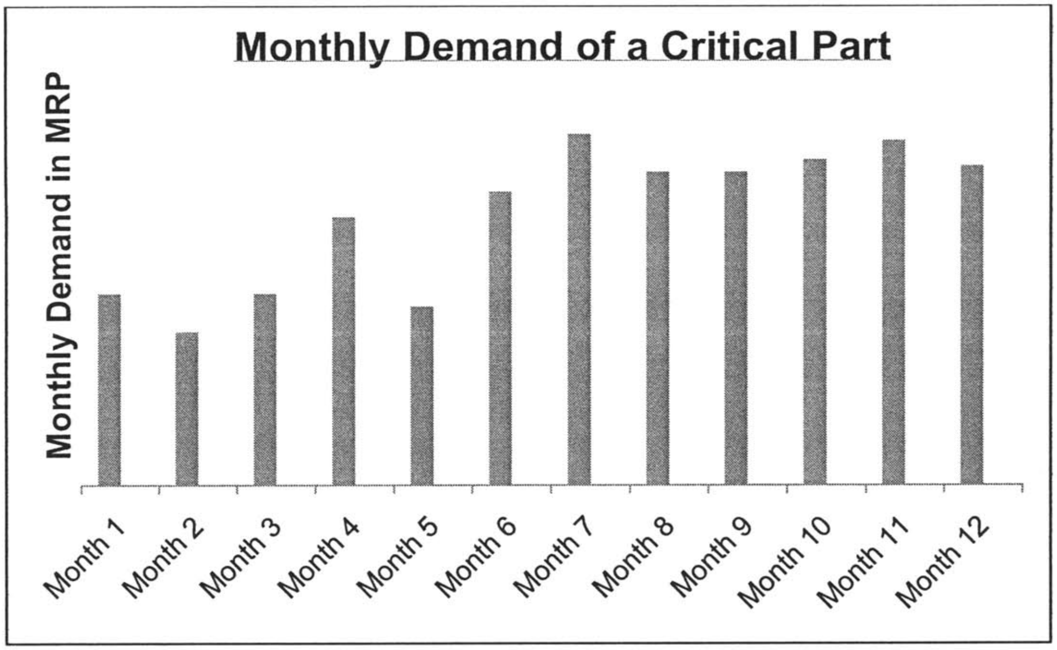

Figure 9: Variability in the Monthly Demand of a Critical Part

To determine the cause of variability in planned ordering and production of the critical parts, interviews were conducted with operations planners. Based on interviews, it became clear that there was not standard work associated with entering spare part demand in MRP. In some cases, an entire year's demand for spare parts was entered for a single month with the expectation that planners would allocate the demand over the entire year as they saw fit, but the planners were often not made aware of this expectation. Because spares demand is typically handled by different planners than original equipment demand, the opportunity to smooth demand over time is often lost. This finding, then, reveals an opportunity for Sikorsky to synchronize planning of original and spare parts demand, and in the process, dramatically decrease the required size of I_{safety}. This could be accomplished by aligning the process of entering original equipment and spares demand into MRP, assigning oversight of entering demand to a group such as the Operations Planning group, or even assigning the responsibility of entering the demand to a single individual or group.

With the inventory requirements known, it was possible to examine the incremental cost of decreasing lead time of the gearbox, as shown in figure 10. In figure 10, the vertical axis represents the cost of the required parts supermarket, at I_{avg}, for a given main gearbox lead time, which is depicted on the horizontal axis, and is decreasing from left to right. In other words, each jump in the figure represents the cost to stock an additional critical part(s) at the calculated I_{avg} in the applicable critical path, and so is the cost to achieve a specific lead time for the gearbox. The data in the figure corresponds to a service level of 99%, a service level that would allow Sikorsky to meet demand for main gearboxes nearly all the time, and thus avoid the major issues associated with stockouts. It is interesting to note the steep jump in the cost once the lead time is reduced from current to approximately halfway to the objective lead time. This jump occurs around a lead time that happens to be a very round number, and is therefore caused by multiple suppliers quoting a particular round number for the associated critical parts.

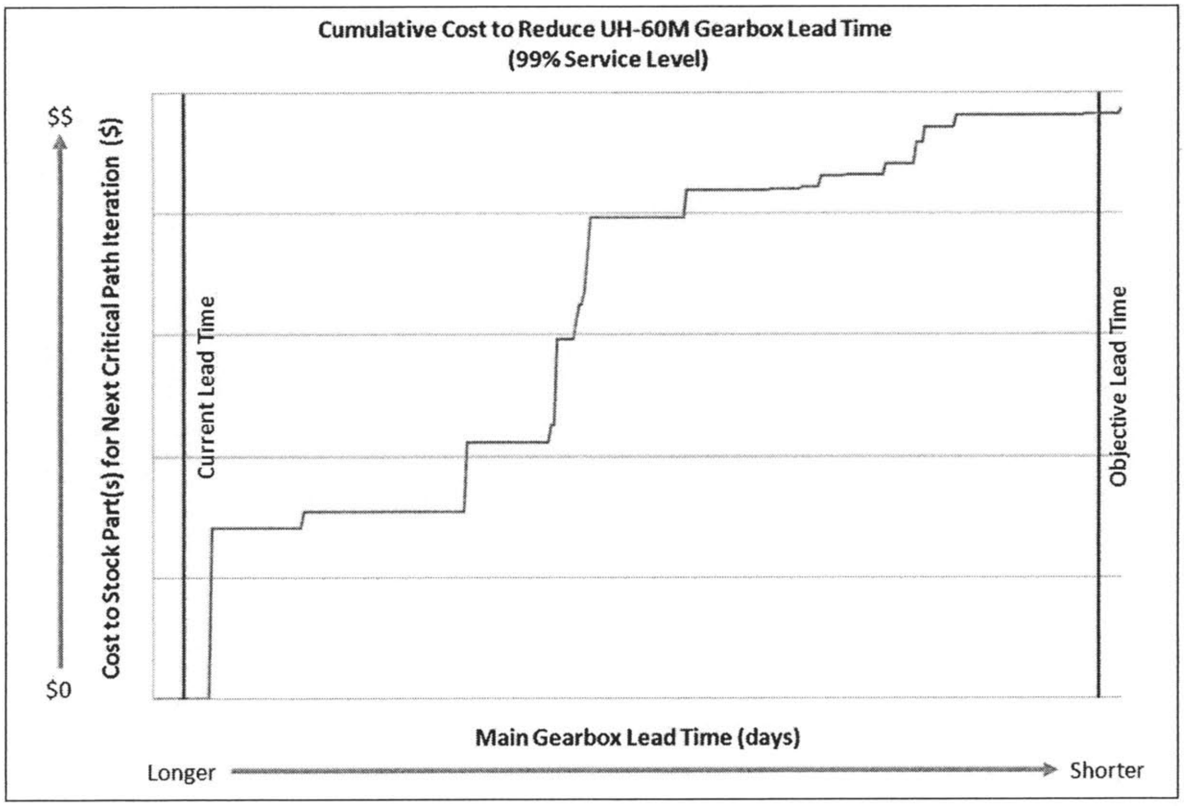

Figure 10: Cumulative Cost to Reduce Lead Time

It should be noted that figure 10 is derived using the quoted lead time from the supplier, as listed in SAP. It was not possible to collect information on historical lead times for the parts in question because the information is not kept at Sikorsky. One could conjecture that the same graph using actual, rather than quoted, part lead time would reveal a much different curve, particularly with regard to the steep jump. For planning and budgeting purposes, then, it makes sense for Sikorsky to closely track actual order and delivery dates, and insist on better information flow with their suppliers so that both can better understand lead time and demand. With detailed financial data determined by the supermarket calculations, it is essential to examine the validity of the model assumptions prior to committing to building the supermarket.

3.3.3 Analysis of Assumptions

The first assumption involved the fixed order cost. The estimated cost was validated by Sikorsky financial analysts, and represents on average, about 10% of the part cost. Since the estimated cost is most likely close to the actual value, represents such a small proportion of part cost, and only affects the EOQ calculation which is substantially less than I_{safety}, this assumption is negligible. However, as a result of the analysis performed during the internship and the subsequent recommendations provided, a more thorough determination of fixed order cost is currently in progress at Sikorsky.

The second assumption involved EOQ. As mentioned earlier, buyers do not currently place part orders based on EOQ and as a result, the gearbox is not assembled within the objective lead time, even at the 50% service level. Therefore, this assumption is not valid, but represents a simple way to optimize parts ordering.

The third assumption involved consistency in supplier lead times. Although historical data could not be obtained in order to further analyze, it should be possible to collect the order and delivery dates of the critical parts in order to track the variation in lead time, and then incorporate the findings into the calculations for determining the optimal size of the parts supermarket. Consistency in supplier lead times is desirable for both simplicity of analysis and reduction in the required safety stock at a given service level; however, the efforts of the buyers and commodity managers to force suppliers to reduce lead time, as described in section 3.2, undermine the consistency in supplier lead time. The equations below illustrate the effect of variable lead time on the standard deviation of lead time demand, which directly affects the size of I_{safety} (Anupindi, Chopra, Deshmukh, Mieghem, & Zemel, 2005).

Steady LT: $\sigma_{LTD} = \sigma_R \times \sqrt{L}$

Variable LT: $\sigma_{LTD} = \sqrt{[(L \times \sigma^2_R) + (R^2 \times \sigma^2_L)]}$

It should be noted that analysis with variable lead times using the above equation assumes that lead times from the supplier are normally distributed with no bias; in Sikorsky's case, however, the variations in supplier lead times are skewed toward lateness, thereby complicating analysis in this case.

With the proposed (s,Q) inventory review system, the suppliers would receive orders that are constant in quantity and at near consistent intervals, provided Sikorsky level loads production. Given this increased consistency, the supply base would be better able to forecast orders from Sikorsky and therefore plan production further out, greatly simplifying their own operations. This should, in turn, enable the suppliers to provide critical parts in a more consistent and reliable lead time.

To better illustrate the undesirable effect of variable supplier lead times, a simple example using some actual data was presented to the operations planners at Sikorsky. This example showed that it is far more important to maintain consistent lead time than it is to continually force suppliers to reduce lead time. This fact yields another recommendation: suppliers should be encouraged to establish a conservative part lead time that can be maintained, rather than advertising an unsustainably short lead time that is affected by market conditions, customer demand, etc., and therefore subject to large variations. Therefore, the buyers at Sikorsky would be better served by working with the suppliers to establish a reliable lead time, rather than pushing suppliers to provide parts in an ever-decreasing, but unsustainable, time frame. In parallel, Sikorsky operations planners should implement the (s,Q) review system and level load production in order to assist suppliers in establishing this reliable lead time by making ordering of parts more consistent.

The fourth assumption is that forecast errors in demand have a normal distribution with no bias. Although the standard deviation used in calculations is based on a small population of data at a given point in time rather than a larger population of data over a longer period of time, Silver et al cites studies by Ehrhardt (1979) that reveal that use of this less accurate standard deviation does not seriously degrade use of this inventory system (Silver, Pyke, & Peterson, 1998).

The fifth assumption involves the ability to level critical parts ordering and production by offsetting variation in original parts demand with spare parts demand, and vice versa. Based on discussions with various operations planners, this is possible but does not occur because planning for original and spare parts is performed separately by different groups within the company. As previously discussed in section 3.3.2, alignment of the planning processes could greatly increase the ability to smooth demand. The analysis presented in this thesis also assumes that the suppliers would be provided more insight into this improved and leveled demand forecast. Sharing this information should help Sikorsky since its supply base would have an improved ability to plan its own production, and therefore provide critical parts on a more consistent basis that may also reduce costs and improve efficiencies for these suppliers.

Finally, although not an assumption, it should be noted that much of the data used for the supermarket calculations came from a single point in time. However, much of the data, such as part cost, lead time, and demand, are frequently changing. Thus, the analysis would yield different required inventory values if the input data was collected on a different day than the original.

3.3.4 Building Inventory Levels

The analysis presented thus far addresses the proper sizing of inventory to minimize costs while meeting an objective lead time. However, as mentioned earlier in this thesis, these critical parts have individual lead times that often exceed desired lead time to customer delivery. Therefore, there are challenges associated with building the safety stock necessary to implement the aforementioned solution.

The most simple and cost effective means to more quickly increase safety stock of the critical parts is to smooth demand, and therefore ordering patterns, as discussed earlier in this thesis. By doing so, Sikorsky would provide its supply base the ability to better forecast its own production. As the bullwhip effect decreases, the suppliers should be able to fabricate parts more efficiently and better anticipate demand from Sikorsky, thus reducing average part lead time by reducing the likelihood of stockouts of raw materials and partially finished supply inventory. As discussed earlier in this thesis, consistency in lead time is more important than temporary reductions in lead time, and this consistency could be most easily achieved once the customer (Sikorsky) reduces variation in ordering. Long term approaches for part lead time reduction, which were discussed earlier, would eventually assist in this effort once they are implemented.

Another option for Sikorsky is to work with the suppliers and increase ongoing order quantities to the maximum allowed by the suppliers' capacity. This solution would require years, in some cases, to build the inventory necessary for certain critical parts for which the suppliers have limited capacity to produce. During this time, costly stockouts of critical parts would continue to occur, and many scenarios within the industry could play out. For instance, those less successful competitors with large finished goods inventory might burn through that inventory, resulting in a diminished or nonexistent lead time gap. On the other hand, Sikorsky's competitors might choose to implement their own solutions for lead time reduction (e.g., acquisition of a supplier), thereby putting Sikorsky at a competitive disadvantage as it slowly addresses the problem.

To build the inventory quicker, Sikorsky could increase the price it currently pays for the critical parts. This would allow the suppliers to either expedite production, or sell a larger proportion of their capacity or the critical parts that have industry-wide applicability to Sikorsky, rather than their competitors. Similarly, Sikorsky could approach certain distributors that already stock some of the critical parts. These distributors, some of whom have already been identified by Sikorsky, have large inventories of certain critical parts that are common throughout the industry and could provide these parts, although at a price premium from current rates. This solution only applies to some of the critical parts, but given the alternative of possibly not having these parts on hand, the price premium may well be worth it for Sikorsky. It should be noted that if

Sikorsky opts to stock the supermarket by paying more for the parts, there will be an effect on the optimal order quantity for each part since the individual part cost is factored into the calculation. Additionally, an accurate assessment of the cost penalty associated with parts underage/overage could impact the decision to build the parts supermarket by paying price premiums.

The investment to build the supermarket is a combination of increased holding costs and any price premiums paid to build the required inventory. The return on investment is difficult to assess accurately prior to implementation, but as mentioned in the background of this thesis, there are numerous reasons to invest in such a project. Regardless of how Sikorsky decides to build this inventory of critical parts, it must plan ahead to properly allocate the budget or time requirements associated with its efforts. The longer it takes to build the inventory, the more unknowns exist.

3.4 Alternative Solutions

Although a parts supermarket provides the most effective solution to Sikorsky's current lead time challenges by ensuring that critical parts are on hand, there are other alternative solutions that might also alleviate the issue.

One such solution is advocated by Subramanian. He proposes using a decoupled supply chain strategy in which parts are handled differently depending on their stability (commonality across products), lead time, and cost (Subramanian, 2008). He defines the threshold lead time, l_t, as the push-pull boundary where parts within l_t are not stocked and are ordered only with a firm demand, and parts outside l_t are held in safety stock. Once l_t is determined for a manufacturing process, parts should be grouped into stable, unstable, or reasonably stable. The stable parts are then to be ordered based on the master schedule; the unstable parts can be expedited, stocked at a lower level (e.g., raw material), or eliminated through the design of new parts with higher commonality; the reasonably stable parts should be expedited or held in safety stock if outside l_t, or treated with pre-existing policies if within l_t. Subramanian's approach could be effective at Sikorsky, particularly once the critical parts are designated as stable, unstable, or reasonably stable based on their forecasted demand across all models and customizations. With this approach, any unexpected increases in demand of long lead parts could be handled by expediting, provided that the supplier has the inventory or production capacity required to do so.

A second solution is to delay major lead time reduction initiatives until future aircraft models are designed. Working with engineers early in the design process could lead to dramatic decreases in production time later in the product's life. Boeing used such a strategy in the design of its 787 Dreamliner. The aircraft was designed with great flexibility to allow for fewer differences in the production of different variations. For instance, the 787 is built with multiple tracks in the aircraft's floor for various seating configurations requested by different airlines. Regardless of the seat configuration desired by an airline, the standard 787 can accommodate. This differs from other models that require pre-specification of desired seating configurations and resulting differences in the production of each aircraft.

As mentioned earlier, variations within a model (e.g. the medevac version of the BLACK HAWK versus the standard BLACK HAWK) require slight changes in parts. These variations increase the complexity of both production and the supply chain, and increase the chance of lead time issues. With a future model, Sikorsky engineers could design an aircraft with standard parts that could accommodate different model variations, thus simplifying the supply chain and lead time requirements. Such designs for commonality are best delayed for future models since introduction into current models would lead to lengthy delays as the parts went through FAA certification and long-established supply chains were altered.

4. Conclusion & Recommendations

Based on the findings of the supermarket analysis, it is possible for Sikorsky to effectively achieve its objections for lead time reduction, even as overall demand continues to increase. Until long term solutions for lead time reduction (e.g., designing for commonality, increasing vertical integration in the supply chain, etc.) can be implemented, the creation of the parts supermarket would ensure that the critical parts are on hand at a pre-determined service level, and eliminate the issue of their associated lead times during those periods with particularly high demand. This solution also allows Sikorsky to greatly reduce the inventory of non-critical parts, which have been identified through their absence in the critical path analysis. The parts supermarket effectively reduces both the customer's and Sikorsky's overall aircraft lead time by building optimally-sized safety stock.

The following steps summarize the take-aways of the analysis and outline the required actions to implement the parts supermarket:

- Work with suppliers to establish shorter and more consistent lead times. It is preferable to establish a conservative, sustainable lead time rather than a constantly changing, although shorter, lead time.
- Level load demand as much as possible. Coordinate planning between original equipment and spare parts to dampen large variations in month-to-month demand.
- Reduce inventory of non-critical parts to offset one-time cost of procuring safety stock. This will minimize the impact on the balance sheet incurred by establishing a parts supermarket.

- Identify physical location for the supermarket. Since the inventory will be managed with kanban controls, it is important to adequately plan the physical layout of the supermarket.
- Employ min/max inventory functionality in SAP to assist in inventory management.
- Implement pull system information flow (e.g. kanban cards, visual indicators, etc.).
- Procure appropriate levels of inventory. This may involve paying a premium on the critical parts or a significant wait time while the long lead parts are produced.
- Establish periodic review policy for right-sizing inventory (e.g. quarterly). As discussed previously, the inputs to determine inventory size are constantly changing; therefore, the inventory size must be reviewed regularly to minimize costs and ensure that lead time objectives can still be met.

These steps can be taken in the near future, allowing Sikorsky to quickly, and consistently, shorten lead time. In parallel, other steps should be taken to implement long term solutions, such as working with engineers on the design of future models.

Appendix: Derivation of the Percentage Cost Penalty

Penalty for Using an Erroneous Value of the Replenishment Quantity (Silver, Pyke, & Peterson, 1998):

Q = replenishment order quantity

A = fixed cost per order

v = unit variable cost

r = carrying cost of the item

D = demand rate of the item (units/unit time)

TRC (Q) = total relevant cost per unit time (sum of those costs per unit time which can be influenced by order quantity Q)

p = percent difference in Q from the EOQ

First, the total relevant costs per unit time are given by

$$TRC\ (Q) = \frac{AD}{Q} + \frac{Qvr}{2}$$

and the total relevant costs of the EOQ are given by

$$TRC\ (EOQ) = \sqrt{2ADvr}$$

Also, the percentage cost penalty is

$$PCP = \frac{TRC\ (Q') - TRC\ (EOQ)}{TRC\ (EOQ)} \times 100$$

where

$$Q' = (1+p)EOQ = (1+p)\sqrt{\frac{2AD}{vr}}$$

Substituting this Q'expression into the equation for TRC, we obtain

$$TRC(Q') = (1+p)\sqrt{\frac{ADvr}{2}} + \frac{1}{1+p}\sqrt{\frac{ADvr}{2}} = \sqrt{2ADvr}\left(\frac{1}{2}\right)(1+p+\frac{1}{1+p})$$

Substituting this result and the TRC(EOQ) equation into the equation for PCP, we thus obtain

$$PCP = 50\left(\frac{1}{1+p} - 1 + p\right) = 50\ (\frac{p^2}{1+p})$$

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