Building Flexibility in the Volatile Aftermarket Parts Supply Chains of the Defense Aerospace Industry

by

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B.S Mechanical Engineering, United States Military Academy, 1996

Submitted to the Sloan School of Management and the Department of Aeronautics and Astronautics in Partial Fulfillment of the Requirements for the Degrees of

Master of Business Administration
and
Master of Science in Aeronautics and Astronautics

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ABSTRACT

Within the Integrated Defense Systems of The Boeing Company, aftermarket support of military aircraft serves as an increasingly large source of revenue. One of the newest contracts between Boeing and the U.S. Government created such a supply partnership at the Army Rotorcraft Repair Depot in Corpus Christi, Texas. At this depot, all Army helicopters, including Boeing's AH-64 Apache Attack helicopter and CH-47 Chinook Cargo helicopter undergo major repair and overhaul. In 2004, Boeing entered an agreement with the U.S. Government to assume responsibility of the repair depot's supply chain for aftermarket parts for Boeing rotorcraft.

Over the last two years, Boeing has been creating and refining Corpus Christi's support structure to ensure that the required repair parts arrive when demanded. In establishing this new supply chain, Boeing has identified numerous inefficiencies as a result of inaccurate and highly volatile forecasts. This thesis examines the impact of volatility within the new support structure and creates flexible solutions to mitigate its negative effects on lead times, multiple sources of supply and inventory management. Efforts to increase communication flow across the supply chain are used to capitalize on economies of scale for cost reduction while safety stock recommendations are made for critical end-items. Monte Carlo simulations are employed to justify and validate the solutions.

The results of the thesis reveal that a strategic selection of raw material safety stock can reduce procurement lead times by an average 61% for a subset of parts while maintaining financial responsibility. Additionally, by leveraging cost reduction techniques, an average increase of 11% in Boeing's income from sales can be achieved while eliminating inefficient administrative delays and increasing customer fulfillment rates. These two recommendations demonstrate specific solutions for mitigating the effects of demand volatility and inaccurate forecasting.

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NOTE ON PROPRIETARY INFORMATION

In order to protect proprietary Boeing information, the data presented throughout this thesis has been altered and does not represent the actual values used by The Boeing Company. The dollar values and markup rates have been disguised, altered or converted to percentages, names have been changed and part numbers and supplier data have been omitted in order to protect competitive information.

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1.0 Introduction

Within the aerospace community, relationships between the manufacturers and the customers extend well-beyond the initial time of sale. In fact, approximately two-thirds of the funds that a military customer spends on its aircraft occur after the original purchase date. As such, aftermarket supply chains must constantly be prepared to deliver spare parts ranging in size from simple washers to composite rotor blades. The best support structures succeed in this requirement, and as a result, are able to capture long-term revenue while keeping the customer satisfied.

This thesis examines the impact of volatility within the aftermarket parts supply chain of The Boeing Company's military rotorcraft. The research is drawn from a six month internship at the Mesa, Arizona site. This internship identified inefficiencies within the support structure and built flexible solutions to mitigate the effects of volatile forecasts, long lead times and multiple sources of supply.

This chapter will provide general information on The Boeing Company, its military rotorcraft, recent trends and challenges within the defense aerospace industry and Boeing's current situation with respect to the aftermarket supply chain. The chapter will conclude with an outline for the thesis structure.

1.1 The Boeing Company

Perhaps the most recognizable name in the aerospace community, The Boeing Company is the world's largest manufacturer of commercial and military aircraft. Additionally, Boeing has a product line that includes helicopters, electronic defense systems, spacecraft, rockets, missiles and communication systems. This thesis explores the aftermarket supply chains of two of these platforms, the AH-64 Apache Attack Helicopter and the CH-47 Chinook Cargo Helicopter.

1.1.1 The AH-64 Apache Attack Helicopter

Assembled by The Boeing Company in Mesa, Arizona, the AH-64 Apache is commonly regarded as the most advanced multi-role combat helicopter in the world. Since 1984, approximately 1,500 Apaches have been delivered to the United States Army and the armed forces of 10 foreign nations ("Apache Overview", 2006). Initially produced as the AH-64A Model, the Apache first gained its lethal notoriety over the sands of Kuwait during Operation Desert Shield / Desert Storm. In 1997, the AH-64D Model, or Apache Longbow, began its fielding. This improved design incorporated advanced sensor, weapons, and flight performance capabilities. Since then, the Longbow has continued to uphold its namesake with combat service in Afghanistan and Iraq. Through continuing service contracts with the U.S. Army and ever-increasing foreign military sales, the need for efficiency in the Apache's parts supply chain has never been greater.

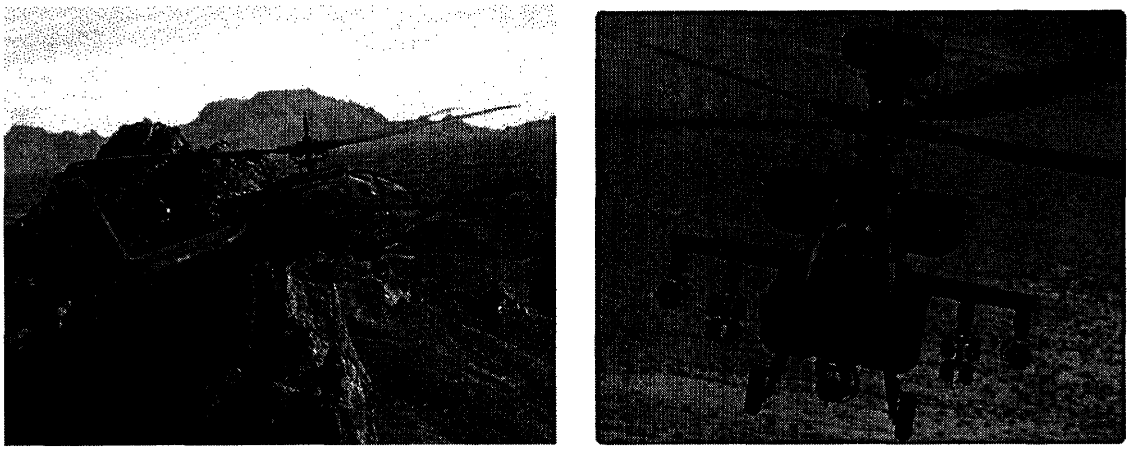

Figure 1.1: AH-64A Apache (left) and AH-64D Apache Longbow (right)
("Apache Image Gallery", 2006)

1.1.2 The CH-47 Chinook Cargo Helicopter

Nicknamed "Big Windy," the Chinook is a multi-mission, heavy-lift transport helicopter. Its primary mission is to move troops, artillery, ammunition, and various supplies around the battlefield. Manufactured by the Boeing Company in Philadelphia, Pennsylvania, CH-47s have been in service since 1962. Since its introduction, approximately 1,200 Chinooks have been produced in five different variations. From Vietnam to Iraq, the CH-47 is the longest running continual production program at Boeing and has an anticipated service life beyond 2030. Similar to the Apache, the demand for Chinooks is expanding beyond America's military and the need for efficiency within its support structure is critical to its continued mission success ("Chinook Overview", 2006).

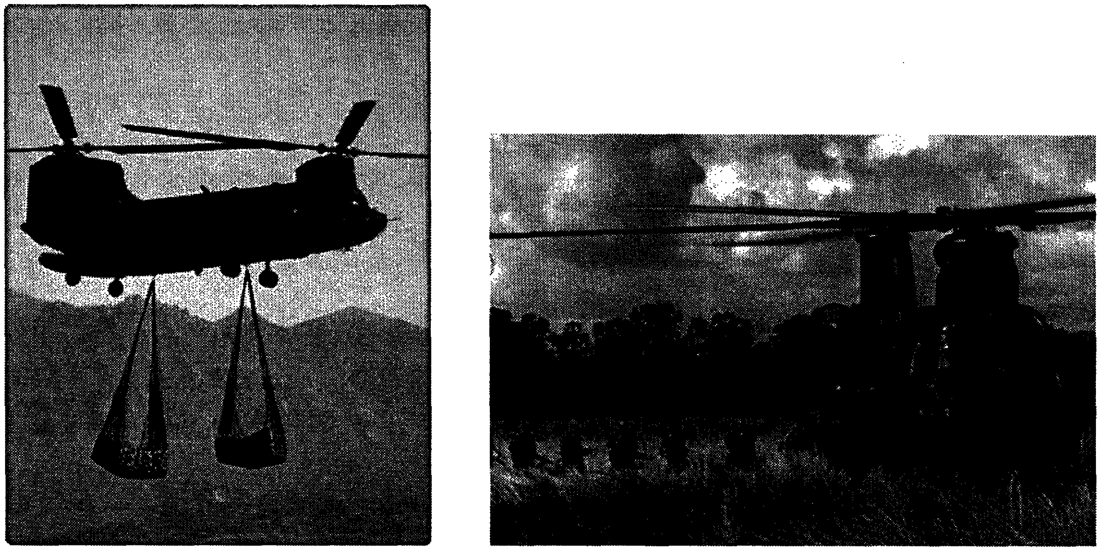

Figure 1.2: CH-47D Chinook Cargo Helicopter ("Chinook Image Gallery", 2006)

1.2 The Defense Aerospace Industry: Post September 11, 2001

With the beginning of the Global War on Terror, the defense aerospace industry underwent a tremendous upheaval. Army helicopters are flying at an operational tempo far in excess of anything previously experienced. During combat rotations, aircraft are flying as much as four times their peacetime average. These continued deployments have raised four issues that the aerospace industry was not fully prepared to deal with.

The first adversity involves demand forecasting. For over a decade, defense contractors have compiled a historical database of peacetime part consumption. However, with the armed forces fully engaged in combat operations around the world, this information is no longer valid. The last major military operation occurred during the Persian Gulf War of 1991. This conflict only endured seven months, providing little comparison to the present. With the "War on Terror" exceeding its fifth year in September 2006, suppliers are struggling to predict the needs of a wartime military. Ultimately, the challenge of accurately forecasting the future parts demand has become even more complicated.

The second issue facing the defense aerospace industry is limited part availability due to increased demand. This occurs for three reasons: battle damage, increased flying, and exposure to harsh environmental conditions. Battle damaged parts present the most difficult challenge. The reality of warfare creates an unpredictable replacement requirement that includes all parts, at any quantity and in various degrees of repair. The next demand problem arises because aircraft components are reaching their design lifetimes much faster than anticipated. This is a result of both the increased flying and the additional stresses imposed on the airframe by the combat flight maneuvers employed. A final cause under this topic results from the Army's continued operations in remote climates. Whether it is the extreme desert heat or elevated mountain altitudes, greater than traditional part failure rates from continuous exposure to environmental conditions are beginning to appear. An example of this is seen in a new type of corrosion damage from ingested sand into rotating components. Regardless of which cause, numerous components are reaching mandatory retirement much sooner than anticipated, driving demand higher than ever.

The third industry-wide issue is an insufficient supply base. There are an extremely small number of suppliers who are qualified to manufacture specialized aerospace components. This partially results from the fact that the components are very specialized, the market is small in size and the government imposes strict requirements on suppliers that requires extensive bookkeeping. However, these suppliers are also reluctant to invest large amounts of capital in capacity expansion. The suppliers realize that the fighting will eventually end, and with it the wartime operational tempo that is driving demand. As a result, competing aerospace contractors struggle to have their demands satisfied at suppliers who are already operating at maximum capacity. Unfortunately, these capacity constraints only serve to increase lead times and cost.

The final complexity facing the defense aerospace community is the availability of certain raw materials. Known as the "Berry Amendment," Section 2533a, Title 10 of the United States Code imposes legal obstacles upon defense contractors. The regulation states that certain, "products, components, or materials...must be grown, reprocessed, reused, or produced wholly in the United States if they are purchased with funds made available to the Department of Defense" (United States, 2006). This list includes certain specialty metals which are essential to military aviation for their high strength-to-weight ratios, corrosion resistance, and thermal properties. Unfortunately, the combination of few domestic suppliers and this procurement restriction often causes lead times for these raw materials to exceed one year. Additionally, suppliers are forced to purchase these materials at highly-elevated prices. In 2005, the price for titanium, one of the regulated metals, surged over 317% (Toensmeier, 2006). Yet despite this cost, titanium is a crucial material. In commercial grades, it possesses the same tensile strength as steel, but is approximately half the weight (Kerrebrock, 1992). This regulation undoubtedly is protecting the jobs of American specialty metal manufacturers; however, it is simultaneously creating waste and inefficiency within every defense contractor's supply chain.[1]

1.3 The Corpus Christi Army Depot

Funded and operated by the United States Government, the Corpus Christi Army Depot (CCAD) is one of a few sites dedicated to repairing the 57 end-item components of the Apache Helicopter and the 119 end-item components of the Chinook Helicopter. An end-item is a major assembly such as transmission, gearbox, pump or hydraulic actuator. Prior to Boeing assuming responsibility for CCAD's supply chain, the depot was responsible for procuring over 7,000 unique part types required to make the scheduled repairs to the above mentioned end-items. However, because of the previously discussed challenges associated with the current aerospace industry, the government's logistical system was unable to adequately meet the Army's demands. As a result, CCAD reported repair turnaround times (RTAT) in excess of twice the other repair sites. To solve this problem, CCAD looked to Boeing as the original equipment manufacturer for technical, engineering, and logistical support.

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[1] The thoughts behind the four industry-wide issues were discussed during numerous conversations with David R. Greenwood (internship supervisor and Boeing Senior Manager in Supplier Management and Procurement for the AH-64 CCAD program). The discussions occurred during June 2006.

In October 2004, Boeing signed a five year, several hundred million dollar contract to partner with CCAD and assume control of the supply chain that supports the overhaul and repair program for the AH-64 Apache and CH-47 Chinook. As such, Boeing became the primary vendor to CCAD for all AH-64 and CH-47 repair parts. Boeing was now responsible for establishing and / or maintaining supplier relationships, ordering and purchasing the repair parts and coordinating for shipment of the parts to the Boeing warehouse at CCAD. At the warehouse, Boeing employees managed the repair parts inventory, issued the parts when demanded by the CCAD production cycle and tracked consumption data. Over the course of the last two years, Boeing has been creating and refining the CCAD supply chain in an effort to reduce the RTAT and increase the part availability.

1.4 Creation of the Supply Chain

After award of the contract, Boeing developed a plan for creation of the CCAD support supply chain. The decision was to implement the following phased plan (Thieven, 2004).

> Phase 1: Provide technical, engineering, and logistics support services and begin to create bills of material (BOMs) to define the support material needed. A BOM lists the relationship between an end-item and the parts that are used to construct the end-item. The required quantities of each part are listed on the BOM.

Phase 2: Provide material support for the Apache's 24 and the Chinook's 27 most demanded end-items and open the parts warehouse.

Phase 3: Provide all remaining material support for the non-critical, lower demanded end-items.

Phase 4: Provide material support for airframe structures. This includes modifications for AH-64A to AH-64D transitions as well as repair for battle or crash damage. A transition is an aircraft modernization. An AH-64A model is delivered to the depot by the U.S. Army. Older technology is replaced with newer versions to increase the helicopter's capabilities. Examples of this include the addition of a target acquisition and identification radar, stronger engines and increased aircraft survivability equipment.

Since establishment of this phased plan, numerous changes have been made to its architecture to include Phases 2a and 2b (expansions of the Phase 2 end-item list). However, the original concept remains the same. At the time of this thesis, Boeing is providing support to CCAD in accordance with Phase 3. Boeing has begun planning for Phase 4 implementation. It should be noted that whenever possible, Boeing has attempted to provide material support regardless of phase assignment.

1.5 Thesis Outline

An introduction was offered in Chapter 1.0. Chapter 2.0 will discuss the current support structure, information and material flow along the supply chain and highlight the areas targeted for improvement. In Chapter 3.0, the flexibility added by implementing a fixed pricing strategy is presented. Chapter 4.0 describes how procurement lead times are reduced by altering the raw material procurement policy. In Chapter 5.0, a methodology is created for identifying inaccurate Depot Overhaul Factors in order to improve fulfillment rates. Finally, Chapter 6.0 will finish the thesis with conclusions, observations and recommendations for follow-on work.

2.0 Integration and Understanding

Before recommendations for improvement can be made, it is necessary to understand how the current system operates. How do people communicate? What is working well? What is not? This chapter will address these and other basic questions in an attempt to explain why the areas chosen for improvement were selected.

2.1 Information Flow

Efficient information flow is critical to a well-organized supply chain. The CCAD support structure is no exception to this statement. In order for a repair part to arrive at CCAD, numerous groups of people must communicate within a complicated system that spans the entire United States. To manage the thousands of information requirements, Boeing utilizes a centralized database and a material management system known as the Advanced Manufacturing Accounting and Production System (AMAPS). Understanding how people interface with each other and the database will highlight where communication inefficiencies occur and provide insight into where improvements can be made. The figure below attempts to map the information network at a high level. Greater detail will be explored in the following sections.

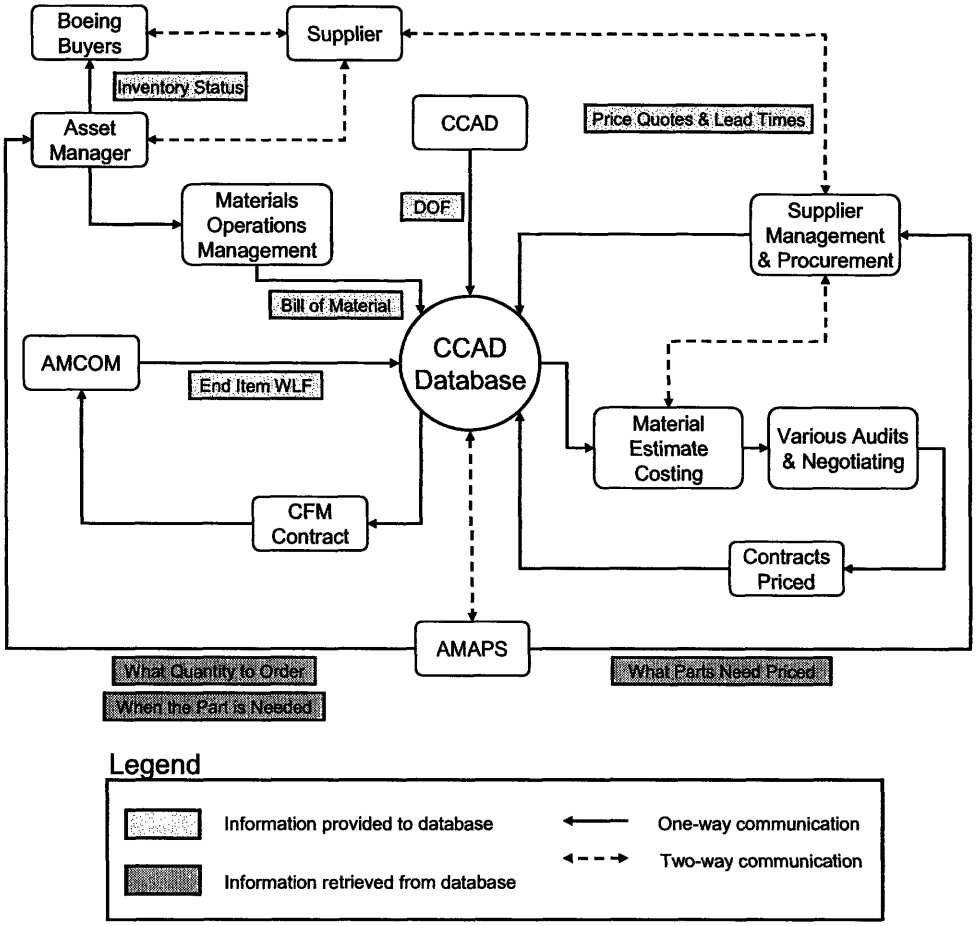

Figure 2.1: Communication Network

2.2 How Parts Arrive at CCAD

For parts to arrive at the Boeing Warehouse at CCAD, coordination and planning must be completed prior to the production cycle. Once all of the preparation is completed, the supply chain begins the physical process of ordering and shipping the actual parts to CCAD. This chapter will describe both steps by referring to Figure 2.1.

2.2.1 Initial Processes

Before a single part moves along the supply chain, a support contract is negotiated between Boeing and the U.S. Government. Of all of the agreements listed in the contract, three of the most commonly referred to are a part's support date, its contract quantity, and its contract price. The support date is the date that Boeing assumes responsibility for providing a part to CCAD. The support date is linked to one of the four phases discussed in Chapter 1.4. The contract quantity refers to the number of parts Boeing promises to provide CCAD once the support date is reached. This quantity is based upon CCAD's forecasted production needs. The contract price is a per-unit price Boeing agrees to charge CCAD for each part. This price is based upon the contract quantity and an agreed upon profit margin. An example of what this information would look like in the contract is listed below.

Part Number	Support Date	2007 Quantity	Price
123	01/01/2005	25	$271.68
456	08/31/2007	3	$23.51
789	05/15/2008	0	n/a

Table 2.1: Contract Data Example

Thus, at of the time of this thesis, Boeing would already be supporting Part Number 123. Boeing is required to provide 25 of Part Number 123 during 2007 and will sell each part to CCAD for $271.68.[2] Part Number 456 is scheduled to

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[2] The contract will actually list each part number's requirements for the next three years. Each part number will have a quantity and price associated with the future production year. Prices are adjusted for inflation. Thus, for this example, the actual contract would list quantities and prices for 2007, 2008 and 2009.

be supported on August 31, 2007. Depending on the lead time of the part, Boeing will take the appropriate action to ensure the part is on hand by the support date. Finally Part 789 is not supported yet. As such, none of these parts are required for the 2007 production year. With the contract completed, parts can be ordered for the upcoming production cycles.

2.2.2 Ordering and Shipping

Each April, the U.S. Army Aviation and Missile Command (AMCOM), provides Boeing with CCAD's Workload Forecast (WLF). AMCOM is the financial arm that controls CCAD's budget. The WLF specifically details the number of overhauls CCAD is funded to repair (per end-item) for the upcoming three years. The WLF forecast is usually updated with changes on a semiannual basis in October. Quite often, the WLF does not reflect what was listed in the contract quantity.

However, with the WLF on-hand, Boeing can determine the type and number of parts to procure. This begins when the Boeing database pairs the WLF with an estimate for the probability of part replacement. This replacement estimate is required because not every end-item overhaul requires each internal part to be replaced. If an inspection determines that a part is still functional, the part will be cleaned and returned to service. Thus, a factor is used to forecast how many parts will be consumed during each end-item overhaul. This replacement estimate is known as the Depot Overhaul Factor and will be discussed in more detail in Chapter 2.5. But for now, for each part, the quantity to order can be determined through the following equation.

$$\text{End-item WLF} \cdot \text{Depot Overhaul Factor} = \text{Quantity to Order} \qquad \textit{(Equation 2.1)}$$

For each of the 7,000 parts, the database calculates the quantity to order with Equation 2.1 and transfers the information into AMAPS. Finally, the asset managers, who are responsible for coordinating with the various suppliers, retrieve the required quantity from AMAPS and work with the Boeing buyers to purchase the parts required to support the WLF.

2.3 Process Timelines

With the flow of information and material mapped, the next step was to gauge the timeliness of the operation. This could provide some insight into where inefficiencies are creating waste within the supply chain. After talking to the responsible parties, the following functional timeline for actual task completion was developed.

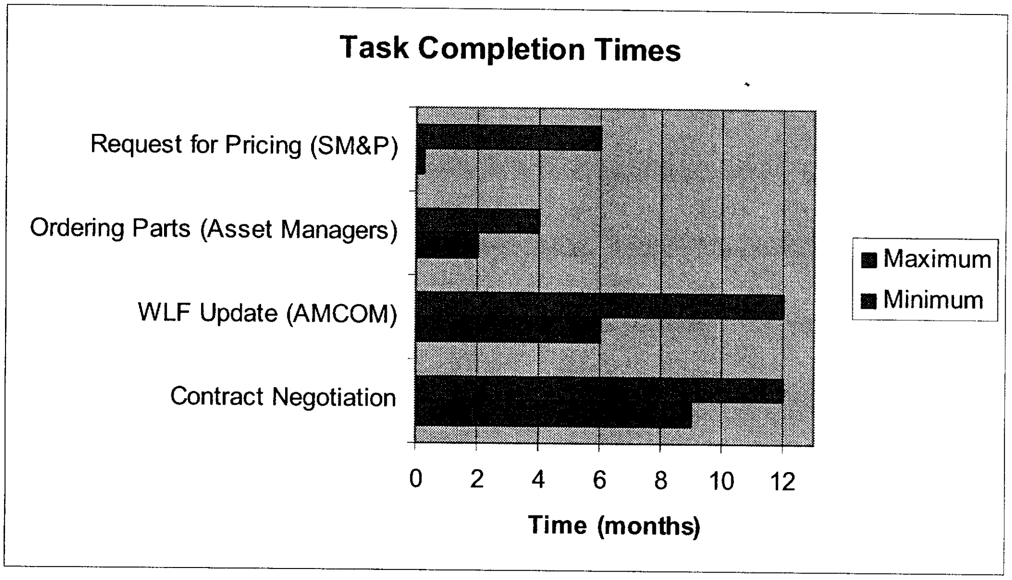

Figure 2.2: Task Completion Timeline

Two functions are absent from this chart: Depot Overhaul Factor updates and BOM updates. These were excluded because they are continually monitored and sporadically changed. It should also be noted that the WLF update is at the discretion of the U.S. Government and contract negotiations are beyond the scope of this project. Regardless, closer examination of Figure 2.2 reveals some interesting results.

When compared with the other functions, a “Request for Pricing” shows a disproportional gap between the minimum and maximum task completion times. According to SM&P personnel, this disparity occurs when numerous parts require repricing at the same time. Recalling Chapter 2.2.1, when a part is placed on contract, it is priced at a specific quantity. However, as mentioned before, CCAD’s WLF will quite often demand quantities that differ from those listed on the contract. This volatility in the required quantity affects the price (as a result of scale). For example, if CCAD originally contracted for 10 pieces and now requires 100, the per-unit cost to Boeing will be less due to economies of scale. Thus, the selling price of the part to CCAD will also decrease. Conversely, decreases in quantities will result in increased procurement costs and selling prices.

The problem inherent in the fixed contract price is revealed whenever a WLF update arrives. This is because the update encompasses the entire parts list and ranges in scale from -100% to greater than + 100% of the original forecasted requirement. This change in the demanded quantities invalidates the quoted contract price for thousands of parts. In addition, because the price is no longer accurate, Boeing is prohibited from selling the part to the depot. The unfortunate result is that even if the part is on the shelf and available for use by CCAD personnel, Boeing cannot proceed with the sale. As a result, production must wait while SM&P staff contacts the various suppliers and has new prices calculated. Figure 2.3 depicts the most recent variability within the CCAD supply chain as a result from WLF updates.

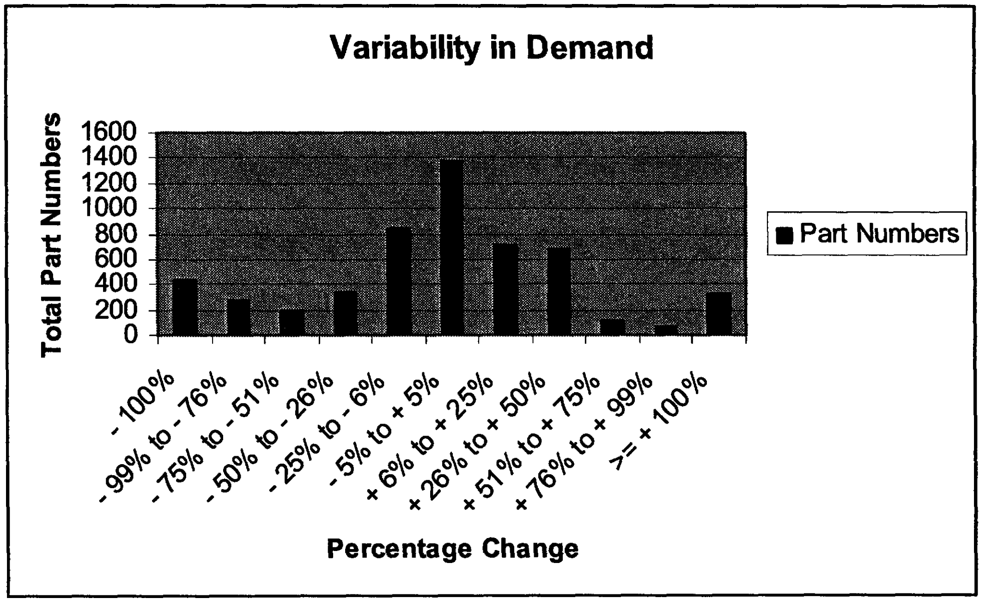

Figure 2.3: Supply Chain Variability in Demand

Figure 2.3 shows magnitude of the change in forecasted demand over a six month period. Only 19% of the 7,000 parts had little to no change in forecast (-5% to +5%). Unfortunately, the remaining 81% of parts experienced significant changes.

While the actual task of submitting a new request for pricing can be completed quickly, suppliers will often take exhaustingly long times to return new quotes. This usually occurs because thousands of parts require repricing at the same time. This delay in acquisition time produces two unfavorable results. First, if an alternate source of supply is available, CCAD will attempt to purchase the part elsewhere.[3] Second, if no alternate source of procurement is available,

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[3] By contract, CCAD must purchase the parts from Boeing is they are already supported. However, if the required part is not on-hand, CCAD may look to other suppliers for support. Examples of this include other Department of Defense warehouses and other suppliers.

production will stop. Regardless of the result, Boeing loses revenue from the missed sale opportunity and customer satisfaction decreases. This administrative repricing delay has significant consequences on the production cycle and can be listed as a cause of the less than optimal RTAT. As a result, this is an ideal area for improvement and will be discussed in detail in Chapter 3.0.

2.4 Implications of Variation on Lead times

The supply chain demand variability depicted in Figure 2.3 showed that approximately 60% of the part numbers increased in quantity. Unfortunately, the majority of parts that Boeing supplies to CCAD do not possess short lead times. For the purpose of this analysis, a long lead time is defined as greater than or equal to six months. Figure 2.4 shows that approximately 59% of all CCAD parts have long lead times.

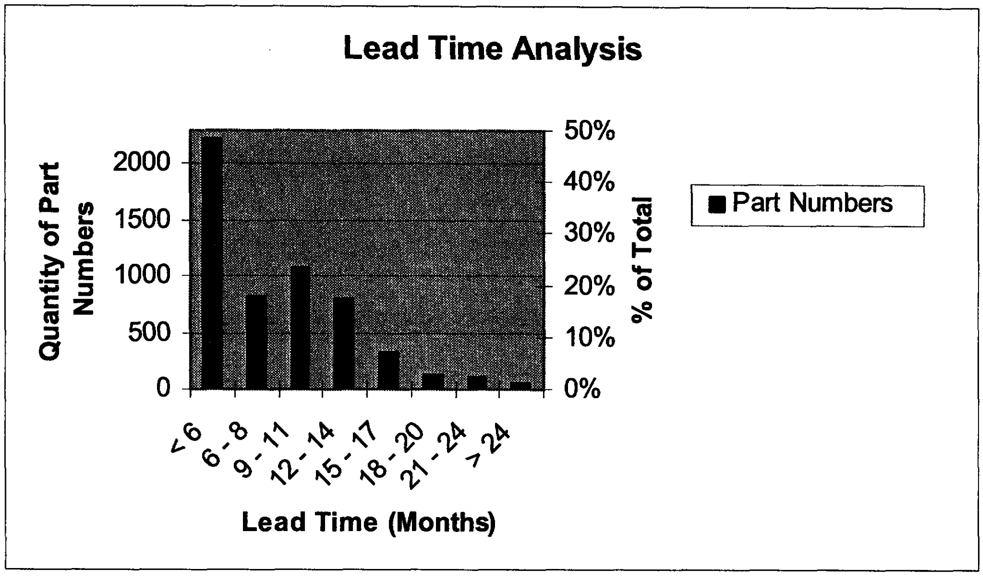

Figure 2.4: Lead Time Analysis

Additionally, some of the most critical parts to CCAD's production fall on this long lead time list. Critical parts are defined as those required for "flight safety" purposes, those without which all production will stop or of those significant importance to CCAD and the U.S. Army. Regrettably, many of these critical long lead time items also experience the increased variability seen in Figure 2.3. However, what Figure 2.4 fails to depict is the specific impact of raw material procurement on a part's total lead time. When raw material lead times are examined, only 66 of the approximate 7,000 parts had four similar qualities. These qualities were (1) total lead times in excess of 12 months, (2) a history of the previously described variability in demand, (3) on CCAD's critical demand list and (4) composed of specialty metal raw materials.

Recalling Chapter 1.3, specialty metal raw materials are difficult to obtain quickly. When looking at this subset of 66 parts, the average lead time to procure the required raw materials equates to 62% of an end-item's total lead time. The corresponding range in raw material lead time spans from 31% to 88%. As such, a theory was developed that stated if the raw material for a critical end-item was available whenever an unforecasted demand was received, the total lead time to produce the end item could be reduced by the raw material procurement time. As a factor of the importance of these parts, Boeing management (with input from CCAD) decided to focus on increasing the fill rate of these 66 parts. An analysis was created to determine if there was a business case to justify maintaining a safety stock of specialty raw materials for the 66 critical end-items. Furthermore, if the safety stock should be procured, what quantity should be maintained? These questions served as the second area for improvement and will be discussed in detail in Chapter 4.0.

2.5 The Depot Overhaul Factor

Briefly mentioned in Chapter 2.2.2, the Depot Overhaul Factor (DOF) is an average component part failure rate that Boeing uses to help forecast the future parts demand. For every part on each end-item, Boeing determined a DOF. Boeing defines the DOF as the quantity of a specific part consumed per 100 overhauls. It is important to stress that a DOF is unique to each end-item. Thus, a part will have a DOF for every end-item in which it appears. However, if a part is used in various locations within a single end-item, the assigned DOF will be common to the part regardless of how it is used (Wart, 2006).

For example, “Gear XYZ” is utilized within two end-items: the fuel transfer valve and the auxiliary power unit (APU) shut-off valve. Within the fuel transfer valve, “Gear XYZ” has a DOF of three, while in the APU shut-off valve; it has a DOF of five. Thus, on average, Boeing anticipates having to replace “Gear XYZ” three out of 100 times in the first case and five out of 100 times in the latter. Utilizing Equation 2.1, if the WLF for the fuel transfer valve is 200 and there is only one “Gear XYZ” per valve, Boeing will order six gears in anticipation of the production year.

The DOF selection is based upon input from a variety of sources. These sources include (but are not limited to) CCAD historical records, engineering specifications, human input and other program recommendations. Unfortunately, the various sources rarely agree upon what the DOF should be. As such, a prioritization scheme was established to choose the appropriate DOF. However, these disagreements have recently caused Boeing management to question the accuracy of the DOF list. As a result, an analysis was created to determine the appropriate selection criteria and usage of the DOF. The third and final aspect of this thesis evolved from this analysis. With a database of thousands of DOF values, a methodology would need to be created to highlight potential focus areas. This methodology along with the associated problems and limitations of the current DOF usage will be discussed in Chapter 5.0.

3.0 Exploring Fixed Unit Pricing

Whenever possible, Boeing and AMCOM personnel will meet face-to-face to discuss issues affecting the operation of the CCAD supply chain. During these coordination meetings, new ideas are proposed in attempts to improve upon any identified problems. In July 2006, one of these meetings took place where an idea was suggested to address the timing problem caused by an updated forecast and the need to reprice parts. The idea was to fix the contract sale price of a part as a constant, regardless of the quantity ordered. In other words, once the part was priced for a certain quantity, the quoted contract value would remain the selling price regardless of what quantity was sold to CCAD.[4] Recalling Table 2.1, Part 123 was priced at $271.68 for a quantity of 25. Under this plan, the $271.68 selling price would apply if CCAD only ordered 11 or 1100.

This idea, which became known as the "fixed pricing" solution, would mitigate the effects of the government's poor and variable forecast by eliminating the need to obtain a new price quote. Without the repricing delay, a part could be sold upon request and the supply chain could eliminate inefficient delays. However, fixed pricing would require Boeing to assume two types of risk from the downside of this pricing solution. These risks are discussed in the following chapters and are the starting point for an analysis to determine if the fixed pricing idea is an acceptable solution.

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[4] The contract selling price was only valid for the specified production year.

3.1 Risk Due to Quantity Fluctuation

The first hazard with fixed unit pricing is classified as risk due to quantity fluctuation. As discussed earlier, contract prices are based upon a specific quantity. Assuming economies of scale hold true, the more parts ordered, the smaller the per-unit cost. This affect occurs because the fixed costs of production are now dispersed over an increasing number of units. The quantity fluctuation risk becomes relevant when Boeing prices a part for one quantity and CCAD orders significantly less. Figure 3.1 below depicts an example of this issue.

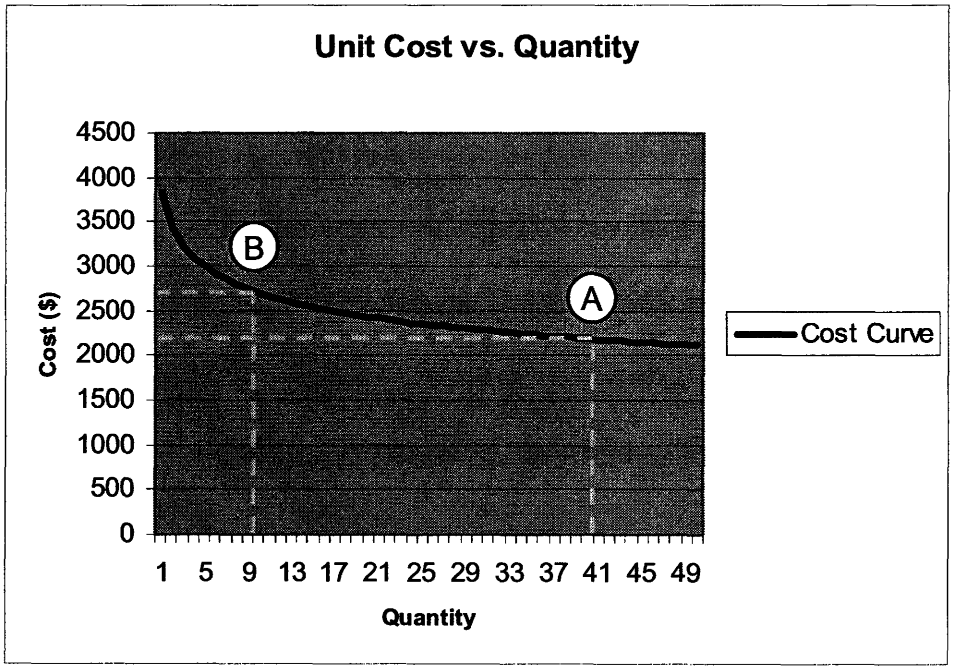


Figure 3.1: Quantity Fluctuation Risk

Assume the contract price is represented by Point "A." Here, a quantity of 40 parts equals a cost of $2200 per unit. However, if CCAD alters their demand to Point "B," the new quantity of ten parts has a higher unit cost of $2700. For this example, a fixed price agreement will cause Boeing to lose $500 per part.

3.2 Risk Due to Material Escalation

The second type of risk generally results from raw material costs. As mentioned during the industry overview, certain specialty metals have tripled in price over the last year. Without long-term price agreements with suppliers, material escalation costs would likely be transferred onto Boeing. Once again, Boeing would lose money in a fixed price scenario as they would be unable to transfer these additional costs onto CCAD.

As an example, refer again to Part 123's contract quantity and price of 25 and $271.68 (from Table 2.1), respectively. Assume that Part 123 is built entirely from Titanium. If Titanium prices rise another 317% as in 2005, Part 123's supplier will undoubtedly pass this additional cost onto Boeing. This would result in a new unit cost of $861.23. Fixed unit pricing would require that Boeing lose $589.55 per unit because they would still be forced to sell the part at the original cost of $271.68.

3.3 Data Gathering

With an understanding of the risks involved, the research into fixed pricing could begin. Responsible parties from the following functional groups involved in a repricing assignment were interviewed: supplier management and procurement (SM&P), asset managers and contracting personnel. It was during a discussion with the asset managers that the first piece of information critical to the analysis was found.

3.3.1 Discussions with the Asset Mangers

Recalling Chapter 2.2.2, asset managers are tasked to supervise and administer Boeing's requirements with key suppliers. Specifically, asset managers coordinate with suppliers to ensure that the requested parts arrive at CCAD to support the production schedule. However, what Boeing failed to capitalize on was that the asset managers also oversaw the parts flow to other assembly and repair programs. Some of these other accounts include the production line, aftermarket part sales direct to the military and other overhaul and repair programs.

The asset managers would determine and load the purchase requirements for the different programs separately. In turn, the buyers would react to these requirements as they were loaded, by placing individual purchase orders. This effectively eliminated the benefits of scale. As all of these parts support the military, they are funded in the same fiscal year. Thus, the demand and financing for these parts are known and available at the same time. There was nothing preventing the asset managers from combining the demand, placing one total order, leveraging economies of scale and achieving cost savings. A revision of Figure 3.1 demonstrates this.

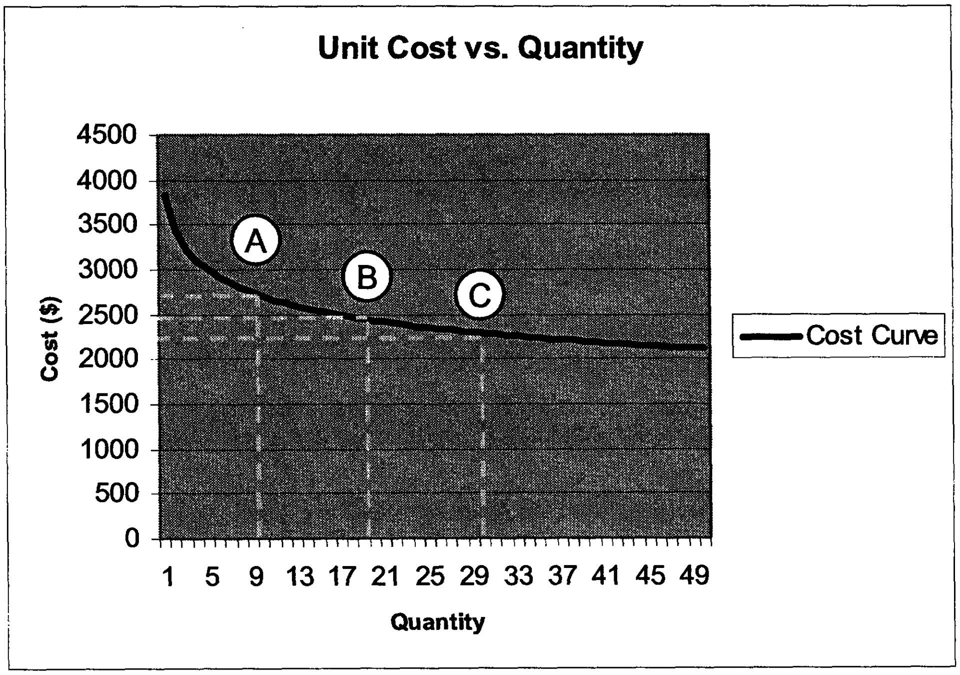


Figure 3.2: Leveraging Economies of Scale

If an asset manager purchases parts for Program A and Program B separately, he would pay $2750 and $2500 per unit, respectively. However, if the asset manager combines the two program's demands and places a single order (represented by Point C), the per-unit cost is now $2250. Thus, the power of economies of scale is revealed.

3.3.2 Non-CCAD Demand for Parts

The next step was to determine the historical parts demand for programs other than CCAD from 2003 through 2006. These years were selected because they isolate the wartime demand. For all the parts that support CCAD, the yearly demand for all the other programs was gathered. The data revealed that these programs were different from CCAD in that when orders were placed, the quantities rarely changed from the original forecast. These programs were not experiencing the fluctuations in demand that CCAD was. Additionally, the other programs provided significant demand (in terms of quantity) to justify exploration into the benefits of economies of scale. This evidence provided the second key to the fixed pricing analysis.

3.4 Data Analysis

In order to support CCAD with repair parts for both the AH-64 and CH-47, Boeing must manage 7,000 unique part numbers. To make this list more manageable and meet an October 2006 implementation goal, a subset of part numbers were chosen for the analysis. Only parts that had an active support date and possessed a unit price greater than $100 would be included. The $100 unit cost cutoff was chosen for three reasons. First, Boeing purchases most parts under $100 in bulk for a four year contract requirement. Second these parts represent approximately 70% of the total part list. By purchasing these parts all at once, numerous transactions can be eliminated and time can be saved. Finally, parts less than $100 equate to only 5% of Boeing's total cost. This safety stock of inventory increases fill rates at a minimal cost. By looking at the active support dates and unit costs greater than $100, the resulting subset equaled 1,793 part numbers and represented 94% of the contract's total revenue.

3.4.1 Risk Mitigation from Quantity Fluctuations

A part is protected against the risk from quantity fluctuation if its cost to Boeing can not increase. Another way of stating this is that if a part is on contract for a small quantity, it can be assumed that the cost to Boeing is already at its maximum. This is true because of a practice commonly employed by Boeing's suppliers. Known as quantity band pricing, a single price is applied to a range of quantities in order to save time. These bands vary in quantity; however, the first tier is frequently from the first unit to the tenth. Thus, the price of the first item is the same as the price of the tenth.

In order to save time, suppliers will often limit their quantity band pricing to the vicinity of the submitted contract quantity. Thus, for Part 123 from Table 2.1, the price of $271.68 might apply for quantities 21 – 30 where a price of $250 might apply to a range of 31 – 50. Figure 3.3 depicts this assumption by overlaying typical quantity band pricing onto the cost curve from Figure 3.1. The bands are applied across the entire cost curve to better illustrate the example. The figure shows how the benefits of scale still exist, but not incrementally.

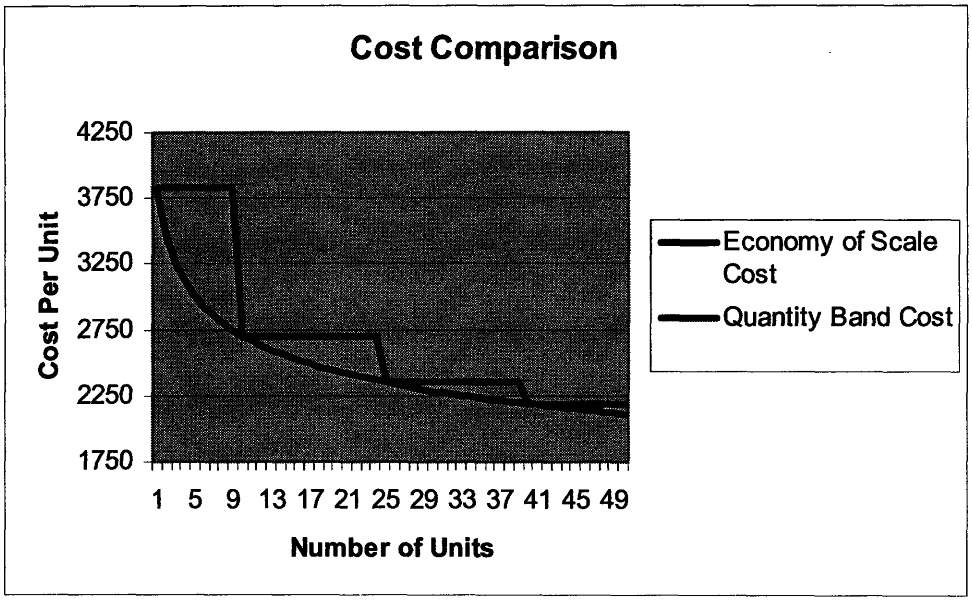


Figure 3.3: Cost Comparison

In looking solely at the economy of scale cost curve, quantity decreases where the slope is steepest would have an enormous impact on the cost of an item. However, in quantity band pricing, a decrease in quantity from nine to three (for example) has no impact on cost to Boeing. This concept was applied to the subset of part numbers in the fixed pricing analysis. As discussed above, the assumption used was that contract quantities less than 10 were already priced at their highest cost to Boeing. Figure 3.4 shows the results.

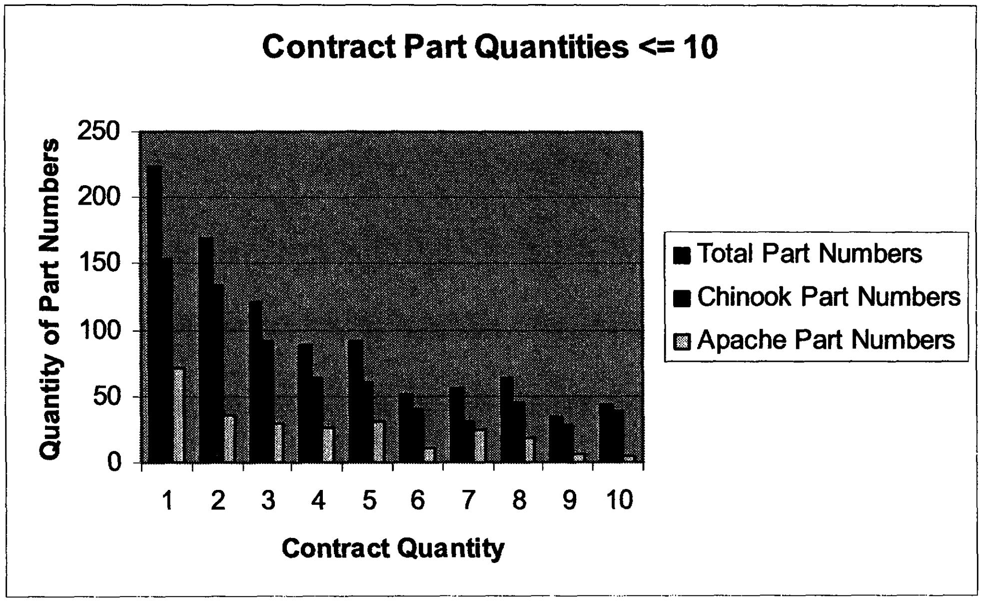


Figure 3.4: Small Contract Quantities

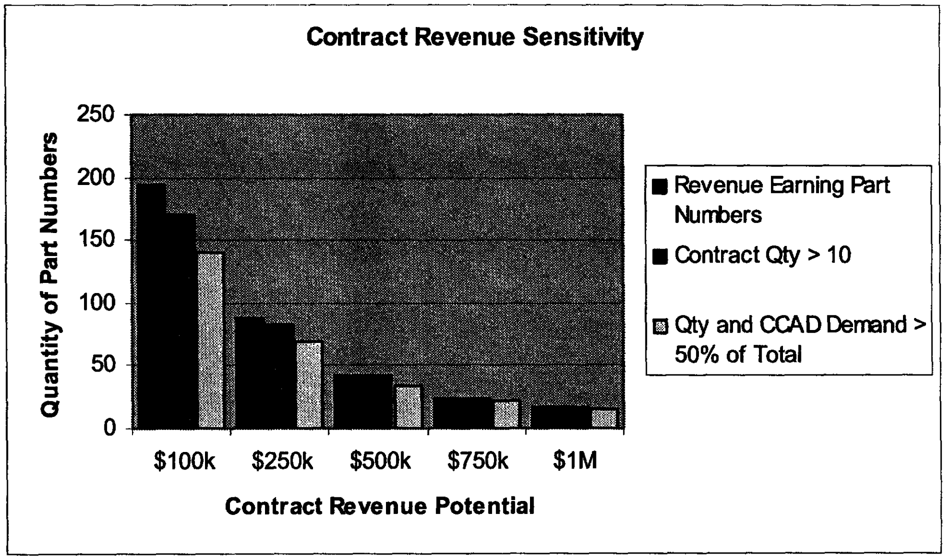
These 945 part numbers represent 9% of the total contract revenue and 53% of the subset of parts. Because these part numbers are on-contract for small quantities, there is little risk associated with fixed pricing. Combined with the small amount of revenue represented, quantity decreases for these 945 part numbers will have minimal to zero effect to Boeing.

3.4.2 Revenue Implications of Fixed Unit Pricing

With 53% of the part numbers essentially protected from quantity fluctuations, the question turned to how will the selected parts influence revenue under fixed unit pricing. The 1,793 parts were examined using three filters: revenue potential, contract quantity, and percentage of demand. Revenue potential represents the amount each part number is expected to earn if the entire contract quantity is sold. For example, if a part number's contract quantity is 10 and the contract price is $100, the revenue potential is equal to $1000. Contract quantity was already discussed in Chapter 2.2.1. Demand percentage evaluates how much of a part number's total demand belongs to CCAD and how much belongs to the other assembly and repair programs. Two assumptions were used in this portion of the analysis.

1. Part numbers with contract quantities greater than 10 represent an increased risk for fixed pricing and the possibility to incur higher costs. This is because quantities greater than 10 are outside of the minimum quantity band price range.
2. If CCAD's share of a part number's total demand across all programs is greater than 50%, the part number is exposed to increased risk from quantity fluctuations and higher costs. This was based on the information discussed in Chapter 3.3.2.

Figure 3.5 below depicts the results of this analysis. It should be noted that the quantities represented under each revenue column are inclusive and represent a minimum level of revenue potential. Thus, a part number included under the $1M column is also included in the $750k, $500k, $250k and $100k potential revenue earning columns.



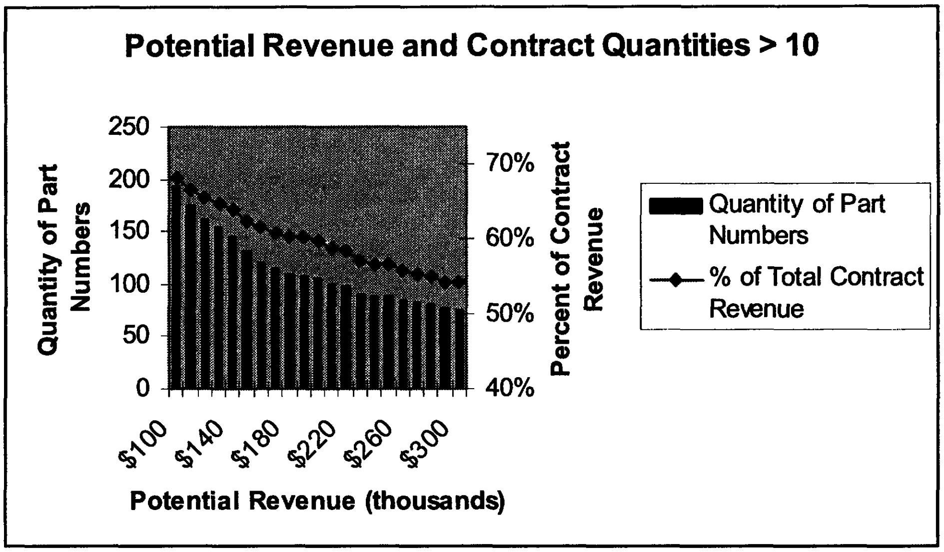
Contract Revenue	Revenue Earning Part Numbers	Contract Qty > 10	Qty and CCAD Demand > 50% of Total	% of Contract Revenue
$100k	194	171	140	68%
$250k	88	83	69	56%
$500k	42	42	34	43%
$750k	24	24	22	33%
$1M	17	17	16	28%

Figure 3.5: Contract Revenue Sensitivity

This figure displays categories of high revenue earning part numbers that have the potential to vary greatly in quantity. For example, there are 88 part numbers with a revenue potential of $250k. Of those 88 part numbers, 83 are on-contract for a quantity greater then 10. This implies that if there is a decrease in the quantity required by CCAD, Boeing would incur additional costs under a fixed unit pricing strategy. Of those 83 part numbers, 69 have greater than 50% of their total demand satisfied by CCAD. This implies that the majority of demand is subject to the quantity fluctuation risk. This again indicates risk to Boeing under fixed unit pricing. The shaded columns represent a request from Boeing management for financial implications. (i.e., the 83 part numbers that have a revenue potential of $250k and are on-contract for quantities greater than 10 equate to 56% of the total contract revenue). As a result, the represented part numbers are good candidates for removal from fixed pricing.

3.4.3 Recommended Exclusion List

Based upon guidance from Boeing management, a decision was made to expand the revenue implication analysis, but only include revenue potential and contract quantity. The CCAD demand filter was removed and the following results were found.



Part Revenue Potential (thousands)	Potential Revenue Part Numbers	Part Numbers with Potential Revenue & Contract Quantity > 10	% of Contract Revenue
$160	121	111	61%
$170	115	106	61%
$180	109	103	60%
$190	108	103	60%
$200	105	100	60%
$210	99	94	59%
$220	97	92	58%
$230	91	86	57%
$240	89	84	57%
$250	88	83	56%

Figure 3.6: Exclusion List Recommendation

The table expands on the previous chart with the shaded cell representing the recommendation to management for exclusion from fixed unit pricing. The 100 part numbers each have a potential contract revenue of $200k or greater and are on contract for quantities greater than 10. By removing the associated 100 part numbers, Boeing protects 60% of the contract's revenue potential from the risk due to quantity fluctuation. As a footnote, management subsequently added an additional 54 part numbers to the exclusion list due to high susceptibility for material escalation risk. The 54 part numbers were linked to suppliers who would not agree to long-term pricing agreements for protection against raw material cost escalation.

With the 154 part exclusion list finalized, 7,044 parts would no longer need repricing from changes in forecasts. However, before agreeing to the fixed pricing strategy, Boeing requested the construction of a Monte Carlo simulation to determine the impact on income from sales due to the effects of fixed pricing on the 7,044 parts.

3.5 Monte Carlo Simulation

A Monte Carlo simulation is a stochastic technique which randomly chooses values for uncertain variables in order to estimate the probability of various outcomes. Crystal Ball software (version 7.2.2) was used to construct the fixed unit pricing simulation. The Crystal Ball software is a Microsoft® Excel-based application distributed by Decisioneering, Inc for risk analysis and optimization studies. The “high-level” flow diagram in Figure 3.7 will be referenced to explain the architecture, assumptions, calculations, and processes employed in the Monte Carlo simulation. Finally, the results from the simulation and from the actual implementation will be discussed.

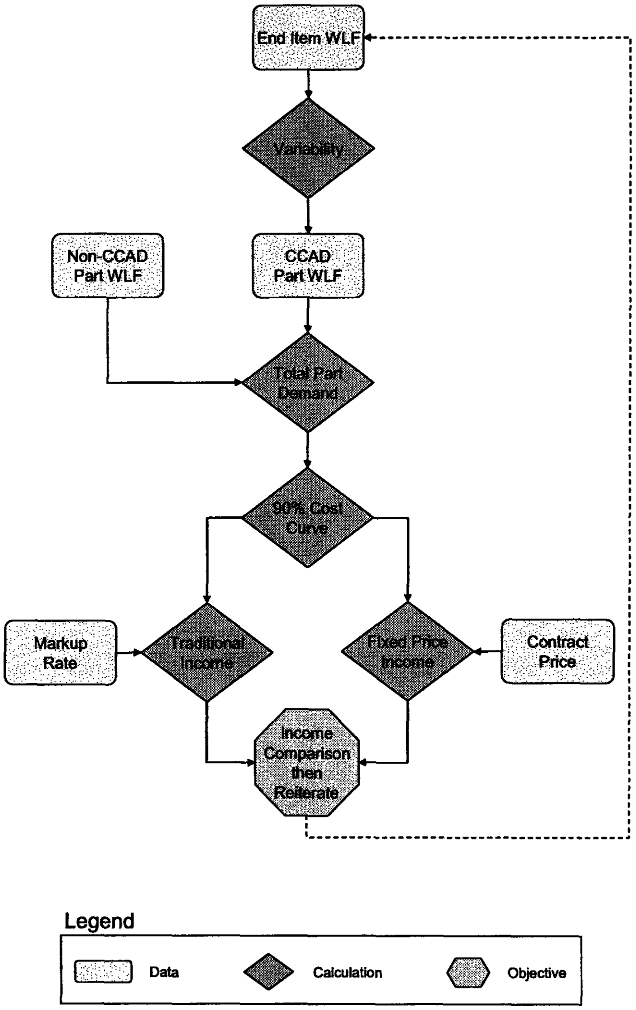


Figure 3.7: Fixed Unit Pricing Monte Carlo Process Flow Chart

3.5.1 Monte Carlo Data Input

Construction of the model began with the input of the following data:

1. 176 end-items for both the AH-64 and CH-47.
2. WLF for each end-item.
3. 1,693 subset part numbers associated with the end-items (The 100 recommended exclusion parts were removed from the simulation. The 54 additional parts removed from fixed pricing were already filtered out by my initial screening of the 7,000 parts).
4. CCAD WLF for each part.
5. Non-CCAD annual demand (four-year historical average from 2003 through 2006) for each part.
6. Contract price associated with each part.
7. Contract quantity for each part.

This WLF data used was based upon 2007 requirements only. Additionally, if a part was priced on either Phase IIA or Phase III contracts, the higher price was utilized.

3.5.2 Assumptions

Probability Distribution

The first assumption made during the construction of the Monte Carlo Simulation was how to replicate the variability within the WLF. Unfortunately, historical variability within each end-item's WLF was not maintained past the previous six-month update. Thus, a customized distribution could not be constructed. However, SM&P managers were able to confirm that the most recent changes in the WLF (depicted in Figure 2.3) were typical of historical trends. As a result, the decision to use a Beta - Program Evaluation Review Technique (PERT) distribution was chosen.

The PERT manipulates the beta distribution and is similar to the commonly known triangle distribution in that a minimum, mode, and maximum value are known. However, the PERT distribution deemphasizes the minimum and maximum values by replicating the distribution with a smooth curve. This prevents skewing the results towards the extreme ends of the distribution. The PERT also converts the mean of the distribution to be the average of the minimum, maximum, and four times the mode. This once again removes the bias of the distribution's tails and is a commonly used technique for procurement studies (Roman, 1962).

As the current trend for variability within the WLF favors an increased demand, the following parameters were chosen to generate the PERT distribution.

1. Minimum: -50% of the WLF
2. Mode: WLF
3. Maximum: +100% of the WLF

By comparing a revised Figure 2.3 with a PERT distribution graph generated by the Crystal Ball software, a visual resemblance can be observed.

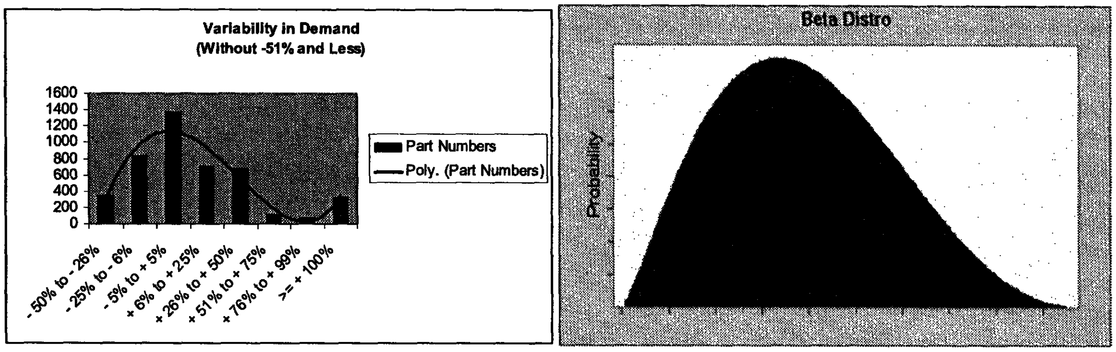


Figure 3.8: PERT Distribution

Replicating Quantity Band Costs

Over the course of each trial, the Monte Carlo simulation has the potential to demand any quantity within the -50% to +100% distribution. However, quantity band costs were not available for each part. Additionally, inputting 1,693 quantity band values would have been extremely time-consuming. As such, the assumption was made to use a 90% log-linear experience curve to replicate the cost of each part at any quantity. Essentially, every time a part's quantity doubles, the cost of the part decreases by 10%. Argote, et al explain how within industrial settings, an 80% experience curve is commonly observed as processes are repeated (1990). However, a 90% curve was chosen to find a more conservative solution.[5] The equation used to construct the curve is listed below ("Cost Estimating," 2006).

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[5] The 90% cost / quantity curve is commonly used within the aerospace industry and is generally accepted by the U.S. Government and their audit agency (the Defense Contract Audit Agency) as a reasonable curve for determining cost with changing quantities.

$$Y = C_1 * X^b \qquad \textit{(Equation 3.1)}$$

Y = Cost of unit
C_1 = Theoretical cost of first unit
X = Number of unit produced
b = ln(90%) / ln(2)

The curve was developed by using the only known cost information: a part's contract quantity and its associated price. Since the contract price is what Boeing charges CCAD, the original cost was calculated by removing the standard markup rate. For example, part "ABC" is listed on the contract at a quantity of 20 and a unit price of $500. Assuming the standard markup rate is 10%, the cost of each part would equal $454.55 when 20 are ordered. This information could then be substituted into the Equation 3.1 to construct a cost for each trial's quantity.

While cost reduction through learning and cost reduction through quantity discount purchasing occur for two separate reasons, an experience curve "reflects the joint effects of learning, technological advances and scale" (Reis, 1991). To validate this assumption, a comparison from known quantity band cost tables and the assumed experience curve was developed. The resulting figures for two sample parts are listed below.

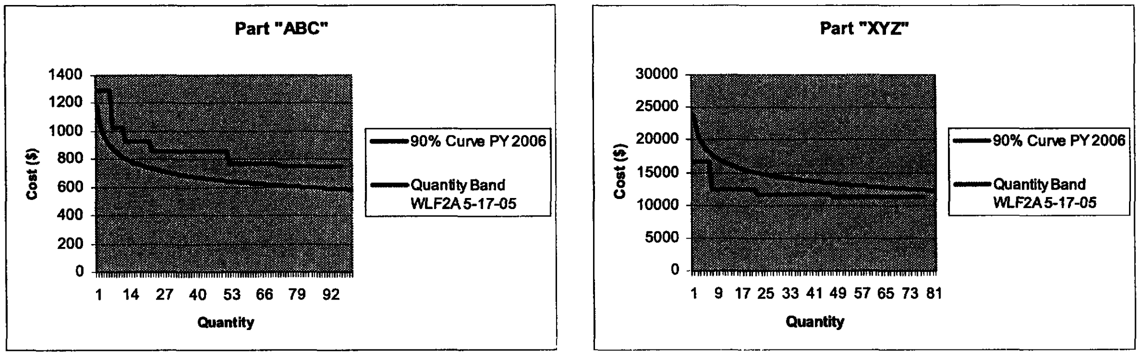
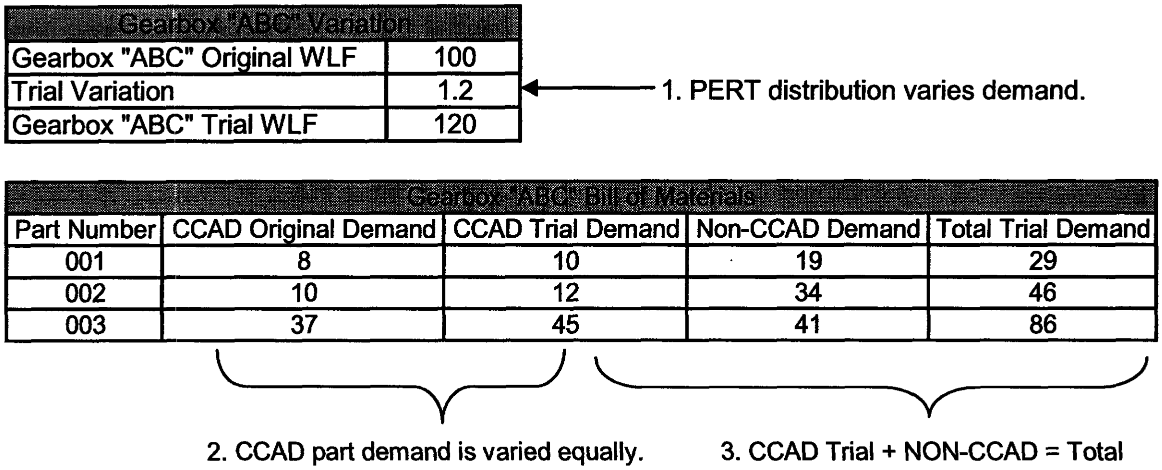


Figure 3.9: Experience Curve vs. Quantity Band Costs

The curves closely follow the quantity bands. However, there is a difference in the magnitude of the costs. This can be explained by looking at the time frame from which the data originated. The experience curve is based upon cost estimates for 2007 using 2006 data. The quantity band curve is an estimate of 2007 costs from 2005 data. These changes in cost estimates could arise for numerous reasons to include raw material escalation or increased labor costs at the supplier. Regardless of the reason, the 90% curve follows the quantity band's trend and is a reasonable approximation for cost.

3.5.3 Trial's Calculations and Process Flow

With the data collected and the assumptions made, the model was constructed. Every time a trial is run, the model alters CCAD's original end-item WLF by a random draw from the PERT distribution. All of the parts within each end-item are changed accordingly and summed with the non-CCAD demand. The non-CCAD demand never fluctuates as it represents demands which experience little to no volatility. An example of these steps can be seen by using "Gearbox ABC" below. Three notional parts (001, 002 and 003) are used to build "Gearbox ABC."



Gearbox "ABC" Variation	
Gearbox "ABC" Original WLF	100
Trial Variation	1.2
Gearbox "ABC" Trial WLF	120

1. PERT distribution varies demand.

Gearbox "ABC" Bill of Materials				
Part Number	CCAD Original Demand	CCAD Trial Demand	Non-CCAD Demand	Total Trial Demand
001	8	10	19	29
002	10	12	34	46
003	37	45	41	86

2. CCAD part demand is varied equally.

3. CCAD Trial + NON-CCAD = Total

Figure 3.10: Demand Calculations

With the total demand for the trial known, the cost for procuring each part will be calculated with the experience curve described in Chapter 3.5.2. This cost is then used to determine the income from sales under both fixed pricing and the traditional method of using a standard 10% markup rate. While the total demand from the CCAD and the Non-CCAD programs is used to calculate the trial's scaled cost, only the income from the sale of the CCAD demand is recorded. The equations used and the example from Figure 3.10 are continued below.[6]

Fixed Pricing Income = CCAD Demand * (Contract Price – Scaled Cost) *(Equation 3.2)*

Markup Income = CCAD Demand * [(Markup % * Scaled Cost) – Scaled Cost] *(Equation 3.3)*

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[6] The contract quantity and price would be retrieved from the contract. The contract cost was calculated by removing the 10% markup rate.

Gearbox "ABC" Contract Information			
Part Number	Contract Quantity	Contract Price	Contract Cost
001	8	$ 1,000.00	$ 909.09
002	10	$ 100.00	$ 90.91
003	37	$ 500.00	$ 454.55

Gearbox "ABC" Scaled Cost and Income from Sales					
Part Number	Total Demand	Scaled Cost	CCAD Demand	Fixed Price Income	Markup Income
001	29	$ 747.46	10	$ 2,525.35	$ 747.46
002	46	$ 72.09	12	$ 334.94	$ 86.51
003	86	$ 399.85	45	$ 4,506.67	$ 1,799.33

<u>Example with Part 001</u>:

Using Equation 3.1: $C_1 = e^{[LN(\$909.09)-(LN(90\%)/LN(2))*(LN(8))]} = \$1,247.03$

$\text{Scaled Cost} = \$1,247.03*29^{(LN(90\%)/LN(2))} = \$747.46$

Using Equation 3.2: $\text{Fixed Price Income} = (10) * (\$1000 - \$747.46) = \$2,525.40$

Using Equation 3.3: $\text{Markup Income} = (10) * [(1.1 * \$747.46) - \$747.46] = \$747.46$

Figure 3.11: Cost and Income from Sales Calculations

For the example with Part 001, the fixed pricing method would yield $1,777.94 more in income from sales than the traditional markup method. However, this financial increase is a result of both increased sales volume (two units) and lower costs. Nonetheless, if the CCAD demand does not increase, but is held constant at eight units while a scaled cost of 27 units (from the total demand) is calculated, an increase in income from sales of $1,350.47 can still be achieved. This shows the cost saving benefits derived from economies of scale.

3.5.4 Simulation Results

We ran the Monte Carlo simulation for 10,000 trials. After each trial, the simulation recorded the difference between the fixed price income and the standard markup income. At the conclusion of the simulation, the fixed price income resulted in a mean increase of 11% over the standard markup income. A histogram from the simulation's outcomes is presented below. The actual values have been replaced with percentages for proprietary reasons.

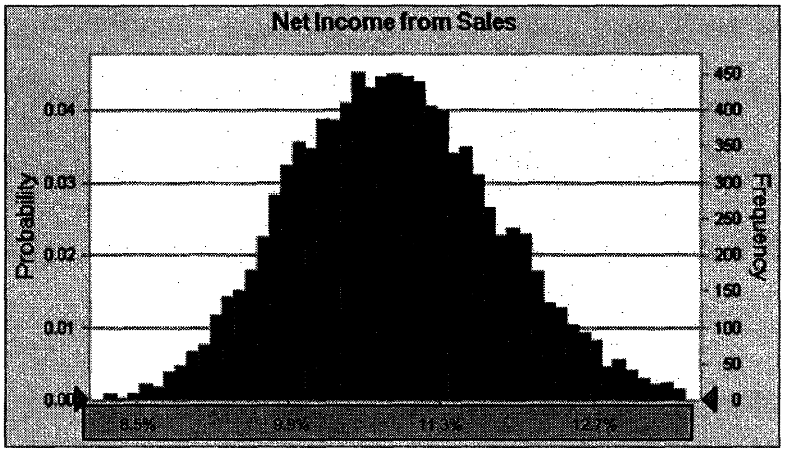

Figure 3.12: Monte Carlo Simulation Results

The rise in the income from sales is dependant upon each end-item's ability to increase to +100% of the original WLF. However, even if all of the end-items were to simultaneously fall to -50% of their WLF, the income from sales would still increase by 3%. Although statistically improbable, this event displays the true benefit of cost reductions and the value of summing the demands from all repair and overhaul programs.

Aside from the increase in income, the fixed pricing methodology provides considerable advantages. Foremost, the repricing delay caused by the variations in demand will be eliminated except for the 154 excluded parts. Recalling Figure

2.2, this can potentially remove six months from the procurement cycle. Assuming the part is on-hand, a sale will occur as soon as the request is made. This will also simplify the maintenance of the contract when CCAD requests parts over-and-above the previously agreed upon quantity. Additionally, customer satisfaction will increase due to the improved responsiveness. The increased flexibility will have a positive impact on CCAD's repair turnaround times since unforecasted parts will arrive much sooner. This will also decrease the holding costs associated with keeping inventory on the warehouse shelves. Finally, Boeing will stop losing sales to alternate sources of supply, further increasing its revenue.

4.0 Raw Material Procurement Policy

The current raw material procurement policy contains two options. First, Boeing purchases no raw material, but simply provides a parts order to the supplier. In this scenario, the supplier is responsible for procuring all required raw material. The total lead time for the part includes the raw material procurement lead time. The second option is for Boeing to purchase the raw material and sell it to the supplier. While not commonly employed, this alternative is used to assist smaller manufacturers by delaying some of their initial costs. These suppliers can instead focus their capital expenditures on operational requirements. In this situation, Boeing purchases the required amount of raw material based upon their parts forecasts.

However, when CCAD increases their parts order inside of delivery lead times and Boeing is providing the raw material to the supplier, production eventually stalls. Without additional raw material on-hand, the increased demands consume the remaining inventory. In an effort to combat this volatility, Boeing chose to explore the idea of purchasing a safety stock of raw materials for a subset of 66 parts. These parts are characterized by lead times in excess of one year, of critical importance to CCAD, have highly volatile demands and are composed of specialty metals. This chapter will discuss the analysis used to determine if maintaining a safety stock would be financially advisable and what quantities, if any, should be procured.

4.1 Building for Flexibility: The Universal Model

At the beginning of the analysis, management communicated a desire to construct a model that could be universally applied to all 66 parts. This "generic" format would shorten the time required for the analysis and allow for the model's continued use in the future. As such, the model would be required to examine the impact of safety stock over a timeline that extended beyond a single year's requirements. Since forecasts are completed in three year intervals and lead times can stretch to over two years, a 36 month time horizon was chosen. The "high-level" flow diagram in Figure 4.1 will be referenced to explain the architecture, assumptions, calculations, and processes employed by the model. Finally, the results from a Monte Carlo simulation will be discussed.

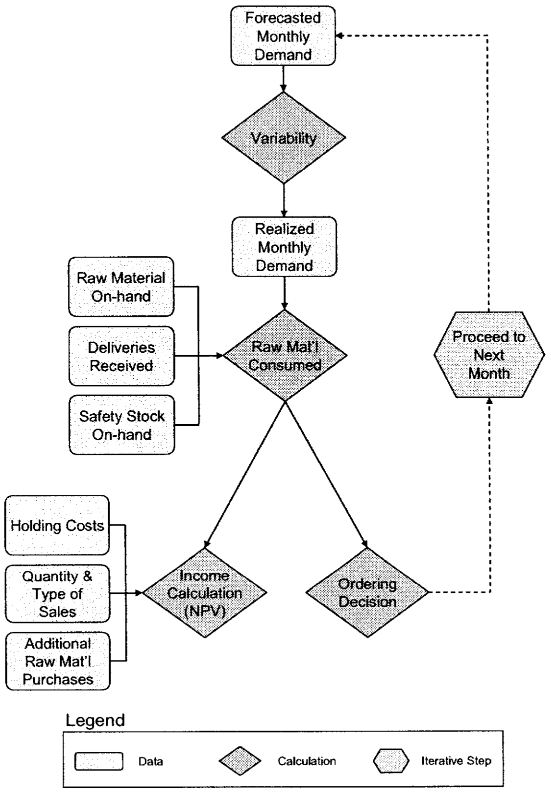

Figure 4.1: Raw Material, Universal Model Process Flow Chart

In general terms, at the beginning of every program year, each part has a known forecast. The appropriate raw material is procured in advance to manufacture the part according to this requirement. However, every six months, AMCOM updates the forecast. If the forecast increases (for parts with long lead times), a manufacturer is left with two choices: (1) consume raw materials now that have been allocated for future production and provide the increased demands or (2) continue with the original production plan and ignore the additional requests. The first choice will satisfy current demands, but fail to provide at a future date. The second choice offers the same results, but falls short in the present. However, if a safety stock of raw materials is available when the updated forecast is received, a manufacturer can adjust its production cycle to supply the additional parts demand. This simulation evaluates different safety stock policies to determine the best solution for each part based upon lead times, cost of raw materials, and income from part sales.

4.1.1 Data Collection

For each of the 66 parts, the following information was gathered.

1. Unit cost to Boeing
2. Markup rate for sales to CCAD
3. Raw material data
    a. Type & description
    b. Unit cost

c. Procurement lead time

d. Quantity of use per part

e. Minimum-buy quantities from raw material supplier

Cost estimates were gathered over the summer of 2006 and utilized escalation factors to estimate future costs. The data was drawn from forecasts for the 2007 through 2009 program years.

4.1.2 Assumptions

Volatility between the Forecasted and Realized Demands

The model begins by assuming a level loading of production. Each of the 36 months has the same forecasted demand. This serves as a baseline for measuring the possible variation that might occur when the simulation runs. Additionally, a steady-state is assumed in that there is sufficient raw material on-hand to complete a minimum of one year of forecasted demand. Whether exact or safety stock levels of raw material exist at the beginning of each trial varies in accordance with the ordering policy programmed into the model. The ordering logic will be discussed in a later chapter.

The 66 parts included in this analysis experience the same volatility described in the fixed pricing analysis from Chapter 3.0. As a result, the PERT distribution discussed in Chapter 3.5.2 is once again employed. Each trial begins with the simulation generating six values from the distribution, one for each semiannual period. The semiannual variation is permitted to fluctuate between -50% to +100% of the forecasted demand. The realized demands for each month are altered according to the variation chosen for their six-month window.

Capacity

If a manufacturer is operating at or near maximum capacity, having a safety stock of raw material would be irrelevant. Production would be constrained by time or machine utilization, not the availability of raw materials. As a result, this analysis assumes that capacity is not a limiting factor in production. This statement can be justified for this situation in that the parts contained in this analysis are given the highest attention. Asset managers set production priorities with their respective suppliers in every attempt to guarantee that these critical parts are produced when demanded. If time permits, suppliers will often alter production plans in response to requests for changes in demand. This is due in part to Boeing's efforts to develop strong relationships with their supply base and to improve efficiency vertically along the entire chain. Thus, it is assumed for this analysis that a six-month notice is sufficient time to adjust production plans and that raw material availability is the only limiting factor in producing additional parts.

4.1.3 Trial's Calculations and Process Flow

Classification of Raw Material

A model was constructed that classified the 66 parts in two ways: raw material procurement lead time and the raw material's percent cost in respect to the part's total cost. For example, if a part's cost was $1000 and the raw material's cost was $100, the percent raw material cost would be 10%. The 66 parts were consolidated into groups of similar classification. The breakdown was as follows.

Raw Material Lead Time (months)	% Raw Material Cost of Total Cost	Quantity of Parts
3	12%	2
3	25%	2
5	1%	4
5	10%	2
5	18%	1
5	70%	2
7	2%	12
7	10%	2
7	25%	3
7	58%	1
8	70%	1
9	35%	1
12	1.5%	9
12	3%	8
12	5%	6
12	16%	3
13	15%	1
15	3%	1
15	20%	1
17	25%	1
17	35%	1
17	68%	1
19	2%	1

Figure 4.2: Raw Material Classification

On-hand Inventory Calculations

With the raw material classifications completed, the logistical and financial influence of safety stock could be studied. Assuming a steady state at the beginning of the simulation, the model pre-stocks the raw material inventory. The initial value of the raw material on-hand (RMOH) is equal to one year's forecasted demand plus the amount required by the safety stock (SS) policy. The initial value of SS varies between 0% to +100% of the forecasted year's requirements. The simulation begins as described in the "Volatility between the Forecasted and Realized Demands" assumption. A trial demand is generated and the appropriate amount of inventory is depleted from the RMOH. Depending on the time period, the simulation would use one of the following equations.

Month 1: RMOH = Starting Raw Material Quantity – Month 1 Realized Demand
Months 2 – 36: RMOH = Previous Month's RMOH – Realized Demand + Deliveries Received

(Equation 4.1)

If the realized monthly demand exceeds the forecasted amount and there is safety stock available, the demanded quantity of raw material will be consumed. However, if there is an insufficient amount of RMOH, the model will consume as much inventory as possible. Failure to provide raw material will result in a lost sale. The possibility for backorders is not incorporated into the simulation. The following example depicts this volatility for the first twelve months. The volatility for the remaining 24 months would follow the same procedure. This example evaluates the effect of a 45% SS policy on a raw material with a forecasted monthly demand of 10 units and a procurement lead time of 12 months. The SS column listed in the example is used as a reference. It only tracks the amount of SS on-hand. Its quantity is included in the RMOH column.

Initial Inventory Status	
Annual Forecasted Demand	120
SS Policy	45%
Starting RMOH	174

1. Initial raw material calculated based upon SS policy.

Months	Variation
1 - 6	1.3
7 - 12	0.8

2. PERT distribution varies demand.

Month	Forecasted Demand	Variation	Realized Demand
1	10	1.3	13
2	10	1.3	13
3	10	1.3	13
4	10	1.3	13
5	10	1.3	13
6	10	1.3	13
7	10	0.8	8
8	10	0.8	8
9	10	0.8	8
10	10	0.8	8
11	10	0.8	8
12	10	0.8	8

3. Variation transferred to appropriate months. Realized demand calculated.

Month	Forecasted Demand	Variation	Realized Demand	RMOH	SS Quantity
1	10	1.3	13	161	51
2	10	1.3	13	148	48
3	10	1.3	13	135	45
4	10	1.3	13	122	42
5	10	1.3	13	109	39
6	10	1.3	13	96	36
7	10	0.8	8	88	36
8	10	0.8	8	80	36
9	10	0.8	8	72	36
10	10	0.8	8	64	36
11	10	0.8	8	56	36
12	10	0.8	8	48	36

4. SS is consumed by 3 per month. Realized demand > forecast demand.

5. No effect on SS. Realized demand < forecast demand.

Figure 4.3: On-hand Inventory Calculation

Ordering Decisions: Reorder Points

Once the impact of consumption on the RMOH is determined, the actual inventory position must be evaluated before an ordering decision can be made. The actual inventory position includes the RMOH and the "pipeline" inventory. Pipeline inventory is defined as inventory that has been previously ordered, but not yet arrived. The actual inventory position is then compared to the reorder point (ROP) and a decision is made on whether additional inventory is required. The simulation's ROP is based upon a continuous review policy that examines the inventory posture at the conclusion of each month's consumption. The ROP is calculated with the following equation.

$$ROP = (L)(AVG) + (z)(\sigma)(\sqrt{L}) \qquad \textit{(Equation 4.2)}$$

where $L \equiv$ Raw material lead time (months)
$AVG \equiv$ Average monthly demand
$z \equiv$ Inverse standard normal cumulative of the service level
Service level $\equiv$ Probability that raw material will be on-hand when needed.
$\sigma \equiv$ Standard deviation of monthly demand

This ROP calculation assumes that if inventory is not on-hand when the order arrives, it is lost. A service level of 98% was used in the model. Additionally, the ROP assumes that holding and fixed costs occur for storing and ordering more raw materials. The costs will be discussed later in the financial analysis (Simchi-Levi et al, 2004).

Ordering Decisions: Required Quantity

With the ROP established, the next step was two-fold. First, the model would determine if a replenishment order is required. If so, the simulation would then calculate the quantity to procure. The following logic was employed to complete these tasks.

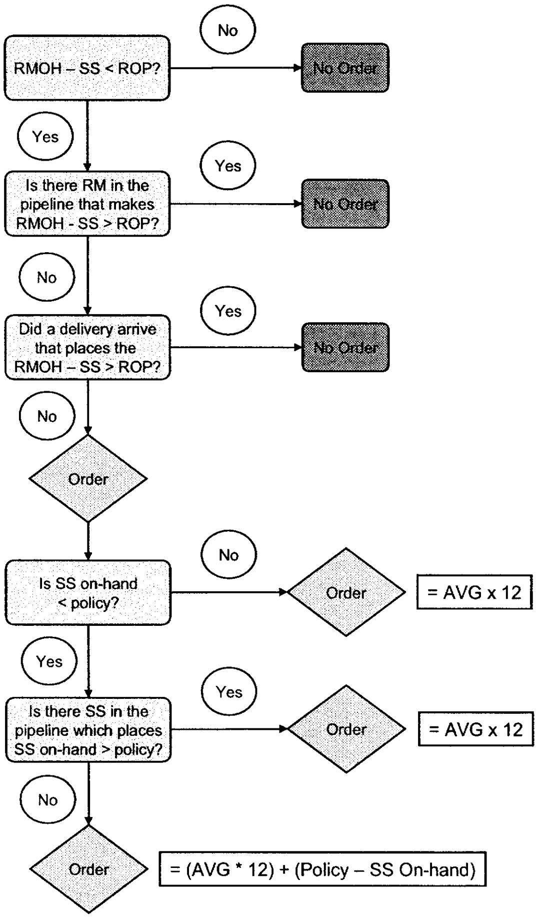

Figure 4.4: Ordering Logic

Under a continuous review policy, the model will determine if the actual inventory position is less than the ROP. If it is not, no action is taken and the model continues to the next month. However, if an order is required, the model will choose one of two options based upon the SS policy. If there is sufficient SS on-hand or in the pipeline to return the SS level to 100% of the policy, the model will order one year's annual forecasted demand. Otherwise, it will order the annual forecasted demand plus additional safety stock to return the level to 100% of the SS policy.

The example below is a continuation from Figure 4.3. It demonstrates how the actual inventory position is evaluated and how the appropriate quantity is determined in order to restore the SS to the 45% policy level (54 additional units). When evaluating if the RMOH falls below the ROP, the model will not include the SS quantity to determine the total inventory. Boeing management viewed the SS inventory as insurance and did not wish to include its quantity into reordering decisions. This provides additional security in that raw material will be ordered sooner. The example is also extended to the 13th month to display the effects of delivered inventory.

ROP Calculation (Equation 4.2)

$$\text{ROP} = (L)(\text{AVG}) + (z)(\sigma)(\sqrt{L})$$

$$\text{ROP} = (12 \text{ months}) * (10) + [\text{NORMSINV}(98\%)] * (2.59) * (\sqrt{12})$$

$$\text{ROP} = 139 \text{ units}$$

Month	Forecasted Demand	Variation	Realized Demand	RMOH	SS Quantity	Quantity Ordered	Pipeline Inventory	Deliveries
1	10	1.3	13	161	51	123	123	-
2	10	1.3	13	148	48	0	0	-
3	10	1.3	13	135	45	0	0	-
4	10	1.3	13	122	42	0	0	-
5	10	1.3	13	109	39	0	0	-
6	10	1.3	13	96	36	0	0	-
7	10	0.8	8	88	36	0	0	-
8	10	0.8	8	80	36	0	0	-
9	10	0.8	8	72	36	0	0	-
10	10	0.8	8	64	36	0	0	-
11	10	0.8	8	56	36	0	0	-
12	10	0.8	8	48	36	138	138	-
13	10	1.4	14	157	35	0	0	123

6. RMOH falls below ROP (161 - 51 = 110 and 110 < 139). An order is placed for the forecasted annual demand + what is required to return SS to 100%. Pipeline inventory is recorded at Month 1.

7. Same event as Step 6.

8. Month 1's order arrives.

Figure 4.5: Ordering Logic Calculation

After the above example is allowed to progress over the full 36 month timeline, the benefits of utilizing this methodology for maintaining and ordering additional raw material is revealed. In the following three charts, the effects of volatility on inventory position and raw material consumed is compared between a policy that maintains safety stock and one that does not.

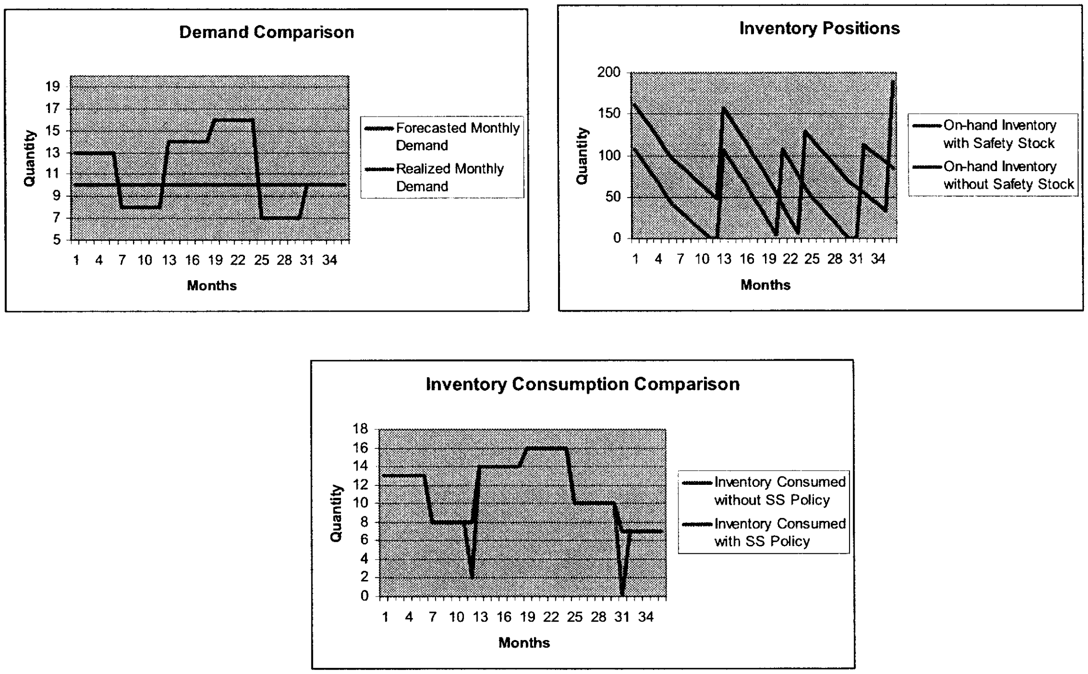

Figure 4.6: Inventory Policy Comparison

The demand comparison chart tracks the difference between what the forecasted demand was and what the actual demand turned out to be. Whenever increases in demand occurred, the safety stock policy expended its extra inventory to cover the higher requirements. However, the non-safety stock policy was forced to consume raw material that was reserved for future production. With the long lead times experienced by this type of raw material, the end result for the non-safety stock policy was an inability to provide 100% of the actual demand or an inventory stock-out. This can be seen during months 12 and 31 of the Inventory Consumption Comparison chart.

While the benefits of maintaining a safety stock are obvious from a fulfillment position, the decision to hold extra inventory may not be financially sound. Additional raw material costs extra money to procure, store, and manage. The next step evaluates the safety stock policy for each of the 66 parts from a business perspective and determines what quantity (if any) should be maintained.

4.1.4 Financial Implications of Safety Stock

In order to determine the appropriate level of safety stock for each critical part, two financial costs must be considered. These are the fixed cost for procuring the additional raw material and the cost incurred for storing the raw material until it is consumed. The fixed cost of each raw material is a known value. Once safety stock is ordered, the model charges the appropriate fixed cost at the time of delivery. Once safety stock is on-hand, a holding cost is incurred until all the safety stock is depleted. An assumption of 20% of the raw material's cost was used to quantify this annual holding cost. In order to translate the future costs observed during months 2 - 36, all monetary values were discounted into present value dollars with the following equation. An annual interest rate of 6% (0.005% monthly) was used in the calculation. A single month constituted one time period.

$$PV = FV \;/\; (1+r)^n \qquad \textit{(Equation 4.3)}$$

where $PV \equiv$ Present value dollars
$FV \equiv$ Future value dollars
$r \equiv$ interest rate
$n \equiv$ time period evaluated

The final financial consideration was to examine the income from part sales to CCAD. To do so, we need to look at two intervals: 1) the cost incurred by Boeing when the part was purchased from the supplier and 2) the revenue earned by Boeing from the part's sale to CCAD. First, if Boeing provided the raw material during periods of increased demand (used its safety stock); the cost of the raw material was subtracted from the part's total cost. Otherwise, Boeing was charged the full cost of the part. The following equations depict the cost calculations from the sale of the parts.

Part Cost

- No raw material safety stock used (Actual monthly demand ≤ Forecasted demand):

  Cost = Quantity of parts sold * Part cost

- Some safety stock of raw material used (Actual monthly demand ≥ Forecasted demand):

  Cost = (Forecasted demand) * (Part cost) +
  [(Total quantity sold – Forecasted demand) * (Part cost – Raw material cost)]

(Equation 4.4)

For example, assume a part normally costs Boeing $100 to purchase. If the raw material cost of the part is $10 dollars and safety stock is used to produce additional units, Boeing will only pay $90 for each additional unit. The following example illustrates this cost breakdown.

Forecasted Quantity	10
Realized Quantity	12
Normal Part Cost to Boeing	$100
Raw Material Cost	$10
Safety Stock Part Cost to Boeing	$90

Normal Part Cost to Boeing	$100
Units Purchased	10
Subtotal	$1,000
Safety Stock Part Cost to Boeing	$90
Units Purchased	2
Subtotal	$180
Total Cost	$1,180

Figure 4.7: Raw Material Cost Example

The revenue calculation is self-explanatory and depicted below. It will use whichever cost is applicable when determining the revenue.

Part Revenue

- Revenue = Quantity of parts sold * Part price *(Equation 4.5)*

The economic value of the safety stock would reveal itself if the revenue from increased sales was greater than the costs incurred by procuring and storing the extra raw material. The revenue from future sales was discounted into present value dollars by the same method discussed in the cost analysis. The simulation would conclude by finding the net present value (NPV) from the revenue and the costs over the 36 month timeline. The assumption made was that the greater the NPV of the safety stock policy, the more effective the policy. If the 0% safety stock policy provided the greatest NPV, the determination made was that there were no financial benefits achieved from procuring additional raw material.

4.2 Simulation Recommendations for Safety Stock

Recalling Figure 4.2, each classification of part was evaluated in the simulation. The first trial conducted for each classification was at a 0% safety stock policy. The NPV from stocking only to forecasted demand was recorded and used as a source of comparison for the various safety stock policies. Each raw material classification was then subjected to increasing safety stock policies, beginning with 5% and increasing at 5% intervals to a 100% safety stock policy. Each policy's NPV was recorded with the greatest value serving as the recommendation. The consolidated results are depicted below with the shaded cells highlighting safety stock recommendations.

Raw Material Lead Time (months)	% Raw Material Cost of Total Cost	Quantity of Parts	Recommended Safety Stock
3	12%	2	0%
3	25%	2	0%
5	1%	4	0%
5	10%	2	0%
5	18%	1	0%
5	70%	2	0%
7	2%	12	0%
7	10%	2	0%
7	25%	3	0%
7	58%	1	0%
8	70%	1	0%
9	35%	1	0%
12	1.5%	9	50%
12	3%	8	45%
12	5%	6	40%
12	16%	3	0%
13	15%	1	0%
15	3%	1	65%
15	20%	1	45%
17	25%	1	50%
17	35%	1	45%
17	68%	1	0%
19	2%	1	100%

Figure 4.8: Safety Stock Recommendation

The results are intuitive in nature. In situations where raw material was relatively inexpensive and lead times were long, a safety stock quantity was recommended. Essentially, the combination of lower cost and longer lead time resulted in greater quantities of safety stock. However, when raw material costs were higher or lead times shorter, no recommendation was made. By purchasing the recommended additional raw material, an average of 61% of the concerned parts' total lead times is reduced. The range in reduction is between 55% and 77% of the total procurement lead time.

After the recommendations were presented to management, further thought was given to consolidating raw material purchasing across the Boeing Integrated Defense Systems. This will allow Boeing to leverage its scale and reduce the cost of the raw material further (similar to Fixed Pricing Analysis). While this decision should be implemented for cost savings, its effects were not incorporated into the previously discussed model. Reducing the cost of each raw material would have a direct impact on the quantities recommended. When future analysis is conducted on Boeing's safety stock policy, the effects of scale should be incorporated. Examining the current recommendations, one could assume that lower raw material costs would serve to increase the quantity of safety stock selected. However, this can not be confirmed without a second analysis.

4.3 Centralized Storage for Common Materials

A final recommendation with respect to consolidating raw material purchases across the entire Integrated Defense Systems concerns how to store the inventory. If Boeing can store raw material that is common to multiple programs in one location, the benefits of physical centralization can be achieved. Stock imbalances between locations would be eliminated by postponing delivery from the centralized location until it was needed. This would prevent one location from storing raw material that was not needed while another went without. The benefits of centralized storage can be quantified through the commonly referred to "square root law." This law states that the total inventory required to provide a specified level of service increases by the square root of the number of locations in which it is held. This can be mathematically expressed through the following equation (Anupindi et al, 2006).

$$I_{safety} = z * \sqrt{N} * \sigma_{LTD} \qquad \textit{(Equation 4.6)}$$

where
I_{safety} ≡ Safety inventory upon centralization
z ≡ Inverse standard normal cumulative of the service level
    Service level ≡ Probability that raw material will be on-hand when needed.
N ≡ Number of locations without centralization
σ_{LTD} ≡ Standard deviation of lead time demand

Simply put, the more storage locations a business maintains, the more safety stock is required. However, by reducing the number of locations from two to one, this equation reveals that the total safety inventory required by the centralized operation is reduced by $1/\sqrt{2}$. Reducing an even greater number of locations down to a single storage point will decrease the safety stock requirement more.

It should be noted that there are disadvantages to consolidation of raw material. Foremost, by maintaining the safety stock of raw material at a centralized place, the response rate and travel time to ship the material to the manufacturer must be added to the lead time. Secondly, the shipping costs should be included in a new analysis. For very heavy materials, long distance shipping will add significant costs. Boeing should consider all of these factors in a future analysis.

5.0 Methodology for Identifying Poor Depot Overhaul Factors

As discussed in Chapter 2, the DOF plays a critical role in determining Boeing's parts procurement. Recalling its definition, the DOF is an estimate of a part's rate of failure. As such, it is understood that the DOF value will never be 100% accurate. However, the DOF is expected to have a high degree of reliability. Unfortunately, this is not the case. This chapter will explore the reasons behind the current DOF problem and suggest a methodology for identifying inaccurate values.

5.1 Disagreement Between Sources

For each part within each end-item, a DOF exists. The DOF is determined by a prioritization process from six different sources. These sources are listed below in order of precedence. For example, if a part has DOF recommendations from sources two, three, and five; source two will be used.

1. Human Input from the CCAD Logistics Manager
2. Recent Review Recommendations
3. Three Year Moving Average of Historical Part Consumption
4. One Year (to date) Average of Historical Part Consumption
5. Asset Manager Recommendation
6. 4% Rule

Source one is generally a recommendation based upon a belief that a part should be replaced due to a safety issue. As this recommendation can only come from one person, it is a rare occurrence. Source two represents the results from a recent coordination meeting where numerous parts were evaluated in an attempt to improve the respective DOF values. Sources three and four are based upon historical parts consumption. Source five is developed by the asset managers when parts are new or no historical information exists. Finally, source six is used when there is no entry for a DOF.[7] The database calculates a 4% recommendation based upon a mandatory replacement of all parts. For example, if 100 transmissions were going to be overhauled and there was a bolt without a DOF that appeared once in the transmission, the 4% recommendation would generate a purchase order of four bolts. If the bolt appeared twice, the recommendation would be eight.

The DOF is selected from the highest priority source, regardless of agreement between the other inputs. Therefore, if the recent review states that the DOF for a part is 10 while the three year and one year average both show that the DOF is 85, the DOF will be 10. A final note on the sources of input is that there are rarely recommendations from more than two sources. As a result, there is no basis of comparison between the various values. Consequently, it is difficult to determine when a faulty DOF exists. Conversely, when there are multiple

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[7] Unfortunately, because the 4% rule is used when there is no usage history, it is possible that the 4% Boeing procures might never be used. Further analysis should be conducted instead of defaulting to a 4% purchase, especially for expensive parts.

sources of input, there is a high degree of variation between the recommendations. The following two charts depict these problems.

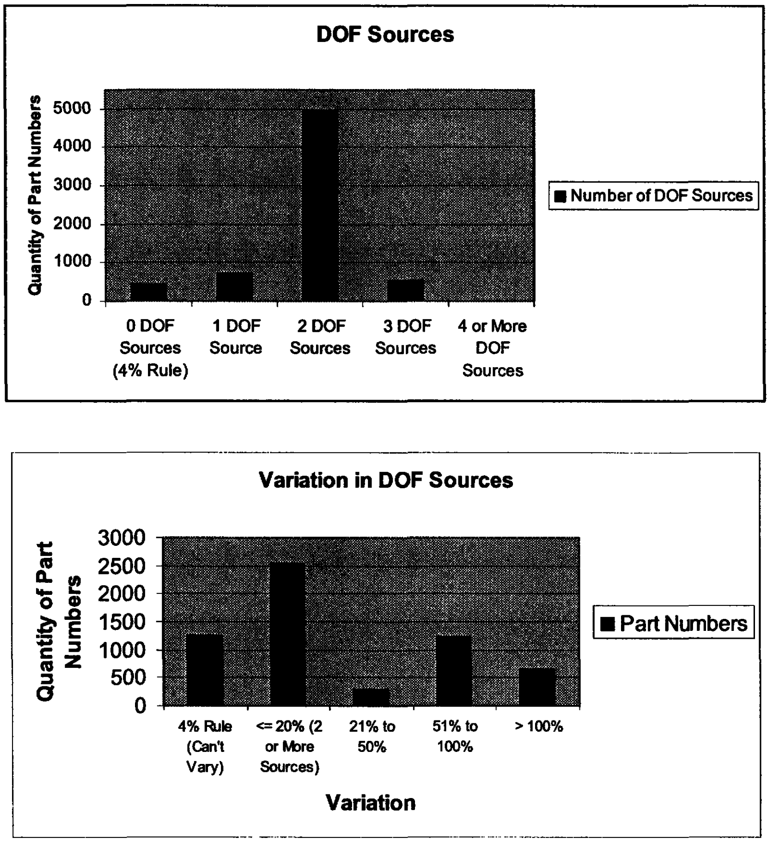

Figure 5.1: DOF Source Analysis

Examining the data behind Figure 5.1, 92% of the parts have two or fewer DOF sources. Excluding the parts that have only one DOF source or a value of zero, 40% of the parts have greater than 50% volatility in their DOF recommendations. This allows us to conclude that potential exists for a high degree of error in the DOF sources. Volatility for this analysis was calculated with the following equations.

DOF Range = Maximum Recommended DOF – Minimum Recommended DOF

Volatility = DOF Range / DOF *(Equation 5.1)*

For example, Part 123's volatility could be calculated by assuming the following information.

Part 123 DOF Recommendations					
Source 1	Source 2	Source 3	Source 4	Source 5	Source 6
-	40	20	-	30	-

Current DOF	40	← Highest priority (Source 2)
Max Recommendation	40	
Min Recommendation	20	
Range	20	← Max - Min
Volatility	50%	← Range / Current DOF

Figure 5.2: DOF Volatility Calculation

5.2 Identifying Focus Areas

With thousands of parts requiring verification, a methodology was developed for identifying which parts needed urgent attention. Four areas were identified to filter out the most demanding parts: volatility in DOF sources, price, lead time and backorder status. These filters can be generalized as uncertainty, parts that are of importance to Boeing and parts that are of importance to CCAD.

As discussed above, DOF source volatility highlights areas where the potential exists for flawed DOF values. Variation greater than 50% was chosen for the analysis. Price is of significance to Boeing in two ways. First, too low of a DOF for high value parts equates to larger amounts of lost revenue due to the inability to sell additional parts. Oppositely, too high of a DOF for high value parts equates to unsold inventory and losses from higher fixed and holding costs. High value parts were defined as having unit prices greater than $100. Next, parts with long lead times and low DOFs will result in a failure to provide the required parts for production when inventory is depleted. The part's inability for fast delivery will generate customer dissatisfaction when production is slowed or halted. A long lead time was defined as greater than six months. Finally, backordered parts show that this possibility is already occurring. Parts are needed and are not on-hand. When these areas were evaluated, the following information resulted.

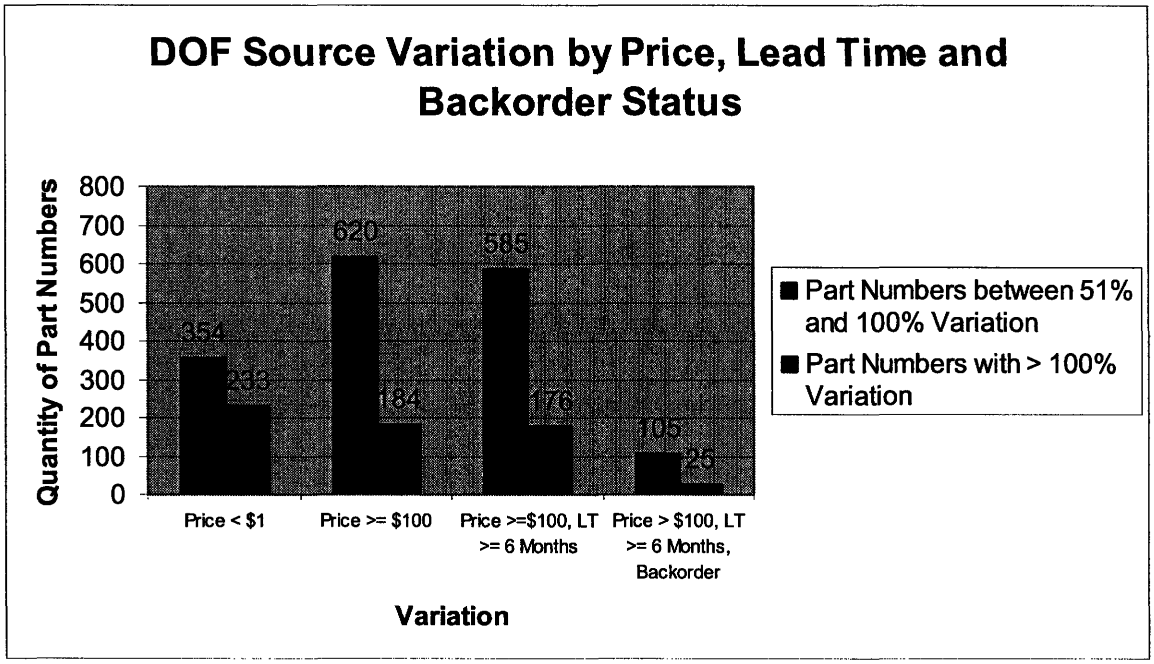

Figure 5.3: Detailed DOF Analysis

5.3 Methodology Insights and Results

One additional column was added to Figure 5.3. On the far left, parts with high variability and low dollar value (less than $1 unit price) were depicted. If Boeing simply applied the highest DOF source, regardless of where it fell within the priority chain, it could assume that the respective parts would no longer have a problem with DOFs. This conservative approach would only cost Boeing an additional 0.01% of the contract value for a single production year of parts with a DOF volatility between 51% - 100%. For parts with a DOF volatility greater than 100%, the annual extra cost equals 0.15% of the contract value. Of note is that the top ten part numbers with each variability classification equate to 0.006% and 0.11% of the contract value, respectively. For perspective, Boeing has the potential under this contract to earn an incentive bonus of up to several % of the contract value for meeting RTAT improvement targets. Since improved material availability is a large factor in RTAT, the increased cost is quite small relative to the potential incentive bonus.

When the four filters are applied, the list of parts to evaluate is significantly trimmed down. Reviewing part DOF recommendations is a tedious process. There is no immediate fix. However, by beginning on the right-hand side of the chart and moving left, parts with high volatility, on backorder, with long lead times and high revenue value can be improved upon. The DOF is of crucial importance to maintaining the production goals at CCAD. Immediate attention should be given to improving upon those DOFs deemed inaccurate.

6.0 Conclusion

In this thesis, the impact of volatility within an aftermarket parts supply chain of the defense aerospace industry was examined. Stochastic simulation techniques were employed to demonstrate how leveraging economies of scale could achieve cost savings while strategic selection of safety stock could provide insurance against uncertainty. Both recommendations provided financially responsible solutions that could allow for increased revenue even if the currently experienced volatility continues.

Within the fixed pricing analysis, it is important to highlight that higher revenue can result for two reasons: increased sales and / or decreased costs. Often, the focus is on selling more parts to the customer. Yet in this instance, the Monte Carlo simulation revealed that cost savings were the driving force to more revenue. On average, an 11% increase in income from sales can be achieved by combining the demands of all Boeing programs into one order. Additionally, benefits are reaped by removing the administrative delays involved in repricing thousands of items. Now, Boeing SM&P personnel can allocate their efforts to more productive tasks. Part sales will also occur on demand instead of sitting on the shelf waiting for repricing. For CCAD, the benefits of fixed pricing can be seen in the mitigation of the government's instable forecasting. As a result, CCAD gains increased responsiveness to WLF changes while the U.S. Government no longer needs to expend resources to audit major contract reproposals. Ultimately, the risk of production stoppage at CCAD due to part unavailability is reduced. This can only lead to a decrease in the average repair turnaround time.

The safety stock analysis provided more than a recommendation for additional raw material procurement. While the results showed an average reduction in total end-item lead time by 61%, Boeing's actions demonstrate a commitment to the entire supply chain. Purchasing raw materials above and beyond what is required shows the CCAD customer that Boeing is willing to spend its own resources to protect against uncertainty. Likewise, Boeing is helping the smaller suppliers by leveraging its purchasing size to keep costs lower. This cooperation vertically along the supply chain can only help to improve its efficiency.

6.1 Observations

Creating and managing a supply chain is an extremely complex task. Countless details and unforeseen difficulties must be planned for and overcome on a daily basis. It is easy to appreciate how overwhelmed those who work to establish the CCAD supply chain must feel. As an "outsider on the inside," it was obvious from the first day of the internship that those who work to supply CCAD are extremely dedicated to their jobs and steadfastly work to complete their assigned tasks (Klein, 2004). Yet there appears to be a belief that the faster a task is completed, the better. This idea might be an attempt to keep one's inbox from growing to large, but it is a prevalent practice. While the fervor with which Boeing employees complete their work is quite commendable, it unfortunately increases the possibility of committing errors. If more time was dedicated to proofing and reviewing submitted work, many mistakes that slip by unchecked could be prevented. An example of this is the 14% of contract revenue dollars of "non or slow-moving" inventory sitting in the CCAD warehouse.[8] In the rush to develop bills of material and Depot Overhaul Factors, errors were committed that resulted in the purchase of inventory that was not needed. These errors are only being discovered now, two years after-the-fact.

Although the principles of lean are most often associated with the manufacturing floor, they can also be applied to the supply chain. The previous paragraph describes many of the types of waste that lean thinking attempts to correct. The excessive inventory at the warehouse coupled with the additional work required to correct mistakes and reorder the required parts reveals that there is a knowledge disconnect in the supply chain. Identifying these types of waste prior to execution will prevent the negative financial impacts currently experienced and allow the support structure to operate more efficiently (Pascal, 2002).

6.2 Recommendations for Future Work

The only thing certain about forecasts is that they will always be wrong. However, the volatility experienced within the CCAD supply chain makes its efficient management extremely difficult. Efforts should be made to improve the

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[8] Inventory status was retrieved in November 2006. It is possible that some of the inventory was bulk-ordered in anticipation of future year requirements. Yet, the bulk-ordered items only account for 1% of the contract value. This is a very small percentage of the total contract value. However, when these items are combined with the approximate 1,800 parts recently added-to or removed from the current BOMs, concern should be raised.

forecasting tools used by Boeing and the U.S. Government. Specifically, the DOF issues raised in Chapter 5.0 should be addressed. The suggested methodology detailed by Figure 5.3 is a starting point in this task. With the most significant parts identified, Boeing and CCAD can work together to improve the replacement factors, and ultimately, the repair turnaround time.

Additionally, efforts should be made to educate employees on the statistical importance of the DOF and how their actions might influence its value. During various conversations over the internship, two practices were mentioned, that if true, would directly corrupt the integrity of the DOF. While there was no proof that these actions were occurring, the frequency of their suggestion raises concerns.

The first of these "rumors" involved using the DOF as a tool to adjust inventory levels. Raising or lowering the DOF to speed up or slow down the parts flow will only degrade the accuracy of the true replacement factor. While this adjustment might provide short-term fixes, it will also guarantee that the long-term health of the supply chain is weakened. A more manageable short-term solution might be to create a safety stock level for various parts.

The second "suggested practice" involved the individual requisition of parts for insurance purposes. Stories were often told of how workers will withdraw as many parts as possible in order to build personal inventories and protect against future stock-outs. CCAD workers have learned that if they want a part with a history of stocking-out, they should procure it from the warehouse whenever it is available. An example of this occurred during a visit to the CCAD back-shop that repairs rotor heads. A worker explained to me how during the process of an overhaul, a certain part was needed to repair the rotor head. When the worker went to withdraw the required items, he discovered that more were available. The worker knew that he was going to perform another rotor head overhaul upon completion of the current one. To make sure that he would have the available parts, he requisitioned more than was presently needed.[9] This type of action adds to the inefficiency of the supply chain, both in the present and for future planning. A part sitting in a drawer cannot be used elsewhere on the shop floor, however, it will still add to statistical consumption data. As a result, future forecasting is affected because Boeing now believes more parts are needed on average for a repair. In the present, inventory managers might also try and expedite the delivery of parts farther up the supply chain because the inventory levels are lower than anticipated. The practice of maintaining "invisible" parts around the shop floor must be stopped in order for the true DOF to be found.

Lastly, collaboration and communication are vital to successful supply chains. The best operating support structures realize this and attempt to share information as often as possible. Knowledge of unforeseen events should immediately traverse the supply chain. Only this way will a solution be found that

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[9] This discussion occurred between the author and an unnamed worker during a September 2006 tour of the CCAD facility. The discussion involved daily operational procedures and how parts are requisitioned.

is in the best interest of all parties. As such, another area of emphasis for future work should be on improving communication along the supply chain. Rapid information flow will reduce the effects of volatility and improve the working relationships between Boeing's suppliers, the CCAD supply chain and the U.S. Government.

The suggestions made in this thesis combined with the recommendations for future work will drastically reduce the impact of volatility within the CCAD aftermarket parts supply chain. By concentrating on these areas, Boeing is investing in the supply chain's continuous improvement and the partnership's future success.

7.0 INDEX OF ACRONYMS

AH-64: Apache Attack Helicopter

AMCOM: Army Aviation and Missile Command

AMAPS: Advanced Manufacturing Accounting and Production System

APU: Auxiliary Power Unit

BOM: Bill of Material

CCAD: Corpus Christi Army Depot

CH-47: Chinook Cargo Helicopter

DoD: Department of Defense

DOF: Depot Overhaul Factor

LTD: Lead time demand

NPV: Net Present Value

PERT: Program Evaluation Review Technique

RMOH: Raw Material On-hand

ROP: Reorder Point

RTAT: Repair Turnaround Time

SM&P: Supplier Management and Procurement

SS: Safety Stock

WLF: Workload Forecast

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