Helicopter Final Assembly Critical Path Analysis

By

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S.B. Mechanical Engineering
Massachusetts Institute of Technology, 2004

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

Master of Business Administration
and
Master of Science in Mechanical Engineering

In conjunction with the Leaders for Global Operations Program at the
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Abstract

Helicopter final assembly involves the installation of hundreds of components into the aircraft and takes thousands of man-hours. Meeting production targets such as total build days and total aircraft man-hours can be difficult when faced with challenges related to parts, workforce, and scheduling. A tool to identify key installations on which to focus efforts for maximum benefit can help improve performance to targets.

The Critical Path Method was developed as a project management tool to aid in scheduling large and complex projects. Its application to manufacturing can provide the insights necessary to improve performance in an environment such as helicopter final assembly.

This thesis provides a case study of helicopter final assembly. A critical path analysis is performed on the assembly process, using predecessor, duration, and resource data. The results of the analysis are used to draw conclusions about the system as a whole and to make recommendations to improve system performance.

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From MIT, I would like to acknowledge my two thesis advisors, Roy Welsch and Dan Whitney, for their support and insights. The LGO Program office was also extremely helpful throughout my entire time at MIT, especially Patricia Eames.

Of course I would not have succeeded at MIT and in life without the support of my family, especially my mother Rosemary Daigh and my father Gary Daigh, and my friends, especially Tatiana Bonnefoi and Limor Zehavi. Perhaps most important was the continuous encouragement from my fiancé Brad Stirrat. Thank you.

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Proprietary Information

Due to the proprietary nature of much of the information contained in this report, steps have been taken to disguise the data. For example, names have been changed, theoretical numbers have been given, and charts have been presented in terms of percentages only (normalized by base numbers). Publicly available figures have been included and appropriately cited.

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1. Introduction

This thesis is based on an internship which took place at Sikorsky Aircraft's Florida Assembly and Flight Operations (FAFO) facility in West Palm Beach, Florida from June through December 2011. The purpose of the internship was to perform a critical path analysis of the final assembly process for one production line at the FAFO facility.

Chapter 2 provides background information to put the problem statement, analysis, results, and conclusions into context. Chapter 3 introduces some of the challenges in the final assembly process and the motivation behind a critical path analysis. Chapter 4 contains a review of relevant literature on the topic of the critical path method. Chapter 5 details the approach taken in this project and presents the general results of the analysis. Chapter 6 draws conclusions and provides recommendations based on the critical path analysis. In addition, chapter 6 identifies some areas for further study.

2. Background

This chapter provides background information necessary for understanding the project statement and results. Section 2.1 introduces the Sikorsky Aircraft Corporation; Section 2.2 describes the facility where the project was located; Section 2.3 details the basics of helicopter final assembly; and Section 2.4 discusses two different assembly methodologies.

2.1 Sikorsky Aircraft Corporation

Sikorsky Aircraft Corporation, a division of United Technologies Corporation (UTC; Public, NYSE: UTX), is a leading manufacturer of commercial and military rotorcraft. The company was founded by Igor Sikorsky in 1925 in New York, later moving to Stratford, Connecticut and becoming part of what would become United Technologies Corporation. Sikorsky is headquartered in Stratford, CT and employs 17,780 people worldwide (About Sikorsky, 2012; UTC, 2011). Sikorsky contributed $7.36 billion in net sales to UTC in 2011; UTC's net sales totaled $58.2 billion in 2011 (see Figure 1; UTC, 2011

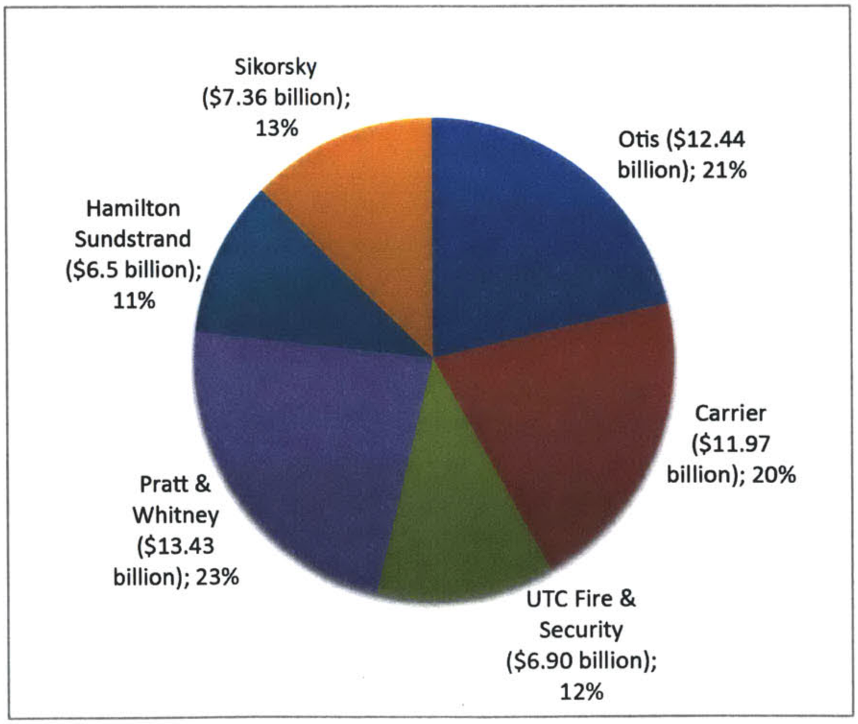


Figure 1. UTC Net Sales by Business Unit, 2011

Sikorsky has three businesses: Sikorsky Military Systems, Sikorsky Global Helicopters, and Sikorsky Aerospace Services. Sikorsky Military Systems manufactures military helicopters for the United States armed forces as well as for select foreign military. Examples include the BLACK HAWK, presidential transport helicopters, and the CH-53 family of heavy-lift helicopters. Sikorsky Global Helicopters manufactures civil and government helicopters used for various purposes including offshore oil transport and search and rescue. Sikorsky Aerospace Services is the service arm of Sikorsky (About Sikorsky, 2012).

2.2 Florida Assembly and Flight Operations

Sikorsky Military Systems (SMS) has three final assembly sites in the United States. This thesis focuses on the Florida Assembly and Flight Operations (FAFO) facility in West Palm Beach, Florida. The FAFO facility is located on the same site as a Pratt & Whitney Rocketdyne facility and the Sikorsky Developmental Flight Center. FAFO was opened in February 2008 to increase Sikorsky's capacity to build military aircraft. The success of the facility led to increased production, reaching 145% of the 2009 level in 2011 (see Figure 2).

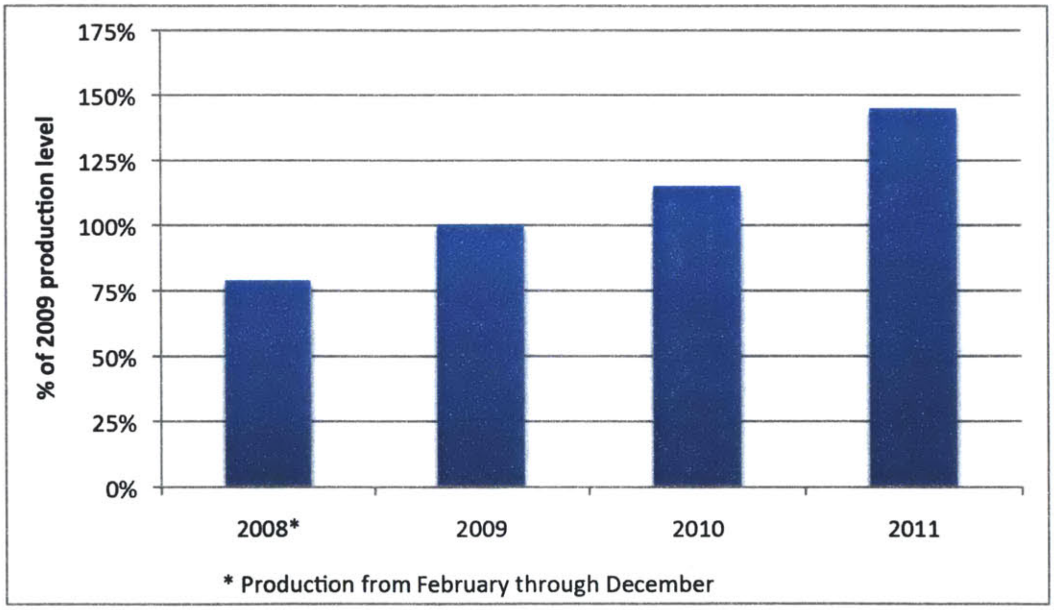


Figure 2. FAFO Production, 2008 to 2011

A variety of military helicopters are assembled at FAFO. At the time of this internship, there were approximately five different products being assembled at FAFO, each on its own production line. In 2011, the FAFO facility assembled 24% of the total aircraft produced by SMS.

Final Assembly is the final stage in the manufacture of a helicopter. During final assembly, subassemblies and other components are installed into the airframe. These parts come from internal and external suppliers around the world. Quality checks and operational checks are performed as assembly progresses.

In addition to final assembly operations, flight operations are also conducted at FAFO. These are necessary steps completed before the final sale of the aircraft. Flight operations include painting and fueling of the aircraft, performing a ground run to ensure proper operation of aircraft systems prior to flight, and passing flight acceptance tests flown by both Sikorsky and customer pilots.

2.3 Helicopter Final Assembly

Final assembly begins with receipt of the airframe. The airframe is the basic fuselage structure of the aircraft and is constructed of sheet metal or, in some cases, composite materials. During final assembly, subassemblies and other components are installed into the airframe. Systems installed include the wiring, tail rotor pylon, exhaust systems, engines, transmission, oil cooler, control systems, and avionics. The final assembly build is comprised of hundreds of installations to install these systems into the helicopter. Each installation is called an AOS (Assembly Operation Sequence). Each AOS consists of many operations that must be followed to ensure proper assembly of the helicopter. These include quality checks performed by the Quality Assurance (QA) department. If there is a problem with the installation of a component, QA inspectors record the problem, and it must be fixed before that operation can be completed and signed off.

QA inspectors also perform detailed inspections of the entire aircraft after assembly is completed. These comprehensive inspections are called shakes. As shown in Figure 3, there are two QA shakes performed after the aircraft is built: Final Assembly Shake and Hangar Shake. Final assembly inspectors perform the Final Assembly Shake to ensure the aircraft has been properly built, and inspectors from flight operations (the "hangar") perform Hangar Shake to verify that the aircraft has been properly built before it is transferred to the hangar. Discrepancies found during the shake process must be fixed before the shake can be completed.

Some AOSs are tests to ensure the systems installed during final assembly are functioning properly. These AOSs are called ATPs (Assembly Test Procedures). The last major ATP performed is the Water Test ATP which is completed after both shakes are performed but before the aircraft is delivered to flight operations (see Figure 3). Since the military helicopters that Sikorsky builds fly in extreme weather conditions, the water test ATP ensures that each helicopter is watertight, i.e. there are no leaks from the exterior of the aircraft to the interior.

Another set of checks is in place to verify the build process of each helicopter. The Defense Contractor Management Agency (DCMA) is a government body that works directly with government suppliers to ensure products and services are delivered as promised. DCMA employees at Sikorsky perform checks at various points in the final assembly process to guarantee the helicopters are being built to the correct specifications.

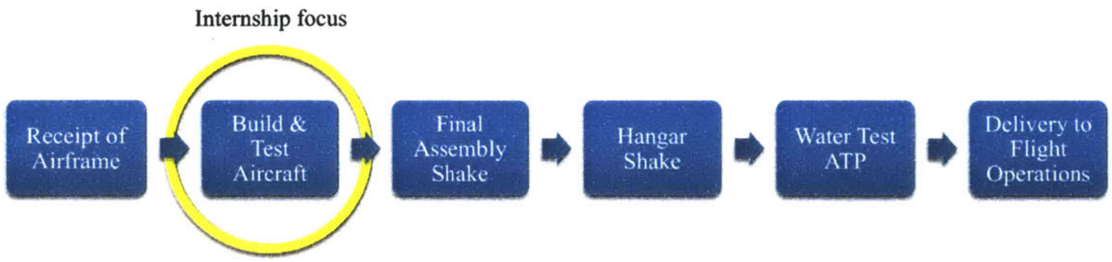


Figure 3. Simplified Helicopter Final Assembly Process

The focus of this thesis is the "Build and Test Aircraft" phase of the Final Assembly process as shown in Figure 3. Included in this phase is the completion of almost all AOSs and ATPs and most of the QA and DCMA verification steps.

2.4 Assembly Methodologies

There are two build methodologies that manufacturers use when assembling a large product in relatively low volumes such as an aircraft. The first methodology is the Position Build, shown in Figure 4. To aid in explanation, assume that final assembly for a helicopter comprises six positions. (This is a theoretical number and is not based on Sikorsky's actual build process.) Ideally, the six positions would physically be located in a line or in a U-shape to facilitate flow from one position to the next. Follow aircraft 1 through the build process. The aircraft starts in position 6 (or position N, where N is the total number of positions). AOSs have been assigned to each position based on past industrial engineering studies. All AOSs assigned to position 6 will be completed in a time less than or equal to the takt time of the line; in this case, assume the takt time is 6 days. (Again, this is a theoretical number and is not based on Sikorsky's build process.) After 6 days have progressed and the AOSs for position 6 are complete, aircraft 1 rolls to position 5. A new airframe is received and is placed in position 6 (aircraft 2). Another 6 days progress, the position 5 AOSs for aircraft 1 are complete, and the position 6 AOSs for aircraft 2 are complete. The line rolls again. This process repeats until 36 days (N x takt time) have passed. At this point, aircraft 1 is complete, and aircraft 2 through 7 are in process.

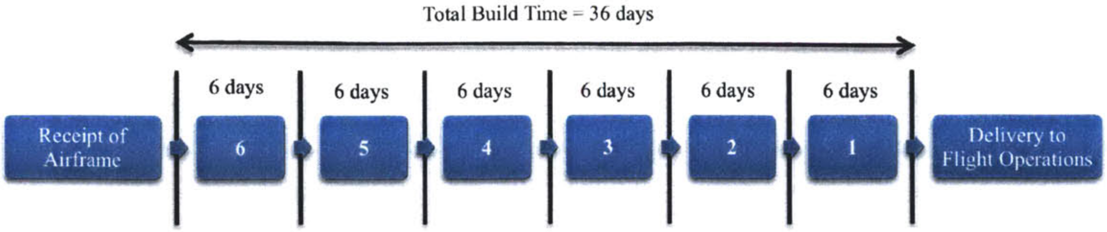


Figure 4. Theoretical Six-Position Helicopter Build with Takt Time of 6 days

The Position Build methodology keeps resources in one position and moves the aircraft from position to position. A mechanic named Johnny will complete Mechanical Install A in position 6 on each aircraft. Since he is repeating the installation every 6 days (the takt time), he will develop expertise doing this installation and will progress along the learning curve. Materials handler Jeremy will always deliver the parts for Mechanical Install A to Johnny in position 6. Similarly, the aircraft will always roll off the line from position 1, from the same location on the factory floor. In the Position Build, the product moves from position-to-position, and the resources (people, parts, and auxiliary equipment) stay in one position.

The second methodology is the Battleship Build. When performing a Battleship Build, the physical product – in this case, the aircraft – stays in one location for the duration of the final assembly process. Using the parameters introduced above, assume it takes 36 days for Sikorsky to assemble an aircraft. On day one, the airframe would be delivered to a specified location in the facility. For the next 36 days, people, parts, and auxiliary equipment would flow to the product as needed. At other specific locations throughout the facility, additional aircraft would be in various stages of completion. At the end of 36 days, when the aircraft is complete, it would roll off the line from wherever it is located.

There are two ways to approach resource allocation with the Battleship Build. The first way mimics the logistics of the Position Build. One day, an associate named Johnny performs Mechanical Install A on aircraft 1 in one location. Six days later, Johnny performs Mechanical Install A on aircraft 2 in another location. In another six days, Johnny will be performing Mechanical Install A on aircraft 3 in a third location. Allocating resources in this manner takes advantage of the learning curve introduced in the Position Build discussion, but it requires people to work in many different locations in the factory. This constant movement of resources can be confusing. The second way to approach resource allocation does not take advantage of specialization. Johnny performs Mechanical Installs A, B, C, and D on aircraft 1 in one location. Jenny performs Mechanical Installs A, B, C, and D on aircraft 2 in another location. Neither mechanic has to move between aircraft, but both mechanics need broader knowledge to perform multiple installations. Now, each mechanic only performs the installation once every 36 days, slowing his movement along the learning curve.

The production line on which this thesis focuses follows the Position Build methodology. There are aircraft being built at FAFO that followed the Battleship Build methodology, but these models are demanded in much lower quantity and are usually built one-at-a-time.

As mentioned, each position has certain AOSs assigned to it. The AOSs were assigned based on knowledge of the overall final assembly process. For example, the wiring must be installed before the avionics can be installed and operational checks performed; therefore, the wiring would be assigned to an earlier position and the avionics installation and the associated operational checks assigned to a later position or a later time slot at the same position. In addition, each AOS has associated target hours. The target hours predict how long it should take to complete the AOS, on average. Industrial engineers developed the target hours based on limited study of the installations. Detailed time studies were not completed.

* * *

This chapter has provided the background information necessary to understand the motivation behind this project. A part of UTC, Sikorsky is a leading manufacturer of commercial and military helicopters. This internship focused on final assembly on one production line at the FAFO facility. On that production line, the assembly methodology of Position Build is employed.

3. Problem Statement

Chapter 3 introduces the project's problem statement. Section 3.1 presents the challenges that FAFO final assembly faces and the consequences of these challenges. Section 3.2 discusses the motivation behind a critical path analysis.

3.1 Final Assembly Challenges

Section 2.4 describes how final assembly is done in an ideal aircraft factory. Every real facility will face challenges when trying to follow the ideal process. The challenges faced at the FAFO facility relate to parts, hourly and salaried workforce, and scheduling and result in carry-forward work, increased aircraft hours, and increased total build days.

Parts

A part is needed on the floor on the day that corresponds with its installation. Sufficient time is necessary for the parts to be received and processed by materials handling before needed on the floor; at FAFO, this time is approximately 48 hours. For example, if the engines are installed on day 15, then the engines are required on day 15. However, materials handling will have received the engines 48 hours previous. Also, parts can be pulled from the parts crib up to 24 hours before they are needed for installation. If a part is not available, the installation cannot be completed. Usually, the associates continue with the aircraft build, completing installs that are not dependent on the part shortage. Sometimes, the associates undertake installations with the knowledge that the work will have to be redone when the part is received. This second behavior occurs since associates want to appear busy and supervisors want to keep associates busy.

At FAFO, every aircraft has many part shortages. Parts are received late to the FAFO facility due to late supplier deliveries, increased production rates, and FAFO's distance from Sikorsky's third-party logistics (3PL) provider. The former two reasons cause the parts to be late, and the latter circumstance exacerbates the problem. Suppliers will experience problems meeting schedule, just as Original Equipment Manufacturers (OEMs) will. In addition, Sikorsky has increased the production rate over the past few years (or equivalently decreased target aircraft build days, see Figure 5). This puts added pressure on the suppliers to keep pace. FAFO's location makes late parts even later. Sikorsky uses a 3PL provider to handle parts inventory. The other SMS final assembly facilities are less than 6 hours by truck from the 3PL provider. In fact, the main assembly site, collocated with Sikorsky headquarters in Stratford, Connecticut, is less than thirty minutes away from the 3PL provider. FAFO, on the other hand, is three days away by truck. This distance puts FAFO at a large disadvantage relative to the other locations. If all three locations are delayed due to a part shortage and have the same delivery date, FAFO will receive the part in three days instead of 6 hours and will automatically be that much farther behind in the build process. In addition, hours would have been building up on the aircraft while waiting for the part (if it was holding up other installations), and employees would have been trying to perform workarounds.

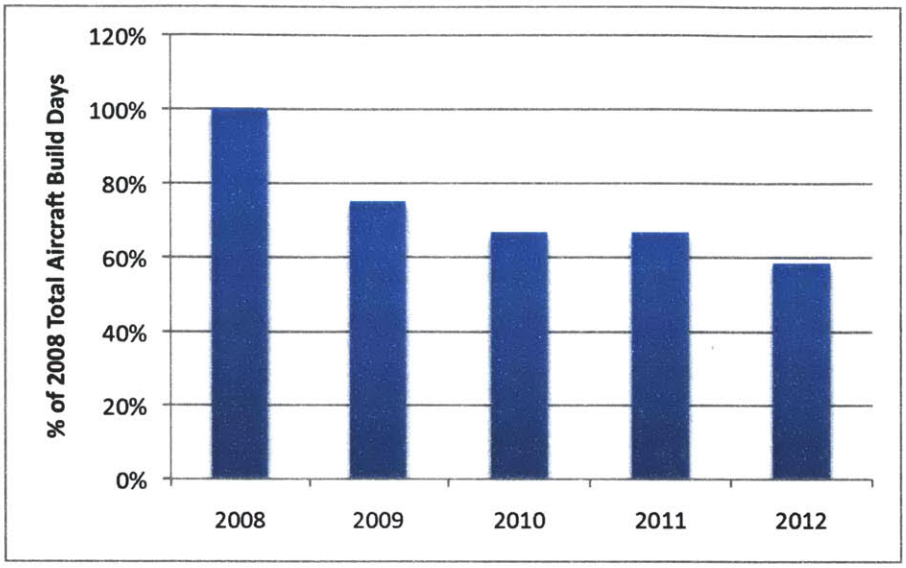


Figure 5. Aircraft Total Build Days, 2008 to 2012

Hourly Workforce

The FAFO hourly workforce is unionized and consists of the leads and associates. The leads work only part of the time as direct labor, applying their hours directly to the aircraft build. The rest of the time, they charge "Shop Supervision" and provide help and guidance for the associates. The ratio of direct labor hours to indirect labor hours for a lead varies from 4:4 to 0:8 for an 8-hour day. Currently, there is approximately one mechanical and one electrical lead per position, and usually one hydraulics lead for an entire production line. (There are relatively fewer hydraulics AOSs compared with mechanical and electrical AOSs.)

At FAFO, hourly employees are not required to belong to the union, but almost everyone does. Disputes with the company, known as grievances, occur on an individual level over actions deemed as inconsistent with the union contract. For example, hourly employees are categorized into different labor grades, depending on their experience. A higher labor grade corresponds to more time with the company and an increased hourly wage. If an associate feels like he has been doing work above his labor grade for 50% or more of his time over the last 90 days, he has the right to be paid at that higher labor grade. To complicate the situation, the AOSs aren't categorized by labor grade, so there is a degree of subjectivity in the assessment of what labor grade of work an associate has been performing. Because of these uncertainties, a grievance over labor grade may be difficult to resolve. Union stewards represent the hourly associate in these matters and argue on his behalf.

When the FAFO facility first opened, 96 employees were transferred from the Developmental Flight Center, and 90 additional employees were hired within 30 days. Due to the quick ramp-up, employees' experience varies greatly. Some associates had years of relative experience as a mechanic or electrician prior to joining Sikorsky. Others had no relevant experience, coming from Starbucks, for example. In addition to hiring, some employees transferred from Stratford. Although this allowed FAFO to start with a more experienced workforce, the transferred employees influenced the culture of the new facility. FAFO was not able to develop its own culture, and negative aspects of the Stratford union culture were transplanted to FAFO. FAFO currently has approximately 600 employees; the additional employees were added over a period of 18 months.

During the second half of 2011, there was some movement of hourly leads and associates between production lines. One program was delayed, and leads and associates were temporarily transferred to other production lines. This had two main effects. First, it introduced more hourly employees than were needed on some lines which drove up aircraft hours. Second, the transferred employees were unfamiliar with the new aircraft and its installations; this unfamiliarity led to increased time to perform AOSs which also led to increased aircraft hours.

The planning function at Sikorsky plans the overall hourly workforce on an aggregate basis. Breakdown of the workforce into specialties (mechanics, electricians, plumbers, electrical checkout) is not considered. Consequently, some production lines are unbalanced. The line studied had too many electricians and not enough mechanics, but the process to switch an associate from an electrician to a mechanic is difficult and requires the willingness of the associate. From time to time, it is possible to borrow mechanics from other lines, but only when the other lines can spare mechanics. Borrowing also introduces the issue of possible unfamiliarity with the AOSs, driving up aircraft hours.

Salaried Workforce

For each program, the salaried production workforce consists of supervisors, line managers, and an operations manager as shown in Figure 6. FAFO currently works three shifts; first shift is from 6:00 AM to 2:30 PM, second shift is from 3:00 PM to 11:30 PM, and third shift is from 11:30 PM to 6:00 AM the following day. Each shift includes a 30-minute lunch break. First and second shifts are of approximately equal size. Third shift is substantially smaller. Figure 6 represents the number of supervisors in mid-

2011. Each supervisor had responsibility for 2 positions, on average. There was only one third shift supervisor due to the size of the third shift crew. In the third quarter of 2011, extra supervisors were hired, and currently, there is one supervisor per position. FAFO supervisors are responsible for 20 employees, on average. (There remains only one supervisor on third shift for all positions.) Similarly, there was one mechanical and one electrical lead for two positions, but there is currently one lead of each specialty per position.

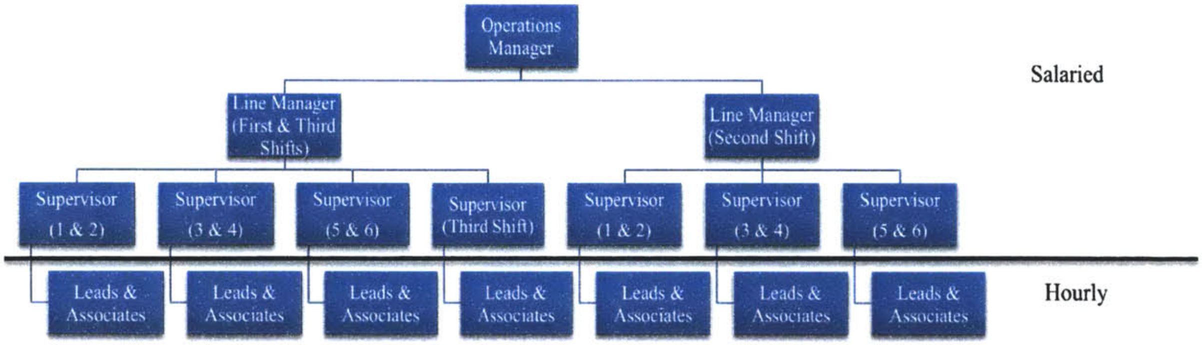


Figure 6. Typical Production Organizational Structure

This trend of increasing the number of supervisors and leads seems beneficial. Unfortunately, FAFO is at a disadvantage because of the set-up of the production line. To build the same helicopter, the Stratford facility has twice as many positions. For example, assuming FAFO follows the theoretical six-position build in Figure 4, Stratford would have twelve positions to build the same aircraft. Each position would perform half the work of a FAFO position. Thus, Stratford positions 1 and 2 would correspond to FAFO position 1. Stratford also has one supervisor, one mechanical lead, and one electrical lead per position. Since there are twice as many positions as at FAFO, each Stratford supervisor and set of leads is responsible for roughly 15 employees and half as many AOSs. This allows the supervisors and leads more time per employee and per AOS. Also, with more employees and AOSs per position as at FAFO, there can be issues of crowding in the aircraft's limited space.

Figure 6 shows the production organizational structure. FAFO also has support functions: quality, materials handling, industrial engineering, manufacturing engineering, planning, finance, and safety/lean manufacturing. Some of these functions report up to the FAFO facility director, and some of them report directly to functional heads at headquarters. The industrial engineers are an example of a function that reports directly to headquarters and has limited dotted-line reporting to the FAFO facility director. Actually, for the helicopter program studied, there was only one industrial engineer (IE) for three different production lines (three different models from one program). He was overwhelmed completing required daily reports and did not have time to perform actual IE functions. Consequently, supervisors had to extract data from the labor-reporting system, analyze the data, and initiate and implement process improvements without support from the IE department.

Scheduling

Target hours exist for each AOS. The target hours are the number of hours it should take, on average, to complete a given AOS. For example, Mechanical Install A may have a target of 8 hours. This means it should take one mechanic 8 hours to perform this AOS. Most AOSs can be completed by one person; however, if two mechanics are necessary, the amount of time per mechanic decreases. The total amount of time to complete the AOS (mechanic 1's hours + mechanic 2's hours) should be no more than the target, in this case, 8 hours.

As with the assignment of AOSs to positions (see Chapter 2), the assignment of target hours to each AOS is based on IE estimates and on tribal knowledge not on detailed time studies. The target hours are determined in Stratford and are passed down to satellite locations. At FAFO, these targets are called "Stratford target hours." Since the FAFO employees have less experience on average than the Stratford employees, FAFO is budgeted more total hours to complete an aircraft. Over time, as FAFO employees gain more experience, the FAFO transfer cost (total aircraft hours) approaches the Stratford transfer cost (see Figure 7). Using a ratio of the FAFO transfer cost to the Stratford transfer cost, a set of "adjusted FAFO target hours" can be calculated. For example, if Electrical Install A has a target of 8 hours at Stratford, its target at FAFO might be 10 hours (8 hours x 1.25, assuming 1.25 is the ratio of FAFO transfer cost to Stratford transfer cost). There has been confusion among supervisors, upper management, and IEs regarding which target hours should be used for standard reports and informal performance evaluations. The operations manager strongly favored using adjusted FAFO target hours while the IEs favored using Stratford target hours. Supervisors were using Stratford target hours. During the internship, this changed, and all parties started using adjusted FAFO target hours.

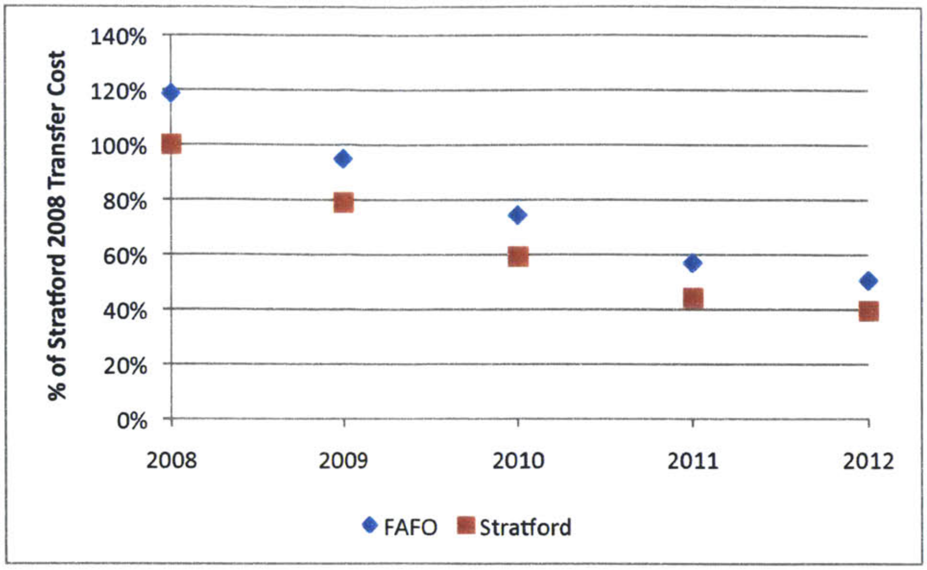


Figure 7. Aircraft Transfer Cost, 2008 to 2012

A consulting study was being completed during the first half of the internship. Sikorsky had hired a consulting firm (hypothetically called Acme Consulting) to study the breakdown of the aircraft build into AOSs. Before the study, target hours per AOS ranged from 96 hours down to 1 hour, depending on the installation. Acme recommended that the AOSs with higher target hours be broken down into 8-hour increments; therefore, one associate should complete one AOS every day, on average. For example, Mechanical Install took 24 hours prior to the Acme changes. After the Acme changes, there were three installs (Mechanical Installs A, B, and C), and each had a target of 8 hours. Acme's logic was that this would create a clear definition of each employee's scope of work every day. In theory, this decomposition of the larger AOSs makes sense. Unfortunately, when implemented, the Acme changes did not have a great effect at FAFO. Often, the AOSs were improperly decomposed: operations were ordered incorrectly in the resulting AOSs. This, as well as a widespread mentality to oppose change, led employees to perform the AOSs in the exact same manner as before the Acme changes.

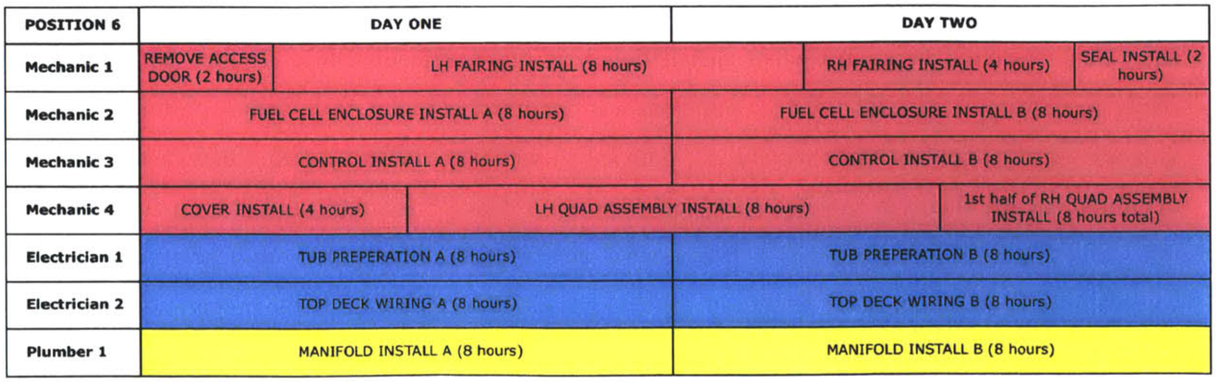
For example, in the Control Install AOS, Jimmy installs three sets of the same equipment. For each set of equipment, there are preparation steps, installation steps, and completion steps. Before the Acme changes, although a specific order of operations was documented in the AOS, Jimmy performed the steps for each set of equipment as he wished. He prepped all sets of equipment together then installed all sets of equipment and finally completed all sets of equipment. Now, Control Install has been decomposed into Control Installs A, B, and C. Control Install A comprises the preparation, installation, and completion of equipment set 1. Similarly, Control Installs B and C comprise the preparation, installation, and completion of equipment sets 2 and 3, respectively. Instead of readjusting his work methods, Jimmy continues to complete all preparation steps first then all installation steps and finally all completion steps. Instead of completing one AOS each day, he works on them simultaneously, completing all three AOSs after three days. Although the results are the same, the perceived benefits of the Acme changes have been lost. (Also, it is difficult to correctly assign labor hours to each AOS when performed in this manner. See Chapter 5 for details of this situation.)

There is a visual tool, a balance chart, that can be used to help manage the completion of AOSs. The balance chart was developed in Stratford and details which AOSs should be completed each day in each position. The balance chart also breaks down the work by specialty. Figure 8 shows a hypothetical balance chart. The balance chart should be displayed at each position, and completed AOSs are colored in to signify completion (see Figure 9). When correctly implemented, the balance chart allows someone to quickly evaluate how well the position is performing to schedule. In reality, the balance chart was rarely used at FAFO. The balance charts available were developed using the standard (Stratford) target hours and represented the ideal manpower allocation. During Q4 of 2011, a supervisor was trying to develop a FAFO-specific balance chart in his spare time.

Table 1. Balance Chart, Days 1 & 2 of Position 6

POSITION 6	DAY ONE	DAY TWO
Mechanic 1	REMOVE ACCESS DOOR (2 hours) LH FAIRING INSTALL (8 hours)	RH FAIRING INSTALL (4 hours) SEAL INSTALL (2 hours)
Mechanic 2	FUEL CELL ENCLOSURE INSTALL A (8 hours)	FUEL CELL ENCLOSURE INSTALL B (8 hours)
Mechanic 3	CONTROL INSTALL A (8 hours)	CONTROL INSTALL B (8 hours)
Mechanic 4	COVER INSTALL (4 hours) LH QUAD ASSEMBLY INSTALL (8 hours)	1st half of RH QUAD ASSEMBLY INSTALL (8 hours total)
Electrician 1	TUB PREPERATION A (8 hours)	TUB PREPERATION B (8 hours)
Electrician 2	TOP DECK WIRING A (8 hours)	TOP DECK WIRING B (8 hours)
Plumber 1	MANIFOLD INSTALL A (8 hours)	MANIFOLD INSTALL B (8 hours)

Table 2. Completed Balance Chart, Days 1 & 2 of Position 6



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Electrician 1	TUB PREPERATION A (8 hours)	TUB PREPERATION B (8 hours)
Electrician 2	TOP DECK WIRING A (8 hours)	TOP DECK WIRING B (8 hours)
Plumber 1	MANIFOLD INSTALL A (8 hours)	MANIFOLD INSTALL B (8 hours)

Despite the available tools, there was widespread failure to meet target AOS hours at FAFO. As mentioned previously, this was due, in part, to a confusion about which hours to use as targets: Stratford target hours or FAFO adjusted target hours. Supervisors, leads, associates, and the IE were using Stratford target hours, and management thought they were using FAFO adjusted target hours. During the internship this inconsistency was rectified; everyone began using FAFO adjusted target hours. Part shortages and manpower shortages also led to overruns on AOS hours. In addition, the lack of motivation and accountability discussed previously exacerbated the failure to meet targets.

Every year since FAFO opened, the total number of aircraft produced at the facility has increased (see Figure 2). At the same time, target aircraft total build days and aircraft total hours (transfer cost) have decreased (see Figures 5 and 7). This scheduling has put added pressure on FAFO employees. FAFO has seen vast improvements due to learning (see Figure 8), but the facility continually faces pressure to improve.

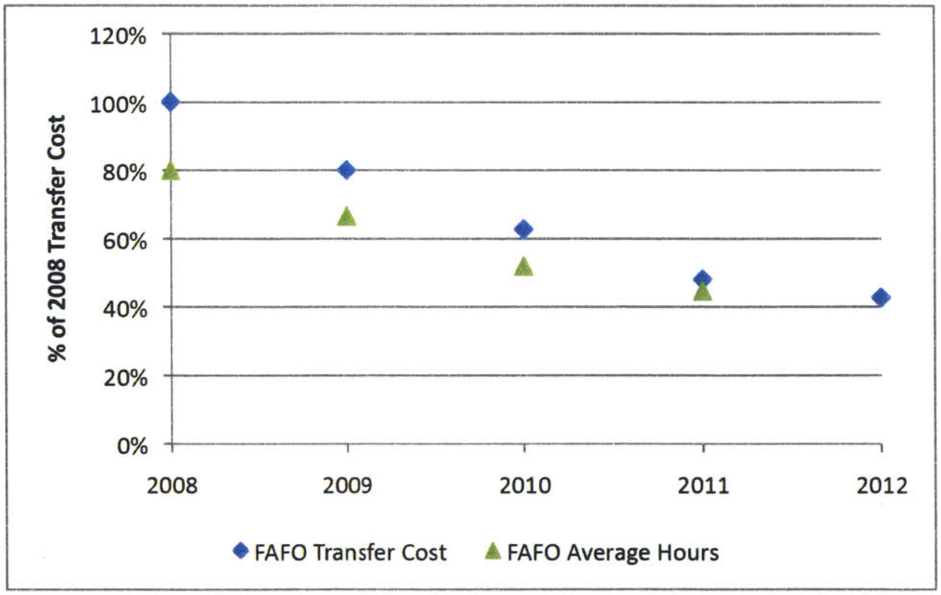

Figure 8. FAFO Average Total Hours and Transfer Cost, 2008 to 2012

In addition to annual production targets, there are also monthly and quarterly production targets. Inevitably, production lags behind the schedule until a few weeks before the end of a period when management makes a huge push to complete all the scheduled aircraft. Priorities are reshuffled, and all resources needed on the front aircraft are pulled from other aircraft to push the priority aircraft through production. An example of this is illustrated in Figure 9 with two aircraft scheduled for delivery in the first quarter and four aircraft scheduled for delivery in the second quarter. As one might expect, this behavior creates a self-reinforcing cycle. In the example shown in Figure 9, the back four aircraft now have fewer resources and will fall even farther behind the schedule. Next quarter, resources will have to be pulled forward to complete these aircraft on time, causing the new aircraft in the back of the line to fall behind once again.

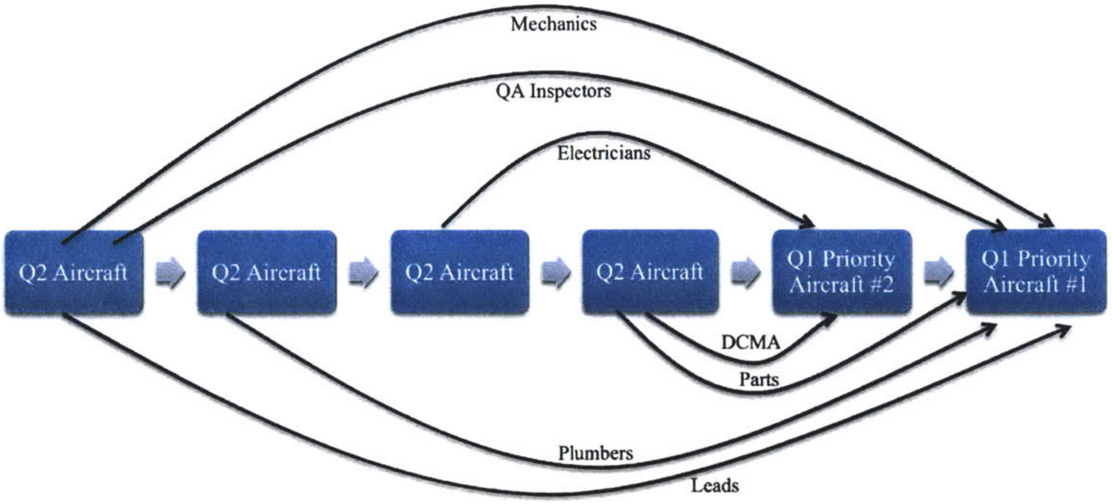

Figure 9. Flow of Resources to Priority Aircraft

Another scheduling challenge relates to the availability of government pilots. Since most of the helicopters built are going to the United States government, their pilots are required to perform a government flight acceptance (GFA) before the aircraft sale can be finalized. Because FAFO is a satellite location, government pilots are not permanently assigned to the facility. Instead, pilots come down each month for a few days to perform the GFAs. Unfortunately, there is often not time for all available aircraft to be flown by the government pilots. If the GFA is not completed on an aircraft, it cannot be sold and must wait until the next scheduled visit by government pilots. Although final assembly and flight operations may have worked hard to complete an aircraft on schedule, it can still be late to the customer due to poor scheduling of pilots.

Carry-Forward Work

Challenges associated with parts, the hourly and salaried workforces, and scheduling lead to carry-forward work. Carry-forward work is work that is not done in the assigned position but is instead "carried forward" to the next position to be completed there. Pushing work forward to the next position means that position now has to complete all of its assigned work plus whatever work has not yet been completed but should have been. An example of the propagation of carry-forward work through the production line is shown in Table 3.

Table 3. Propagation of Carry-Forward Work

	Assigned	Carried Forward	Target to Complete	Actual Completed
Position 6	100	--	100	90
Position 5	100	10	110	90
Position 4	100	20	120	100
Position 3	100	20	120	95
Position 2	100	25	125	115
Position 1	100	10	110	110

Aircraft Total Build Days and Total Hours

Carry-forward work leads to overruns of target total build days and target total hours. The target total build days is equal to N (the number of positions) times the takt time. In the examples given previously, there were six positions with a takt time of six days for target total build days of 36. To meet this target, the line must roll every six days. In reality, the line rolls when the first aircraft is completed. When there is carry-forward work, it often takes longer than the takt time to finish all the installations. The aircraft may roll a day or two later than scheduled, increasing the length of the takt. This increase affects all the aircraft in the line because rarely do associates fall back and start working on the next aircraft. In fact, the presence of carry-forward work assures that the back positions are behind as well.

The target total hours is the FAFO transfer cost (see Figures 7 and 8). If the target build days are being exceeded, the target total hours will also be exceeded. This follows from having a constant number of direct labor employees on the line. If target build days are exceeded by one day, there is a extra 8 hours for each associate that needs to be allocated somewhere. Management exerts substantial pressure not to charge indirect time (overhead) when not absolutely essential, so these extra hours will end up on the aircraft. There are also other reasons for the target total hours to be exceeded, but most of them relate to challenges already discussed. For example, part shortages sometimes cause employees to perform workarounds to keep busy. When the part is available, a portion of the workaround installation is actually removed or uninstalled, the late part installed, and the workaround installation done again. Since the same work is being performed more than once, the aircraft hours will exceed the target. Another case of work being performed more than once occurs when there is a discrepancy that has to be reworked. For example, if a wire is nicked and has to be replaced, the installation of that wire will essentially be performed twice, taking (at least) twice the amount of time and exceeding the target hours for the installation.

3.2 Critical Path Analysis Motivation

To combat these challenges, there are twice daily site-level and program-level production meetings. The site-level meetings are held via teleconference with Stratford and the other SMS site. These meetings are mainly status updates with the Vice President of Operations, and the site director, operations mangers, line managers, and relevant support staff attend. Program-level meetings are run by the operations manager and attended by the line managers, supervisors, and relevant support staff. These meetings are in-depth status updates as well as an opportunity for the operations manager to pass down messages to his production staff. Both sets of meetings are used more to fight fires on a daily basis than to move toward a smoother mode of operation.

There is a great need for tools to aid in attacking the challenges described. A critical path analysis would highlight where efforts should be made to achieve the greatest benefit. Instead of trying to improve performance on every AOS, knowledge of the critical path will help management focus on the AOSs that determine the overall build duration. In addition, the critical path analysis will illustrate a feasible schedule and provide useful information to supervisors. Currently, many of the supervisors are unfamiliar with the aircraft build and do not understand the interdependencies among AOSs. Since the critical path analysis will record this information, which in the past has been tribal knowledge, supervisors will be able to manage the build more effectively.

* * *

This chapter has described some of the challenges that the FAFO facility faces, particularly related to parts, workforce, and scheduling. These challenges lead to carry-forward work which results in difficulty achieving targeted total aircraft hours and total build days.

4. Literature Review of Critical Path Method

This chapter provides an introduction to the Critical Path Method (CPM) and reviews the literature related to it. Section 4.1 details the history and development of CPM for project management. Section 4.2 explains the methodology of CPM. Section 4.3 discusses some common applications of CPM.

4.1 History and Development

James E. Kelley, Jr. of Remington Rand UNIVAC and Morgan R. Walker of DuPont introduced CPM in their submission to the 1959 Eastern Joint Computer Conference, "Critical-Path Planning and Scheduling" (Weaver, 2007). They had been tasked with developing a computer-oriented system for managing large and complex projects. CPM was the resulting tool which could plan and schedule a large project with many interdependencies. The method took into consideration such factors as task predecessors, duration, cost, and resources. CPM had been developed over the preceding couple of years and had been tested on a few DuPont projects. The results were impressive; for example, the required downtime in a plant maintenance schedule was reduced by over 25% by improving performance along the critical path (Levy et al, 1963).

4.2 Methodology

CPM is most easily conveyed through a visual diagram of project tasks. As introduced by Kelley and Walker, activities are depicted by arrows from node to node, and nodes are events or points in time at which all activities leading to that node had been completed (Kelley, Jr. and Walker, 1959). The activity-on-arrow depiction has a few drawbacks, the discussion of which are beyond the scope of this paper. Levy et al describe another depiction method, activity-on-node (Levy et al, 1963). This method depicts activities as nodes and the interdependencies between activities as arrows. All nodes with no predecessors are linked to a Start node, and all nodes with no successors are linked to an End node. On the following page, Figure 10 presents an example of a project graph using the activity-on-node representation. The letter labels represent activity identifiers, and the numbers represent activity time requirements or durations.

The critical path of a system such as the one in Figure 10 is the longest duration path through the system. The duration of this path determines the overall duration of the project. Delays along the critical path will delay the project. Delays to activities on non-critical paths will only delay the project if the delay duration is large enough to shift the critical path. For example, in Figure 10, there are three paths:

- Path 1: Start → A → B → C → H → End; Duration = 24

- Path 2: Start → A → B → D → H → End; Duration = 26
- Path 3: Start → E → F → G → H → End; Duration = 27

Since Path 3 has the longest duration, it is the critical path and is highlighted in red. If any of the activities on Path 3 (E, F, G, or H) are delayed, the project will be delayed. Now consider two additional cases:

1) Activity A is delayed by time 0.5.
2) Activity A is delayed by time 2.

In case 1, the length of Path 1 becomes 24.5, and the length of Path 2 becomes 26.5. Path 3 is still the critical path, so the delay of activity A has had no effect on the duration of the project. In case 2, the length of Path a becomes 26, and the length of Path 2 becomes 28. The critical path has shifted, and now Path 2 is the critical path. The delay of activity A has delayed the entire project.

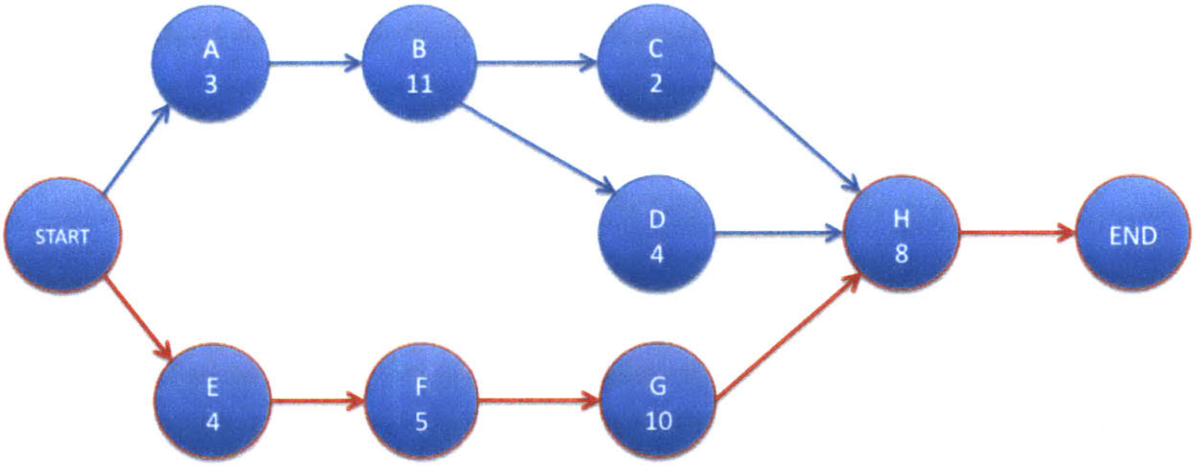

Figure 10. Sample CPM Project Graph

The critical path algorithm does not just determine the critical path, it also schedules the activities. As this thesis does not rely heavily upon the scheduling aspect of the algorithm, it will not be discussed here. Explanations of the algorithm can be found in a variety of sources (Kelley, Jr. and Walker, 1959; Kelley, Jr., 1961; Levy et al, 1963).

4.3 Applications

Even at the time of the introduction of CPM, it was identified as a method having many possible applications. Kelley, Jr. and Walker discuss the use of CPM for construction and maintenance of chemical plants and suggest its use in construction and maintenance of civil engineering projects, retooling programs for high volume production plants, and government contractor management (Kelley, Jr. and Walker, 1959). The applications that Kelley, Jr. and Walker suggest are all unique, single-occurrence projects. Levy et al note that its use can extend beyond this type of project management to manufacturing applications, as well (Levy et al, 1963). Others have also suggested the extension of CPM to manufacturing (Gupta, 1991) and discussed its application (Song et al, 2001; Suri, 2010), but extensive literature on this subject is difficult to find. The author's personal anecdotal evidence suggests there are manufacturing companies, specifically aerospace manufacturers, that have successfully used critical path analysis to improve operations. Results of these applications are not public knowledge due to the proprietary nature of the information and the desire to keep sources of competitive advantage in-house.

* * *

The Critical Path Method was originally developed in the late 1950s as a project management tool and has been widely applied as such. In addition to scheduling tasks, the methodology identifies a critical path, the duration of which determines the overall duration of the project. Improvement to critical path tasks will improve the project length (at least, until the critical path shifts). Applications to manufacturing are appropriate but extensive literature is not readily available on this subject. It is the purpose of this thesis to provide an additional example of the application of CPM to manufacturing.

5. Critical Path Analysis

Chapter 5 delves into the critical path analysis of one production line at the FAFO facility. There are three key elements of the critical path analysis: predecessor relationships, duration data, and resource allocation. Section 5.1 introduces the methodology for creating the database of installations and collecting the predecessor information. Section 5.2 discusses the actual and target duration data and explains which was used for the analysis. Section 5.3 discusses the allocation of resources and its effects on the analysis. Section 5.4 presents the results of the critical path analysis. Note that DCMA processes (see Section 2.3) were not considered for this analysis.

5.1 Predecessor Relationships

It was necessary to completely document every predecessor relationship for each installation. To compile the predecessor relationships for the hundreds of installations in the aircraft build, the following procedure was implemented:

1. Decompose aircraft build
2. Interview key personnel
3. Group installations
4. Map aircraft build
5. Create database
6. Incorporate QA processes

This procedure is detailed fully in the following subsections. In reality, steps two through five were first completed for the AOSs in the last position and then iterated until all the positions were covered. After the whole database was built, the QA processes were incorporated.

The system was modeled with all predecessor relationships being finish-to-start. This means that a subsequent task could not be started until all of its predecessors were completed.

Decompose Aircraft Build

Decomposing the aircraft build into smaller segments allowed the project to become more manageable. First, the aircraft build was decomposed by position, by skill or specialty required, and by shift. A summary of the aircraft build decomposition is presented in Table 4. As mentioned in section 2.4, the AOSs are assigned by position. For example, Mechanical Installs A, B, and C are scheduled to be completed in Position 6 (using the aforementioned theoretical build schedule). Every AOS can also be classified by skill or specialty required to perform the installation. The specialties are mechanics, electricians, plumbers (hydraulics specialist), electrical check-out technicians, and riggers. Electrical check-out technicians perform the ATPs to verify proper functioning of the aircraft systems. Riggers perform the "rigging" of the aircraft. This involves calibration and checking of all the flight control systems.

Table 4. Decomposition of Aircraft Build by Skill and by Shift (based on target hours)

	% of Total Build
Mechanical	29%
Electrical	40%
Hydraulic	7%
Electrical Check-out	10%
Rig	4%
Shakes	10%
Total	100%

	% of Total Build
1st Shift	45%
2nd Shift	35%
1st or 2nd Shift	17%
3rd Shift	3%
Total	100%

Every AOS is also assigned to a shift. These assignments detail a scope or statement of work (SOW) for each position on each shift. Often, common sense has led to the shift assignments. For example, one team of first shift electricians installs wiring in the tubs (belly) of the aircraft. Another team installs wiring on the top deck of the aircraft. These teams can perform their work on the same shift, in the same position because they are working in different areas of the aircraft. The overhead wiring is installed by a team on second shift. Since the tub wiring and the overhead wiring both are in the cabin, there would not be enough room for the two teams to perform these installations at the same time (on the same shift). In this specific case, to work in the tubs, the temporary floors are removed, and the electricians lie on their stomachs. To work in the overheads, however, the temporary floors must be installed, and the electricians sit on stools and reach up into the overhead area. It is obvious that the tub wiring and overhead wiring must be completed on different shifts.

In other cases, an AOS can be performed on either shift but has traditionally been completed on one specific shift. In this way, employees on that particular shift have developed experience with the AOS. Transferring the AOS to another shift would temporarily decrease performance due to unfamiliarity with the AOS. Occasionally, employees do transfer among shifts, and their assigned AOSs could, in these cases, transfer with them. Finally, there are some AOSs which are performed on either first or second shift depending on availability or performed on both shifts. These include all rigging operations, some mechanical installs at the front of the line, and the final assembly and hangar shakes.

Interview Key Personnel

Once the build was decomposed, many interviews were conducted with supervisors, leads, and associates. These interviews aimed to collect information about the order in which AOSs had to be performed. Until this point, that information was mostly tribal knowledge. The assignment of AOSs to positions implies some predecessor relationships, but the true predecessor relationships cannot easily be deduced from this information. For example, take the Armored Wing Installs. The armored wings are sliding shields that protect the pilots from enemy fire. Assume they are installed in Position 6. Is that because these installations need to be done before any of the work in Position 5 is performed? Or were these AOSs thus assigned to balance the number of associates working in each position? It turns out that the Armored Wing Installs do not need to be performed this early in the build. In fact, if installed early in the build, the armored wings impede other installations.

Group Installations

After completing the interviews, it was possible to group installations together to reduce complexity in the system. Groups were created for two reasons. First, a group was created if the installations were related, performed by the same person or people, and created a chain of predecessor relationships. For example, the AOSs that install the wiring, shelves, and avionics in the aft transition section of the aircraft were grouped together as shown in Figure 11. (The aft transition area is the aft section of the transition area from the cabin to the tail cone.) The second reason to create groups was if installations were related, performed by the same person or people, and had the same predecessors and successors. In this case, the AOSs do not follow in a chain as in Figure 11. They are instead installations that could be performed in parallel with the exception that the same person usually completes all of them. For example, there are multiple cabin dome lights, and each has its own AOS. They have the same predecessor relationships (namely, that the overhead wiring and clamping is completed) and have no successors. Usually, one electrician completes all of these; thus, the AOSs could not be completed in parallel. Since the installations are related, they were grouped together as Cabin Dome Lights.

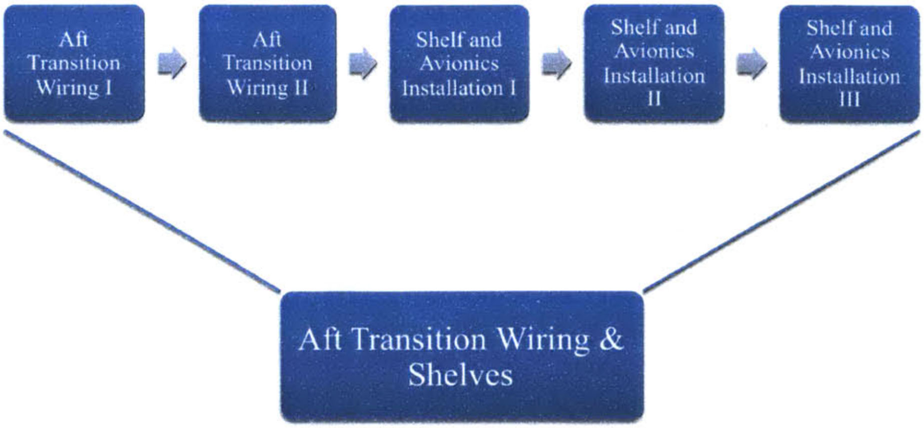

Figure 11. Grouping of Installations into Aft Transition Wiring & Shelves

Map Aircraft Build

Maps were created for each decomposition of the aircraft build to facilitate visualization of the network of interdependencies. For the initial positions in the production line (for example, Position 6), it was relatively easy to create these maps. At this stage, electrical installations are only dependent on other electrical installations, and there are many installations with no dependencies at all. Partial build maps are shown in Figure 12. As the build progresses, the interdependencies become more and more important. Mechanical, electrical, and hydraulic installations become intertwined, and partial build maps such as shown in Figure 12 fail to capture the real picture. Unfortunately, as the number of installations involved grows, an overall build map becomes too large and cumbersome to present in a useful format. Even when the database of installations was imported into Microsoft Project, the resulting diagram was too complex to properly present with available software support. Due to this effect, the effort to create a visual tool was not pursued.

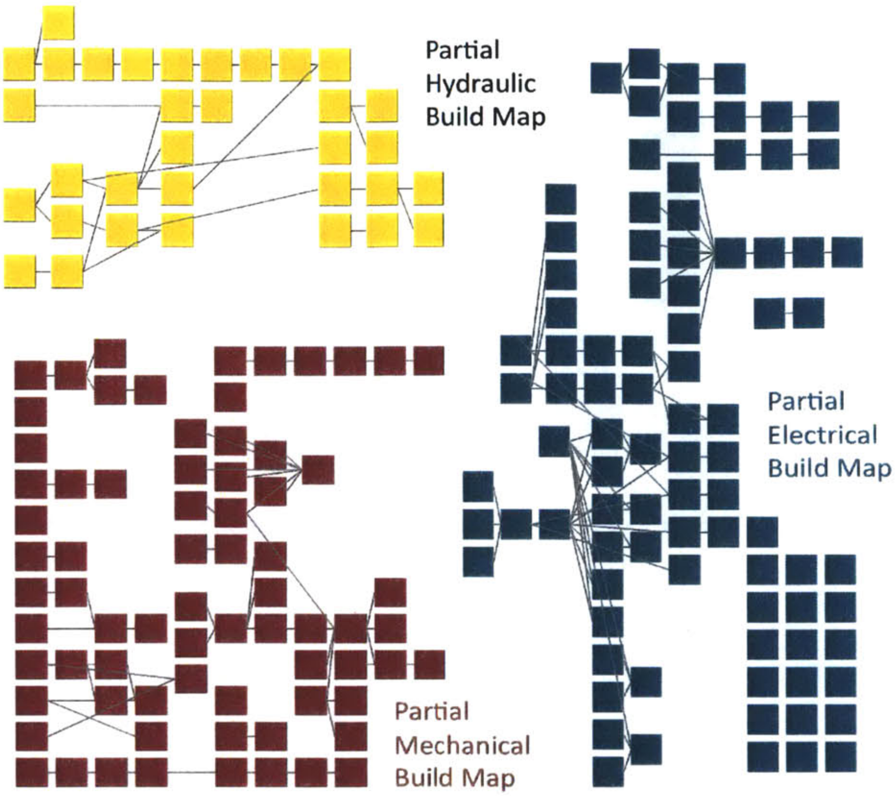

Figure 12. Hydraulic, Electrical, and Mechanical Partial Build Maps

Create Database

Table 5 shows a sample of the Excel database created with the predecessor information. Column descriptions are described as follows:

- **ID** – Unique number assigned to task or summary task
- +/- Identifies first- and second-level tasks (see accompanying description in text)
- **FAFO Pos.** – Position to which the AOS is assigned at FAFO
- **Position** – Position to which the AOS is assigned at Stratford and in internal computer system
- **Part No.** – AOS part number for Sikorsky internal computer system
- **Description** – Name of task or summary task
- **Skill** – Skill or specialty required to complete AOS
- **Shift** – Shift to which the AOS is assigned
- **Predecessors** – IDs of predecessors for that task or summary task

Table 5. Sample Database Entries

ID		FAFO Pos.	Position	Part No.	Description	Skill	Shift	Predecessors
241	+	FAFO x	x	70000-xxxxx-xxx	LH STRUT - ENGINE INSTL.	M	1	257,258
242	+	FAFO x	x	70000-xxxxx-xxx	RH STRUT - ENGINE INSTL.	M	1	257,258
243	+	FAFO x	x	70000-xxxxx-xxx	XMSN/RTR/BRK	M	2	229,82
244	+	FAFO x	x	70204-xxxxx-xxx	AFT FLOOR INSTL	M	1	56,60
245	+				Engine Drip Pan Fairings			4
246	-	FAFO x	x	70207-xxxxx-xxx	CARGO DOOR SEAL L/H	M	1	
247	-	FAFO x	x	70302-xxxxx-xxx	FAIRING INSTL	M	1	246
248	-	FAFO x	x	70207-xxxxx-xxx	CARGO DOOR SEAL R/H	M	1	247
249	-	FAFO x	x	70302-xxxxx-xxx	FAIRING ENG INLET	M	1	248
250	+	FAFO x	x	70212-xxxxx-xxx	BEAM INSTL	M	2	251
251	+	FAFO x	x	70219-xxxxx-xxx	OIL COOLER SPT	M	1	
252	+	FAFO x	x	70219-xxxxx-xxx	FAIRING & DUCT INSTL	M	2	272
253	+				Brackets - Oil Cooler Support			251
254	-	FAFO x	x	70221-xxxxx-xxx	BRACKET ASSY	M	2	
255	-	FAFO x	x	70221-xxxxx-xxx	INSTALL, BRACKET	M	2	254
256	+	FAFO x	x	70232-xxxxx-xxx	LOUVER INSTL	E	2	
257	+	FAFO x	x	70301-xxxxx-xxx	CONTROL INST (L.D.S. Cables)	M	1	
258	+				Shield Installs			243
259	-	FAFO x	x	70302-xxxxx-xxx	SHIELD INSTL.	M	2	
260	-	FAFO x	x	70302-xxxxx-xxx	SHIELD INSTL	M	2	259
261	+	FAFO x	x	70303-xxxxx-xxx	MOUNT INSTL	M	1	
262	+	FAFO x	x	70303-xxxxx-xxx	SUNDSTRAND APU	M	1	261,272,335,438
263	+	FAFO x	x	70303-xxxxx-xxx	APU INSTL-HYD	H	2	262
264	+				ESSS Lines Install			21
265	-	FAFO x	x	70307-xxxxx-xxx	LINES INSTALL INSTL A	H	2	
266	-	FAFO x	x	70307-xxxxx-xxx	LINES INSTALL INSTL B	H	2	265
267	-	FAFO x	x	70307-xxxxx-xxx	LINES INSTALL INSTL C	H	2	266
268	+				Fire Ext & Lines			22
269	-	FAFO x	x	70310-xxxxx-xxx	FIRE EXT SYS	H	1	
270	-	FAFO x	x	70310-xxxxx-xxx	FIRE LINE INSTL	H	1	269
271	+	FAFO x	x	70350-xxxxx-xxx	DRIVE SHAFT INSTL (No. 3 - 6)	M	1	272,547
272	+	FAFO x	x	70350-xxxxx-xxx	OIL COOLER INSTL	M	1	178,241,242,268,251
273	+	FAFO x	x	70400-xxxxx-xxx	CONTROL INST (Fwd & Aft Bridge)	M	1	243

To further explain the database excerpt presented in Table 5, take Task 253, Brackets – Oil Cooler Support. This task is first-level task because it is denoted by a "+." (A first-level task either is a stand alone AOS or a summary task that groups together AOSs performed in an uninterrupted sequence.) It is also a summary task because it contains two sub-tasks, each denoted by a "-." Since Task 253 is a summary task, it does not correspond to an AOS; therefore, it does not have a FAFO Position, Position, Part Number, Skill, or Shift assigned to it. Task 253 does have a predecessor: Task 251 (Oil Cooler Support). This means that Task 251 must be completed before Task 253 can begin. The summary task has no duration; it is only a grouping mechanism to simplify the build by aggregating certain installations. When imported into Microsoft Project, the database can be collapsed such that only the first-level tasks are shown. The sub-tasks of Task 253 are performed in series, as can be determined from studying their predecessors. Task 254 precedes Task 255. Mechanics (denoted "M") on second shift perform both Tasks 254 and 255.

For a second example, take Task 243 in Table 5. This is the installation of the transmission (XMSN/RTR/BRK). It is a first-level task because it is denoted by a "+." It is not a summary task because it does not contain any sub-tasks. A second-shift mechanic performs the installation. It has two predecessors: Tasks 229 and 82.

The duration data was also included in this database; details on the collection and manipulation of that data is described in Section 5.2.

Incorporate QA Processes

Once the database was created and imported into Microsoft Project, the applicable quality processes were incorporated. This incorporation was delayed so that two different Project files could be analyzed: one without QA processes and one with QA processes. Currently, Sikorsky does not take the impact of QA processes into consideration when creating the build schedule. Only the manufacturing processes are considered. It was desirable to see if adding QA processes would provide additional insight.

As discussed in section 2.3, each AOS includes QA operations or processes. In the model created for this project, it is assumed that the QA processes stand alone and follow each AOS directly. As will be discussed in section 5.2, the manufacturing and QA duration data are gathered separately on the shop floor, supporting this assumption.

There are two types of relationships between QA processes and the installations themselves. The first is when there is a group of installations performed in series that form a link of predecessors. Here, the QA process is inserted after each AOS, and the QA process must be completed before the next AOS can begin. The second relationship occurs when one person performs a group of installations in a series that do not form a link of predecessors. The installations are performed in series only because the same person is responsible for all of them. Examples of both relationships are presented in Table 6 which shows the AOSs related to the installation of the catwalk fairings. Task 20 is a summary task with no predecessors, and it is comprised of Tasks 21 through 28. Tasks 21 and 22 are the installation of the left-hand fairing and the associated QA process. Task 21 is the predecessor of Task 22 because the installation must be completed before it can be inspected. Note, however, that Task 21 is also the predecessor of Task 23. Once Task 21 is completed, Task 23 can begin. Task 23 relates to the catwalk fairings on the right-hand side of the aircraft, thus work can begin before the left-hand side catwalk fairing is inspected. This is an example of the second relationship described. The remaining installations and QA processes (Tasks 23 through 28) are examples of the first relationship described. They form a predecessor chain, so Task 23 must be inspected (Task 24) before Task 25 can begin and so on.

Table 6. Sample Database Entries with QA Processes

ID		FAFO Pos.	Position	Part No.	Description	Skill	Shift	Predecessors
20	+				Catwalk Fairings			
21	-	FAFO x	x	70217-xxxxx-xxx	L/H FAIRING INST	M	1	
22					QA - L/H Fairing Inst			21
23	-	FAFO x	x	70217-xxxxx-xxx	FAIRING GROUNDING INSTL	M	1	21
24					QA - Fairing Grounding Instl			23
25	-	FAFO x	x	70217-xxxxx-xxx	FRG INSTL,RH STA 308-353	M	1	24
26					QA - Frg Instl, RH STA 308-353			25
27	-	FAFO x	x	70217-xxxxx-xxx	COVER INST	M	1	26
28					QA - Cover Inst			27

Note that inserting QA processes will change the unique IDs of each task. Microsoft Project will automatically update the predecessors to keep the appropriate links intact. This is another reason that the QA processes were added after the database was imported into Project.

5.2 Duration Data

The next set of data needed to perform a critical path analysis is the duration data. These data were not difficult to acquire, but it was difficult deciding which data to use. Sikorsky records and stores the actual manufacturing time it takes to complete each installation. As mentioned in section 3.1, there are also target manufacturing hours for each AOS. After collecting both sets of data (actual and target hours), it was decided to perform the critical path analysis with the target data. Reasons for this will be explained in the following subsections. For QA, the actual data is also recorded and stored, but there are no QA targets. Equivalent QA target hours were calculated based on the actual data. The process is described in the following subsections.

Target Manufacturing Data

The target hours for each AOS were compiled. The standard, or Stratford, target hours were used in this compilation. Due to complaints that had been voiced about the appropriateness of some of the targets, supervisors and leads were asked to provide their input. Each supervisor and lead was given a list of the AOSs assigned to his position and the associated target hours. Each was invited to "correct" the target hours as he saw fit based on his experience. Was the target achievable? Was it too low? Or was the target too high? Did it provide more time than was necessary to complete the AOS? The supervisors and leads were instructed not to review the actual data but instead to rely on their sense of the process. This activity provided some useful insight. Despite general complaints about the targets, the supervisors and leads validated most of the targets. A few of the targets were increased, but a few of the targets were lowered. Also, recall that the standard hours, not the adjusted FAFO hours, were used.

Actual Manufacturing Data

The actual manufacturing data for every AOS was extracted from Sikorsky's internal production management tool and compiled for 14 previous aircraft. Means were calculated for each AOS, and at first glance, these seemed to be the appropriate data to use. Upon closer investigation, significant variability was present in the data (see Figure 13). Table 7 presents a sample of the data with the mean, standard deviation, and coefficient of variation calculated. The first AOS shown in this table has actual duration values ranging from 0.10 hour to 8.60 hours. While some variation from aircraft to aircraft was expected, the observed levels of variation were concerning.

Variations in actual manufacturing duration data for a single AOS have four possible causes. First, different people with varying proficiency levels may have performed the installation on different aircraft. Second, manufacturing engineers may have changed some of the operations in the AOS; however, major changes would most likely necessitate the creation of a new AOS. Third, the number of discrepancies created, reworks required, and removals performed for a specific AOS varies from aircraft to aircraft. Finally, it is possible that the installer logged his time incorrectly. The first three reasons are not sufficient to cause levels of variation such as those shown in Table 7. Incorrectly laboring ("mislaboring") also plays a significant role.

Mislaboring has a few causes. First, it is possible that the employee forgot to labor off an AOS before moving to the next one. The added pressure from trying to catch up with the schedule might increase the likelihood of this reason. The root cause behind forgetting is that correctly logging labor hours has not been sufficiently stressed to employees. It is not part of the culture. The second reason for mislaboring also stems from a weak laboring culture. There is constant pressure on employees not to charge their time as indirect (i.e. to overhead) to avoid going over the indirect budget. Although management does support charging indirect when it is warranted, the message is not communicated clearly enough. Employees hear, "Don't charge indirect," and think they need to hide hours on the aircraft when doing things like training, cleaning the work area, and moving the helicopters. A third reason for mislaboring was described in section 3.1: employees are working multiple AOSs at the same time. When the employee goes to clock his time, the system assigns all of his time to the first AOS he inputs. He waits a few minutes and then labors off another AOS, resulting in actual manufacturing time of 0.1 hr, for example. Mislaboring also occurs when an employee is just trying to hide his hours. He may be working slower than he is capable, he may be charging time to another shift's AOS, or he may be charging time to the top collector. (The top collector is the overarching AOS for a position. It is a catch-all for many operations and tends to rack up hours quickly. It is hard to determine if someone is legitimately working a top collector operation or not due to many reworks charged there.)

Due to the lack of confidence in the actual manufacturing data's integrity, the target manufacturing data was used for the critical path analysis.

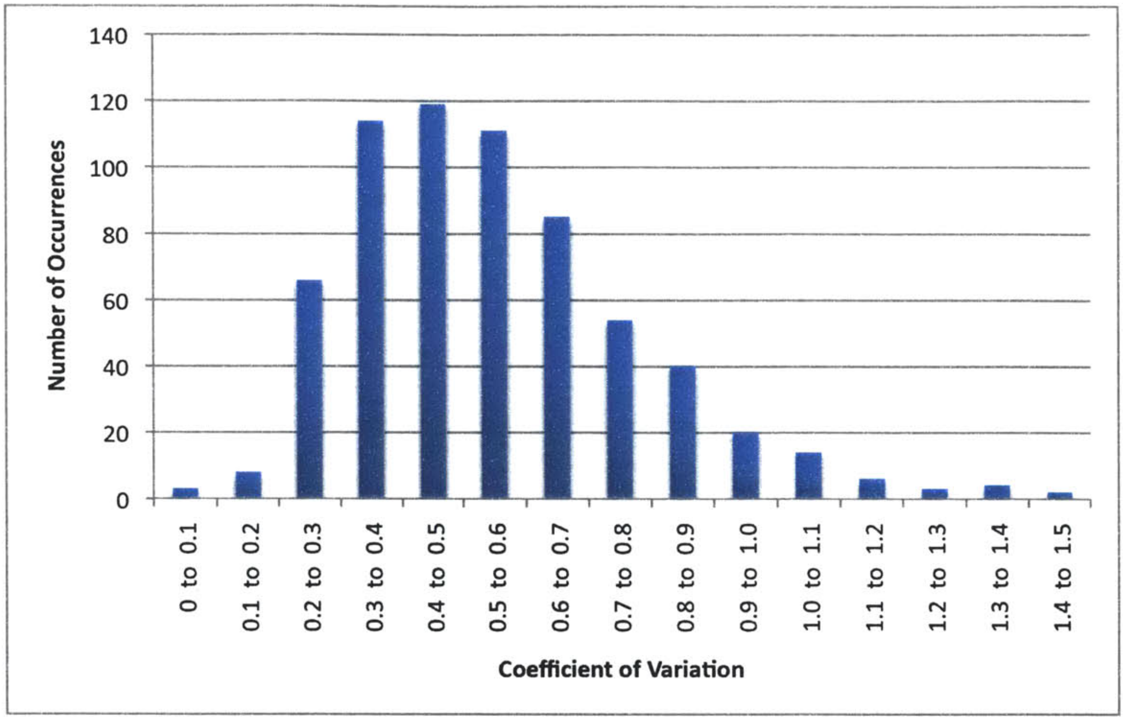

Figure 13. Distribution of Coefficients of Variation for Actual Manufacturing Duration Data

Table 7. Sample Actual Manufacturing Duration Data

Part Number	AC 1	AC 2	AC 3	AC 4	AC 5	AC 6	AC 7	AC 8	AC 9	AC 10	AC 11	AC 12	AC 13	AC 14	Mean	Standard Deviation	Coeff of Variation
70550-xxxxx-xxx	1.12	0.77	0.10	1.07	1.22	7.77	0.72	0.30	4.43	8.60	1.05	4.96	1.73	3.45	2.66	2.78	1.04
70212-xxxxx-xxx	5.28	4.36	2.70	10.14	20.41	31.64	6.89	2.71	2.62	6.69	19.04	5.70	7.88	4.72	9.34	8.50	0.91
70600-xxxxx-xxx	2.23	2.18	2.86	4.83	4.86	2.10	3.15	3.28	20.38	2.90	0.10	2.84	1.20	4.22	4.08	4.87	1.19
70550-xxxxx-xxx	9.43	2.83	2.24	5.17	3.95	24.94	3.62	7.87	2.37	14.43	3.22	4.45	4.35	0.80	6.41	6.39	1.00

QA Data

As with the manufacturing data, the actual QA data was easily extracted and compiled. Upon examination, these data also contained high levels of variability. Unfortunately, no target QA durations exist on the individual AOS level. There is a target for the total QA hours on an aircraft; it is around 20%

of the aircraft transfer cost. A straightforward way to estimate target QA durations would be to apply this percentage to every AOS' target manufacturing duration. In reality, the amount of QA time needed per AOS varies. For example, an AOS which logs wire harness serial numbers into a database will have relatively fewer QA processes than an AOS which defines some critical characteristics of the aircraft. To better represent reality, a ratio of actual duration averages was taken (actual average QA duration/actual average manufacturing duration) and then multiplied by the target manufacturing duration to give an equivalent target QA duration for each AOS. Two example calculations are presented in Table 8. Table 8 also illustrates the range of actual QA to Mfg duration ratios.

Table 8. Calculation Example of Equivalent Target QA Duration

AOS Description	Mfg Avg (hr)	QA Avg (hr)	QA/Mfg	Mfg Target (hr)	Equiv QA Target (hr)
W/I PHBK TRANS RH	82.3	9.60	11.7%	59.0	6.88
BROMCLST FLT CONT RODS	19.7	10.62	54.0%	16.0	8.64
Total	101.9	20.22	19.8%	--	--

5.3 Resource Allocation

To correctly schedule tasks performed by the same person, it was necessary to allocate resources in Microsoft Project. One method of resource allocation would be to identify each resource's capabilities and allocate accordingly. This would require cataloguing which installations each of hundreds of workers can perform. This method also ignores potential flexibility achieved through cross-training. It was determined that more insight could be achieved by following a second method of resource allocation.

In the second method, resource pools were created and assigned to installations. The following might be some of the resource pools utilized in a six-position build:

- Position 6 Mechanics, 1st shift
- Position 6 Mechanics, 2nd shift
- Position 6 Electricians, 1st shift
- Position 6 Electricians, 2nd shift
- Position 6 Plumbers, 1st shift
- Position 6 Plumbers, 2nd shift

Since the installations were already categorized by position, skill, and shift, it was straightforward to assign the appropriate resource pools to the installations. To determine the size of each resource pool, some software experimentation and back-of-the-envelope calculations were performed. Microsoft Project contains a workload balancing tool which introduces delays on non-critical paths in order to balance work across a resource pool. For example, instead of needing 5 mechanics on Day 1 and 1 mechanic on Day 2, the program would try to balance the workload by delaying some of the tasks from Day 1, if possible. Ideally, this would result in 3 mechanics needed both on Day 1 and on Day 2. Note the workload balancing algorithm becomes more complicated when Day 2 tasks depend on Day 1 tasks.

5.4 Results

The results of the critical path analysis included the identification of a critical path for each of the build positions, allowing key observations to be made regarding the final assembly process. In some positions, the theoretical critical path was also observed as causing delays in the build process. In other positions, the theoretical critical path was not causing delays in the build process; the duration of other paths had been lengthened due to poor performance to target AOS hours. For example, a position near the beginning of the build had a critical path comprised of the chain of overhead wiring installations. In reality, due to the abundance of electricians and their effective management of the tasks, this path did not cause delays in practice. The poor performance of the plumbers caused the observed delays at this position. The value from the theoretical critical path in this example is that it highlights the excellent performance of the electricians and emphasizes just how much the plumbers' performance is hurting the build process.

Another key observation involves the riggers. After balancing resources, the appropriate number of two-person rigging teams was calculated. The number of teams that are needed to complete the work on schedule is the same as the number of teams currently working on this production line. Generally, rigging has not been the cause of delays to the build process, and the critical path analysis validates those results.

Additional general observations were made during the critical path analysis process. First, there were quite a few AOSs out of sequence. This means some AOSs were assigned to positions that preceded a position containing some of their predecessors. For example, say Hydraulic Install A was a predecessor to Electrical Install A. In some cases it was found that Hydraulic Install A would be assigned to position 3, but Electrical Install A would be assigned to position 4. Thus it was impossible to complete Electrical Install A in position 4 because not all of its predecessors were complete. Electrical Install A could not be completed until position 3. In order for the software to correctly model the critical path of each position, there could be no out-of-sequence tasks. Some tasks were reassigned to later positions to overcome this problem. For example, in the case presented above, Electrical Install A would be reassigned to position 3. In practice, this AOS would not be completed until position 3 anyway because it would have to wait until all predecessor tasks were completed.

The second observation centered around the imbalance of the work. In most positions, there was an obvious critical path because one path was significantly longer in duration than the others. Unfortunately, this creates an imbalance in the work. When the other paths have been completed but the critical path work is still in process, there are many idle resources. Unfortunately, since these resources are people, their time must be counted toward an aircraft build or toward indirect overhead. Even if they do not have tasks to perform, these employees must still be paid. The company sees this as inflated AOS and aircraft build hours or as over-budget overhead.

A final observation came from comparisons between the critical paths without QA processes and with QA processes. The inclusion of QA processes did not alter the position critical paths, but it did increase the critical path lengths by over 35%, on average. This is a significant increase in path duration and extends the position critical paths beyond the target takt time. Inclusion of QA processes is not an optional part of the build; the QA processes included are a required part of the aircraft build. In the current planning and scheduling methodology, QA processes are ignored. Without modeling and accounting for the entire build process, including QA, it is impossible to create a schedule that can be achieved.

* * *

This chapter described the approach used for the critical path analysis as well as its results. The approach consisted of documenting the predecessor relationships, compiling the duration data, and appropriately allocating resources to the tasks. The results of the analysis indicate that the current build schedule is not optimized and should be revisited with these results in mind.

6. Conclusions and Recommendations

Chapter 6 concludes this report with conclusions and recommendations based on the critical path analysis and observations made during the internship. Section 6.1 draws conclusions based on the results presented in chapter 5. Section 6.2 make managerial recommendations based on six months of observations of the FAFO operations. Section 6.3 suggests some opportunities for further study.

6.1 Critical Path Analysis Conclusions

Three conclusions can be drawn from the results of the critical path analysis. All three were alluded to in section 5.4. First, AOSs need to be reassigned to positions keeping predecessor relationships in mind. As discussed in section 2.4, the assignment of AOSs to positions was based on past industrial engineering studies. From time to time, AOSs were reassigned to new positions to target improved performance. Despite attempts to optimize the build process through assignment of AOSs to the appropriate positions, the lack of a thorough understanding of the predecessor relationships prohibits true optimization. With out-of-sequence AOSs, it is impossible for the build to proceed as scheduled. Some installations will be necessarily delayed while predecessor installations are completed. Continuing with this work schedule sets the team up for failure. In addition, it becomes difficult to determine when the build is progressing appropriately and when there are delays since the schedule to which performance is being measured is not achievable. The assignment of AOSs to position must be revisited now that all predecessor relationships have been documented.

Second, QA processes must be included in work schedules. Creating a build schedule which ignores the QA function is another way to set up the team for failure. The inclusion of the QA processes significantly increases the critical path duration. As stated in section 5.4, these QA functions are absolutely essential to the build process, so it is unrealistic to overlook them in the planning process. Updated balance charts should be created that account for QA processes in their schedule. Creating these balance charts will allow the build process to be better understood and will allow improvements to be made.

In addition to correcting out-of-sequence work and including QA processes in schedules, assignment of all AOSs to positions should be reconsidered. As discussed in section 5.4, the build process remains unbalanced across different predecessor chains, leading to idle resources. Since these resources are people, their idle hours increase AOS and aircraft hours or eat into the overhead budget. The system must be balanced to maximize resource utilization.

6.2 Managerial Recommendations

Based on six months of observations of FAFO operations, four general managerial recommendations can be made:

- Introduce a labor-on clock system
- Automate daily IE reports and align IE interests with facility performance
- Hold status meetings on the shop floor
- Increase supervisor engagement

As discussed in section 5.2, there are many reasons for the mislaboring that was observed. After discussions with various stakeholders, it is recommended to introduce a labor-on clock system to track labor hours. Currently, Sikorsky uses a labor-off clock system. Employees only enter work into the system once it is completed or when they switch tasks. For example, at the beginning of the day, Jesse scans his ID badge to report to work. He then proceeds to work on an installation. When he has completed his work on that installation for the present, he "labors off" the installation. Up until this point, there was no record of which installation Jesse was working on. Close observation of Jesse's work during this period is the only way a supervisor could tell what he was doing. There is no real-time monitoring capability in the software as it is currently utilized. Consequently, corrections to labor charges cannot be made until the following day. A labor-on clock system would allow for real-time monitoring of employee performance. It would also create a better mental model for employees to follow. Instead of falling into some of the mislaboring traps discussed in section 5.2, the employees would more clearly understand that each segment of time must correspond to work performed on only one installation. Most importantly, a labor-on clock system and strong emphasis on good laboring practices would improve the data quality of actual manufacturing and QA hours. Improved data quality would allow management to make better informed decisions and become more data-driven.

There is insufficient IE support at FAFO to drive process improvements. IE resources spend countless hours a day pulling data from the production database and manipulating these data in various Excel spreadsheets. These data are presented in an array of required reports. The reports are standardized across all sites and production lines. Unfortunately, very few of the reports are used at FAFO. The generation of these standard reports should be automated through investment in a software solution. Also, the reports should be stored on a server and accessed in an online format as opposed to complicating the system by having too many Excel files floating around. Instead of focusing on report generation, the IE resources should be focused on industrial engineering analysis of the build process and identification of improvement opportunities. Currently, this analysis falls on supervisors. Part of the problem here is the misalignment of incentives for IEs. They report to supervisors in Stratford and have performance metrics based on completion of daily standard reports. To effectively engage the IEs, the dotted-line reporting to facility management should be highlighted through a revised incentive structure. Part of IE performance reviews should be based on the performance of a specific production line or of the facility as a whole. Aligning incentives in this way will motivate IEs to demand automated standard reports and more time for process analysis and improvements.

To tackle daily production challenges, the operations manager holds daily production meetings with supervisors, line managers, and support staff. Currently, these meetings are held in a small conference room located off the main production line. The meetings are twice daily for thirty minutes to an hour. During the meetings, the floor is empty of all management supervision. In addition to the daily status meetings, there are other daily and weekly meetings with mandatory supervisor attendance. Removing supervisors from the floor for extended periods of time allows for lulls in production. Daily status meetings need to be held on the production floor to keep supervisors engaged with the workforce and aircraft build. FAFO should implement a "boardwalk" system, where the meeting moves from position to position to receive the status updates. In addition, status meetings are currently comprised of a report of the number of AOSs outstanding on each helicopter on the production line but do not include the performance of the line to a schedule. The structure of each supervisor's report must be updated to include information such as how many tasks were scheduled to be completed, which of those tasks were completed and which weren't, and for those that were not completed, what were the system constraints that prevented their completion.

Finally, supervisor engagement must be increased. Most supervisors do not feel directly responsible for the performance of the facility. Many supervisors are discontented with their positions and are searching for new jobs. Supervisors must be held accountable for the performance of their positions, but they also must be empowered to initiate change and improve the build process.

When aiming to improve operations, it is necessary to choose projects wisely and then sustain them until results can be observed. Currently, many small changes are introduced and then promptly forgotten. This behavior was observed countless times during the internship. When changes are introduced and not supported, enforced, or sustained, it sends the message to the employees that the changes are not critical or important to operations. This behavior also undermines faith in future changes. Management must identify select opportunities for improvement and then follow through with implementation and sustainment.

6.3 Future Opportunities

There are three opportunities for future work stemming from this project's results and the managerial recommendations noted above. First, the labor-on clock system, which should be implemented company-wide, could be piloted at FAFO. This would require a dedicated team to help with the transition from the current system to the new system. (It should be noted that the current software used for recording labor hours can be configured to support a labor-on system.) This project would need to be run for a sufficient length of time to allow for workers to become familiar with the system. Part of the project would involve emphasizing the value of properly laboring. Another facet would involve highlighting the value of improved data quality to the organization.

A second opportunity for future work lies in the detailed analysis of actual AOS manufacturing and QA hours. The critical path analysis based on target hours that was completed as part of this internship provides a solid base from which to probe the actual hours. Comparisons between the current and target states and between different facilities could be made. Related to this proposed project is a third opportunity which involves the decomposition of the major electrical ATP AOS into multiple AOSs. Currently, the major electrical ATP AOS is comprised of many individual ATPs, each which take a few hours. There are predecessor relationships among these ATPs, and these relationships were documented as part of the critical path analysis. Because all of these ATPs are part of one AOS, the time spent on each ATP cannot be broken out. It is very difficult to monitor performance and improve the build process when the actual hours for four dozen ATPs are amassed into one AOS. The decomposition of the major electrical ATP AOS will aid in the detailed analysis of actual manufacturing and QA hours.

* * *

This chapter concludes the report by drawing conclusions from the analysis presented earlier. Sikorsky's FAFO facility has been under increasing pressure as aircraft deliveries grow and target aircraft hours and target build days decline. The facility has improved its performance when faced with these challenges, but many fires are still being put out on a daily basis. In order to move to higher levels of performance, the facility should take advantage of several improvement opportunities discussed in this report. When appropriately implemented and sustained, these opportunities should lead to a more controlled process overseen by proactive management.

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