OPTIMIZING THE ASSEMBLY SEQUENCE OF AN AEROSPACE MANUFACTURING PROCESS

by

James Aaron Wolters II

B.S., Aerospace Engineering, United States Naval Academy, 1988

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 Science in Management
and
Master of Science in Aeronautics and Astronautics

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Abstract

The 1990's were a time of downsizing and consolidation for much of the defense aerospace industry. Many defense contractors sought to integrate lean manufacturing principles and techniques into their business, as a means of becoming more cost-competitive in bidding for a shrinking defense budget, and to enable moves into commercial product lines. UTC-Sikorsky Aircraft Company began a series of restructuring and re-engineering initiatives in the late 1990's aimed at addressing these issues.

This internship focused on cost reduction in Sikorsky's main product line - the UH-60 Blackhawk helicopter. The final assembly line for the UH-60 was subject to cost and schedule overruns, along with high inventory levels. The assembly line was also characterized by a high degree of variability, and a major source of variability was believed to be the lack of a defined and repeatable sequence for the installations that comprise final assembly. The introduction of an optimized assembly sequence, and subsequent adoption for daily use by shop floor personnel, was expected to reduce variability and improve performance. The use of a sequence itself was expected to produce the following benefits:

1. Provide a significant improvement in the use of visual tools for line management.
2. Help capture valuable information about installations from workers, and then transfer this knowledge to management, planners, and new workers as personnel are rotated through the factory.
3. Enable significant inventory reduction through introduction of a just-in-time (JIT) material delivery methodology, by linking material delivery to the order in which it is consumed.

Implementation was expected to aid in identifying the shortcomings and limitations of the systems that have prevented the use of a sequencing methodology in the past. More importantly, it would elevate the importance of addressing and solving these issues as a means to achieve company-wide goals for cost and inventory reduction. Through implementation of this sequence, key issues were identified:

- JIT inventory levels are difficult to achieve in a large, complex aerospace assembly process,
- The manufacturing system, along with systems and processes which support it, must be capable of supporting JIT prior to implementation (and may need to be redesigned to do so), and
- Process re-engineering to support JIT is best accomplished through a combination of top-down and bottom-up change processes.

Thesis advisors: Stephen Graves, MIT Sloan School of Management
Deborah Nightingale, MIT Department of Aeronautics and Astronautics

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- Thank you to the following individuals for arranging site visits to their organizations as part of a benchmarking study conducted during the internship:
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Chapter 1: Introduction

Sikorsky Aircraft Corporation

Sikorsky Aircraft Corporation (hereafter referred to as Sikorsky), a United Technologies Company, employs about 7000 people in the production of medium and heavy lift helicopters for commercial and military markets. This thesis concentrates on final assembly operations for the UH-60 Blackhawk helicopter. The UH-60 Blackhawk is a medium-lift utility helicopter produced primarily for the U.S. Army, and is shown below. Over 2,400 have been delivered, and variants have been produced for both commercial and military applications in over twenty countries.

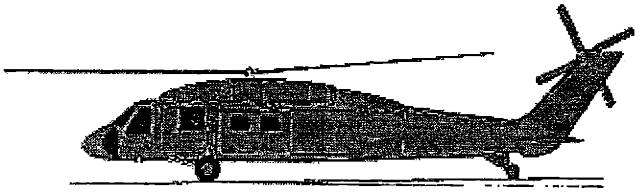


Figure 1
UH-60 BLACKHAWK HELICOPTER (U.S. ARMY VERSION)

Sikorsky exercises a high degree of control over the manufacturing process, by retaining most production capabilities and activities within the company. They produce the airframe, rotor blades, gearbox and other rotating components, wiring, and many other internal items; purchased components are generally limited to engines, avionics, and fuel and hydraulic system components.

Main Facility, Stratford CT

A general process flow for the UH-60 is shown in figure 2. Helicopter production begins with the build up of component sub-assemblies from a variety of make and buy parts. Most structural components for the UH-60 are built-up from sheet metal parts, using jigs and fixtures. As part of a company-wide restructuring effort, Sikorsky is consolidating these operations (previously dispersed around the local area) into their main facility. There, sub-assemblies are combined into larger components (tailcone, cabin, and cockpit) in Major Assembly. These major assemblies are joined together and then delivered to Final Assembly, where the various mechanical, electrical, and hydraulic component installations take place. Most of the value of the helicopter is added during final assembly, after which the helicopter is delivered to the hangar. The hangar completes a few remaining installations (e.g. rotor blades), routes the aircraft for painting, and then completes a series of ground and flight tests prior to acceptance by the customer.

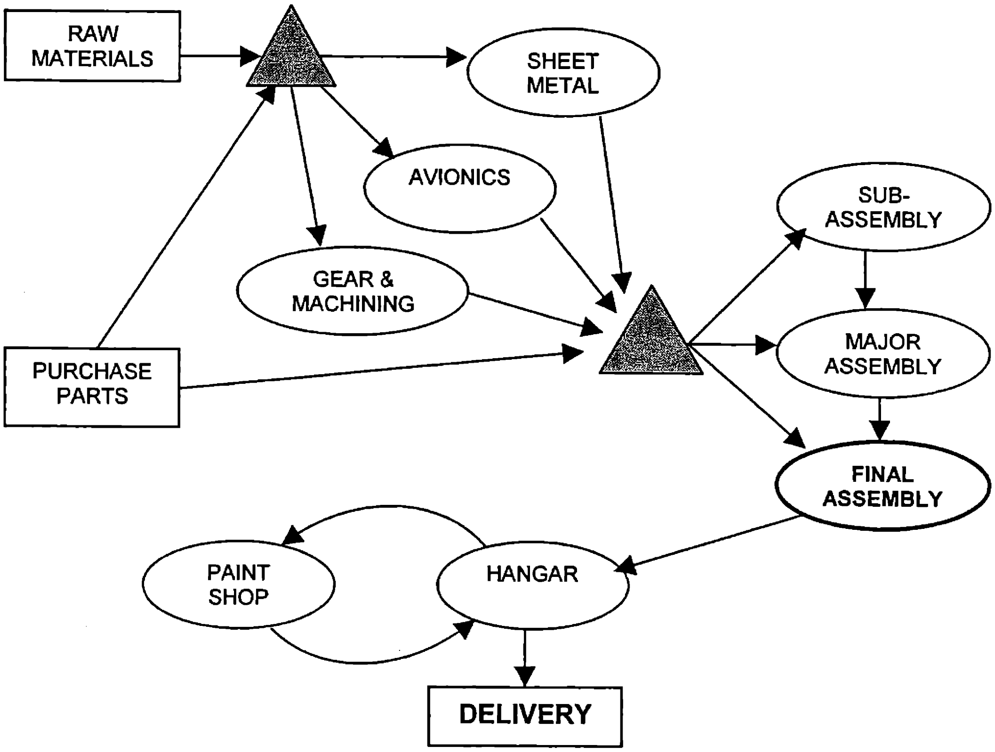


Figure 2
PROCESS FLOW CHART FOR SIKORSKY HELICOPTER PRODUCTION

UH-60 Blackhawk Final Assembly

There were three configurations of the UH-60 Blackhawk in production during the period of the internship: the baseline U.S. Army UH-60L, the S-70A foreign military export version, and the U.S. Navy CH-60 cargo helicopter. Final assembly employs about 60 workers (a mix of mechanical, electrical, and hydraulic technicians) in a three-shift, five-day workweek, with an approximate personnel split of 30/20/10 between shifts. There are about 400 individual installation operations (or jobs) in final assembly. A complete listing of UH-60 installations is provided in Appendix D (the term "installation" hereafter refers to one of these jobs, as opposed to the "act" of installation). Each installation has an AOS (Assembly Operation Sheet) which contains the work instructions, material requirements (both parts and tools), and drawings for the particular installation. Material for final assembly is received, kitted and stored by Production Control in the "crib" (inventory stocking location), and workers retrieve the kits when needed. The installations themselves usually take anywhere between 0.5 and 14 hours. Most operations take one person; a few take two or three. The S-70A and CH-60 aircraft are made up of a mix of baseline UH-60 (i.e. common) and derivative (i.e. unique) installations. These two aircraft take longer to produce than the baseline aircraft.

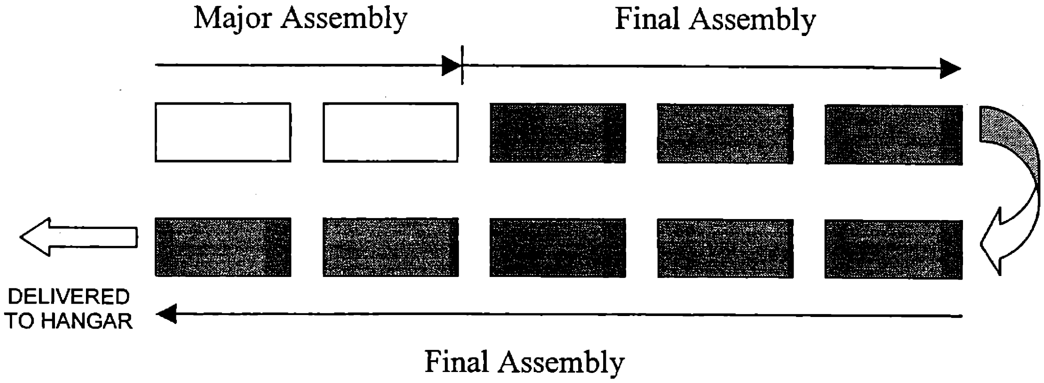


Figure 3
FLOOR LAYOUT OF EIGHT FINAL ASSEMBLY STATIONS FOR UH-60

A general floor layout for UH-60 final assembly is shown above in figure 3. Aircraft flow into final assembly after major assembly, get routed through final assembly as shown, and are then delivered to the hangar for completion. Assembly operations are driven by the Master Schedule (MPS), which sets a roll rate for the entire assembly line (major and final assembly, plus hangar operations). This roll rate corresponds to the number of manufacturing days (M-days) desired between deliveries; this rate fluctuated throughout the course of the internship. Ideally, all of the eight aircraft currently in production (WIP) at each of the eight final assembly stations shown above are rolled on dollies or landing gear to the next station in line at this interval. The roll rate and required delivery date for each aircraft are communicated to the foremen in assembly operations, who manage the day-to-day assignment of workers to jobs on each aircraft.

Thesis Organization

This chapter described the situation at Sikorsky, as it existed at the start of the internship. The remainder of the thesis is devoted to the issues that arose during the implementation of a company-sponsored improvement project. The following section details how the thesis is organized, and how it will show the approach taken and the results obtained during the internship.

Chapter 2: *The Manufacturing Environment* will describe the problems faced by final assembly operations, and how they relate to the manufacturing environment at Sikorsky. The issues involved with possible re-engineering options will be investigated, and the solution chosen by the company will be detailed along with the goals for the improvement effort.

Chapter 3: *Producing a defined build sequence for final assembly* will document the steps taken to develop a new method for scheduling operations in final assembly.

Chapter 4: *Implementing a defined build sequence* will describe the introduction and results of the new process in final assembly operations, including the integration of this approach with the inventory-reduction goals of a company "JIT" team.

Chapter 5: *Managing a complex aerospace assembly process* will explore the other functional areas, and other manufacturing processes, which impact the performance of final assembly operations. Specifically, those issues that aid or detract from the ability to implement precision assembly scheduling and Just-In-Time material delivery are addressed, as these areas were identified during the course of the pilot project.

Chapter 6: *Strategies for lean implementation* will explore the higher level issues involved with implementation of the JIT project. Examples from literature, case studies, and benchmarking results will be used to assess options for the company. Overall recommendations, based on these results, are presented to address the issues.

Chapter 2: The Manufacturing Environment

Production activities at Sikorsky were aligned into functional organizations. Figure 4 shows the general organization and relationships within manufacturing, as they existed during the time period of the internship:

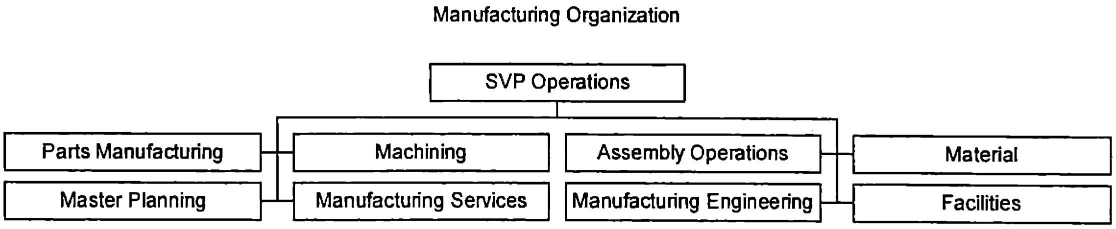


Figure 4
ORGANIZATIONS (VP LEVEL) REPORTING TO MANUFACTURING AT SIKORSKY

Current operations at Sikorsky

The 1990's were a time of downsizing and consolidation for much of the defense aerospace industry. After a decade of decline, total worldwide helicopter production (commercial and military) was forecasted to continue falling, from 913 units in 1999 to 821 units in 2001 [Aboulafia, Aviation Week & Space Technology, 1999]. At the same time, Sikorsky has been losing market share, dropping from 41% of total helicopter production in 1994 to 31% in 1997. Sikorsky is making changes throughout the company to deal with the new competitive environment. Some of the issues that they have to deal with during these changes are:

1. A cost-plus mentality and heavy overhead structure
2. Lack of cross-functional teams or mechanisms to implement change
3. Lower production compared to cold-war levels
4. A shrinking and aging workforce
5. Model proliferation (as additional versions are developed for new customers)

Manufacturing operations at Sikorsky were observed to have the following two over-arching priorities: meeting schedule and maintaining final product quality. Following through on these priorities over the years, however, has produced the following behavior:

1. Schedule
    - The company has a long history of meeting contract delivery dates.
    - However, they have accomplished this by maintaining:
        - High Raw Material (RM) inventory buffers,
        - High Work-in-process (WIP) inventory,
        - Heavy use of overtime for schedule recovery, and
        - Long flowtimes.

2. Quality
    - The company is devoted to producing safe, high-quality flight vehicles.
    - But again, they have accomplished this by maintaining:
        - Numerous inspection actions and lots of inspectors,
        - Resistance to change in either production process or product design,
        - Centralized processes to maintain control of standards, and
        - Lengthy processes for anything that involves engineering.

The combined effect of these factors has led to the Blackhawk's reputation and market position of a high-performance - but costly - aircraft. The following quotations, obtained from workers or foremen involved in final assembly operations, depict some of the frustrations experienced in manufacturing:

> *"We can't tell what is on shortage until we go to pull the kit cart. There needs to be some way to visualize existing shortages that impact us."*
>
> *"I spend a lot of time chasing parts. There is also a lot of rework done, and most of it is done at the end of the line, when everyone is in a big hurry."*
>
> *"My workers spend a lot of time doing things besides production: getting parts, filling out paperwork, attending meetings and training, etc."*
>
> *"There is a lot of variability in everything we do."*

The remainder of this chapter will focus on two separate efforts - by the manufacturing and material organizations - to improve operations at Sikorsky, and how these efforts were eventually combined into an attempt to introduce lean manufacturing techniques into assembly operations.

The first problem: excess Direct Labor charges in assembly operations

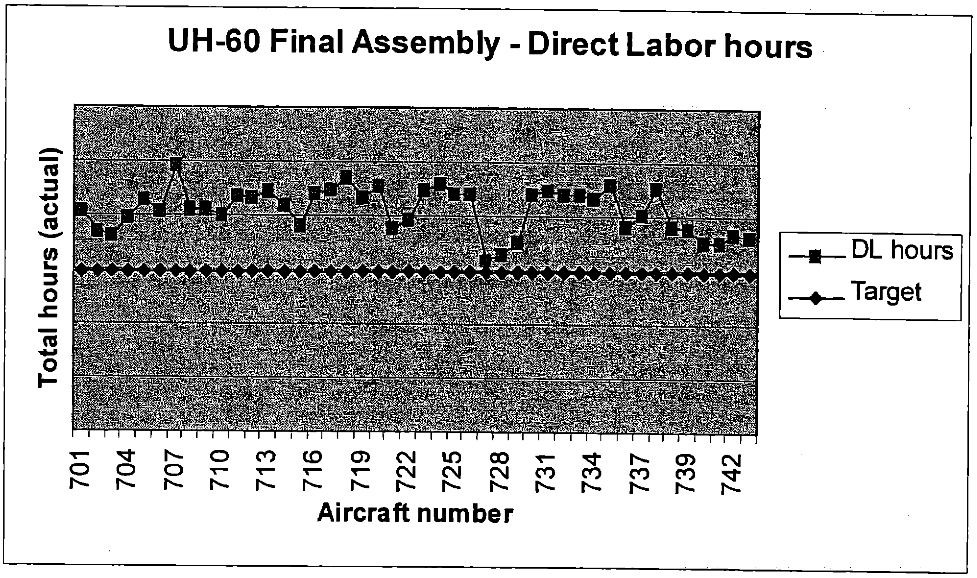


Figure 5
UH-60 FINAL ASSEMBLY DIRECT LABOR (DL) TREND - Q1 TO Q3 CY1999

As depicted in the figure above, there was significant aircraft-to-aircraft variability in the amount of direct labor charged in final assembly operations. In addition, each charge was significantly over the target value allotted to final assembly. As with many traditional manufacturing companies, Sikorsky allocated product cost into direct and indirect labor charges plus material. Manufacturing was intently focused on direct labor; its use as a performance metric was widespread, and it was used in most decisions regarding assembly operations. Considerable thought had been given to the origin of direct labor overruns and variability. The direct labor *trend* is very stable over time (that is, it has a stable mean and a consistently high variance, even if prior year data is included). The manufacturing process had "resisted" previous attempts to lower the amount of direct labor spent in final assembly. The steps taken by the company and reflected in this thesis represent another attempt on the part of management to address the problem.

Also absent from the direct labor trend shown above was any evidence of traditional "learning curve" effects. This last point is actually consistent with research and experience in the aerospace industry. Information available through "learning by doing" is difficult to generate at low production rates, and given the production environment is often "lost in complexity" [Von

Hippel and Tyre, 1993]. Additionally, even at higher rates with low worker turnover, the oft-quoted aerospace axiom of "every aircraft a snowflake" means that each aircraft is essentially unique and opportunities for learning are reduced.

Thus, the company sought to both reduce the variability and decrease the amount of direct labor charged in final assembly. The source of these problems was essentially unknown, but the company believed that worker performance in assembly operations was a primary factor, and sought to institute methods to improve the tracking and control of direct labor. Previously, all direct labor had been collected and tracked at the "unit" level; that is, all direct labor data were aggregated at the level of the eight final assembly stations shown previously. For a given aircraft, there was no way to know how much time any particular installation was charged.

Obviously, this would be useful data to have, in order to analyze each installation individually, noting which installations -- or which workers -- were consistently over the target. The method for capturing (and planned uses for) this data will be described below. The choice of this approach is not surprising, given the accepted wisdom that "what gets measured gets changed," but it was not clear that worker performance was a root cause in failure to meet direct labor targets. After the initial interviews with assembly workers, it was apparent that numerous other factors were at work to produce the behavior observed. One consistent comment was the large amount of out-of-sequence work done in final assembly operations. Every installation was allocated to one of the eight units in final assembly, but once the inevitable parts problems and shortages arose, the work "moved" forward and backward among the units. The problem was not that a 4-hour operation ended up having 6.5 hours of labor charged, but that it was finished significantly (sometimes days) later than it should have been. This failure to adhere to the critical path for assembly cascades through the entire process, as time lost on the critical path adds to flowtime, and the highly coupled nature of the installations causes further problems.

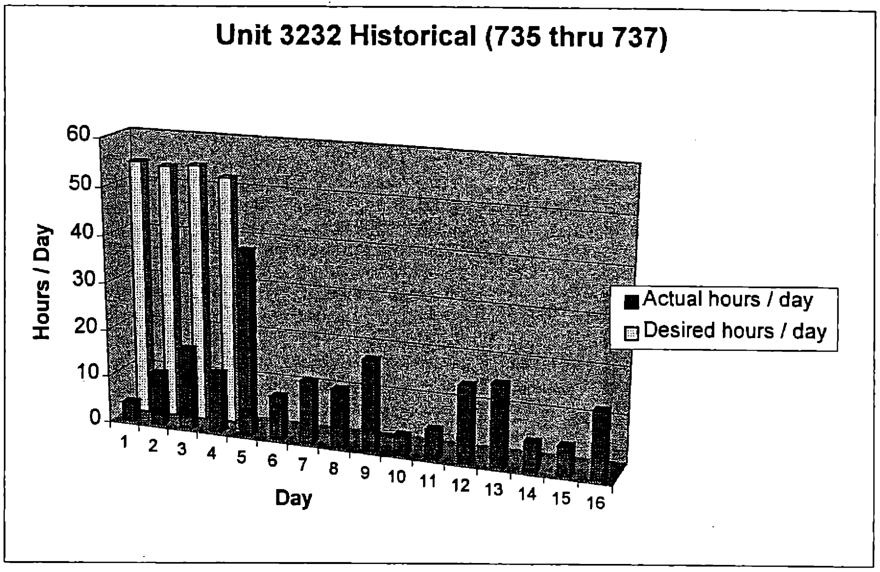


Figure 6
ACTUAL HOURS WORKED PER DAY (AVERAGE) IN A SINGLE UNIT

Figure 6 shows that the actual flowtime for a given unit was much longer than desired. In the chart, the "Desired hours per day" shows that all of the work content for this unit should have been completed in four days (given that the line was working to a four-day roll rate). The "Actual hours per day" show that this unit actually completed the work sporadically over a period of sixteen days (on average). Actual flowtimes for the other units in final assembly are provided in Appendix A. All of the work was eventually completed, and the total flowtime for the eight units in final assembly was generally only a few days over target. But mid-way through final assembly, it was almost as accurate to say that the eight units were working in parallel as opposed to working in sequence. The aircraft, however, continued to move through final assembly according to the scheduled roll rate – it was the workers who moved back and forth among the aircraft to accomplish the "float" described above. Figure 7 compares an ideal relationship between work units (working in serial), to the situation found in final assembly, using flowtime data from one aircraft:

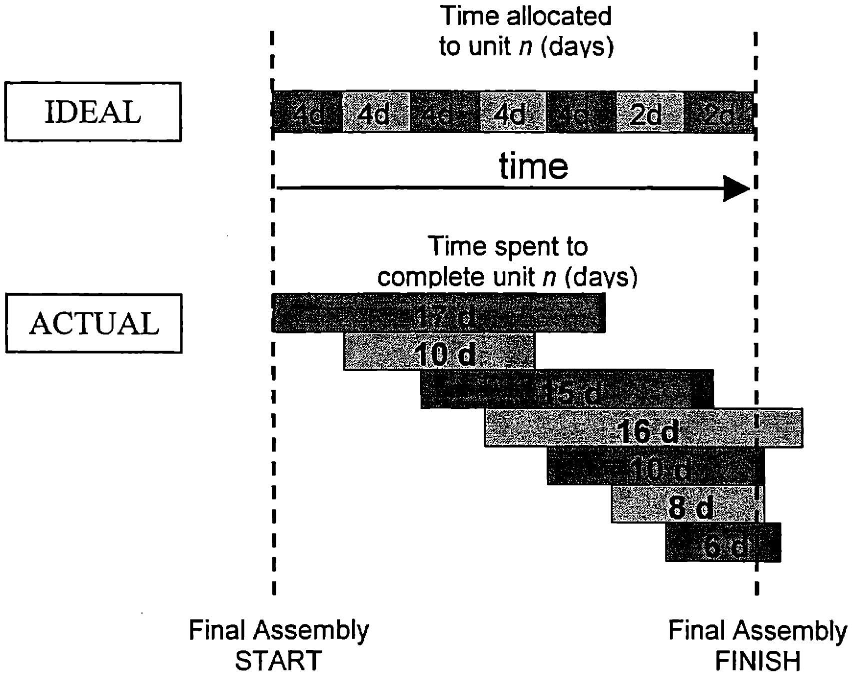


Figure 7
COMPARISON OF IDEAL UNIT FLOWTIMES TO ACTUAL DATA

There was widespread recognition by workers, foremen, and first level management that the amount of out-of-sequence work done in assembly operations had a significant impact. Exactly what this impact was, and how it could be quantified, was a different story. The most obvious impact was the inability to maintain the desired work sequence, as each operation that was not completed on time would have a ripple effect throughout the remainder of the process. However, since foremen were given direction to meet delivery schedule and direct labor goals, but were not accountable for adherence to a prescribed build order, it seemed that the process had settled into a "least resistance" path for assembly operations.

The second problem: excess inventory for assembly operations

During the internship, the company began a significant restructuring effort. Aggressive targets for cost and inventory reduction were assigned to various divisions within manufacturing operations. The inventory targets in particular were so dramatic, it was decided that an integrated approach (involving both material and assembly operations) would need to be used.

As noted earlier, most of the value of the aircraft was added during final assembly. The following table shows the accumulation product cost during the final assembly process:

Table 1
PRODUCT COST ALLOCATION (PRE AND POST-FINAL ASSEMBLY)

Accumulated Value	Direct Labor	Overhead	Material Cost
START	$ 117,818	$ 282,765	$ 285,718
FINISH	$ 324,759	$ 779,427	$ 1,931,558

It can be seen that the largest component of cost added during final assembly is material. As depicted in figure 2 and described earlier, material for final assembly arrived at the "crib" and was held as inventory, prior to delivery of an aircraft from major assembly to final assembly. During the internship, the quantity of each particular part held in the crib varied on average between 4 to 12 pieces. Depending on the aircraft roll rate, this amount of inventory corresponded to between 12 to 42 days of buffer inventory. Delivery dates for all of this material were set by MRP, based on the date set for the start of final assembly by the Master Schedule (MPS). There was, however, a disconnect of approximately 24 days between the MPS start date for final assembly and the actual start date, which was reflected in an internal assembly operations document titled the Green Plan. The Green Plan showed the difference between MPS and actual dates, determined a "recovery" plan to make up the difference, and set an "internal" roll rate for the line (faster than the MPS roll rate, in order to catch up with MPS).

As a result of the large buffer held by the crib, inventory turns during the internship were generally around two (they varied from 1.8 to 2.1), representing a significant value of inventory laying idle prior to its use by final assembly. Under the system in use at the time, all of the material for final assembly was scheduled for delivery prior to day one. Therefore, material for installations that occurred at the *end* of final assembly would sit in the crib for at least 24 days (the average total flow time for final assembly) before being drawn for use. This was the only practical option, however, since the actual start time for a particular installation was never known in advance. Theoretically, all of the material for an individual unit could be scheduled to arrive in the sequence of each unit, but as described above, so much work was done outside of the designated time frame for each unit that it was not feasible to do so.

To address this problem, the company decided to implement precision scheduling through the existing MRP system. First, manufacturing operations had to begin producing in a planned and repeatable sequence. This sequence would be communicated to MRP using the MPS, so that the material for each unit arrived "just-in-time" for consumption by assembly. Then, the amount of the buffer, or disconnect between MRP and MPS, would be reduced.

Company plans and goals for cost reduction: The JIT Project

As indicated above, the company decided to solve these two separate problems (direct labor performance and excess inventory) using an integrated approach. What eventually became known as "The JIT Project" started with a team in Manufacturing Services investigating ways to reduce inventory through scheduling policies (MRP and MPS), but later included personnel from other departments (such as operations and material), all working towards the dual goals of cost and inventory reduction. Efforts were underway prior to the start of the internship, and were eventually grouped into the following sequence of activities:

- Designation of Final Assembly units involved (eventually limited to the eight units that produce the UH-60 and variants).
- Time study of all installations in these units, and certification of direct labor targets (time required for completion) by Industrial Engineering (IE).
- Rewrite of certain jobs to allow for easier scheduling on one shift (making time required less than eight hours), or disaggregating operations to allow for discrete tracking of DL trends.
- Production of new "travelers" (labor tracking sheets) with barcodes for each individual installation, so that workers could use the shop floor system (time and attendance) to record labor charges to the particular job and aircraft being worked.
- Identification of desired assembly sequence for installations within each unit (for each of the three aircraft models).
- Identification of JIT parts (make and buy) to receive special handling instructions (the material organization intended for the very high cost items to flow directly to the line).
- Integration of backshops and suppliers into process (e.g. schedule changes).
- Master Schedule adjustments and updates to align MRP with consumption of parts.
- Followed by *implementation* of all these activities into assembly operations.

The goal of all these activities was to place all inventory for UH-60 Final Assembly under *control* of the new JIT system, so that all material flowed directly (or at least quickly) to final assembly and was consumed on the date planned. The system was planned to work as follows:

1. Manufacturing Operations produces their own build schedule (the Green Plan), based on required delivery dates, assembly status, shop loading, and priorities among different programs.
2. Each week, the Master Schedule is adjusted to match the revised dates in the Green Plan.
3. Need dates and priorities within MRP are adjusted to this new schedule (for all material that flows into the eight units in final assembly) and deliveries are rescheduled accordingly.

Implementing a Hybrid MRP/Pull system

In their effort to reduce waste (cost) and become lean, the company thus sought to introduce a hybrid MRP/pull methodology into manufacturing planning and operations. Use of such a hybrid system can have many benefits for companies which previously relied solely on their MRP system [Deleersnyder et al., 1992]. Major reasons for moving in this direction include:

1. Inability to maintain MRP data at a high level of reliability,
2. Lack of an inherent improvement mechanism in MRP,
3. Lack of real-time coordination among the consecutive stages, requiring frequent rescheduling to keep the total system under control, and
4. Approximations within the MRP leading to excess safety stocks.

While a pure-pull approach, such as the kanban cards used within the Toyota Production System [Monden, 1981], has obvious advantages, there are some key reasons why implementing this in an aerospace manufacturing environment would be problematic:

1. Inherent scope and complexity in aircraft products (e.g. parts count),
2. The basic pull mechanism relies on conditions of repetitive manufacturing and a reliable production/stable demand environment, and
3. Information flow becomes tied to material, so valuable demand information is not sent to all stages of production as soon as it is available, which creates large information lead times where there are large material flow lead times.

Thus, the goal for a hybrid MRP/Pull system should be to integrate the *end-to-end information flow* capabilities of MRP, with the *local control and highly reliable local information* available in pull systems. Seen in this light, the approach used by the company does not utilize a true hybrid structure; the pull signal is being provided by another scheduling mechanism, and not by the work units themselves. Introduction of this additional loop in the system has the following effects:

- It adds to complexity (additional coordination is required),
- Increases the lead time for pull information to be incorporated into the MRP system,
- Is not really true to the JIT axiom of quantity control, as opposed the schedule control methodology familiar to managers,
- Reduces the quality of pull information by reducing it to a weekly, not real time, update, and
- Acts as a filter between the manufacturing units and the MRP schedulers.

Although company implementation of the JIT project did not utilize a true Hybrid MRP/Pull approach, there was still potential for significant cost savings. If the JIT project was successful, it would (1) eliminate or reduce the inventory buffer between MPS and the Green Plan and (2) eliminate or reduce lead time buffers imposed by the discontinuity between MRP and the actual final assembly installation sequence. Additionally, use of a defined sequence was expected to have "second order" effects as well (such as scheduling efficiency, improved quality, and less workarounds) that would reduce both overall flowtime and direct labor charges.

Chapter 3: Producing a defined build sequence for final assembly

As describe in Chapter 2, the company sought to create a defined and repeatable build sequence for final assembly. This would be a critical element for success of the JIT project – precision scheduling of material deliveries through MRP would not work without it. Normally, this type of activity would be done by IE or ME personnel, but none were available on a full time basis. Fortuitously, the focus of the internship had already changed from direct labor charging (implementation of the new barcoded labor tracking sheets) to the issue of variation reduction. Baseline data on schedule performance was already being gathered by the intern, who was then assigned to the JIT team, and using additional resources (as described below) created a build sequence for use by the JIT project.

Previous sequencing attempts and current methods for scheduling assembly operations

Manufacturing Engineering functions at the company had organized the installations assigned to final assembly into the eight discrete units (i.e. control points) described previously. This was done utilizing the mainframe computer applications at the company to access the Manufacturing Bill of Material (MBOM) where this information was stored. Work was then planned at a lower level using crewload charts (depicting installations vs. time) prepared by Industrial Engineering, and were posted next to each aircraft during production. These hand-drawn charts were frequently changed over the years by Industrial Engineering personnel based on improvement activities or worker input, but due to downsizing at the company had not been changed for the few years prior to the internship. As installations were changed, or planned to a different unit, the crewload charts lost relevance as a scheduling mechanism, and were used more as a checklist to show that the applicable items had been completed.

Sources of data

The build sequence for the aircraft is dictated primarily by physical build-up considerations, such as having to complete wiring installations before flooring is laid over them. Other factors include ergonomic considerations (number of people that can safely work in a given area of the aircraft), testing (e.g. some hydraulic and electrical installations are tested before additional components are installed), and inspection (many components or installations must be inspected prior to subsequent work). To begin the data collection effort, a list (spreadsheet) of all the installations in final assembly was obtained. It provided the following information: installation part number (15-digit identifier for each installation), nomenclature (description), labor skill required (M-mechanical, E-electrical, or H-hydraulic), and labor target (hours to complete job). Then, a series of interviews were conducted with workers and foremen to obtain additional information regarding each individual installation, as shown in figure 8:

Target	Installation No.	Description	Group	Tech	Location	Precedents	Dependents
3.00	70210-02100-813	Bellcrank Instl (flight controls)	1	2nd shift	interior, mid L & R	tracking fairing (majors)	elect wiring install (Max) and pitot static lines
1.00	70216-02405-013	Latch Instl (gunners window)	1	Louis	gunner 's window L	none	elect wiring install (Max) and pitot static lines
11.00	70219-03002-511	(Fuel Cell) Enclosure	1	John Fitz	interior, aft cabin	DO TOGETHER	before aft cabin work, before fuel lines
1.00	70307-42406-812	Instl Support H-Bar	1	John Fitz	interior, aft cabin		

Figure 8
SAMPLE OF DATA COLLECTED TO DEVELOP A SEQUENCE FOR INSTALLATIONS

The figure above shows how data were collected to develop the critical path for installation within each unit. For example, the first entry shows that installation number 70210-02100-813 (Bellcrank Installation) was identified as part of group one - the first set of installations that need to be completed in this unit. At a more detailed level, the installation is located on both sides of the interior mid-cabin, the tracking fairing (installed in major assembly) needs to be completed *before* this can be worked, and certain electrical installations and pitot static lines *wait* for this operation to be completed.

In parallel with this effort, data were gathered to document the following parameters:

- Actual flow time of work through final assembly
- Actual flow time for each unit
- Actual labor required for each installation
- Actual sequence in which final assembly installations were completed

Because the current IT systems at the company did not provide any of this data, all of this information was gathered by manually tracking three aircraft through final assembly, early in the internship. This consisted of, at a minimum, daily visits to the final assembly area to use the paper tools (various charts and checklists) available, copying down this information, and discussing these observations with workers and foremen. Although the sample size was small, it was believed by line foremen to be fairly representative of the actual operations conducted in final assembly - and it was also the only source of this data for use by the project.

Using the data to generate a desired assembly sequence

After compiling the comments of workers, foremen, and previous efforts by ME and IE for work sequencing, the data was organized into a desired assembly sequence. Where operations could not be distinguished from each other (they shared precedents and dependents, and could be done in parallel), they were aggregated into groups, and sequenced within each group based on historical order of completion and line balancing / leveling considerations. This rough draft was then compared to the documented performance of the line (order that operations were actually completed) and presented to line foreman for review.

Target (hours)	Install Part Number	Description	PROPOSED SEQUENCE	Historical DAY COMPLETED	Historical ORDER FINISHED	Comments
1.00	70211-04803-812	Beam Inst	1.01	3.0	6	
9.00	70551-02105-843	WI L/H Main Ckpt	1.02	3.0	9	
9.00	70551-02106-848	WI R/H Main Ckpt	1.03	3.0	10	
1.00	70551-02111-800	Wrg Instl C Hook	2.01	1.0	1	
0.50	70550-01150-011	Box Instl	3.01	2.7	4	
0.50	70550-01150-012	Box Instl	3.02	2.7	5	

Figure 9
SAMPLE ROUGH DRAFT OF ASSEMBLY SEQUENCE

The example in figure 9 above shows the sequence developed, using the more detailed information. Each group was broken down further into an intra-group sequence, shown in the "PROPOSED SEQUENCE" column. Listed alongside for comparison is the historical data showing both the average day and average order in which the operations were actually completed. These sequence numbers (e.g. 1.01, 1.02) were loaded into a master file (Excel database) that contained all part numbers for all final assembly units of the three aircraft models in production on the Blackhawk final assembly line.

One of the first insights generated by production of a defined assembly sequence, was the relationship between roll rate and unit flow time. Using the assembly sequence generated for the first unit in final assembly (unit 3232), a Gantt chart was produced as shown in figure 10:

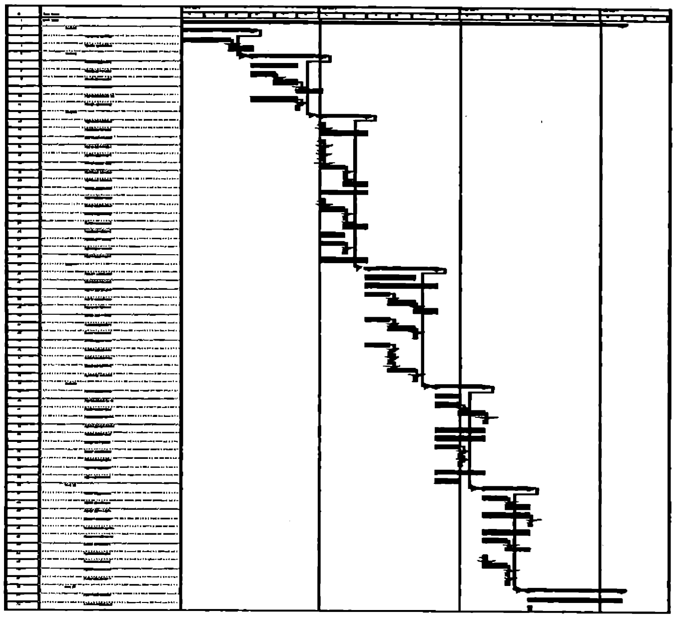


Figure 10
GANTT CHART REPRESENTATION OF UNIT 3232: TOTAL FLOW = 3.04 DAYS

Foremen in this area were specifically asked to identify how many operations could be done at the same time (in parallel) so that the shortest total flow time was obtained. Generally, assembly cannot utilize more than five or six personnel on an aircraft at the same time. Using this information, the Gantt chart computes a total project time of just over three days. That is, the statement of work for this unit cannot be physically completed in less the total computed project time. This computation assumes 24 hour per day operations, complete availability of all required labor and material, and perfect adherence to the schedule (no delays, overruns, rework, etc.) If the information regarding installation times and dependencies is correct, then this figure represents the "minimum theoretical flowtime" which this unit takes to complete. In light of past operations at the company, it is immediately obvious that installations are *not* completed in order, because roll rates have (in the past) been as low as 1.5 days! If this were true, then assembly operations would be putting more than six people on the aircraft at one time, or violating the many dependencies involved in the assembly sequence. However, as the data in figure 6 showed, the work was never completed that fast, but merely carried forward (or back).

Data accuracy and workforce participation

The analysis of manufacturing operations conducted before and during the JIT project relied heavily on qualitative data. Where quantitative analysis was done, data collection was generally done by hand, since existing IT systems at the company did not easily support changes in input or output. An important feature of the process implemented at Sikorsky was the elimination of these manual tracking and control techniques, and gathering of more discrete assembly data (i.e. direct labor for each individual installation). An important Statistical Process Control (SPC) tool for the future will be the ability to tell, in near real time, which installations have moved "out of control" and are experiencing significant problems and overcharges. An example of this type of analysis, using the labor charging information, is shown:

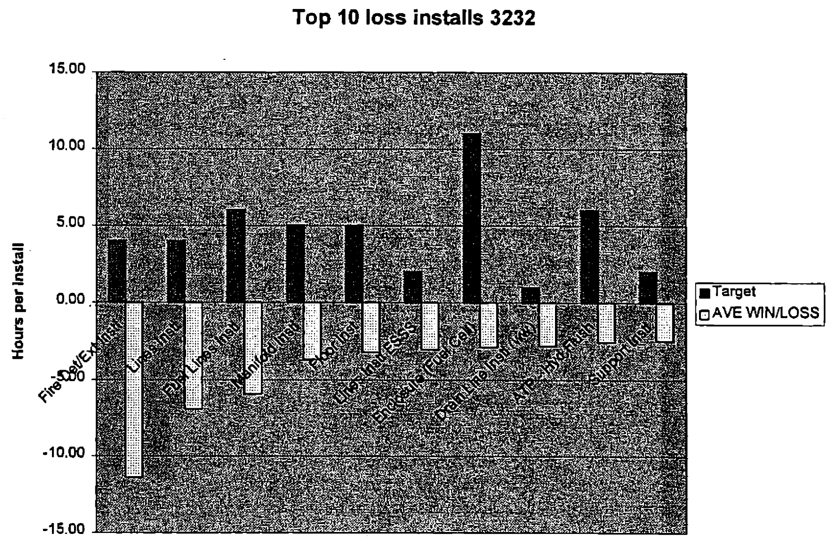


Figure 11
TOP TEN INSTALLATIONS WITH LABOR OVERRUNS (ON AVERAGE) FOR UNIT 3232

Figure 11 shows ten installations ranked according to how much they exceeded the labor target (the target is shown above the axis, and the difference between actual labor and the target is shown below the axis). In order for this system to work correctly, it was incumbent upon the workers in final assembly to participate in the process. One of the ways for them to do this was by providing feedback on the newly-created assembly schedule itself. Indeed, after the initial assembly sequence for each unit was identified, a primary means of determining the correctness of this particular build order was the acceptance and use of this schedule by the foremen and workers on the line. Input provided by them was critical to the ongoing improvement of this schedule, and it provided a means to capture knowledge regarding the way things "actually got done" on the assembly line. The following is an example of some of the types of comments made to help revise and improve the schedule over time:

INSTALL	SEQ NO	HRS	DESCRIPTION	ACTION	DATE	STATUS
70551-02111-800	2.01	1.00	Wrg Instl C Hook	Move to 3233 3rd day (approx. seq. 7.04) - need ME'S to move AOS	21-Sep	OPEN
70000-08000-818	11.01	5.00	Xmsn/Rtr Instl	Move to 1st day; at least before 3.03	21-Sep	OPEN
70308-03610-821 70308-03610-822	10.01 & 10.02	8.00	HIRSS Instl L/H & R/H	Move to 2nd day (approx. seq. 7.01) ** this was placed day 3 due to cost and location off of critical path	21-Sep	OPEN
70308-03611-011 70308-03611-012	12.01 & 12.02	6.00	Extndr Instl LH & RH	Move to 3rd day (approx. seq. 8.02) ** this was placed day 4 due to cost and location off of critical path	21-Sep	OPEN

Figure 12
CHANGES TO ASSEMBLY SEQUENCE MADE WITH WORKER INPUT (EXAMPLE)

Figure 12 shows how workers made input to the assembly sequence during the time period of the pilot project. This data was then incorporated into the sequence after consultation with line foremen. Another important task for the workers to participate in was the charging of labor to individual installations. Not only was this important for IE and ME to begin to discern which operations were the source of excess labor charges, but perhaps more importantly, this data can eventually be used to track the status of final assembly in near-real time. Starting with the first implementation of the bar-coded travelers and subsequent changes made to labor charging procedures, the following compliance was noted on the part of workers to the new procedures during the internship:

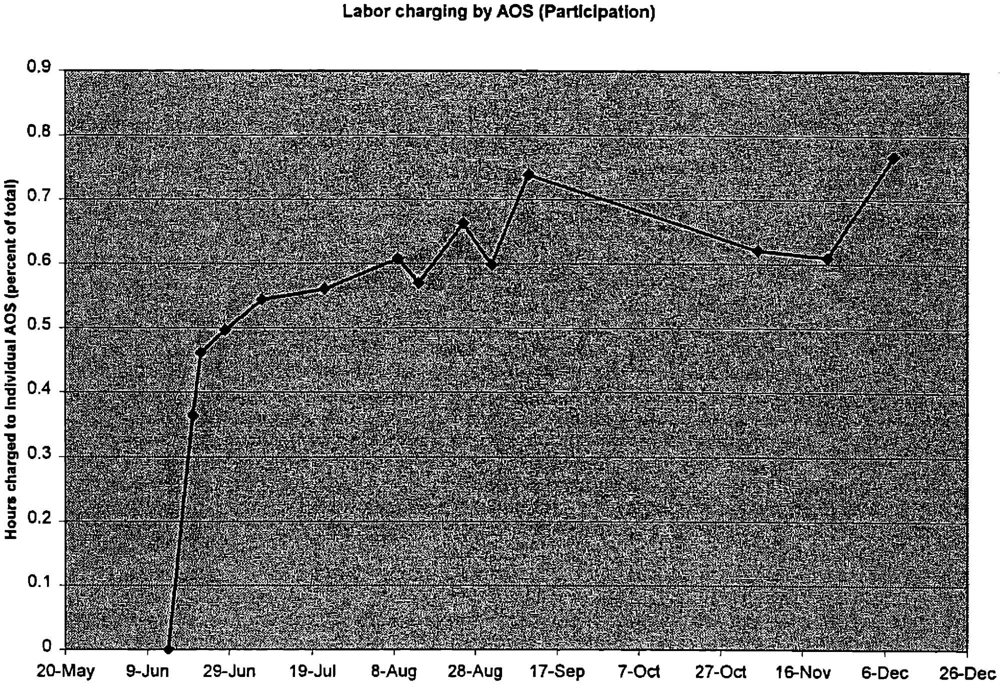


Figure 13
WORKER PARTICIPATION IN NEW LABOR CHARGING PROCEDURES

Figure 13 shows that the initial use of the new system by the workers jumped up to 50%, and then began a slow climb during the remainder of the internship. It is important to note that by not using the system, labor time and attendance data were still obtained for the workers, just not at the detailed level envisioned by the project. While 2/3 of workers were using the system at the end of the internship, this level was still not good enough to begin to implement any of management's ideas regarding use of the data, which are described below.

Sikorsky uses a structured query language (SQL) application to access a variety of data housed in a central data warehouse server. These data replicate data developed and stored by the mainframe and shop floor applications at Sikorsky; the advantage is that the SQL application is much easier to use and can be transported to standard desktop computing applications (such as spreadsheets or relational databases). Once the labor charging data are accurate, the warehouse can be queried to provide auto-formatted reports of final assembly status for use by numerous other organizations throughout the enterprise, such as:

- Percent complete for each aircraft
- Direct Labor performance (actual vs. desired)
- Flowtime performance (percent complete vs. schedule)
- Estimated completion date and EAC (Estimated Actual hours at Completion)
- Process performance (such as actual hours charged vs. calendar hours from job start to finish, or time from completion to inspection)
- More importantly, it will allow the shop floor to begin to develop their own methods and metrics for improving performance

Chapter 4: Implementing a defined build sequence

Pilot Project

A key aspect of the JIT project was the implementation of the assembly scheduling portion of the system. Use of the existing shop-floor system was mandated. This imposed the following constraints on the project:

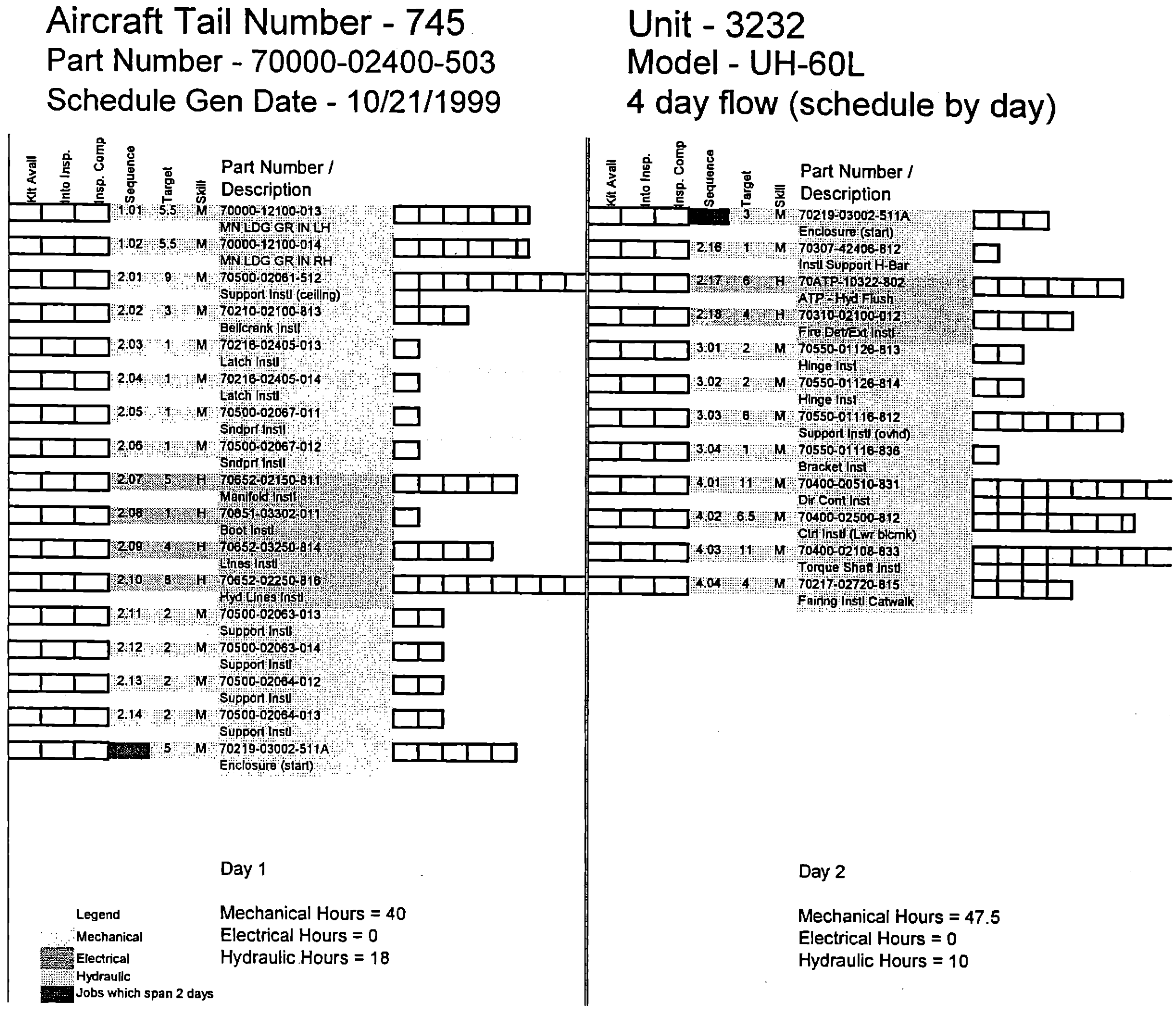
- Schedules would need to be printed out on large sheets of paper, and posted next to the aircraft. Status would have to be filled in by hand.
- Labor charging was done at a handful of time and attendance stations, which were not always located next to the aircraft. Schedules could not be used for charging; separate sheets would be required. Any changes would have to be manually transferred between the two.

Thus, the solution chosen was a compromise between automation and manual intervention. A common database was developed using MS Excel and hosted on a shared file server at the company. This database contained the information on the desired sequence (developed as shown in the previous chapter) and was used to feed the following products:

- *Assembly schedule* (specific to model, aircraft serial number, and desired roll rate),
- *Barcoded travelers* (needed to gain visibility into, and control over direct labor charges; workers now used the shop floor system to "clock" labor onto each individual job), and
- *Daily labor report* (compares actual individual charges to target for each installation, using the data generated by worker charges as described above).

All these items worked together to enable the JIT pilot project to begin: the assembly schedule printout showed the workers the desired sequence, the barcoded travelers allowed them to charge labor direct to the installation, and the daily labor report summarized these activities each day.

The database used a visual basic application (developed in-house by an IE with Manufacturing Services) to generate the assembly sequence chart for each aircraft based on a few user inputs. An example is shown in figure 14 below:



Aircraft Tail Number - 745
Part Number - 70000-02400-503
Schedule Gen Date - 10/21/1999

Unit - 3232
Model - UH-60L
4 day flow (schedule by day)

Kit Avail	Into Insp.	Insp. Comp	Sequence	Target	Skill	Part Number / Description
☐	☐	☐	1.01	5.5	M	70000-12100-013 MN LDG GR IN LH
☐	☐	☐	1.02	5.5	M	70000-12100-014 MN LDG GR IN RH
☐	☐	☐	2.01	9	M	70500-02061-512 Support Instl (ceiling)
☐	☐	☐	2.02	3	M	70210-02100-813 Bellcrank Instl
☐	☐	☐	2.03	1	M	70216-02405-013 Latch Instl
☐	☐	☐	2.04	1	M	70216-02405-014 Latch Instl
☐	☐	☐	2.05	1	M	70500-02067-011 Sndprf Instl
☐	☐	☐	2.06	1	M	70500-02067-012 Sndprf Instl
☐	☐	☐	2.07	5	H	70652-02150-811 Manifold Instl
☐	☐	☐	2.08	1	H	70851-03302-011 Boot Instl
☐	☐	☐	2.09	4	H	70652-03250-814 Lines Instl
☐	☐	☐	2.10	8	H	70652-02250-816 Hyd Lines Instl
☐	☐	☐	2.11	2	M	70500-02063-013 Support Instl
☐	☐	☐	2.12	2	M	70500-02063-014 Support Instl
☐	☐	☐	2.13	2	M	70500-02064-012 Support Instl
☐	☐	☐	2.14	2	M	70500-02064-013 Support Instl
☐	☐	☐	■	5	M	70219-03002-511A Enclosure (start)

Day 1

Mechanical Hours = 40
Electrical Hours = 0
Hydraulic Hours = 18

Legend
░ Mechanical
▨ Electrical
▒ Hydraulic
■ Jobs which span 2 days

Kit Avail	Into Insp.	Insp. Comp	Sequence	Target	Skill	Part Number / Description
☐	☐	☐	■	3	M	70219-03002-511A Enclosure (start)
☐	☐	☐	2.16	1	M	70307-42406-812 Instl Support H-Bar
☐	☐	☐	2.17	6	H	70ATP-10322-802 ATP - Hyd Flush
☐	☐	☐	2.18	4	H	70310-02100-012 Fire Det/Ext Instl
☐	☐	☐	3.01	2	M	70550-01126-813 Hinge Inst
☐	☐	☐	3.02	2	M	70550-01126-814 Hinge Inst
☐	☐	☐	3.03	8	M	70550-01116-812 Support Instl (ovhd)
☐	☐	☐	3.04	1	M	70550-01116-836 Bracket Inst
☐	☐	☐	4.01	11	M	70400-00510-831 Dir Cont Inst
☐	☐	☐	4.02	6.5	M	70400-02500-812 Ctrl Instl (Lwr blcrnk)
☐	☐	☐	4.03	11	M	70400-02108-833 Torque Shaft Instl
☐	☐	☐	4.04	4	M	70217-02720-815 Fairing Instl Catwalk

Day 2

Mechanical Hours = 47.5
Electrical Hours = 0
Hydraulic Hours = 10

Figure 14
NEW BLACKHAWK CREWLOAD CHART (AIRCRAFT #746, UNIT 3232, DAYS 1 AND 2)

The existing shop floor system did not allow the database to be linked or displayed using any devices on the factory floor; therefore, the chart was printed and posted on a large cart located next to each aircraft. Key features of the charts include:

- Every chart is unique based on aircraft model and serial number, and desired roll rate,
- Each installation is listed - *in sequence and by day* - by part-number, nomenclature, labor target, and skill required,
- Each installation is color-coded to indicate the worker skill (electrical, mechanical, or hydraulic) required,

- The labor target is shown using empty boxes (corresponding to the number of target hours) which are colored in when the work is completed (using a color-coding scheme specific to assembly shift),
- Provides a visual means to aid line foremen in work assignments and prioritization,
- Clear, visual means to track schedule performance,
- Used to highlight where the most important problems (e.g. parts shortages) were, and
- Includes columns for keeping track of the status of parts kitting and installation QA (quality assurance / inspection) operations,

Early results

Beginning in early October 1999, just after the mid-point of the internship, the JIT project was introduced as a pilot in final assembly. Starting with aircraft #743, all subsequent aircraft used the new methodology to schedule work and deliver material. Based on the results and experience of Blackhawk final assembly, the company hoped to implement the program in other areas. The results obtained early in the project (during the internship) are shown below.

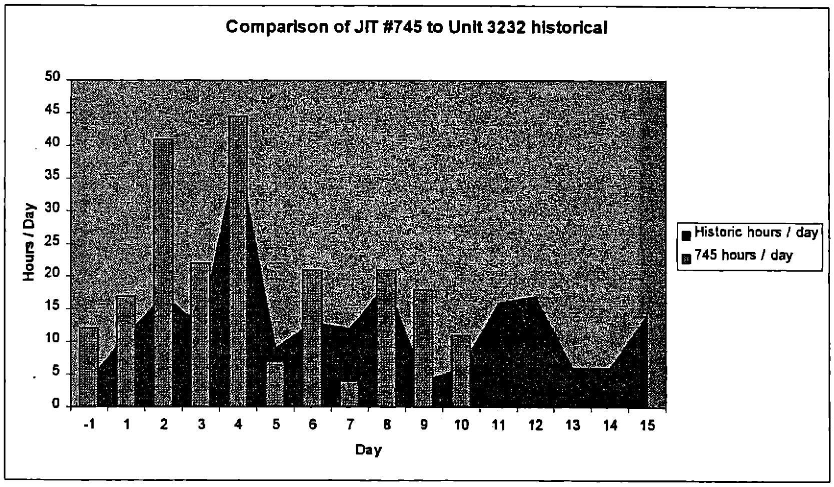


Figure 15
FLOWTIME REDUCTION SEEN DURING PILOT PROJECT

Figure 15 shows some initial progress in flowtime reduction using the new scheduling methodology. The area in the *background* of the chart represents the work profile (in hours per day) of this unit prior to the pilot project (as shown in Figure 6 previously). The columns in the foreground represent the hours per day worked in this same unit, but for aircraft #745 only (the third aircraft built under the pilot). The same amount of work is now completed in eleven days instead of sixteen - but still more than the desired target of four days. The start date of "-1" represents that this unit started work one day prior to the date identified in the master schedule. After using the new crewload charts provided to final assembly as part of the pilot project, these units generally showed flowtime reductions of about 25%. When parts were available, the new charts were generally seen as more effective in planning the application of labor to specific installations on a shift-by-shift basis. A comparison of flowtime for one aircraft (serial number 745) to the previous (historical) flowtime is shown for each unit in appendix B.

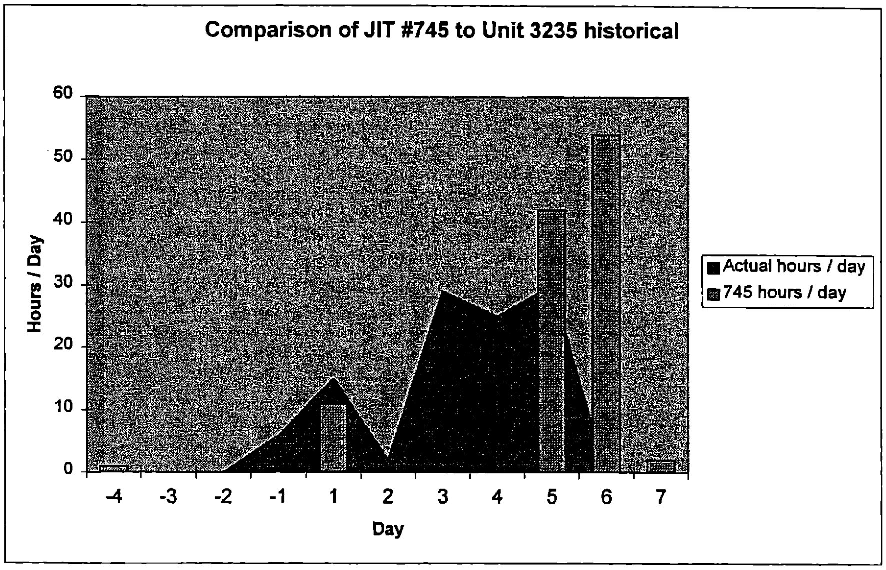


Figure 16
FLOWTIME INCREASE SEEN DURING PILOT PROJECT

However, conditions did not always support adherence to the desired assembly sequence. The above chart shows the pilot project having the opposite effect from the flowtime reduction seen in figure 15. For this unit, the work should have been performed on days one and two; historically, it averaged six days to complete this work, and for this particular aircraft most of the work was not even started until day five.

The pilot project showed that the production and use of a detailed daily build schedule, representing the best engineering judgement of the IE/ME functions, and incorporating input and lessons learned from line workers, is not enough to guarantee in-sequence production.

It was predicted that the use of a detailed daily build schedule would aid in the identification and quantification of those problem areas preventing the use of such a system in the past. Indeed, the stated purpose of some managers in the organization for pursuing this initiative was to generate and document this type of data and information. The timing of the internship allowed for the detailed analysis of five aircraft produced under the new process, and these results are the focus of the remainder of the thesis.

Initial identification of problem areas

As aircraft progressed using the work scheduling and material delivery methodology in the JIT pilot project, it became apparent that the approach would not provide the results hoped for by the company. The focus of the internship then changed to capturing the reasons for this failure, and the subsequent analysis that would lead to further recommendations for manufacturing. The following issues were identified:

- Shortages
- Rework / turnbacks
- Inspection
- Labor Management
  - availability
  - cross-training
  - performance
  - non-value added activity (NVA)

Why were these particular issues chosen? Using the new assembly sequence charts (which aided with data visibility and collection), along with attendance at production status meetings, JIT project review meetings, and employee discussions/interviews, these were the issues that gained prominence.

It is interesting to compare this list with the list generated by worker input prior to the JIT project implementation. The JIT project was pursued in the face of significant "anecdotal" evidence that it would be very difficult to implement. Discussions with workers, foremen, and others involved in final assembly operations had brought to light a list of issues, relating to schedule performance, that would need to be dealt with as the project progressed:

- installation (job) tracking and accountability
- metrics
- management of labor / current way of doing things
- specialized proficiency (not specialized skills; e.g. lack of cross-training on jobs)
- labor attendance
- carry forward work
- carry back (early) work
- turnbacks (parts quality)
- inspection
- spares production (and cannibalization of production material)
- kit carts
- shortages

This worker input, reflecting a great deal of specialized knowledge gained over many years of experience with the product and process, could have been incorporated in the redesign of the process by the JIT project. This could have helped with methods for dealing with the "intangible but known" factors, as opposed to relying strictly on the "quantified and known" (i.e. direct labor) factors. While there were issues generated by the workers that proved not to be significant, they were successful at capturing all of the reasons that were subsequently identified through implementation of the pilot project. These issues will be developed and explored in the next chapter.

Chapter 5: Managing a complex aerospace assembly process

Managing a complex aerospace assembly process means dealing with complexity and variability. To do this, leadership must design a process that is both robust and flexible. The problem areas identified in Chapter 4 by the JIT project represent sources of variability or constraints on system design. In this chapter, the results are first validated and substantiated. Second, their effect on manufacturing is shown or predicted. Third, the issues are linked to the higher-level questions of manufacturing system design, and the effects of high variability and utilization on the process.

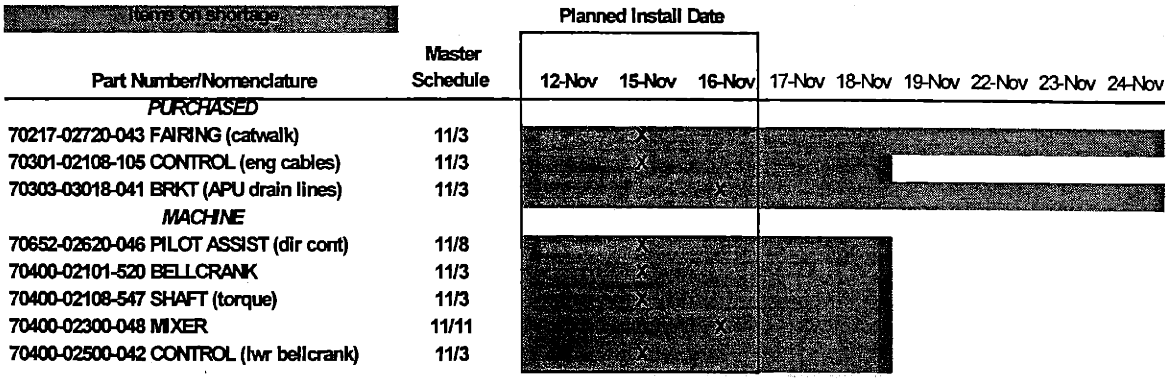
How did these problems impede progress of the Just-In-Time project?

By the end of the internship, it was readily apparent that there were a set of issues which precluded the successful introduction of the JIT project. Compared to aircraft #745, the experience of aircraft #747 was even worse. This aircraft, still in production at the end of the internship, had made the following progress in implementation of precision scheduled assembly:

- Installations completed on date scheduled in MPS = 4
- Installations done early = 12
- Installations completed late = 163

Clearly, without predictability of installation completion, the JIT project could not schedule material deliveries and achieve inventory reduction. The following sections develop further the observations made in chapter 4.

Shortages



Items on shortage

Planned Install Date

Part Number/Nomenclature	Master Schedule	12-Nov	15-Nov	16-Nov	17-Nov	18-Nov	19-Nov	22-Nov	23-Nov	24-Nov
PURCHASED										
70217-02720-043 FAIRING (catwalk)	11/3	▨	X	▨	▨	▨	▨	▨	▨	▨
70301-02108-105 CONTROL (eng cables)	11/3	▨	X	▨	▨	▨				
70303-03018-041 BRKT (APU drain lines)	11/3	▨	▨	X	▨	▨	▨	▨	▨	▨
MACHINE										
70652-02620-046 PILOT ASSIST (dir cont)	11/8	▨	X	▨	▨	▨				
70400-02101-520 BELLCRANK	11/3	▨	X	▨	▨	▨				
70400-02108-547 SHAFT (torque)	11/3	▨	X	▨	▨	▨				
70400-02300-048 MIXER	11/11	▨	▨	X	▨	▨				
70400-02500-042 CONTROL (lwr bellcrank)	11/3	▨	X	▨	▨	▨				

Figure 17
SAMPLE OF FINAL ASSEMBLY SHORTAGE DATA

Shortages were widely believed to be the most significant of the factors affecting the JIT project. Figure 17 above shows a representative sample of shortage data, copied from a database used by the Production Control organization (part of the Material department) for tracking parts shortages. This data is for a single aircraft and a single unit, and shows a mix of purchased (buy) and machined (make) parts being tracked due to late status. The "Master Schedule" column shows the date assigned by MRP for the part to be delivered to the crib (stocking location) for final assembly. All delivery dates are prior to the start date of this unit (12 Nov). Some delivery dates are only one day early and hence "just-in-time" - this was another part of the JIT project instituted by the material organization. Certain high-value parts were identified as JIT parts, meaning their deliveries were adjusted within MRP to be only one day prior to use, requiring special handling instructions (they would not be received, inspected and stocked with all the other material, but would be delivered straight to the assembly line).

All installations for this unit were to occur on 12 through 16 Nov; an "X" in these columns shows the date each install was to be completed. The shaded bars extending to the right show the dates that these parts were on shortage; for example, the BELLCRANK should have been delivered 03 Nov and installed 15 Nov, but was on shortage until 19 Nov. Given the highly coupled nature of jobs in final assembly, shortages represent a critical obstruction to remaining on the critical path. In addition, timely knowledge of shortages is critical; Production Control is not the ultimate customer of these parts - it is line management in manufacturing that needs most to have this information. Notably, shortage issues gained prominence during the internship, and the shortage information shown above began to be posted next to the assembly sequence charts next to the aircraft.

The idea of a minimum theoretical flow time was introduced earlier. Taking the Gantt chart developed previously (figure 10) as a baseline, a test case was constructed using shortage data from figure 17. Start dates for those installations with shortages were modified (using actual delivery dates) in a new Gantt chart, yielding the following theoretical flowtime for this unit:

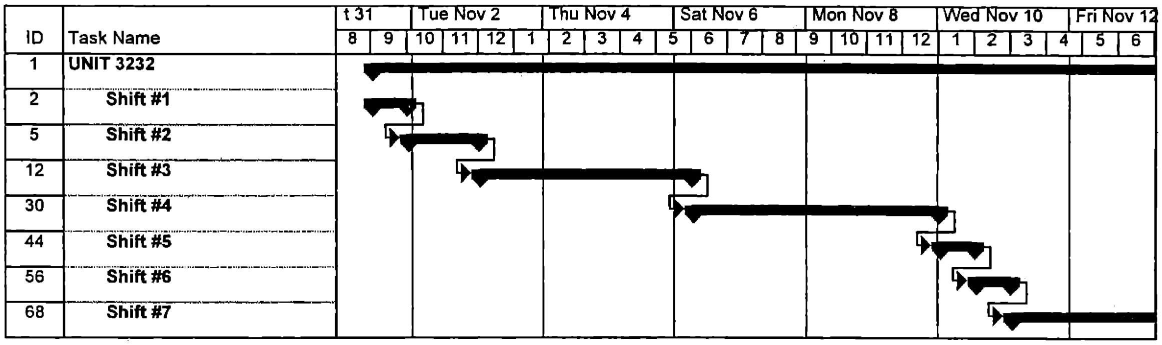


Figure 18
FLOWTIME FOR UNIT 3232 MODIFIED BY SHORTAGE DATA

Significantly, the total flowtime for just this unit expands to over twelve days - and this accounts only for shortages, and not for the other factors such as labor, inspection, or rework. In reality, the assembly line would begin conducting workarounds in this situation - but it is exactly this behavior that introduces variability (i.e. unknown start and stop times) and precludes the use of JIT scheduling.

Quality issues: Rework and Turnbacks

Final assembly was also plagued by persistent quality problems, both in jobs that had to be redone (rework) and incoming part quality that resulted in material rejections (turnbacks). There were several aspects to the problem:

- The overall process relied heavily on inspectors to find and report problems,
- Worker turnover led to quality problems, and made identification of "root cause" and permanent correction of problems difficult,

- Requirement for 100% inspection of installations during assembly, with an additional overall inspection at the end of the process (using different criteria),
- Lack of an effective go-between mechanism for manufacturing and engineering, and
- Lack of experience with and usage of a new quality reporting system.

The following chart depicts the data recorded for two aircraft in final assembly using the new quality feedback and measurement process (QCPC) at the company:

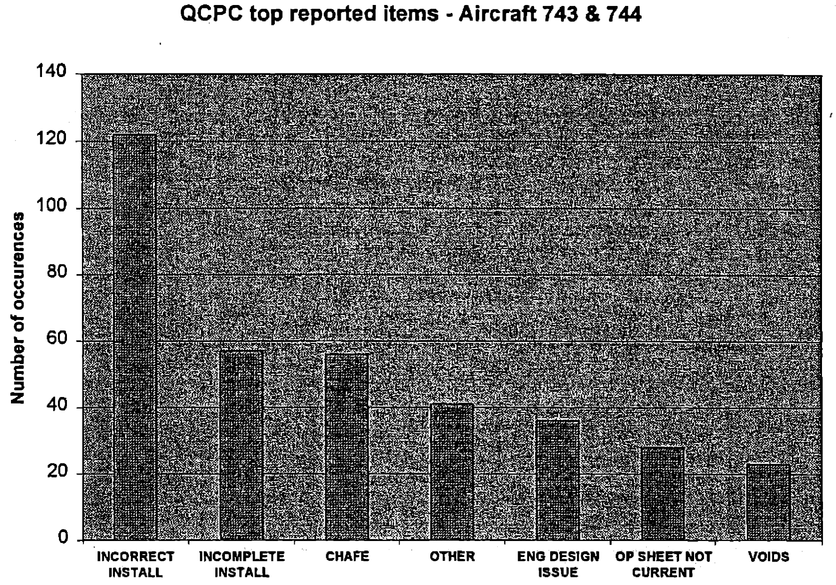


Figure 19
FINAL ASSEMBLY TURNBACK (INSPECTION FAILURE) DATA FOR TWO AIRCRAFT

In relative terms, the data show that quality problems in the manufacturing process continue to be a significant issue. Foremen and lead men frequently complained about the impact these problems created in day-to-day management of assembly operations. Quality problems are "double-trouble" for manufacturing, because they increase both variability (occurrences and associated delays/costs are unpredictable) and utilization (doing work more than once reduces the effective time available).

Inspection

Timely inspection was another issue highlighted during JIT project implementation. The following chart shows the time from job (AOS) completion until the associated inspection operation was finished, for a sample of 140 installations on one aircraft:

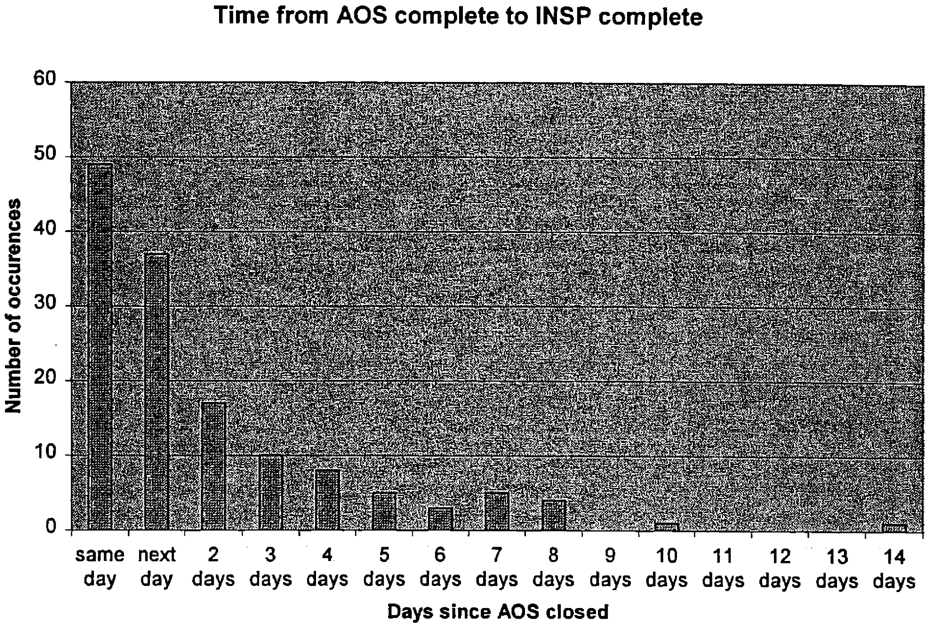


Figure 20
SAMPLE OF TIME DELAY BETWEEN JOB COMPLETE AND INSPECTION DONE

On average, over a third of jobs are inspected on the same day; the overall average time to inspect for this sample was 1.91 days. Because the inspection operations were critical to schedule management and keeping on the critical path, even a single day's delay can impede the completion of other installations. Similar to previous issues, this also contributes to variability (i.e. start and stop times are unknown).

Labor Management

Among the factors involved with labor management problems - availability, cross-training, performance, and Non-Value Added activity (NVA) - there was considerable interdependence. For worker performance in particular, given the complexity of operations and the numerous other factors whose influence could not be quantified, it was difficult to find reliable data. The issues of availability and NVA were closely linked, and are developed in the next section.

Labor planning and forecasting are conducted by Industrial Engineering at the company. Foremen on the line frequently complained that there were not enough workers available to meet all requirements, a view not supported by the company. A detailed analysis of the labor situation is provided in Appendix C, and summarized as follows:

Total required actual hours per day: 386

This value was computed using four aircraft in flow during the JIT project. The required hours to be earned for each aircraft (based on the assembly schedule and roll rate) was determined, then multiplied by the current performance index (ratio of actual to desired labor hours) for final assembly. These values were added together to provide the total number of hours required to be "clocked" by labor in final assembly each day.

Total actual labor hours available: 437.9
Total actual labor excess each day: 52.4

Using labor attendance data gathered over a four-day period, the amount of labor available to work on the aircraft was computed, and is also shown in appendix C. The number of workers absent or working in other areas was subtracted from the total assigned, loan-ins were added in, and the result multiplied by the number of hours assigned to each shift. The result was an average of 437.9 hours, which was 52.4 hours more than the calculated amount of 386 hours required to meet production schedule.

However, not all of this labor was spent earning hours against the aircraft. As mentioned previously, there were a variety of other activities that kept workers from working on the aircraft for 100% of the time they were in attendance. The company kept track of this issue with a metric they called "Direct on Indirect" or DOI. It included all time charged by direct labor personnel on indirect activities; as such, it only captured activities for which indirect charge codes existed (e.g. for training, "5s", or union steward). This figure varied between 18 and 42% in and around the time of the internship. Other factors were not included in DOI, but increased the amount of labor charged to the aircraft, such as:

- Setup time for jobs that could not be completed (for some reason),
- Looking for lost parts, tools, or paperwork,

- Troubleshooting (at least, some portion of this which could not be charged back to indirect),
- Rework (again, the amount which could not be charged back to indirect), and
- Obtaining parts.

The following chart shows the result of including these factors in the calculation:

Using DOI of 30%	*0.3*
plus additional NVA of 10%	*0.1*
Total fraction of actual labor hours available for productive touch labor	*0.6*
Total actual labor hours available:	**262.7**
Total actual labor hours SHORT each day:	**122.8**

Figure 21
ACTUAL EFFECTIVE LABOR

When DOI (using an average of 30%) is included along with unproductive NVA (estimated by shop floor personnel as an additional 10%), then the amount of labor available each day (262.7) is *short* by 122.8 hours. This calculated value of 262.7 hours compares more favorably with the hours actually worked each day during the three-month timeframe of the JIT project (the actual value obtained from direct labor reports was 243.2).

Lastly, there were the issues of labor availability and cross-training. As seen from the attendance data presented in Appendix C, absenteeism varied between 11 and 15 percent (during the time the sample was taken) in final assembly. Although there were only three labor classifications in assembly (mechanical, electrical, and hydraulic technicians), over the years the workforce had settled into a high degree of job specificity. Certain installations were always completed by the same worker, even though (theoretically) any worker of their skill classification could do the same job. This practice led to the following conditions in final assembly:

- Workers gained proficiency on a small subset of installations, as opposed to all of those that they were qualified to complete,
- Each installation generally had only one worker who was proficient enough to complete it within a reasonable amount of time,
- Knowledge of job peculiarities and workarounds was trapped at the worker level, and

- Workers developed a stash of tools and parts (such as nuts, bolts, and washers) needed for - and specific to - the jobs for which they were proficient; this material was not always indicated on the AOS and not included in the kit.

The combination of these issues resulted in a severe reduction of flexibility in final assembly operations. When the day arrived for a particular installation to be completed, and the worker normally assigned to complete was not available, there was no realistic option for line management to address the situation. Normally, this job would simply wait for the worker to become available later; hence the observation that work moved back and forth through the line instead of adhering to the schedule. Workers actually thought it more productive to take one installation and repeat it on every aircraft currently in WIP on the assembly line. Sometimes workers would even "bank" installations by doing them far in advance, if they were going to leave on vacation, for example. For the JIT project to be successful, there had to be some way for manufacturing to adhere to the assembly schedule.

A Tough Game to Win

> *"As a result of the pilot project, shortages and turnbacks are getting worse. The buffer is going away."*

A primary consideration in the design of a final assembly process is the amount of flexibility incorporated in the process. At Sikorsky (and many other aerospace companies), the diversity and complexity of tasks, model proliferation, and low production volumes result in assembly operations that are organized in a job shop flow. As Buzacott and Shanthikumar [1993] warn, however, this choice incurs some natural tendencies in the resulting process:

- High WIP,
- High flowtimes,
- Difficulty meeting delivery dates,
- Difficulty in knowing progress and in controlling flow, and
- Diversity in process times and routings.

Traditionally, Sikorsky did as many other companies and put a flowtime buffer in between operations using excess inventory. The inventory served to hide as many problems as possible, and schedule changes (e.g. hot-lists, expediting, MPS changes) were used if the problems became too severe.

Many examples in lean literature draw an analogy between reducing inventory (as done by the JIT project) and "lowering the level of water in the river to expose the rocks" [Suzaki, 1993; Black, 1991]. It is useful to consider another dynamic, in light of the hybrid MRP/pull system which the company sought to implement:

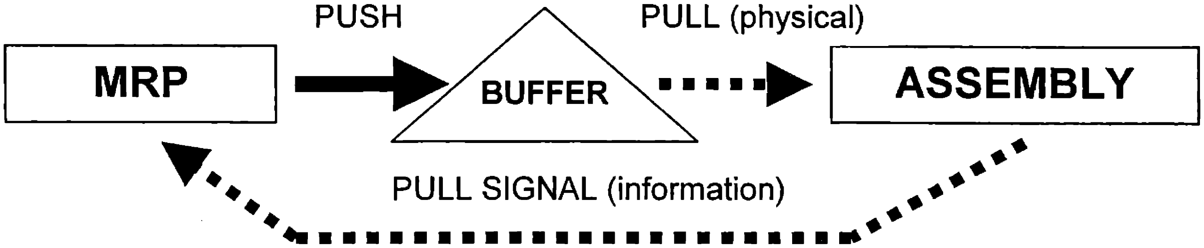


Figure 22
IDEAL HYBRID MRP / PULL SYSTEM

The figure above illustrates how the goal of the JIT project was to create an information link from final assembly to the MRP system, enabling the performance improvements documented by Buzacott for hybrid systems. In reality, the implementation of JIT resulted in a situation more analogous to the following:

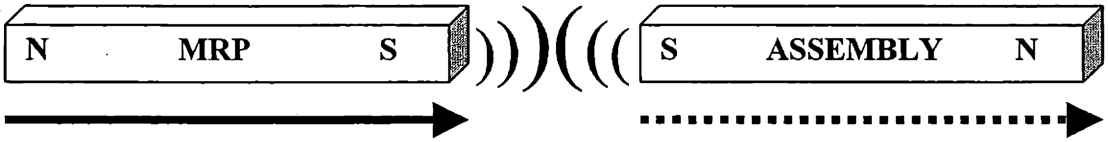


Figure 23
MRP SYSTEM WITH SHORTAGES "PUSHES" ASSEMBLY SCHEDULE TO THE RIGHT

The graphic above shows the MRP supply system and assembly operations represented by two magnets, with the opposite poles facing each other. As delivery dates in MRP were pushed to the right, shortages became more severe, and not having the capacity to recover, assembly would slide further to the right - then MPS would change and delivery dates in MRP would slide right to "catch up" …etc.

The twin evils: variability and utilization

Two equations are introduced for discussion purposes:

Equation 1: Little's Law

$$TH = \frac{WIP}{FT}$$, where

TH is Throughput
WIP is Work In Process
FT is Flow time

Equation 2: Cycle Time as a function of process time (t)

$$CT = \left(\frac{C_e^2 + C_a^2}{2}\right) \bullet \left(\frac{u}{1-u}\right) \bullet t$$, where

CT is Cycle Time (or Flow Time)
C_e^2 is the squared coefficient of variation (SCV) for the process
C_a^2 is the squared coefficient of variation (SCV) for arrivals
u is utilization (varying from 0 to 1)
t is the nominal process time

Equation 1 ("Little's Law") relates throughput to WIP and flow time; e.g. 8 aircraft in WIP with a 24 day flow time = throughput of 1/3 aircraft per day (inverted, this equals a 3-day roll rate). Equation 2 develops the concept of flow time further. MRP uses some costly (and fundamentally incorrect) assumptions of infinite capacity and fixed lead times. Equation 5.2 shows that actual flow time is not fixed, but will vary from the process time (t) according to variability (in both process and arrivals) and utilization. Assembly operations have already been shown in Chapter 5 to be subject to significant variability, but they also suffer from high capacity. Figure 24 shows the total amount of labor required to complete each unit:

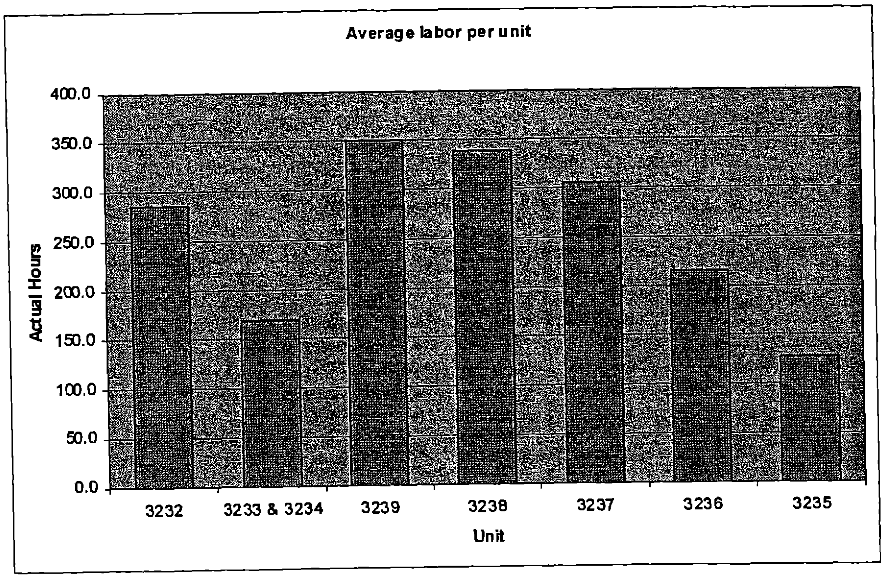


Figure 24
AVERAGE TIME TO COMPLETE WORK IN UNITS 3232 THROUGH 3239

As discussed in chapter 3, some of these units would have considerable difficulty completing all the installations in that unit (if held to a strict assembly schedule) at fast roll rates (i.e. three days of less), even under ideal conditions. Using the unit with the highest average labor content, utilization varies from about 0.8 to 1.0, depending on assumptions for production rate and number of workers available per aircraft. Knowing that the variation of cycle time with utilization is as depicted below:

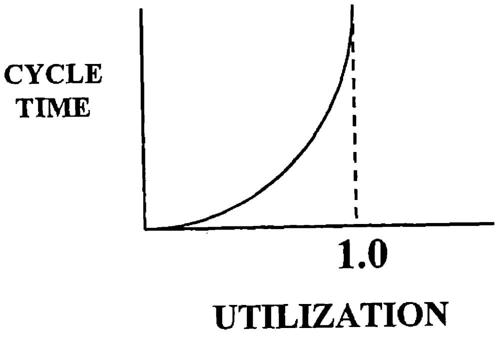


Figure 25
RELATIONSHIP BETWEEN CYCLE TIME AND UTILIZATION

it follows that high levels of utilization in final assembly only contribute to performance problems.

In summary, the situation faced by final assembly was as follows:

- Support organizations external to final assembly (including both the company and its suppliers) are a source of variability, which precludes the precise scheduling of assembly operations envisioned by the JIT project.
- Although the sequence of operations within each unit is sufficient to implement sequenced material delivery by the JIT project, the overall allocation of installations to units is not optimal, and final assembly cannot attain a purely "serial" unit-by-unit production within the desired overall flow time.
- The design and management of labor operations in final assembly itself, specifically the high utilization rate of personnel and relative inflexibility of labor scheduling, leaves final assembly unprepared to deal with problems when they do arise.

Chapter 6: Strategies for lean implementation

The real problem

As opposed to the two symptomatic problems (direct labor overruns and excess inventory) identified earlier, the real problem with manufacturing operations at Sikorsky was a more systemic, higher level problem, associated with the transformation from the "Sikorsky of old" to a newer, leaner company. Essentially, the JIT project represented the introduction of lean manufacturing techniques in an environment where the groundwork required for lean manufacturing had not been laid. This view was supported through the identification of collateral factors that were outside the scope of the project, but all of which adversely affected implementation success. These numerous factors were grouped into five over-arching categories (shown below). Included with each is a short prescriptive statement, representing an idealized description of what the customer (manufacturing) was asking for at the company:

Supply chain management

> *The organizations responsible for managing the supply chain must coordinate to ensure on-time delivery of quality parts to their customers throughout manufacturing.*

Product design and development

> *The organizations responsible for design (and design changes) must coordinate for the timely delivery of accurate and easy-to-use build information to manufacturing, and should incorporate "DFX" criteria in the design process.*

Manufacturing organizational design

> *The company needs to eliminate the structural barriers that create disincentives for functional groups to communicate with and help each other.*

Labor relations

> *Management needs to create an environment of trust, acceptance of change, cooperation and continual learning within the workforce.*

Leadership

Top management needs to articulate a clear direction for change, and demonstrate a 100% commitment to making the changes necessary for success.

Where the detailed problems identified in Chapter 5 represent barriers to JIT implementation, the five areas described above are a step closer to identification of the root cause of these problems. In essence, shop floor personnel would claim that the problems identified in Chapter 5 were widely known – and that a primary reason they have never been solved is due to deficiencies in the five over-arching areas shown above. These personnel believed (rightly so) that bottom-up action alone would not be successful in solving these problems. The remainder of this chapter will accomplish the following:

- Document some of the observations leading to identification of these five areas,
- Present insights from research on how to solve these issues through implementation of lean manufacturing methods, and
- Summarize the findings of this project with specific recommendations for Sikorsky.

Symptoms of the real problem

There were many problems encountered by the JIT project, some of which (such as parts shortages and quality) were documented in Chapter 5. There were other problems, however, that were not captured or commented on specifically in that analysis. These problems would include such issues as poor work instructions, late design changes, or lack of participation in the JIT project. While these other problems are too numerous to list, they can be aggregated into the five over-arching areas that have been proposed. This section develops these ideas further and provides some additional details, in order to understand the link between these issues and problems encountered by the JIT project.

Supply chain management

Shortage problems in final assembly were indicative of a larger, more pervasive supply chain management problem at the company. Quality and delivery issues seen in manufacturing operations were both frequent and random, indicating that (1) the problems were systemic and pervasive and (2) they were not limited to one supplier, one product line, etc. In addition, shortage and quality problems had existed for basically the entire history of Blackhawk production (dating back to the late 1970's). Some of the issues identified with supply chain management at the company included:

- Many parts had very long lead times, sometimes longer than the contract lead time for the aircraft itself (especially when the aircraft was sold at less than the standard lead time),
- Sikorsky has lost bargaining power with suppliers due to extremely low productions rates,
- Production of spare parts for the after-market was difficult to plan, and sales of spare parts sometimes cannibalized parts designated for production aircraft, and
- There have been problems with the procurement process, such as delays turning engineering requirements into requisitions, and delays turning requisitions into purchase orders.

Managers were understandably reluctant to begin a comprehensive analysis of material management practices at the company. Earlier efforts had led to the conclusion (or capitulation) that holding inventory buffers was the easiest way to "solve" the supply chain problem. However, failure to complete the difficult task of supply chain analysis will preclude the success of the JIT project – or any other lean manufacturing process which seeks to fulfill the stated company goal of inventory reduction.

Product design and development

The engineering organization at Sikorsky is still organized along functional lines, although integrated product teams (called "Platform Teams" at the company) are being phased in. The company suffers from very poor connectivity between IT systems (even within engineering); for example: links between computer systems which handle drawing & document management, bill of material, engineering specifications, and engineering change orders are either weak or non-existent [Ambrose et al., 1999]. Engineering is typically understaffed by up to 25%, and must deal with externally-imposed project timelines. As a result, it is not uncommon for design activities to be occurring well after lead-items have begun final assembly, creating a very chaotic situation within the material and manufacturing organizations. Workers note that because of other pressures, it is nearly impossible to get engineering to participate in re-design initiatives to improve assembly or manufacturability. Given this environment, it is even more important to use DFM/DFA techniques up front when designing low-production volume products, since these items rarely undergo design reconsideration [Boothroyd, Dewhurst, Knight, 1994]. Yet at

Sikorsky, these low-volume items have been in production for many years (over twenty for the Blackhawk), so worker frustrations have been ongoing for decades.

Manufacturing organizational design

Managers at Sikorsky recognize that many of the problems with coordination across functions will not be solved without some organization redesign, such as the creation of cross-functional teams. A case study in "Lean Thinking" [Womack and Jones, 1996] depicts how Pratt and Whitney (another UTC company) began their journey to lean manufacturing with a reshaping of the organization, to eliminate many of the structural and functional barriers to company-wide implementation and cooperation. Organizational redesign and cross-functional teams have already begun to be implemented at the company, but are encountering significant organizational resistance. Issues with implementing cross-functional teams have been extensively researched. Some managers at the company were understandably concerned about the 'balance of power' and incentives within a matrix structure. Katz and Allen [1985] demonstrate that team performance is highest when project/program managers ('outwardly focused') had the most influence over ratings, salary, promotions and assignments, and functional managers ('inwardly focused') over training and maintenance of technical standards. Additionally, Fowler [1995] addresses team formation, Zetlin [1996] provides guidelines for team functioning, and Zigon [1997] provides team measurement methodologies. These and other resources can be used to effectively solve the problem of developing effective cross-functional teams.

Labor relations

As with many companies in the aerospace manufacturing industry, Sikorsky employs a unionized workforce. There are several issues regarding the relationship between management and the union at the company which impact the success of change initiatives:

- Individually, workers are mildly supportive of change, but overwhelmingly skeptical and pessimistic of chances for success,
- They do not always provide input, even when they know problems and/or solutions, and
- There is a historical lack of trust on both sides, which affects the ability of management to introduce changes.

These conditions make it extremely difficult to implement any kind of process improvement in the shop floor environment. Management needs to take steps to improve the informal working relationship between labor and supervision, and also change the formal contract with the union, to provide flexibility and align incentives to support change.

Leadership

The JIT project did not have a level of interest and involvement by top management necessary to ensure its success. This involvement was needed in order to:

1. Demonstrate commitment on the part of top management to the change initiative, so that trust and acceptance were built up in the workforce, and
2. Provide the vision and goals for the project, and relate how they fit into the overall goals for the company, so that line management understood what the priorities were and could make decisions on their own that were in support of company policy.

An interesting research validation of the need for top-management involvement is provided by Shiba, Graham, and Walden [1993], who state that successful change: (1) requires top management involvement and (2) cannot have strong opposition from workers. Middle and upper management do not, in fact, determine the chance for success; the best they can do is influence the other parties.

Approaches from literature

Failure to take a systematic, comprehensive approach to solving the enterprise-wide problems noted above is not unique to Sikorsky. A widely-circulated article in Aviation Week & Space Technology titled "People Issues Are Cracks in Aero Industry Foundation" asserts:

> *"A chronic lack of vision, an emergence of 'survival' management and worker priorities, a Wall Street-driven focus on stock prices and short-term returns at the expense of research and development, ten years of downsizing and a never-ending preoccupation with cost-cutting have taken their toll on the [aerospace] industry [Scott, Aviation Week & Space Technology, 1999]."*

The JIT project was viewed as having significant promise, but initially enjoyed only limited success in implementation. For a manufacturing process to be able to create a build plan based on master schedule, then have all the required parts arrive on time and be consumed on the date planned (as the JIT project sought to do), it must be a capable and robust process. An outline of the steps necessary to prepare a hybrid MRP / Pull process to reduce inventory to the JIT goal of "zero inventory" was given by Edwards [1983]:

The "seven zeroes:"

1. Zero defects
2. Zero excess
3. Zero setups
4. Zero breakdowns
5. Zero handling
6. Zero lead time
7. Zero surging

These seven "ideal" conditions are certainly a goal for any manufacturing company. Toyota has made perhaps the most progress of any large manufacturing company towards these goals, through the use of the Toyota Production System (TPS). TPS consists of many lean manufacturing techniques, such as the use of linked cellular manufacturing systems (L-CMS), JIT, and pull production with kanban cards. But the real key to the success of TPD is that Toyota had created a "community of scientists" – both labor and management – that constantly improve every process and solve every problem using the scientific method [Bowen and Spear, 1999]. Philosophically, Toyota is in alignment with the "seven zeroes" – they do not even consider kanbans or andon cards to be solutions; they are temporary "countermeasures" on the way to some future, more perfect system.

How should Sikorsky begin? The high-performing, continuously-improving Toyota Production System described above is an excellent model, but even companies that have been emulating TPS for years have not achieved their level of excellence. In the "Fifth Discipline Fieldbook" [Senge, 1994] the following seven common characteristics of failed or stalled change initiatives are outlined:

1. Lack of a clear shared mental model throughout the organization,
2. Lack of shared values and vision for the organization,
3. Compliance rather than commitment as the driving force,
4. "Steel-reinforced concrete silos,"
5. Non-systemic approach to implementation,
6. Senior managers with incomplete transformational leadership skills, and
7. Inability to learn collectively.

Research suggests that Sikorsky should adopt a two-pronged approach for change: (1) Top-down and (2) Bottom-up. The leadership of the company has responsibility for policy, structure and resource allocation decisions that shape the organizational culture as a whole [Baba et al., 1996]. However, change initiatives can still be thwarted by local cultures at the bottom of the organization. These local cultures grow out of the work practices and experiences that people have in "getting work out the door," creating a powerful set of shared beliefs. Top-down and bottom-up change processes are interdependent. Change at the top of the company enables change on the floor, and cultural change on the shop floor makes it possible to enact new strategies. Together, these two approaches will help (1) solidify and drive top management determination to embed the change throughout the company and (2) change the traditional ways of doing things at the bottom level, so the company can evolve into a progressive, learning organization.

There are many excellent resources for structuring these two types of change, but two resources in particular can be of great help to Sikorsky:

1. Top-down: "Transition-to-Lean Roadmap," Production Operations [Lean Aerospace Initiative, 2000].
2. Bottom-up: "The New Shop Floor Management: Empowering People for Continuous Improvement," [Suzaki, 1993].

Transition-to-Lean Roadmap: Lean Aerospace Initiative

The Lean Aerospace Initiative (LAI), founded in 1993, is a cooperative research program comprised of government, industry and academic partners. The goal of LAI is to identify, and translate into practice, principles that will aid the transition of aerospace companies from cold-war era producers into "faster, better, cheaper" lean manufacturing enterprises. One of the primary products of LAI is the Lean Enterprise Model (LEM) – a framework for capturing the research results and best practices of LAI members.

The LEM consists of the following top-level elements:

Meta Principles:

- Responsiveness to Change
- Waste Minimization

Enterprise Principles:

- Right thing, right place, right time, right quantity
- Effective relationships within the value stream
- Continuous improvement
- Optimal first delivered unit quantity

Within the LEM are overarching practices, which identify the capabilities required for implementation of lean manufacturing in the organization; these are shown below:

Table 2
LEAN ENTERPRISE MODEL – OVERARCHING PRACTICES

1. Identify and Optimize Enterprise Flow	*Optimize the flow of products and services, either affecting or within the process, from concept design through point of use.*
2. Assure Seamless Information Flow	*Provide processes for seamless and timely transfer of and access to pertinent information.*
3. Optimize Capability and Utilization of People	*Assure that properly trained people are available when needed.*
4. Make Decisions at Lowest Possible Level	*Design the organizational structure and management systems to accelerate and enhance decision making at the point of knowledge, application, and need.*
5. Implement Integrated Product Process Development	*Create products through an integrated team effort of people and organizations that are knowledgeable of and responsible for all phases of the product's life cycle from concept definition through development, production, deployment, operations and support.*
6. Relationships Based on Mutual Trust and Commitment	*Establish stable and on-going cooperative relationships within the extended enterprise, encompassing both customers and suppliers.*
7. Continuous Focus on the Customer	*Proactively understand and respond to the needs of the internal and external customers.*
8. Promote Lean Leadership at All Levels	*Align and involve all stakeholders to achieve the enterprise's lean vision.*

Table 2 (continued)

9. Maintain Challenges of Existing Processes	*Ensure a culture and systems that use quantitative measurement and analysis to continuously improve processes.*
10. Nurture a Learning Environment	*Provide for the development and growth of both organizations' and individuals' support of attaining lean enterprise goals.*
11. Ensure Process Capability and Maturation	*Establish and maintain processes capable of consistently designing and producing the key characteristics of the product or service.*
12. Maximize Stability in Changing Environment	*Establish strategies to maintain program stability in a changing customer driven environment.*

A recent product of LAI has been the construction of a checklist or "roadmap" for companies to implement the processes, policies and practices found in the LEM. The LAI Production Operations team used a wide variety of implementation models and academic research, along with examples and case studies from industry, to develop the roadmap. It is not a strict "cookbook," but the elements serves as checkpoints in the process: they should be in place (to some degree) or should have a plan to address them, before proceeding to the next phase. The Transition-to-Lean roadmap consists of the following:

Table 3
THE LAI TRANSITION-TO-LEAN ROADMAP

Lean Implementation Phase	Enabling Processes
Phase 0 – Adopt Lean Paradigm	0.1 – Build Vision 0.2 – Establish Need 0.3 – Foster Lean Learning 0.4 – Make the Commitment 0.5 – Obtain Senior Leadership buy-in
Phase 1 – Prepare	1.1 – Integrate with the Enterprise Level 1.2 – Establish Operations Lean Implementation Team 1.3 – Develop Implementation Strategy 1.4 – Develop a Plan to Address Workforce Changes 1.5 – Address Site Specific Cultural Issues 1.6 – Train Key People 1.7 – Ensure System of Metrics is Aligned
Phase 2 – Define Value	2.1 – Select Implementation Scope 2.2 – Define Customer 2.3 – Define Value

Table 3 (continued)

Phase 3 – Identify Value Stream	3.1 – Record Current State across Value Stream 3.2 – Map Product and Information Flow 3.3 – Chart Operator Movement 3.4 – Chart Tool Movement 3.5 – Collect Baseline Data
Phase 4 – Design Production System	4.1 – Develop a future state value stream map 4.2 – Identify Lead Time and Takt time requirements 4.3 – Review Make/Buy decisions 4.4 – Plan new layout 4.5 – Integrate suppliers 4.6 – Design visual control system
Phase 5 – Implement Flow	5.1 – Achieve Process Control 5.2 – Implement TPM 5.3 – Implement Self-inspection 5.4 – Eliminate / Reduce waste 5.5 – Cross train workforce 5.6 – Standardize Operations 5.7 – Reduce set-up times 5.8 – Mistake proof processes 5.9 – Implement cell layout 5.10 – Implement visual controls
Phase 6 – Implement Total System Pull	6.1 – Select appropriate production system control mechanism 6.2 – Establish single piece flow where appropriate 6.3 – Level and balance production flow 6.4 – Link with suppliers 6.5 – Draw down inventories 6.6 – Re-deploy people 6.7 – Re-deploy / dispose of assets
Phase 7 – Strive for Perfection	7.1 – Optimize Quality 7.2 – Institutionalize 5s 7.3 – Institute Kaizen Processes 7.4 – Remove System Barriers 7.5 – Expand TQM 7.6 – Evaluate Against Target Metrics 7.7 – Evaluate Progress using Lean Maturity Matrices

A graphic that illustrates the process envisioned by the Transition-To-Lean Roadmap is provided in Appendix G.

Considering the table above, it appears that the JIT project proceeded as follows:

0.2 – Establish Need
1.3 – Develop Implementation Strategy
2.1 – Select Implementation Scope
3.5 – Collect Baseline Data
6.1 – Select appropriate production control mechanism
6.4 – Link with suppliers
6.5 – Draw down inventories

Given the pressure with the company to reduce inventory, the JIT project was essentially a "race" to get to step 6.5 (Draw down inventories). There were significant aspects missing in this strategy:

- Phases 0 through 4 (primarily, enterprise-wide considerations) were given limited consideration. Generally, the appropriate players were not even involved.
- Phase 5 addresses the shop floor. The JIT project did not include changes to improve the capabilities of the manufacturing process – it was imposed externally, without consideration of the capability of manufacturing to support it.

Overall, the Transition-To-Lean Roadmap provides a useful framework for the planning and coordination of lean implementation projects. Using the proposed structure of phased implementation, flaws can be seen in the approach used by the company. The framework should be used in the future to guide managers to a more successful enterprise-wide approach to organizational change and lean implementation.

Bottom-up strategies: The New Shop Floor Management

In The New Shop Floor Management [1993], Suzaki presents a summary of effective shop floor management techniques and practices, distilled from the experience of numerous successful Japanese companies. There are three fundamental tenets for managing shop floor operations:

1. **Focus on reality**

   Getting out on the floor as a means to understand problems:

   - Genba – real place
   - Genbutsu – real thing
   - Genjitsu – real fact

2. **Simplify management processes**

   Suzaki advocates the "QCDSM" set of simple management metrics:

   - Quality
   - Cost
   - Delivery
   - Safety
   - Morale

3. **Worker involvement for continuous improvement**

   As individuals:

   - Base judgement on facts
   - Develop a customer orientation
   - Use problem solving skills such as PDCA

   As an organization:

   - Share the vision
   - Develop a comprehensive management system (i.e. measure all of the right things)
   - Educate, train and celebrate success

Suzaki recognizes that mindset issues and worker attitudes can be significant barriers to any change, and the experience of implementing JIT during the internship certainly supported this view. The following are some "attitudes that block improvement" from the book (these in fact were heard nearly verbatim during the internship):

- *I know everything is fine. There is not a problem.*
- *We have tried everything. I know all the reasons why things will not work.*
- *This is how we have done it for many years. This is the best method for us.*
- *It's not my responsibility to make improvements.*
- *Improvements cost money. Give me money, then I will fix it.*
- *I'm too busy to do anything else.*
- *What's in it for me?*

Suzaki presents counter-attitudes, which need to be modeled and reinforced by everyone involved in the change process, especially lower-level managers and supervisors:

- Always consider the current situation as imperfect.
- Do away with a fixed mindset. Think from a broader perspective.

- Keep working on improvement until fire-fighting goes away.
- Ask "why" repeatedly to get to the root cause and fix it – permanently.
- Collect people's wisdom, as opposed to depending on one's own wisdom.
- Implement good ideas immediately. Stop bad habits immediately.
- Even if it isn't perfect, move ahead in the right direction, one step at a time.

In addition, Suzaki advocates a number of problem-solving techniques, many of which are commonly used or cited in literature: pareto charts, control charts, PDCA cycle, the five why's, Gantt charts, etc. Given the level of worker participation in change initiatives and improvement projects at the company, the most effective recommendation for Sikorsky is the elimination of the "eighth waste" – wasting people's talent. Once top management articulates the real goal for final assembly (is it to reduce labor, or reduce inventory, or reduce flowtime?) then shop floor management should bring workers into the process, to design a process that will utilize their knowledge and creativity, and also meet their needs and concerns. How will management know when they are being successful? Sikorsky needs to begin observing, evaluating and measuring levels of the following:

- Use of QCDSM
- Number of suggestions
- Absenteeism, claims and grievances
- Housekeeping and organization
- Visual tools (charts, graphs, pictures) on the floor
- Information sharing (newsletters, etc.)
- Meetings on the shop floor
- Top management participation in recognition of progress
- Visibility of top management on the floor
- Effectiveness of education and training
- Clarity of the management process
- Reduction of variation and implementation of SOP
- Mechanisms to expose problems

Benchmarking and Case Studies

During the course of the internship, benchmarking studies were conducted to develop solutions or recommendations for some of the key difficulties identified in final assembly. The template used for collecting data at the companies is provided in Appendix E. Site visits were conducted at the following facilities:

- Pratt & Whitney, Middletown CT (Final Engine Integration facility)
- HamiltonSundstrand, Windsor Locks CT (Environmental Control Systems)
- Instron Corporation, Canton MA (Industrial Test Equipment)
- Narragansett Shipwrights, Newport RI (Custom boat construction)

A detailed listing of findings from benchmarking visits is provided in Appendix F. The following is a summary of the key points identified during these visits:

- Create a simple, visual factory
- Manufacturing support functions are critical to success
- Manufacturing must create flexibility (excess capacity)
- Design innovative ways to cross functions and create ownership
- No throwing stuff over the fence
- Even assembly operations should be sequenced
- Need to get the incentive structure right

In addition to the valuable information obtained through benchmarking visits, the author recommends the site visits themselves as a valuable opportunity for manufacturing personnel at Sikorsky. As with other companies, there was a tendency to view outside material with suspicion - the "Not Invented Here" syndrome. As a UTC company, Sikorsky employees have ready access to other companies within the UTC structure: Pratt and Whitney, HamiltonSundstrand, Carrier, and Otis. Each company has its strengths and weaknesses, just as Sikorsky does, but they can be an invaluable source of practical solutions and empirical evidence for process improvement. For Pratt and Whitney and HamiltonSundstrand in particular, there are operations in the local area which have been singled out as "best practice" operations, and written up in literature or case studies. It would be very beneficial for Sikorsky employees (managers, engineers, and line workers) to see these operations for themselves, so they can judge which techniques could best be applied at their own company - and be convinced through first-hand knowledge of the results which can be obtained.

Putting it all together

As opposed to the fairly narrow view of "assembly process optimization" originally intended for this project, the internship (and thus, this thesis) moved to cover a lot of ground. Large-scale manufacturing processes can be, in the words of an MIT colleague, "dauntingly complex." It would be easy to accept the status quo as somehow being "optimum" – the result of some least-resistance path process, which cannot be improved by tinkering. Managers at the company were heard to tell visitors in manufacturing "*Now* you see how difficult it is," satisfied that this difficulty was sufficient explanation for the current state of affairs.

The key learning for this intern, and hopefully for the company as well, was that a complex manufacturing process can be improved – not by the ad-hoc solutions of individuals or small groups, but through systematic application of widely-known and proven manufacturing management techniques:

- Large-scale systemic problems require enterprise-wide action and solutions,
- Local processes can (should!) be constantly improved through focus on basic principles, and
- The entire workforce needs to be infused with a culture for change and continuous learning.

Numerous recommendations, both general and specific, have been provided herein. Without repeating all of them, it can be said that they fall into the two methods for change proposed earlier of (1) top-down and (2) bottom-up. Some key recommendations include:

- Draw in senior leadership from organizations which surround (and support) manufacturing.
  - Demonstrate the tight coupling between functionally-aligned processes in the company.
  - Gather the type of data that will show the shortcomings in processes which support manufacturing (such as late material deliveries or recurring quality issues).
  - Begin to attack system-wide problems from an enterprise perspective.
  - Focus on metrics which are better indicators of system performance (such as schedule compliance, instead of Direct Labor).
- Begin a dialogue with union workers, and transform shop floor management processes.
  - Workers have to be involved with the redesign of shop floor processes; if not, change initiatives simply become the "program of the month."

- Utilize insights generated by the JIT project to conduct more appropriate tradeoff studies. These will support investments in people and processes to reduce flowtime and cost.

The JIT project is essentially a "middle management" strategy – it is neither top-down nor bottom-up, and has thus been stymied by the types of problems described earlier. If used correctly, however, the JIT project could prove invaluable – combined with the research sources highlighted in this thesis, it provides a clear case with compelling evidence to actually begin the processes of top-down and bottom-up change, that will enable Sikorsky to become a truly lean aerospace manufacturing company.

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APPENDICES

Appendix A: Schedule performance prior to JIT project (aircraft serial numbers 735, 736, and 737)

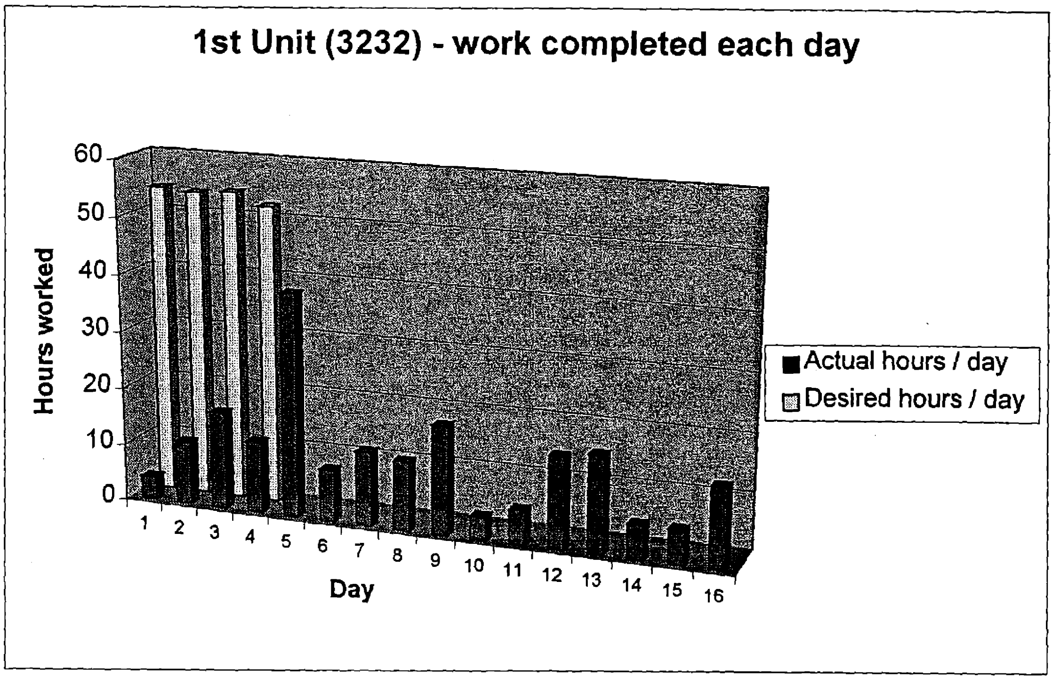


Figure A.1 – ACTUAL HOURS WORKED PER DAY PRE-JIT (UNIT 3232)

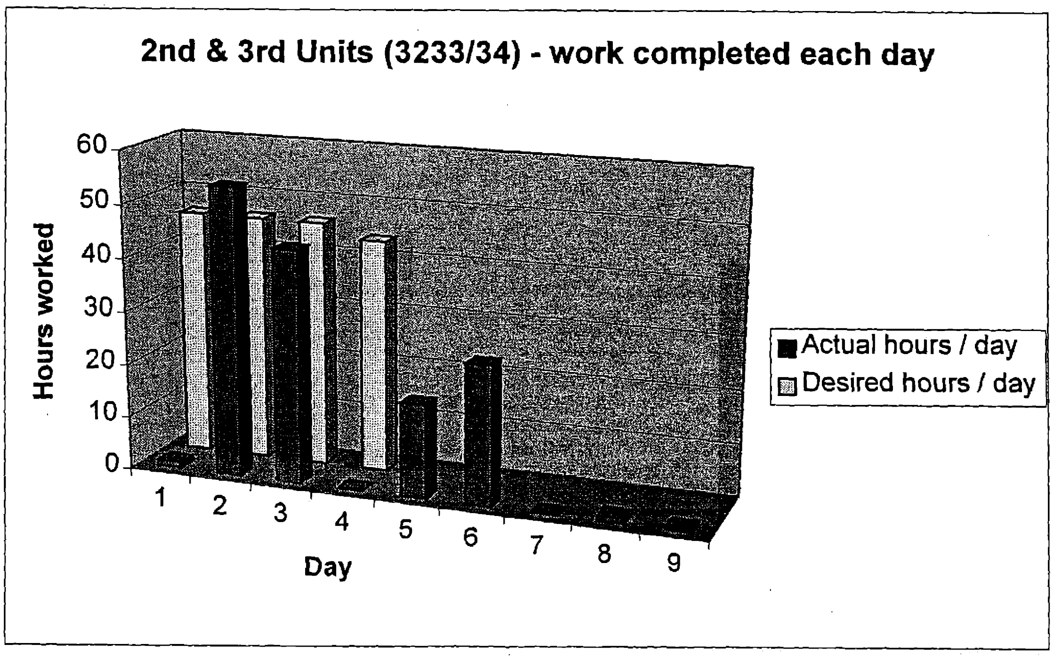


Figure A.2 – ACTUAL HOURS WORKED PER DAY PRE-JIT (UNIT 3233 AND 3234)

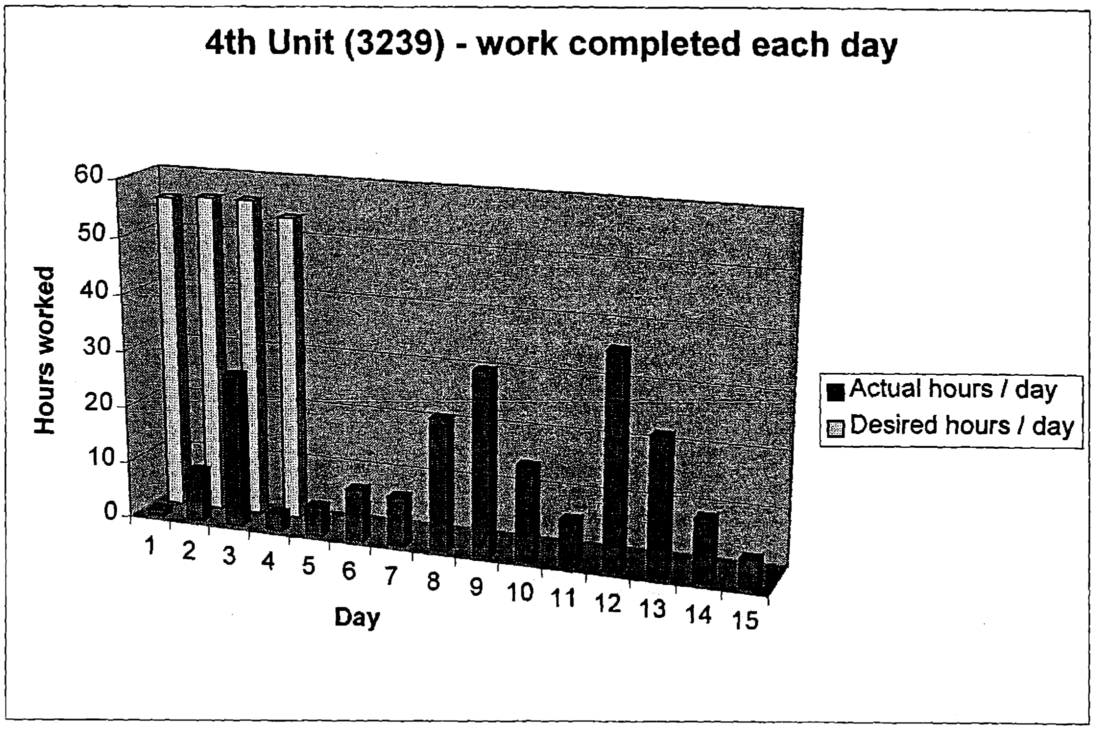


Figure A.3 – ACTUAL HOURS WORKED PER DAY PRE-JIT (UNIT 3239)

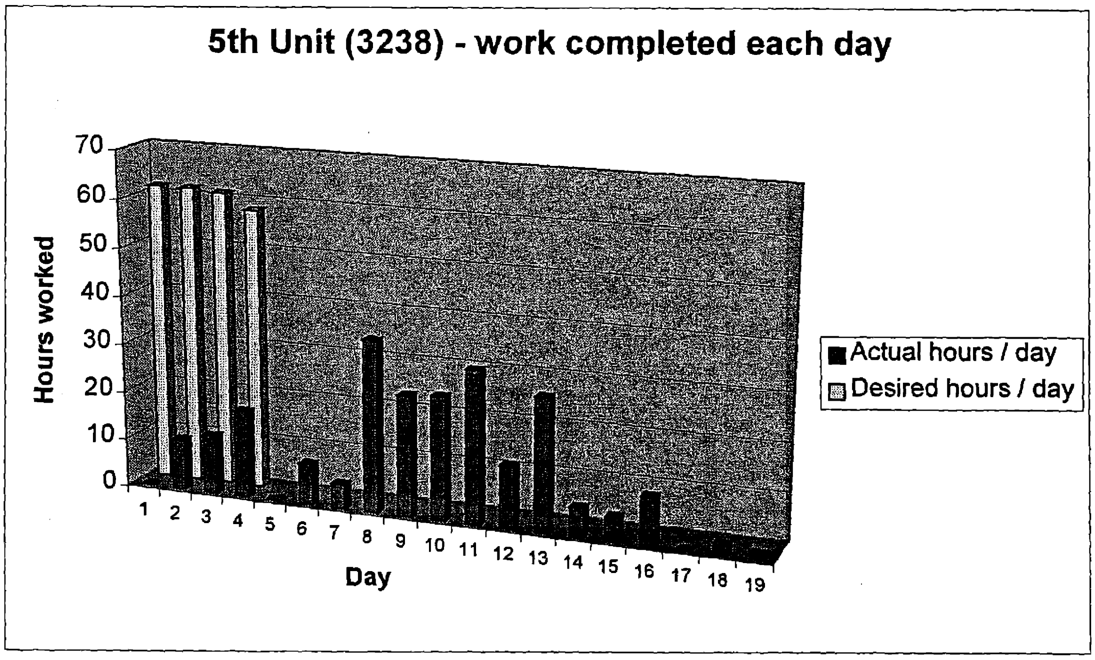


Figure A.4 – ACTUAL HOURS WORKED PER DAY PRE-JIT (UNIT 3238)

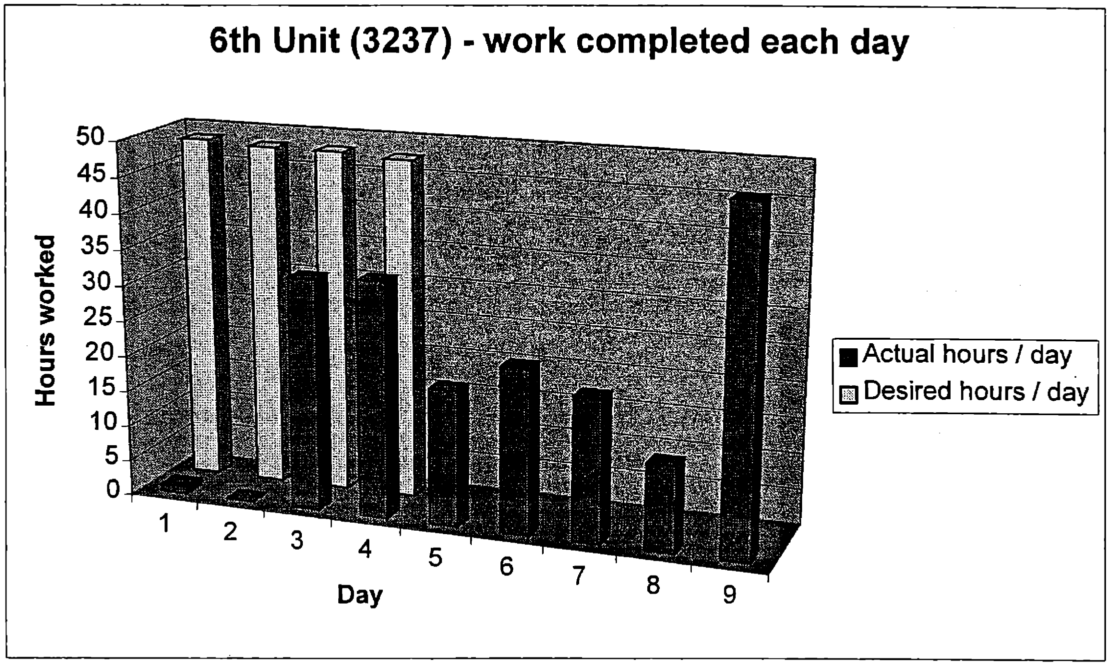


Figure A.5 – ACTUAL HOURS WORKED PER DAY PRE-JIT (UNIT 3237)

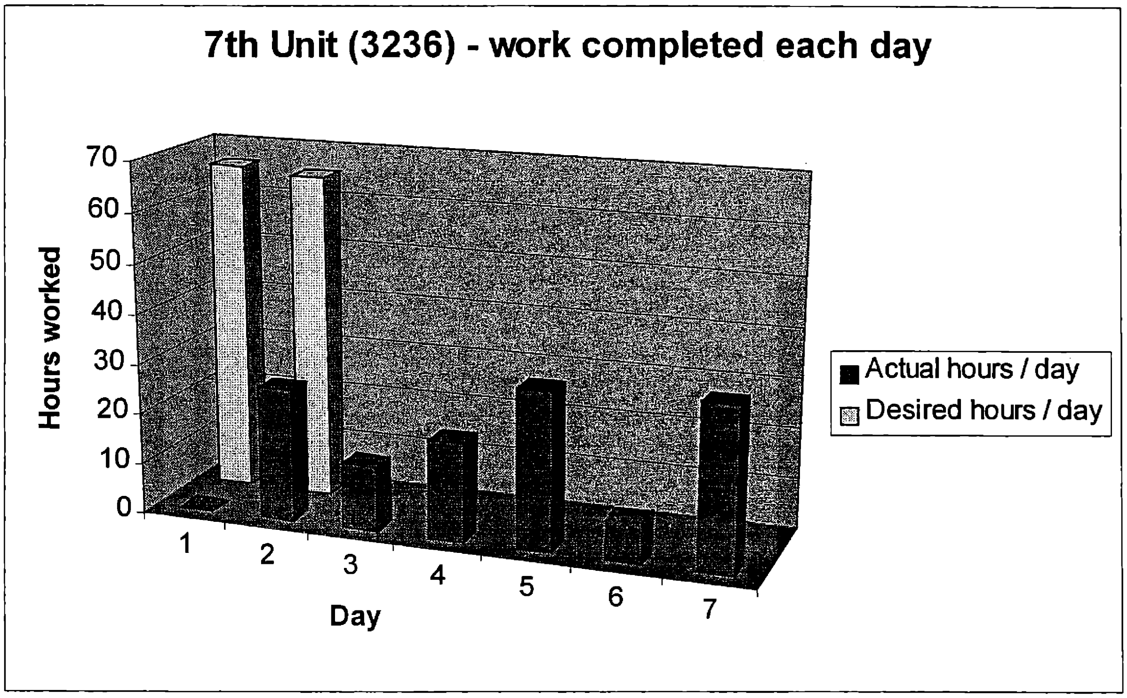


Figure A.6 – ACTUAL HOURS WORKED PER DAY PRE-JIT (UNIT 3236)

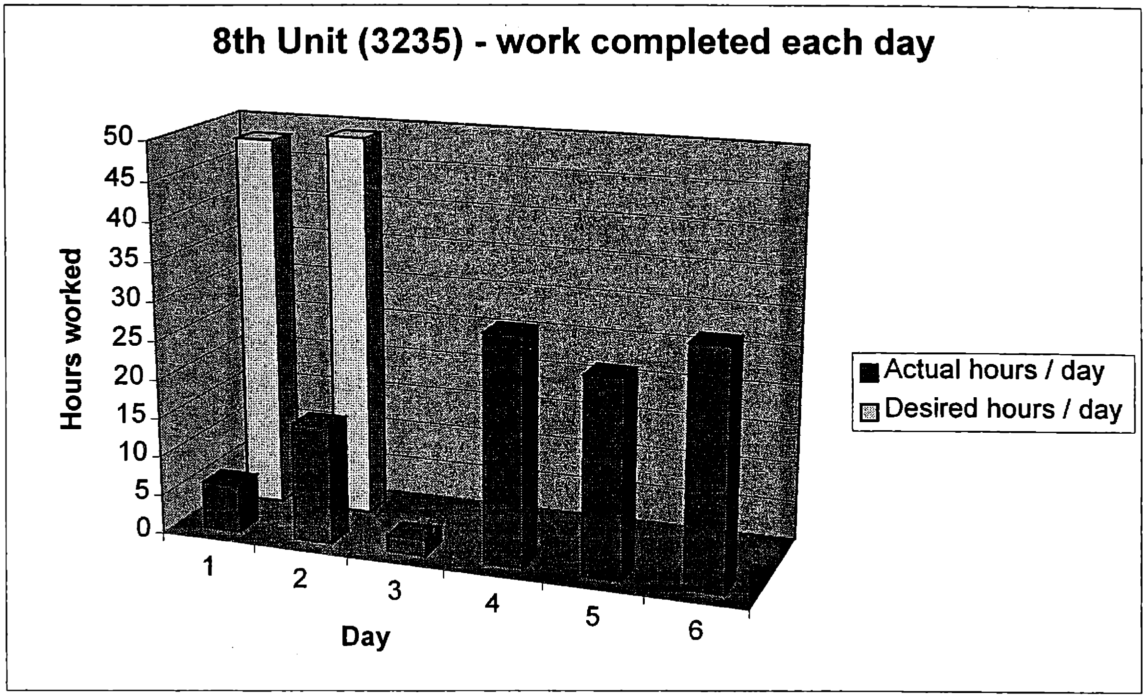


Figure A.7 – ACTUAL HOURS WORKED PER DAY PRE-JIT (UNIT 3235)

Appendix B: Schedule performance for 3rd JIT aircraft (serial number 745)

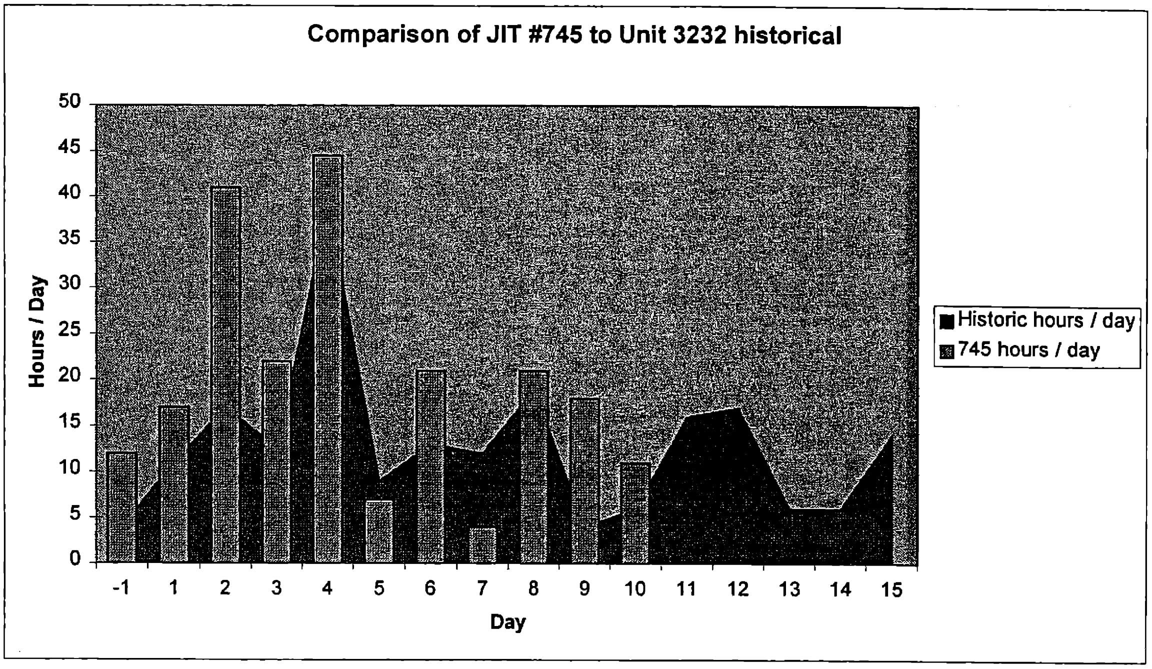


Figure B.1 – ACTUAL HOURS WORKED PER DAY ACFT #745 (UNIT 3232)

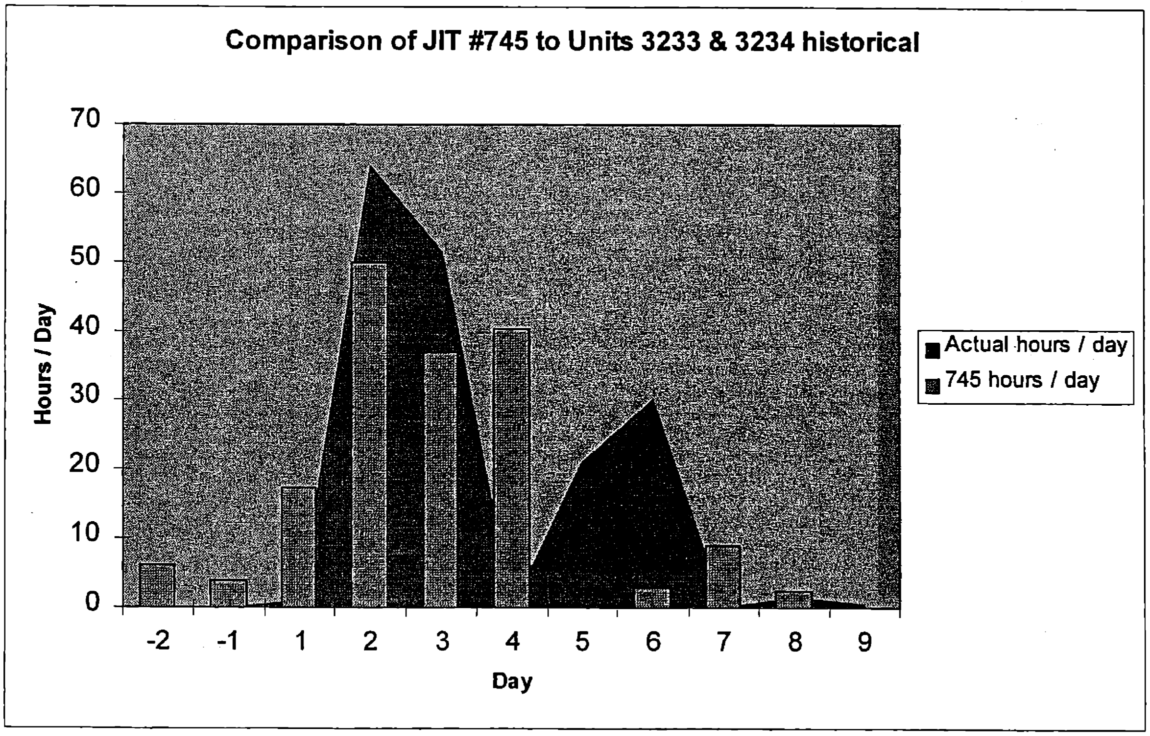


Figure B.2 – ACTUAL HOURS WORKED PER DAY ACFT #745 (UNIT 3233 AND 3234)

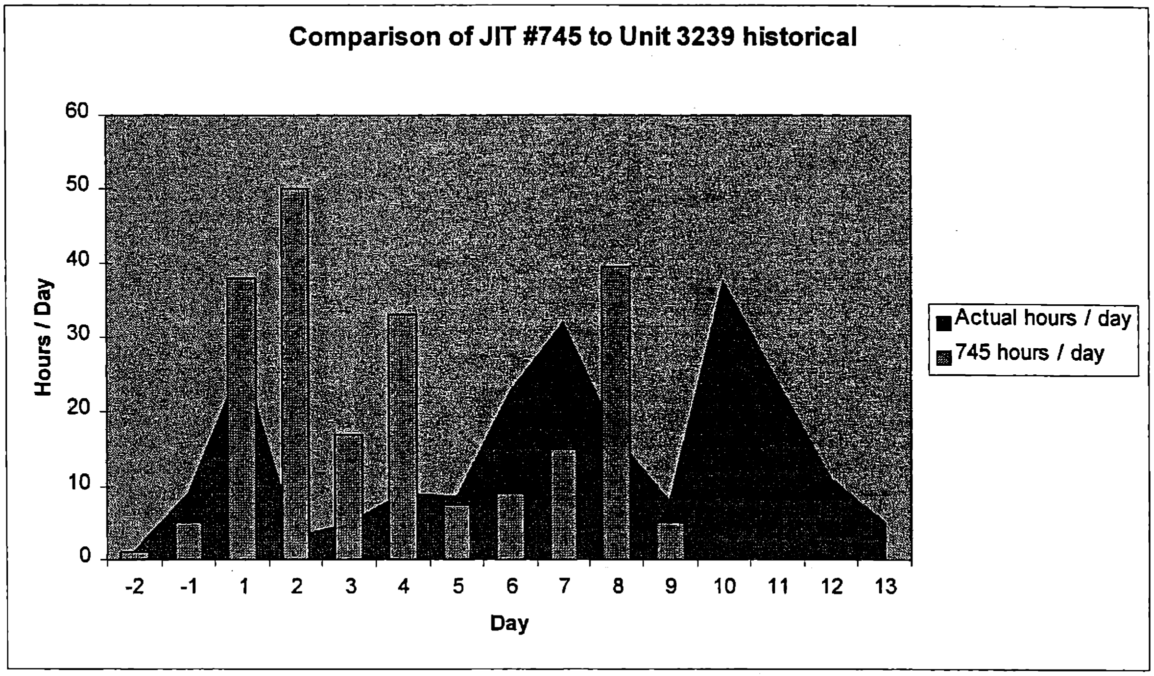


Figure B.3 – ACTUAL HOURS WORKED PER DAY ACFT #745 (UNIT 3239)

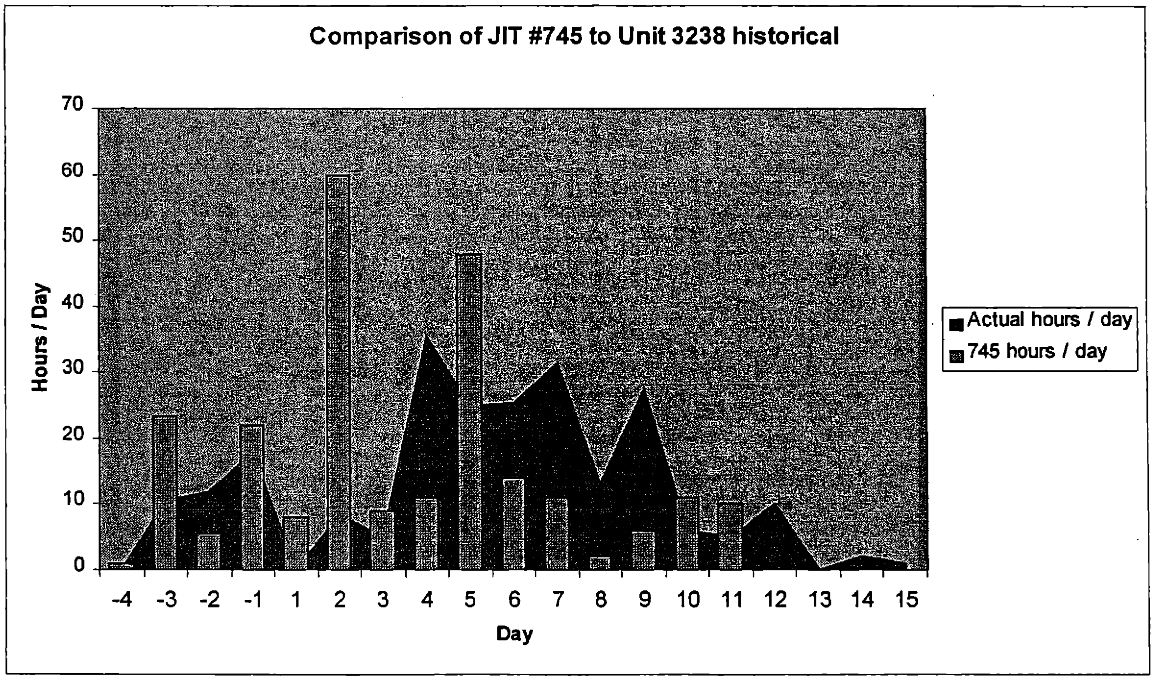


Figure B.4 – ACTUAL HOURS WORKED PER DAY ACFT #745 (UNIT 3238)

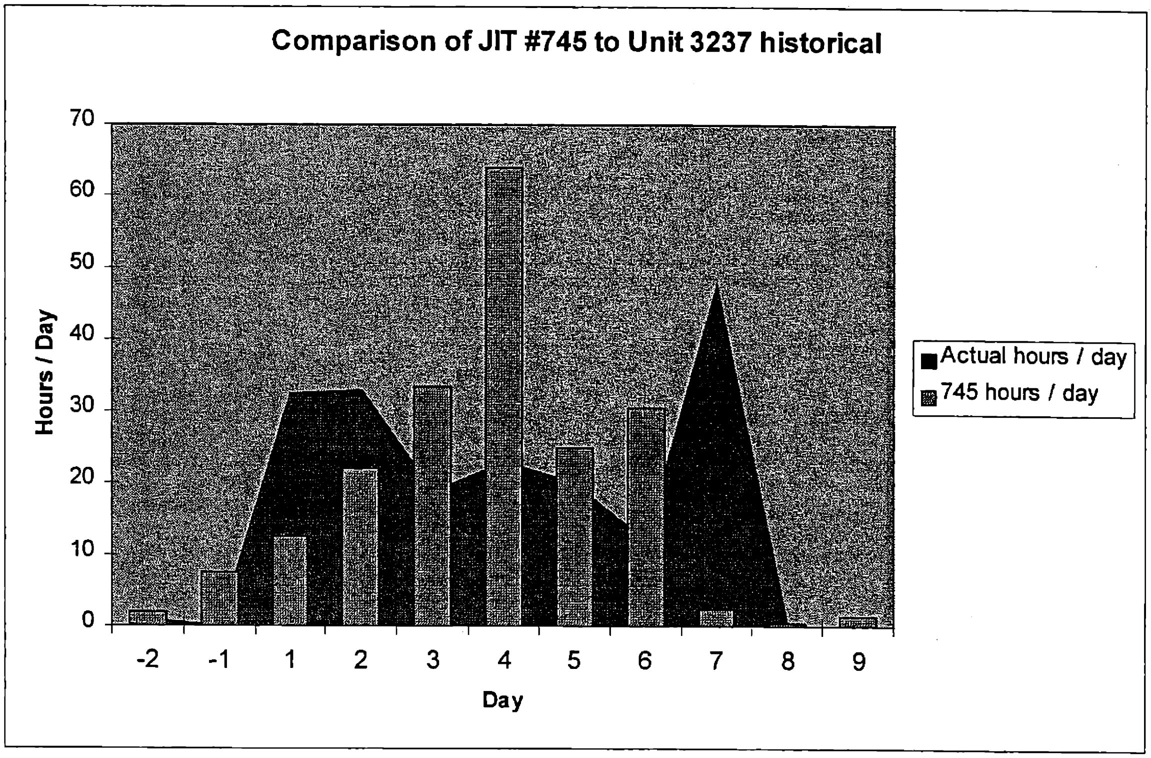


Figure B.5 – ACTUAL HOURS WORKED PER DAY ACFT #745 (UNIT 3237)

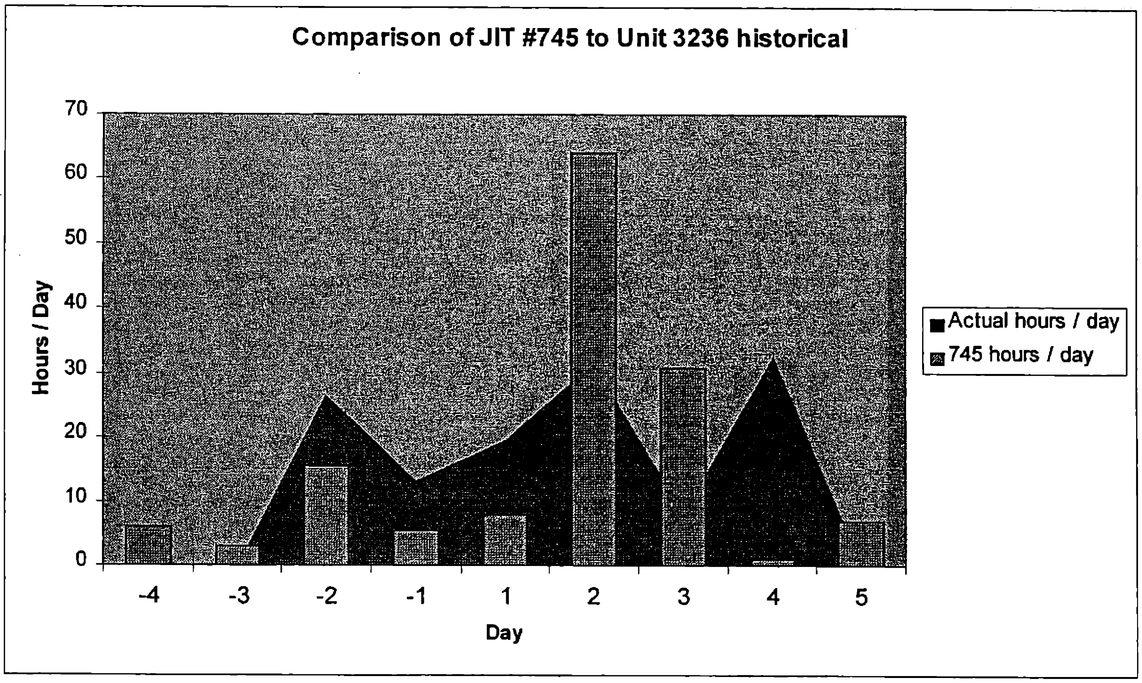


Figure B.6 – ACTUAL HOURS WORKED PER DAY ACFT #745 (UNIT 3236)

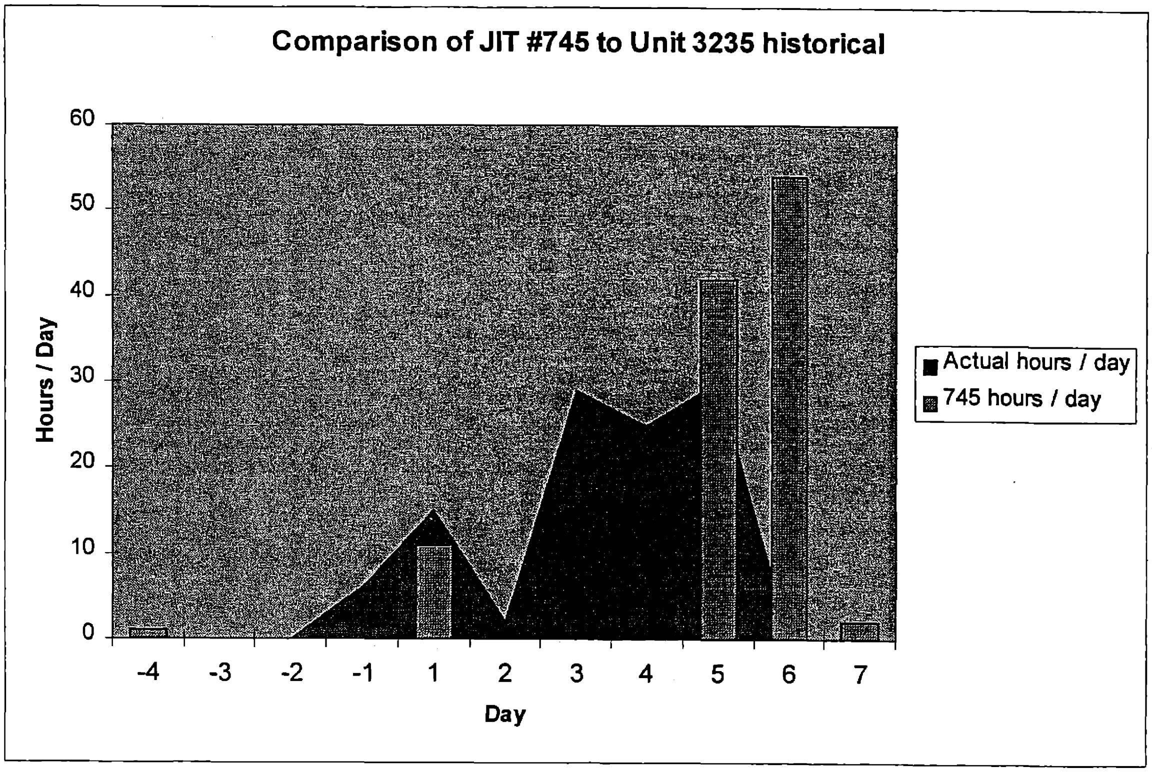


Figure B.7 – ACTUAL HOURS WORKED PER DAY ACFT #745 (UNIT 3235)

Appendix C: Analysis of labor availability

Required Manning	Roll Rate	Hours / Day (Earned) based on 1230hr crewloads	Current PI	Mult by 1474/1230	Hours / Day (Actual)
744	4	60	1.41	1.69	101
745	4	60	1.41	1.69	101
746	3	75	1.31	1.57	118
Turkey D	?				65
	Total required actual hours per day:				**386**

Figure C.1
REQUIRED LABOR COMPUTATION (ALL FINAL ASSEMBLY, ONE DAY, FOUR ACFT)

1st shift		*1st shift*					
3232-3239	16	3232-3239	13	13	10	13	
3238-3235	14	3238-3235	13	13	15	17	
		Total unavail:	4	4	5	6	
		absent	3	2	4	4	
		S-76	1	2	1	2	
2nd shift	28	*2nd shift*	21	19	24	23	
	(6 loan-ins)	Total unavail:	7	9	4	5	
		absent	5	6	2	3	
		CH-60	2	2	2	2	
3rd shift	9	*3rd shift*	9	7	6	6.5	
	(1 loan-in)	Total unavail:	0	2	3	2.5	
		absent	0	2	3	2.5	
							Average:
Total actual labor hours available:			**439.0**	**409.0**	**434.0**	**469.5**	**437.9**
Total actual labor hours SHORT each day:			**-53.5**	**-23.5**	**-48.5**	**-84.0**	**-52.4**

Figure C.2
AVAILABLE LABOR CALCULATION (ALL FINAL ASSEMBLY, ONE DAY, THREE SHIFTS)

Appendix D: Baseline Blackhawk build sequence (as of 24 November 1999)

BH 3232 (70000-02400-503)

Installation Number	Hours	Description	Build Sequence
70000-12100-013	5.50	MN LDG GR IN LH	1.01
70000-12100-014	5.50	MN LDG GR IN RH	1.02
70500-02061-512	9.00	Support Instl (ceiling)	2.01
70210-02100-813	3.00	Bellcrank Instl	2.02
70216-02405-013	1.00	Latch Instl	2.03
70216-02405-014	1.00	Latch Instl	2.04
70500-02067-011	1.00	Sndprf Instl	2.05
70500-02067-012	1.00	Sndprf Instl	2.06
70652-02150-811	5.00	Manifold Instl	2.07
70651-03302-011	1.00	Boot Instl	2.08
70652-03250-814	4.00	Lines Instl	2.09
70652-02250-816	8.00	Hyd Lines Instl	2.10
70500-02063-013	2.00	Support Instl	2.11
70500-02063-014	2.00	Support Instl	2.12
70500-02064-012	2.00	Support Instl	2.13
70500-02064-013	2.00	Support Instl	2.14
70219-03002-511A	8.00	Enclosure (start)	2.15
70307-42406-812	1.00	Instl Support H-Bar	2.16
70ATP-10322-802	6.00	ATP - Hyd Flush	2.17
70310-02100-012	4.00	Fire Det/Ext Instl	2.18
70550-01126-813	2.00	Hinge Inst	3.01
70550-01126-814	2.00	Hinge Inst	3.02
70550-01116-812	6.00	Support Instl (ovhd)	3.03
70550-01116-836	1.00	Bracket Inst	3.04
70400-00510-831	11.00	Dir Cont Inst	4.01
70400-02500-812	6.50	Ctrl Instl (Lwr blcrnk)	4.02
70400-02108-833	11.00	Torque Shaft Instl	4.03
70217-02720-815	4.00	Fairing Instl Catwalk	4.04
70217-02720-816	4.00	Fairing Instl Catwalk	4.05
70307-03150-812	4.00	Drain Instl (ENG)	5.01
70500-02076-011	1.00	Drain Line Instl (ww)	5.02
70500-02076-012	1.00	Drain Line Instl (ww)	5.03
70651-03000-816	4.00	Lines Instl (accum)	5.04
70219-03002-511B	3.00	Enclosure (finish)	5.05
70551-02107-825/6	8.00	TOP DECK WIRING (3233)	5.06
70306-03100-011A	2.00	Tube Instl (mech)	5.07
70301-02200-812	8.00	Ctrl Instl (Eng cables)	5.08
70400-01100-811	2.00	Ctrl Instl (Ckpt rods)	5.09
70307-02111-011	6.00	Fuel Lines Instl	6.01
70307-02200-812	4.00	Fuel Sys Instl	6.02
70307-02110-801	2.00	Lines Instl ESSS	6.03
70307-03029-800	1.00	Valve Instl	6.04
70303-03018-014	3.00	Line Instl (APU drains)	6.05
70651-03000-014	2.00	Lines Instl	6.06
70307-03050-011	4.00	Fuel Syst Upr	6.07
70ATP-15116-801	2.00	ATP - Fuel Sys In	6.08
70214-01003-891	6.00	Floor Inst	7.01
70500-02062-015	1.50	Recpt Instl	7.02
70500-02062-016	1.50	Recpt Instl	7.03
70551-02107-825/6	8.00	TOP DECK WIRING (3233)	7.04
70500-02160-510	1.00	Support Instl	8.01

70500-02160-515	2.00	Support Instl	8.02
70500-02160-815	2.00	Support Instl	8.03
70306-03100-011B	3.00	Tube Instl (hyd)	8.04
70307-03150-011	4.00	Fuel Vent Sys	8.05
70214-01003-892	5.00	Floor Inst	9.01
70500-02059-011	1.00	Support Instl	9.02
70500-02059-012	1.00	Support Instl	9.03
70500-02059-013	1.00	Support Instl	9.04
70500-02059-014	1.00	Support Instl	9.05
70400-02700-813	14.00	Ctrl Instl (mixer)	10.01
CORSN-00042-802	1.00	Corsn Protect	10.02

BH 3233 (70000-02400-501) **BH 3234 (70000-02400-502)**

Installation Number	Hours	Description	**Build Sequence**
70551-0210X-845A	6.00	PREP / HANG MAINS	1.01
70551-0210X-845B	4.00	L/R FWD MAINS	1.02
70000-02400-501	5.00	Top Deck Power Feeds	1.03
70202-02732-011	0.50	Kick Plate Assy	1.04
70202-02732-012	0.50	Kick Plate Assy	1.05
70600-02019-011	0.50	Blade Antenna	1.06
70551-02174-811	6.00	W/I, SGRS, GPS/DPLR	1.07
70551-02169-815	7.00	W/I ICS TUB & J-BOX	1.08
70551-02169-816	4.00	W/I ICS TUB	1.09
70550-02111-011	2.50	L/H J-Box Instl	1.10
70550-02111-012	2.50	R/H J-Box Instl	1.11
70551-0210X-845C	8.00	L/R DROPOFFS	1.12
70551-0210X-845D	8.00	SIDES / AFT MAIN	1.13
70551-02157-815	0.50	Wrg Inst L/H Hom	2.01
70551-03103-822	2.00	Wrg Instl-Trnsn	2.02
70551-03104-823	2.00	Wrg Instl	2.03
70551-02107-825	4.00	FINISH Wrg Instl L/H T/Deck	2.04
70551-02107-826	4.00	FINISH Wrg Instl R/H T/Deck	2.05
70551-02102-012	1.00	Wrg Instl R/H Gen	3.01
70551-02103-012	1.00	Wrg Instl L/H Gen	3.02
70551-02109-817	1.00	Wrg Inst Hyd Pwr	3.03
70551-02113-811	1.00	Wrg Inst 1 Gen	3.04
70551-02113-812	1.00	Wrg Inst 2 Gen	3.05
70551-02113-825	2.00	Wrg APU Gen	3.06
70551-02172-822	2.00	W/I Up Fuselage	3.07
70551-02163-813	6.00	Wrg CMD ICS	4.01
70551-02151-011	1.00	Wrg Inst T Cmdr	4.02
70551-02050-815	1.00	Cover Instl	5.01
70551-02104-819	7.00	Wrg Instl Lwr CB Tub Wrg	5.02
70551-02111-813	1.00	Cargo Hook W/I	5.03
70551-02150-811	1.00	VHF/FM#1 W/I	5.04
70551-02152-812	1.00	Cmps Rmt Xmtr	5.05
70551-02153-812	1.00	UHF/AM W/I	5.06
70551-02154-811	1.00	VOR/ILS W/I	5.07
70551-02156-812	1.00	Chaff Disp W/I	5.08
70551-02159-012	1.00	W/I ADF	5.09
70551-02160-811	1.00	MKR Beacon W/I	5.10
70551-02171-811	1.00	Wrg Inst IFF CX	5.11
70551-02173-811	1.00	RDR Warning W/I	5.12
70551-02109-015	4.00	Wrg Instl Ext Pwr	6.01
70551-02157-816	0.50	Wiring Instl R/H	6.02
70600-02004-015	1.00	Switch Instl,Foot,Cab	7.01

70551-02109-016	4.00	Wrg Inst Cab FDS	7.02
70550-02034-011	0.50	Recpt Instl	7.03
70551-0210X-845E	4.00	COMPLETE MAINS	8.01
70551-02105-846	10.00	Wrg Instl L/H Main	8.02
70551-02106-846	10.00	Wrg Instl R/H Main	8.03
70551-02105-844	1.00	Wrg Instl Gust Lock	8.04
70550-02160-012	1.50	Jct Box Instl BDI	9.01
70550-02159-012	1.00	Cont Instl Rot	9.02
70551-02106-842	8.00	MN BDI Harn Ins	9.03
70550-02161-011	1.50	Jct Box Instl BDI	9.04
70551-0210X-845F	6.00	L/R MEDIVAC	9.05
70551-0210X-845G	4.00	ESSS WIRING	9.06
70550-02033-011	0.50	Panel Instl	10.01
70550-02043-011	0.50	Flasher Instl	10.02
70550-02047-013	0.50	Cond Instl	10.03
70550-02007-016	0.50	Cont Instl Gen	10.04
70550-02044-012	0.50	Ampl Instl Fire	10.05
70600-02023-012	0.50	Accel Inst	10.06
70550-02007-015	0.50	Cont Instl Gen	10.07
70550-02048-013	0.50	Cont Instl	10.08
70550-02052-012	0.50	Pot Instl	10.09
70550-02108-011	0.50	Switch Instl	10.10
70550-02008-013	0.50	Cont Instl APU	10.11
70550-02019-013	0.50	Cont Unit Instl	10.12
70550-02019-014	0.50	Cont Unit Instl	10.13
70550-02059-011	0.50	Cont Unit Instl	10.14
70550-02009-013	0.50	Converter Instl	11.01
70550-02009-014	0.50	Converter Instl	11.02
70553-02101-011	0.50	Light Instl R/H	11.03
70553-02101-012	0.50	Light Instl R/H	11.04
70553-02101-013	0.50	Light Instl R/H	11.05
70500-02063-812	2.00	Instl	11.06

BH UNIT 3235 (70080-00550-543)

Installation Number	Hours	Description	**Build Sequence**
70500-02050-891	3.00	Furn Instl	1.01
70200-06150-845	2.00	Cover Instl	1.02
70219-04200-841	2.00	Sliding Fairing	2.01
70216-01000-811	3.00	Window Instl-LH	2.02
70216-01000-812	3.00	Window Instl-RH	2.03
70ATP-23152-801	4.00	ATP Door Jett	2.04
70219-04902-011	1.00	Platform Instl	2.05
CORSN-00042-804	1.00	CORSN PROTECT	2.06
70000-00555-807A	37.00	ELEC SHAKE	3.01
70000-00555-807B	32.00	MECH SHAKE	3.02
70000-00555-807C	22.00	A/C CLEAN	3.03

BH 3236 (70080-00550-544)

Installation Number	Hours	Description	**Build Sequence**
70000-07050-011	3.00	Stab Instl	1.01
70500-01152-015	2.50	Armored Wing (3235)	1.02
70500-01152-016	2.50	Armored Wing (3235)	1.03
70000-00550-815	3.50	Duct Instl	1.04
70000-00550-816	3.50	Duct Instl	1.05
70400-06712-011	3.00	Sensor Instl	1.06

70400-06636-014	3.00	Acctuator Instl	1.07
70205-06051-011	1.00	Fairing Instl (3235)	1.08
70205-06052-811	1.00	Fairing Instl (3235)	1.09
70205-06053-811	1.00	Fairing Instl (3235)	1.10
70205-06054-811	1.00	Fairing Instl (3235)	1.11
70205-06055-811	1.00	Fairing Instl (3235)	1.12
70ATP-10316-800	6.00	ATP Hyd Flt Cntl	1.13
70SER-70199-802	8.00	ENGR Rigging	1.14
70ATP-20822-805	27.00	AVIONICS ATP	1.15
70209-01013-800	1.00	Cover Instl	2.01
70214-01003-513	5.00	Cover Instl	2.02
70600-01033-011	1.00	ANTENNA INSTL	2.03
70600-01033-012	1.00	ANTENNA INSTL	2.04
70600-06006-011	1.00	Antenna Instl	2.05
70ATP-27000-801	21.00	AFCS ATP	2.06
70350-05000-803	1.00	Wear Indict Inst	3.01
70350-06000-814	3.00	T.P. Shaft Instl	3.02
70550-02021-016	2.50	Batt Inst DTLS	3.03
70550-02023-811	0.50	JCT Box Instl	3.04
70ATP-20892-801	6.00	AN/ARN-147 VOR/ILS	3.05
70ATP-20692-800	4.00	SINCARS ATP	3.06
70ATP-21681-800	2.00	GPS DOPPLER ATP	3.07
70302-02200-812	2.00	Cowling Instl	4.01
70ATP-30074-802	2.00	Elect Inst ATP	4.02
70ATP-21384-800	6.00	ANVIS HUD ATP	4.03
70400-01433-012	2.00	Cover Instl	5.01
70309-02115-011	2.50	Tube Instl Htr	5.02
70ATP-22918-801	4.00	Bonding Chk ATP	5.03
70500-01052-011	0.50	Cover Instl	6.01
70500-01052-012	0.50	Cover Instl	6.02
70551-02169-834	0.50	ICS Cord Instl	6.03
70553-01000-011	1.50	Light Instl SEC	6.04
70600-01050-011	1.00	ANTENNA INSTL	6.05
CORSN-00042-805	1.00	Corsn Prot	6.06
70551-05103-813	1.50	W/I RH Seatwell	6.07

BH 3237 (70080-00550-545)

Installation Number	Hours	Description	Build Sequence
70600-03009-011	1.00	Antenna Instl	1.01
70551-03153-812	0.50	Wrg Inst UHF AM	1.02
70450-01092-011	1.00	OAT Sensor Instl	1.03
70080-00550-545A	5.00	AIR DATA PREP	1.04
70080-00550-545B	1.00	HYD POWER ON	1.05
70350-03000-815A	2.00	Shaft & Hose (hyd)	1.06
70216-02400-811	4.00	Window Instl	2.01
70216-02400-812	4.00	Window Instl	2.02
70219-04300-011	2.00	Fairing Instl	2.03
70219-04300-012	2.00	Fairing Instl	2.04
70307-02110-800	2.00	ESSS Lines	2.05
70219-04400-011	2.00	Cover Instl	2.06
70216-02408-811	1.00	Seal Instl	2.07
70216-02408-812	1.00	Seal Instl	2.08
70216-02409-011	0.50	Security Device	2.09
70216-02409-012	0.50	Security Device	2.10
70000-08000-818	1.00	QCA Lines Inst	2.11
70400-00003-801	8.00	Rig Set Up	2.12

70553-04001-012	0.50	Light Instl	2.13
70553-04003-011	0.50	Light Instl	2.14
70600-03042-011	0.50	A/I, GPS ANTENNA	2.15
70ATP-10316-801	4.00	ATP Bleed Brakes	3.01
70ATP-21178-801	4.00	Varidrive ATP	3.02
70600-02003-015	1.00	Antenna Instl	4.01
70600-02003-016	1.00	Antenna Instl	4.02
70ATP-30074-801	35.00	Elect Inst ATP	4.03
70217-01002-011	6.00	Crew Door Instl	4.04
70217-01002-012	6.00	Door Instl RH	4.05
70217-01005-013	0.50	Striker Instl	4.06
70217-01005-014	0.50	Striker Instl	4.07
70217-01024-011	0.50	DR Chk Instl	4.08
70217-01024-012	0.50	DR Chk Instl	4.09
70217-02700-811	3.00	Cargo Door Instl LH	4.10
70217-02700-812	3.00	Cargo Door Instl RH	4.11
70217-01010-011	4.00	Nose Door Instl	5.01
70207-01028-081	1.00	Strut Instl	5.02
70215-42410-811	3.00	Fairing Instl	5.03
70215-42410-812	3.00	Fairing Instl	5.04
70551-02113-834	3.00	W/I Gen 1,2,APU	6.01
70400-02700-814	20.00	Control Instl	6.02
70400-00003-802	8.00	Main Rotor Rig	6.04
70551-01165-823	2.00	Wiring Instl	6.05
70600-01035-812	2.00	Ckpt Nose Avio Instl	6.06
70400-00003-805	8.00	Tail Rotor Rig	7.01
70000-11100-815	6.00	Tail Rotor Instl	8.01
70350-03000-815B	1.50	Shaft & Hose (mech)	9.01
70217-02718-013	0.50	LATCH INSTL LH	9.02
70217-02718-014	0.50	STOP INSTL	9.03
70000-10101B015	3.00	LH ENG Air Instl	10.01
70000-10101B016	3.00	RH ENG Air Instl	10.02
70000-10101C015	0.50	LH ENG Duct	10.03
70000-10101C016	0.50	RH ENG Duct	10.04
70306-02200-012	3.00	STARTER INSTL	11.01
70215-42402-513	1.00	Receptacle Inst	11.02
70215-42402-514	1.00	Receptacle Inst	11.03
70207-03007-018	0.50	Cover Instl	11.04
70351-08400-881	2.50	Gust Lock Instl	12.01
70219-02160-811	2.00	Vib Absorb	12.02
70ATP-15117-801	2.00	Dry Cal ATP	12.03
70600-02016-011	1.00	Antenna Instl	12.04
70551-02107-835	1.50	Top Deck Conn Instl	12.05
70600-03007-011	1.00	Antenna Instl	12.06
70600-01044-811	3.00	Glide Slope Ant	12.07
70600-05003-012	1.00	VOR/LOC Ant Instl	12.08
70600-02005-812	0.50	ICS Instl	12.09
70600-01032-511	1.00	Doppler Ant Instl	12.10
70500-01150-811	2.50	PLT/Coplt Seat	13.01
70500-01150-812	2.50	PLT/Coplt Seat	13.02
CORSN-00042-800	0.50	Corsn Prot	13.03
70551-01167-815	1.00	Wrg ICS Cord L/H	14.01
70553-01112-011	1.00	Light Instl	14.02
70600-01046-011	0.50	CONTROL PNL INS	14.03
70550-01140-012	0.50	Dimmer Instl	14.04
70551-01167-816	1.00	W/I RH Seat	14.05
70600-01046-012	0.50	CONTROL PNL INS	14.06

BH 3238 (70000-00550-546)

Installation Number	Hours	Description	Build Sequence
70200-06051-812	2.50	JOINING INSTL	1.01
70450-01050-818	6.00	Instr Panel Instl	1.02
70600-01041-014	2.00	Conv Instl CMC	1.03
70450-01015-012	1.00	Compass Instl	1.04
70551-01103-813	1.00	Wrg Instl Instr	1.05
70450-01050-817	6.00	Support Instl	1.06
70400-00510-014	3.00	Dir Cont Instl	2.01
70350-05000-812	8.00	Bracket Alignmt	2.02
70350-03000-814	5.00	Oil Cooler Instl	2.03
70ATP-10322-803	3.50	ATP HYD Flush	2.04
70553-01001-011	1.00	Light Instl UT	2.05
70553-01001-012	1.00	Light Instl UT	2.06
70550-01042-012	1.00	Resistor Instl	2.07
70550-01057-011	2.50	Cntor Instl ESSS	2.08
70550-01135-011	1.50	Panel Instl	2.09
70551-01100-806	5.00	WI Ckpt/Cab Jng	2.10
70551-01100-807	5.00	WI Ckpt/Cab Jng	2.11
70550-01116-835	1.50	Console Instl	2.12
70550-01126-028	2.00	Panel Instl CB RH	2.13
70550-01126-029	2.00	Panel Instl CB LH	2.14
70211-04803-812	1.00	Beam Instl	3.01
70207-02728-813	3.00	Seal Instl L/H	3.02
70207-02728-814	3.00	Seal Instl R/H	3.03
70302-02142-011	3.00	Fairing Instl	3.04
70302-02142-012	3.00	Fairing Instl	3.05
70219-04600-011	1.00	Support Instl	3.06
70303-03029-011	2.00	Mount Instl	3.07
70303-03100-811A	2.00	APU Instl (mech)	3.08
70551-02172-832	2.00	W/I Up Fuselage	3.09
70551-03104-814	1.00	W/I Transition	3.10
70215-42409-511	5.00	Fairing Instl	3.11
70215-42409-512	5.00	Fairing Instl	3.12
70551-03103-832	1.50	W/I Up Fairing	3.13
70450-01079-018	3.00	Cont Pnl Instl	4.01
70450G01055-042	1.00	Rear Xmtr	4.02
70551-42401-011	1.00	Ctr Cnsl Brkt	4.03
70600-01031-011	1.00	Junct Box Instl	4.04
70600-01040-012	1.00	SAS/FPS Cmptr	4.05
70303-03100-811B	3.00	APU Instl (hyd)	5.01
70310-03150-811	4.00	F Det/Ext Instl	5.02
70ATP-23125-800	1.00	ATP-Fire Ext	5.03
70206-01001-813	6.00	Window & Gutter	6.01
70206-01001-814	6.00	Window & Gutter	6.02
70216-01002-812	12.00	W/Shield & Gutter	6.03
70350-05000-813	7.00	Drive Shaft Instl	6.04
70400-02000-814	4.00	FLT Cntl Instl	6.05
70551-01155-825	1.00	Wrg Inst GPS	6.06
70600-01001-817	6.00	AVI NOSE FL IN	6.07
70600-01002-017	3.00	Avio Instl	6.08
70600-01003-013	2.00	Avio Instl	6.09
70600-01004-816	1.00	AV Instl Bottom	6.10
70600-01004-824	1.00	Gyro Instl	6.11
70450-01051-563	4.00	Instr Panel Assy	6.12

70219-04619-011	4.00	Duct Instl	7.01
70219-04704-841	2.00	L&R Door Instl	7.02
70219-04802-811	6.00	Cover Assy	7.03
70219-04802-813	4.00	Fairing Instl	7.04
70219-04802-814	4.00	Fairing Instl	7.05
70219-04901-011	2.50	Fairing Instl	7.06
70500-02057-014	10.00	Duct Instl	7.07
70309-01100A013	4.50	Heat/Vent Instl	7.08
70309-01100B013	1.00	Heat/Vent Instl	7.09
70450-01913-011	0.50	Therm Instl	7.10
70450-01913-012	0.50	Therm Instl	7.11
70551-01100-805	3.00	W/Shield Wrng	7.12
70209-01003-801	1.00	Wiper Arm Intsl	8.01
70212-04702-011	1.00	Beam Instl	8.02
70219-04500-841	1.00	L&R PNL Instl	8.03
70301-02200-813	3.00	CONTROL INSTL	8.04
70400-01623-812	1.00	Pedal Adj Cable	8.05
70500-01054-811	1.00	Duct Instl	8.06
70500-01054-812	1.00	Duct Instl	8.07
CORSN-00042-804	1.00	CORSN Protect	8.08
70550-01139-011	1.00	Dimmer Instl	9.01
70550-02076-011	1.00	OV Speed Rly	9.02
70550-02076-012	1.00	Relay Instl	9.03
70550-02107-013	1.50	Relay Pnl Inst	9.04
70550-02107-014	1.50	Relay Pnl Inst L/H	9.05
70550-02113-012	1.00	Cont Instl , APU	9.06
70551-06101-800	1.00	Pylon Conns	9.07
70600-01021-015	1.00	FT SW Instl LH	9.08
70600-01021-016	1.00	FT SW Instl RH	9.09
70600-01022-815	4.00	RCVR Instl	9.10
70600-02022-012	1.00	Stab Amp Instl	9.11
70600-06007-011	2.00	Antenna Instl	9.12
70600-06012-011	2.00	Whip Ant	9.13
70000-10101A015	5.00	LH Engine Instl	10.01
70000-10101A016	5.00	RH Engine Instl	10.02

BH 3239 (70000-00550-547)

Installation Number	Hours	Description	**Build Sequence**
70211-04803-812	1.00	Beam Inst	1.01
70551-02111-800	1.00	Wrg Instl C Hook	1.02
70551-02106-847	2.00	BDI W/I TO TB7	1.03
70551-02105-843	9.00	WI L/H Main Ckpt	2.01
70551-02106-848	9.00	WI R/H Main Ckpt	2.02
70550-01150-011	0.50	Box Instl	3.01
70550-01150-012	0.50	Box Instl	3.02
70000-08000-818	5.00	Xmsn/Rtr Instl	3.03
70250-02350-014	2.00	BK Lines Instl	3.04
70250-02350-823	1.00	Lines Instl	3.05
70400-01400-812	5.00	Collective Stick	4.01
70400-08200-813	7.00	Control Instl	4.02
70550-05001-012	1.50	Pwr Sply Instl	5.01
70553-01103-011	1.00	Light Instl	5.02
70551-01100-825	30.00	WI CKPT/CAB JNG	5.03
70219-02121-811	2.00	Vibr/Step Instl	5.04
70219-02121-812	2.00	Vibr/Step Instl	5.05
70215-02319-811	3.00	Fairing Instl Stub Wing	5.06

70215-02319-812	3.00	Fairing Instl Stub Wing	5.07
70553-02013-012	3.00	INST, NVG LT, CRGO HK	6.01
70553-05000-013	1.00	Light Instl	6.02
70553-05001-012	1.00	Light Instl	6.03
70553-05003-011	1.00	Light Instl	6.04
70551-03101-814	8.00	Wrg Instl Top	6.05
70551-02104-820	20.00	Wrg Instl	6.06
70308-03610-821	4.00	Hirss Instl L/H	6.07
70308-03610-822	4.00	Hirss Instl R/H	6.08
70551-03102-834	8.00	Wrg IN Tie RH LW	7.01
70551-03102-835	8.00	Wrg IN Tie LH LW	7.02
70551-01151-824	2.00	COAX CBL INSTL	7.03
70551-02109-819	2.00	WI Battery Relay	7.04
70551-03101-011	8.00	Wrg Instl LHS Aft Trans	7.05
70551-03101-015	8.00	Wrg Instl RHS Aft Trans	7.06
70308-03611-011	3.00	Extndr Instl LH	7.07
70308-03611-012	3.00	Extndr Instl RH	7.08
70551-03150-811	2.00	Wrg inst IFF	7.09
70551-03153-811	2.00	Wrg inst UHF AM	7.10
70551-03155-012	2.00	Wrg inst	7.11
70551-03152-012	1.00	Wrg inst compass	7.12
70553-01003-012	1.00	Light Instl	7.13
70302-02163-011	2.00	Shield Instl	7.14
70302-02163-012	2.00	Shield Instl	7.15
70305-02200-017	1.00	Strut Instl	7.16
70305-02200-018	1.00	Strut Instl	7.17
70600-02002-012	1.00	Antenna Inst	9.01
70450-02029-813	4.50	P/S Lines - CLST	9.02
70450-02022-815	4.50	PT Tube Instl	9.03
70652-06256A011	1.00	Pump Suppt Inst	9.04
70652-03250-015	3.00	Lines Instl	9.05
70600-03001-013	2.00	Ant, ADF Inst	9.06
70550-02023-801	1.50	Box Instl	9.07
70600-03041-011	0.50	IFM AMP INST	10.01
70600-03005-011	0.50	XMTR 7 COMP	10.02
70551-05102-836	1.00	BDI H/A Instl Aft Trans	11.01
70214-02555-814	4.50	Floor Instl	12.01
70214-02556-815	4.50	Floor Instl	12.02
70800-02501-013	2.00	Cargo Hook Inst	13.01
70550-02212-011	1.50	JCTN BOX INSTL	14.01
70214-02554-811	4.50	Floor Instl	14.02

Appendix E: Benchmarking Template (used during internship site visits)

Massachusetts Institute of Technology
Leaders for Manufacturing Program
UTC Sikorsky Aircraft

Final Assembly Cost Reduction: Benchmarking template

Company visited: ____

Personnel contacted: ____________________________________

____

Workforce management

- *How many employees are in the work center?*
- *How many shifts? Employees per shift?*
- *Would you rather have a lot of employees on one shift, or spread employees out over multiple shifts for 24hr operations? Why?*
- *How many different skills are called for? How many different jobs are there?*
- *How do you know what employee to assign to a job? Is this tracked?*
- *Do workers get their own parts / kits? Tools? Work instructions?*
- *What about perishable items (e.g. touch up paint) or HAZMAT?*
- *How are tools stored? Delivered to the line? Tracked, maintained, etc.?*

- *Would you rather work faster with less WIP, or slower with more WIP?*

- *What do workers do during a work stoppage?*

- *How are slots due to absenteeism accounted for and filled?*

Inspection

- *Do you have any operations that are inspected? How many / what percentage?*

- *How do inspectors know what the priorities are? Who sets them?*

- *Where do the inspectors come from? Who do they work for? Do they eventually return to operations?*

- *Do inspectors conduct training for operators?*

- *Do inspectors have specialized training not available to operators?*

- *How much self-inspection is done by the workers?*

Parts & Quality

- *Do you have problems with incoming parts quality?*

- *Do you have problems with rework?*

- *How have you addressed these issues?*

- *Do you hold inventory to buffer poor quality?*

- *What metrics do you track?*

- *How does the cleanliness and organization of the line affect quality?*

- *How do you work around parts shortages? How do you deal with them to make sure they do not reoccur?*

Other

- *What metrics are tracked by mgmt? By the line? What visual tracking mechanisms are used?*

- *Are workers held accountable for cost? Foremen? How do they know their cost status?*

- *How are changes (derivative products) implemented without affecting the schedule?*

- *What type of AOS's or paperwork are used? Do the various sources of work instructions, part numbers, etc. match? How are they linked to one another?*

Appendix F: Benchmarking visit reports

Pratt & Whitney (Middletown - FEI):

- Op sheets are set up sequentially
- BOM parts release is done sequentially
- MORE THAN ONE set of kit carts
- UR parts come out on kit carts
- Workers get full carts; crib retrieves empties
- ANDON lighting system:
    - Awaiting inspection
    - Material division billed for work stoppage
- Aligned ACE to existing business metrics
- Support functions are product-aligned
- Most tools stored at work station
- Customer Service Center - "a hospital emergency room for defective hardware" using DIVE/CURE/QCPC tools
    - Mix of QA and engineering personnel
    - Workers take part straight to CSC (on floor)
    - CSC drives fast resolution
    - Responds to needs of manufacturing ("customer focus")

Hamilton Sundstrand (Windsor Locks ECS):

- Inspection works for assembly center supervisor (but report back through QA organization)
- Structured union contract to simplify re-assignment of labor to different areas
- Use a flexible cart and kitting system (generic "baker's racks" which can be loaded with the desired kit(s) provided in color-coded bins)
- Workers track their own inventory
- Tools stored at each work station

Instron (industrial test equip), Canton MA:

- Material is kitted and delivered to line
- Company bought enough tools for everyone
- Inspectors check real-time status (through shop floor system) for assignment / prioritization
- Inventory moved onto the floor
    - Provides visibility
    - Visual means of control

Narragansett Shipwrights, Newport RI

- Experienced workers responsible for training
- Maintain close coordination with designers, including frequent visits by architects (remember Skunk Works Kelly Johnson - engineers should spend at least 1/3 of time on the floor)
- Extensive use of visual instructions / full size plots
- Small portable tooling (do rework on the line)

John Deere Company, Moline IL [Lean Aerospace Initiative, 1994]. The following points, drawn from the case study, provide ideas for creative approaches to the types of problems faced by Sikorsky:

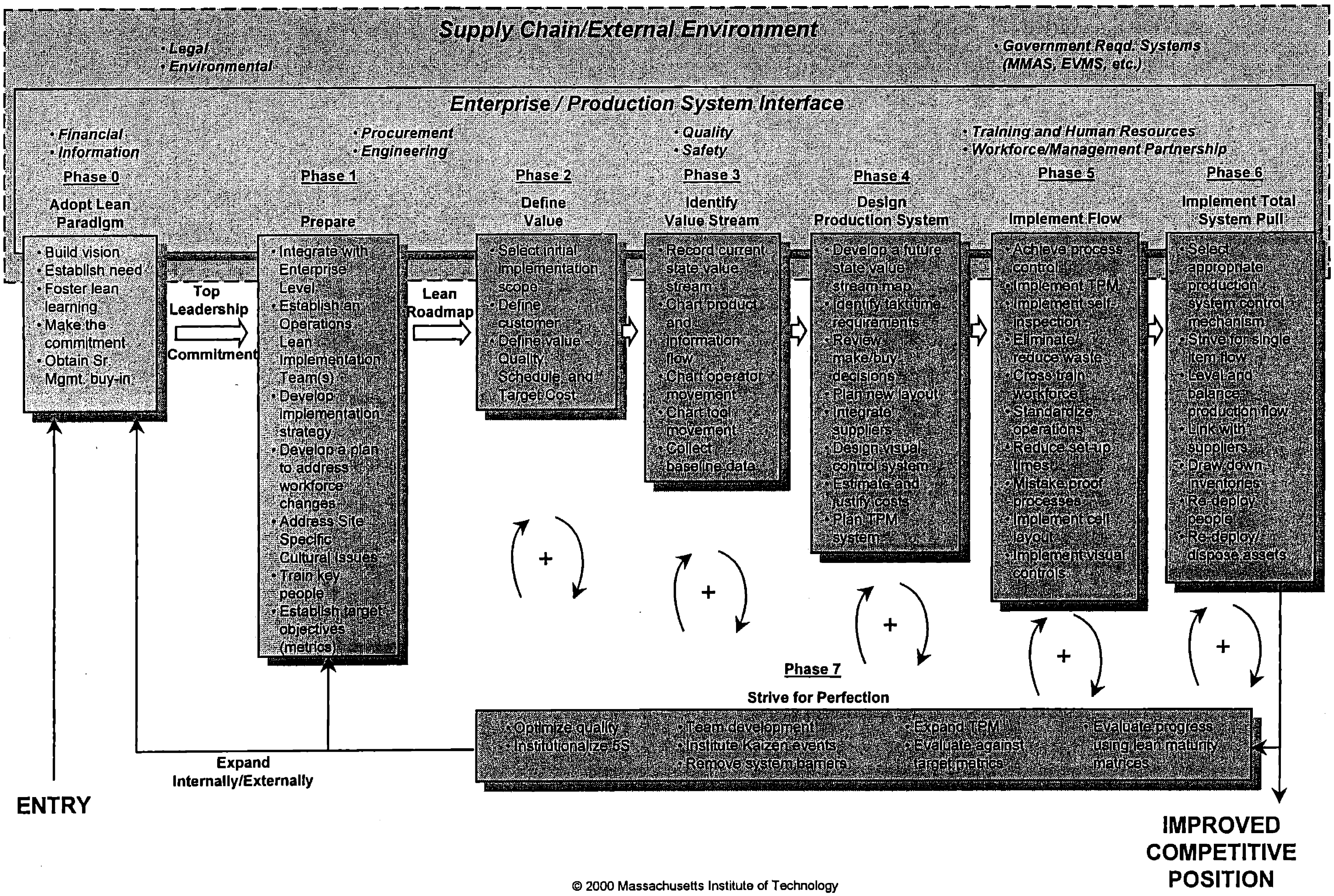
- Subassembly production is located right next to final assembly - module workers build subassemblies *then install them in final assembly*
- Supplier control divided into strategic and tactical:
    - Strategic - LTA's and MS/MRP/PR/PO
    - Tactical - *workers* schedule deliveries of ordered parts
- Kit carts *are* the kanban system - they are sized to one day's production
- Productivity Incentives:
    - Target is set for a year (e.g. 1700 hours per aircraft)
    - At end of year, average performance is determined
    - Workers are paid 2x bonus if below target:
        - e.g. if yearly average was 1600 hours
        - bonus equals 2 x 100hrs x hourly rate x # of aircraft / # of workers
    - But - next year's target = 1600 hours
- Everyone in company participates in benchmarking visits
- Deere does not believe in 100% JIT in MRP environment; essentially they are JIT'ing the "A's" in an A-B-C- inventory classification
- High degree of self-inspection by workers
- "Change = Success" and "Inventory is Evil"
- Workers participate in product design (DFM/DFA)

What to expect - just some of the dramatic improvements realized by John Deere:

- 30% inventory reduction / turns up to 12 per year
- Cycle time reduced 46% (make) 42% (buy)
- Material handlers down to 80 from 200
- Sales per employee up 55%
- Floor space down between 20% to 55%

Appendix G: Lean Aerospace Initiative – Transition-to-Lean Roadmap

Production Operations Transition-To-Lean Roadmap



Supply Chain/External Environment

- *Legal*
- *Environmental*
- *Government Reqd. Systems (MMAS, EVMS, etc.)*

Enterprise / Production System Interface

- *Financial*
- *Information*
- *Procurement*
- *Engineering*
- *Quality*
- *Safety*
- *Training and Human Resources*
- *Workforce/Management Partnership*

Phase 0

Adopt Lean Paradigm

- Build vision
- Establish need
- Foster lean learning
- Make the commitment
- Obtain Sr. Mgmt. buy-in

Top Leadership Commitment

Phase 1

Prepare

- Integrate with Enterprise Level
- Establish an Operations Lean Implementation Team(s)
- Develop implementation strategy
- Develop a plan to address workforce changes
- Address Site Specific Cultural Issues
- Train key people
- Establish target objectives (metrics)

Lean Roadmap

Phase 2

Define Value

- Select initial implementation scope
- Define customer
- Define value Quality, Schedule, and Target Cost

Phase 3

Identify Value Stream

- Record current state value stream
- Chart product and information flow
- Chart operator movement
- Chart tool movement
- Collect baseline data

Phase 4

Design Production System

- Develop a future state value stream map
- Identify takt time requirements
- Review make/buy decisions
- Plan new layout
- Integrate suppliers
- Design visual control system
- Estimate and justify costs
- Plan TPM system

Phase 5

Implement Flow

- Achieve process control
- Implement TPM
- Implement self-inspection
- Eliminate/reduce waste
- Cross train workforce
- Standardize operations
- Reduce set-up times
- Mistake proof processes
- Implement cell layout
- Implement visual controls

Phase 6

Implement Total System Pull

- Select appropriate production system control mechanism
- Strive for single item flow
- Level and balance production flow
- Link with suppliers
- Draw down inventories
- Re-deploy people
- Re-deploy/dispose assets

Phase 7

Strive for Perfection

- Optimize quality
- Institutionalize 5S
- Team development
- Institute Kaizen events
- Remove system barriers
- Expand TPM
- Evaluate against target metrics
- Evaluate progress using lean maturity matrices

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