Process and System Variation Impacts on 777 Wings Manufacturing

by

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B.S., Massachusetts Institute of Technology, 2009

Submitted to the Mechanical Engineering Department and the MIT Sloan School of Management in partial fulfillment of the requirements for the degrees of

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and

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Abstract

The Boeing 777 has seen an increased the rate of production from one plane every 7 days to one plane every 2.5 days. Wing production has relied on a sizeable work force and the use of overtime to meet this demand. The primary objective is to improve build efficiency by reducing variability in the production system. The impact of eleven variables was determined using a stepwise regression to predict for total labor hours across 250 airplanes. Three variables – travelers, defects, and quality assurance response time – accounted for almost 50% of the variability in labor hours. Other variations included engineering changes and rate breaks. Moving forward, the Wing Majors shop will redirect resources to control travelers, improve quality, and minimize quality assurance delays.

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Chapter 1

1 Introduction

1.1 Background

In large component, low volume production systems, process variations are difficult to control and mitigate. Through the Toyota Production System, manufacturing was transformed by new methods and tools such as Lean, Six Sigma, Kanban, and Standard Work to cite a few (Stevenson 2012). It has been well documented that variation in any production system must be reduced as it compromises quality, leads to delays, and prevents accurate scheduling of work. To accomplish this, products have been designed to simplify the manufacturing process and thereby, reducing build variation. This method is known also as design for manufacturability (Niu 1999; Anderson 2014).

The Boeing Company, a leading manufacturer of military and commercial aircraft, produced 648 commercial airplanes in 2013, earning revenues of $86.6 billion in total revenues (Boeing Annual Report 2013). Boeing's product line offers four commercial aircraft of different passenger loads, range capabilities, and interior plans. According to Boeing's long term strategy, the demand for commercial aircraft is projected to be 15,500, valued at $5.2 trillion ("Boeing: Long-Term Forecast" 2015) . Recognizing airlines are seeking more fuel efficient planes, Boeing has improved the aerodynamic properties of current aircraft and began production of the first carbon composite aircraft, the 787 Dreamliner.

This paper is based on research conducted in Boeing's facilities in Everett, Washington from June to December 2014. The research focuses on the complex manufacturing process and assembly of the 777 wing by the Wing Majors shop. The shop is responsible for the assembly of the wing's major structural components including spars, panels, and ribs represented in Figure 1. Because they contain the fuel tanks in which jet fuel is stored, wings are also designed to contain internal pressure from liquids and vapors (Niu 1999). In this paper, I present the results and recommendations from my research with the Wing Majors shop. These recommendations, detailed in Chapters 5 and 6, are aimed to reduce the process and manufacturing variability of the wing assembly.

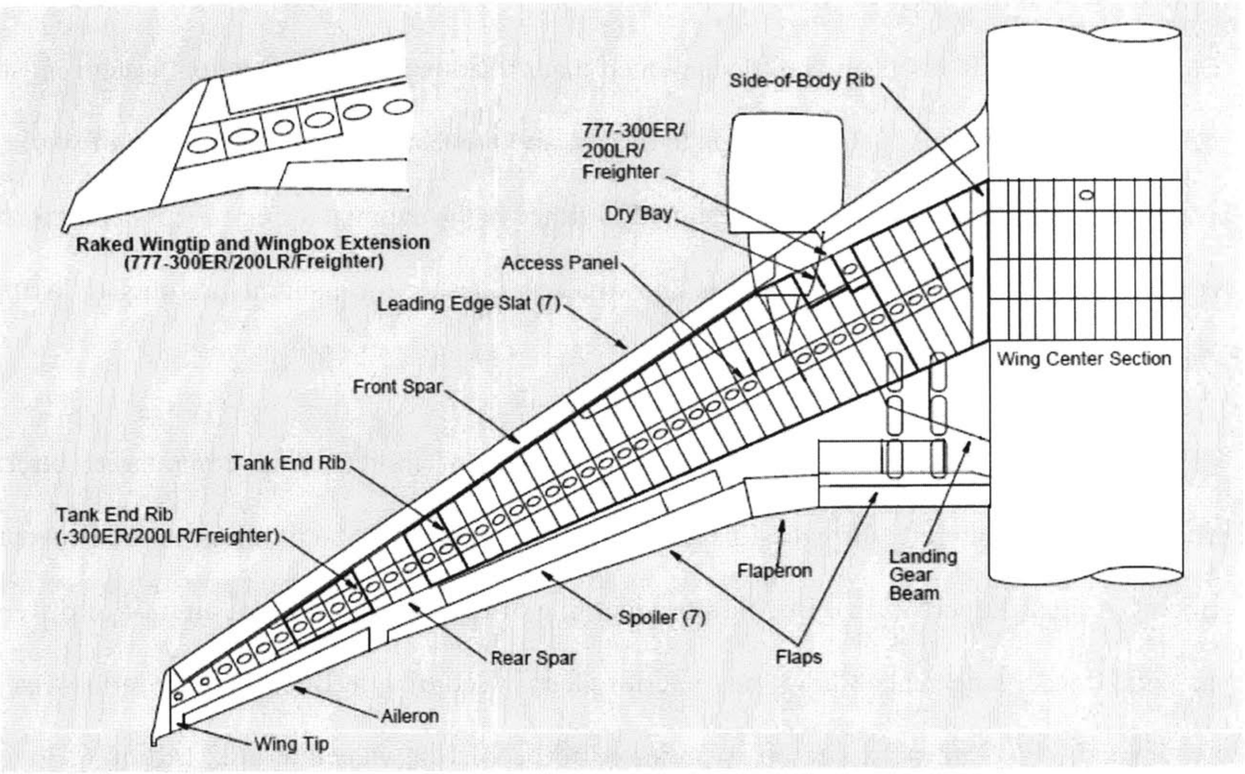


Figure 1: Diagram of major wing components

The Everett facility where the research was carried out houses four airplane programs all with various production rates, supply chain models, and component sourcing strategies. For example, the 787 Dreamliner sources major components from suppliers and final assembly occurs in house. On the other hand, the 747 produces all major structures including the wing and fuselage in Everett. This results in limited resources within the factory and the frequent transportation of parts and equipment by crane or ground vehicles.

1.2 Problem Statement

Before the methods and tools associated with the Toyota Production System took root in the United States, Boeing had designed aircraft and invested in its extensive manufacturing infrastructure (Yenne 2002). Process control and variability reduction had not become popular factory management techniques when the 777 program began development in 1988 (Birtles 1998).

Since the delivery of the first 777 in 1994, Boeing has increased the program's rate of production from one plane every 7 days to one every 2.5 days, implementing new technologies and forms of automation to support the accelerated build rate. Every two and a half days, a 777 completes final assembly, leaving the factory to be painted and tested. The total time required to build one 777 is 46 days. Figure 2 illustrates the Number One Flow, a diagram that depicts the amount of time required for each shop to build its required components. Several components are built in parallel, for example, fuselage and wings, before finally converging in final assembly. The Number One Flow diagram also illustrates the number of days required to build or assemble a component.

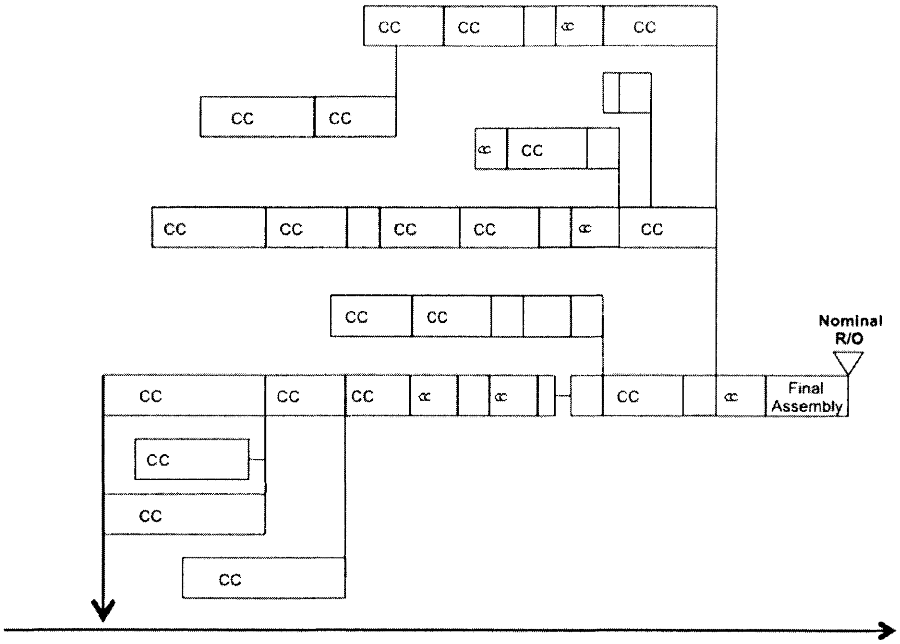


Figure 2: Number One Flow illustrating the control codes that produce in parallel and series ultimately culminating before final assembly

Traditionally, Wing production has not experienced the same technological advancements due to its capital intensive infrastructure and complex manufacturing process. Unlike final assembly, wing manufacturing cannot supplement production with additional lines due to the extensive infrastructure involved. Instead, the Wing Majors shop has relied on a sizable work force and the use of overtime to meet demand. As headcount reduction from continuous learning and engineering improvements continues to constrain the production schedule, wing manufacturing is challenged to produce with greater efficiency.

The 2.5-day production rate has been the fastest the 777 program has achieved. As so, Wing Majors has been challenged with a number of quality, scheduling, and overtime issues. The precedence build network, which details the sequence jobs must be completed, prevents work to be done in parallel or from starting earlier. In addition, physical space constraints limit the number of mechanics in one area. To complete jobs on schedule and meet delivery deadlines, mechanics are inclined to speed up while dealing with the existing process variations, leading to quality and safety concerns. Overtime is regularly required in Wing Majors, affecting cost targets and frequently, morale. Figure 3 illustrates the actual labor hours against budgeted labor hours per airplane.

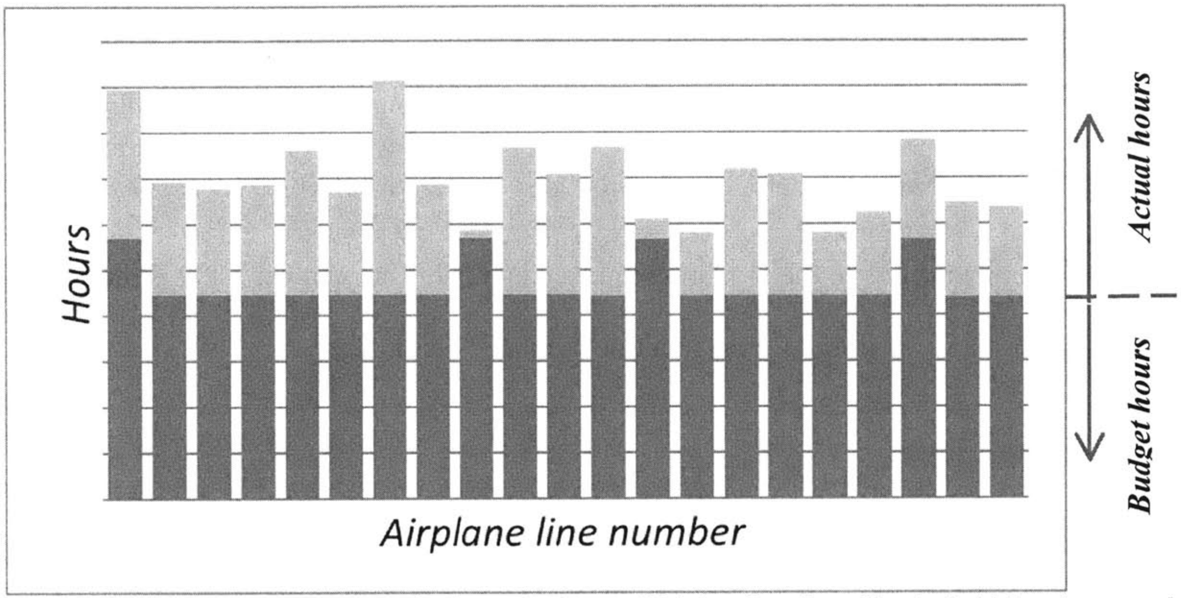


Figure 3: Actual labor hours required per airplane, which is a function of budgeted labor hours and overtime.

To alleviate some quality concerns and reduce the backlog of behind schedule jobs, my research seeks to identify and evaluate the process variations within wing assembly ultimately to eliminate them. Reducing such variation will allow for a consistent build process, improving mechanic efficiency and increasing the shop's capacity.

1.3 Factory Organization and Terms

The term 'job' refers to a quantity of work as determined by manufacturing engineering. Jobs can range from 20 minutes to 13 hours, and can be broken up and arranged as engineering deems necessary often with manufacturing feedback. Each job has a unique identifier of at least seven digits followed by Installation Process (IP), e.g., IP-0R12345. Jobs are organized by operational work units or departments called Control Codes (CC). There are three control codes in Wing Majors. They correspond to work done on upper panel, lower panel, and lower trailing edge as shown in Figure 1.

The term 'flow day' refers to the day of work for individual control codes. For example, lower panel has five flow days and on the sixth day, upper panel work begins, resetting to flow day 1. The amount of work scheduled on each flow day changes which then implies that some days are more critical than others.

Line number refers to the airplane sequence number. Line number 1000 is the 1000th 777 to have been built. My research focuses on line numbers 996 to 1250.

1.4 Methodology

My research methodology was derived through the understanding of current state manufacturing issues in Wing Majors (Chapter 3) and a comprehensive literature review of previous research done at Boeing concerning manufacturing improvements, scheduling, and process variation. Current state issues were determined through direct observation and the interviews with major stakeholders of wing manufacturing, including Wing Majors managers, mechanics, team leads, quality assurance, tool services, materials and parts, multiple engineering functions, and other support functions. The methodology used to measure process and manufacturing variation was statistical regression.

Everyday mechanics arrive aware of the work they've been scheduled. Despite this, there are many uncertainties that arise including the number of mechanics who are absent or the amount of work the previous shift completed. It is the responsibility of the first line managers and the team leads, also known as lead mechanics, to prioritize the day's work and reassign jobs as necessary. The mechanic then begins his or her work by tracking down the tools and parts required for the job. Occasionally, the tools require maintenance and must be replaced and the parts go missing or are damaged. This adds additional time to the day and may delay the start of other jobs. Once a job is completed, Quality Assurance, henceforth referred to as QA, is alerted. QA is responsible for validating the product is built as designed and the accuracy and quality of the job. If a defect is identified, a rework order is issued for a known repair or engineering is notified to determine a custom repair. Throughout the day, the mechanic is faced with multiple variables that affect the time required to complete a job. At any point in the outlined process, an issue may arise causing a ripple effect of delays.

My research documents all the variables mechanics may face throughout the day. This was done through the perspective of the mechanic as they are the sole group that assembles the wing. Once these variables were identified, the quantitative ones were measured. Data were collected for 255 sets of wings and a regression model was developed to predict the number of labor hours, including overtime, required to build each set of wings. This allows Wing Majors to gauge the impact of each variable with respect to adding time to total labor hours.

This chapter provides a brief history of how 777s are manufactured at the Boeing Everett Facility, specifically highlighting how wings are produced. There are challenges associated with manufacturing the 777 at historically high rate, which is the basis and motivation for this study. The study aims to provide a relative as well as absolute impact to total labor hours by each process variation in Wing Majors. Basic factory terms are introduced so that Boeing specific termology can be used going forward. In addition, this chapter introduces the methodology used to define the project as well as in the analysis. The project was shaped by the current state manufacturing issues in Wing Majors and a comprehensive literature review of previous research done at Boeing. Analysis in measuring the impact of process variations on total labor hours would be conducted using statistical analysis.

Chapter 2

2 Literature Review

This chapter aims to provide a synopsis on existing research in the field of lean concepts, process and system variation in manufacturing, and factory scheduling. Based on existing work, my research builds upon these concepts and applies them to commercial airplane wing manufacturing.

2.1 Implementation of Lean Concepts

Lean manufacturing and the Toyota Production System (TPS) constitute the foundation of Boeing manufacturing. The TPS core principles include (Ōno 1988) –

1. Just-in-time Production – deliver parts right before you need them
2. Automation – automated defect control and prevention
3. Continuous Improvement – constantly striving to better the production system
4. Flexible Workforce – ability to vary the number of works and tasks as demand changes

The methods and tools associated with achieving these principles include the andon cord to signal problems on the line, visual controls designed to convey information quickly, standard work to reduce variation in the build, load leveling to ensure all stations are utilized appropriately, and reduced set-up time to facilitate faster change overs (Ohno 1988). Many of these tools have been implemented at Boeing in pursuit of operational excellence. While similar to TPS, lean manufacturing focuses on reducing waste created by unbalanced workloads and the overburdening of machines and staff (Hanna 2007). Examples of waste are transporting parts when it's not required in the manufacturing process, keeping excess inventory on hand, inspecting and amending defects, producing a surplus ahead of schedule, pushing machines and staff beyond their physical limits, just to name a few (Hopp 1996).

This research is particularly interested in how lean manufacturing and TPS aids in the reduction of process variability. Reducing waste corresponds directly to the reduction of process variation (Todorova and Dugger 2015). For example, external systems variations such as delays in QA response or shim production constitutes as a waste of resources as mechanics are simply waiting.

TPS was developed for high volume manufacturing where every job spans the same length of time, which is typically very short (Wheelwright 1984). There are four major classes of manufacturing structure and product life cycles as depicted in Figure 4 (Wheelwright 1985) and TPS was developed specifically for Class III. Commodities such as sugar are produced continuously with standardized processes and integrated equipment at very high volumes (Class IV). Automobiles, which require the assembly of multiple components, are produced on assembly lines at high volumes (Class III). Heavy equipment, comprising of multiple components and typically commanding higher margins, is manufactured in batches at low volumes (Class II). Commercial printers, which are made to order and highly customizable, do not have a standardized manufacturing process because they are usually one-of-a-kinds. Commercial printers are typically produced in a job shop at very low rates (Class I).

Airplanes, wings included, are categorized as Class II. Components of an airplane are manufactured on disconnected lines until they are joined for final assembly. The rate of production is measured in days, which is considered to be a low volume production compared to that of automobiles. However, TPS was established for Class III products where the rate of production can be measured in minutes. The tools and methods of TPS manage processes that only require several minutes. Therefore, applying TPS to airplane manufacturing has some inherent flaws.

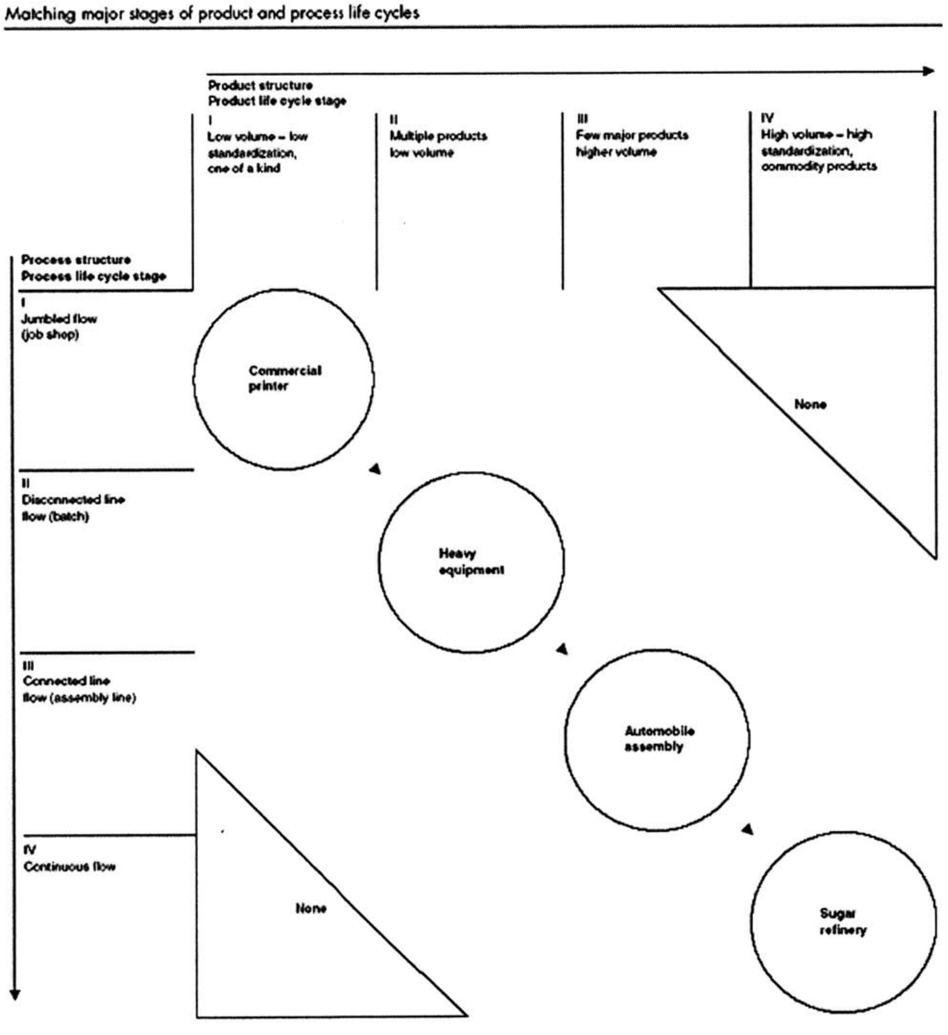


Figure 4: Manufacturing process structure typically used for different product life cycle stages.

2.2 Process and System Variation

There has been extensive research on process variation including both physical variation of key part characteristics and external systems variations. Physical variations of part geometry are, for example, the distortion in the panel curvature, size of holes, or thickness of applied sealant (Stevenson 2012). External systems variations include rework loops, machine reliability, part shortages, and any external disruptions to the process.

Both physical and external variations should be reduced to ensure high quality and overall machine effectiveness (Shewhart, 1980). Overall Equipment Effectiveness (OEE) is a commonly used metric that measures the actual performance of a tool relative to its performance capabilities under optimal manufacturing conditions (Pomorski 1997; "SEMI E10 Specification for Equipment Reliability, Availability and Maintainability | SEMI.ORG" 2015).

There are several statistical methods to analyze whether slight variations in a data set are directly attributed to variations. Walter Shewhart first introduced the concept of statistical quality control in 1942 at Bell Telephone Laboratories. His research asserted that while "the manufacturer tries to eliminate those causes which produce irregular, cyclic, or secular trends in any one characteristic," continual process adjustment in reaction to non-conformance actually increased variation and reduced quality. Shewhart applied statistics to differentiate between assignable causes and randomness in the process (W. A. Shewhart 1938). The same statistical analysis is used in this research.

2.3 Factory Scheduling and Utilization

In the late 1950s, Booz Allen Hamilton and the U.S. Navy Special Projects Office developed the Program Evaluation and Review Technique (PERT) to improve the management of the Polaris missile project. According to Hajek, "the basic concept of PERT is that the program is divided into discrete, detailed, scheduled tasks which are drawn up into an integrated network. All the significant variables of time, resources, and technical performance are allocated to each task or activity." (Hajek 1977) PERT allowed planners to identify the risks in a schedule from a high level perspective. Much of the scheduling at Boeing is based on PERT where discrete tasks requiring some quantity of resources are jobs.

Critical Path Method (CPM) was established around the same time as PERT. Developed at the DuPont chemical company, CPM was used to map out the longest path of planned activities, known as the critical path, to assess the risk of delays at each task (Goldratt 1997). Critical Chain Project Management, which is widely used at Boeing, differs slightly from CPM as it also includes resource constraints as well as task dependencies (Leach 2014). Together, CPM and PERT form the foundation to scheduling work at Boeing.

In summary, this literature review examines three topics pertinent to wing manufacturing – implementation of lean concepts, process and system variation, and factory scheduling. While the methods and tools associated with lean manufacturing are ubiquitous throughout Boeing, lean manufacturing was developed for high volume products, such as automobiles, that are produced on continuous assembly lines. Process and system variations have been well documented in manufacturing and the statistical tools to measure variation impact are commonly cited. The field of factory scheduling and utilization is rooted in PERT and CPM. Both were used to develop the barchart used to schedule jobs across Boeing.

Chapter 3

3 Current State Manufacturing Issues

This chapter aims to provide a detailed summary of the manufacturing issues that affect the Wing Majors shop. All shops in the 777 program follow a master schedule generated to meet customer delivery deadlines which allows them to operate at the same rate. Some shops have the capacity to meet the demand while others manage with a substantial backlog of jobs behind schedule. At the time of this research, the Wing Majors backlog ranged from 400 to 600 jobs behind schedule. Because a job can span from 20 minutes to 13 hours and any incomplete jobs due to quality issues are considered 'behind schedule,' it is difficult to determine the equivalent number of labor hours behind schedule. To calculate the number of labor hours behind schedule, Boeing must sum the associated job hours of every IP or redistribute the work required per IP so that each job is given the same amount of time. "Jobs behind schedule" is a common metric of performance at Boeing even though it provides less information than labor hours behind schedule. To understand why Wing Majors struggled with this backlog, the current state manufacturing issues must be understood.

3.1 Fixed Assembly Jig

Wings are assembled vertically within large fixed tools called jigs. There are four units, referred to as Fixed Assembly Jig (FAJ), each capable of holding a pair of wings. The FAJs are considered major capital investments and additional units will not be funded. The FAJs were built in 1993 without significant consideration for future automation. They also constrain how wings are assembled because the tools cannot be rearranged or substantially modified. Each unit consists of two slots for the wings and tools that secure the major components, spars and panels, in place. In the vertical position, the height of the wing spans over four stories so an infrastructure of platforms connected by stairs and elevators was put in place to support the build.

At the 2.5-day production rate, almost every unit is occupied at any given time. As a result, maintenance is hardly done on the FAJs. In fact, there is no scheduled maintenance plan because the availability of the FAJs is unpredictable. The tools, therefore, shift and move out of alignment. While managers are aware of the issue, it is not quantified as a cost opportunity and the program production schedule does not allow for major delays.

The slot for the wing is confined. The lower panel is loaded by gantry after the ribs and spars are installed. This process is painstaking as the space for the panel to be lowered down is quite narrow. Mechanics gather on either side of the panel to manually push and pull to prevent the panel from scratching. Jobs that fasten the ribs to the front spar are done on the upper two levels. To reach the work area, a short platform must be placed across the slot, bridging the two sides. Without the platform, the mechanics risk falling through the slot. These are only two examples of the issues stemming from the tight space and awkward configuration of the FAJs.

Inside the FAJs, it is dimly lit, often crowded with mechanics, toolboxes, and staged parts, and covered with aluminum chips and lubricant used for drilling. Despite efforts to improve the lighting, the low ceiling and awkward configuration inside does not allow for the installation of many new lights. Advances have also been made to reduce the number of toolboxes. Mechanics are accustomed to having individual toolboxes so this change will be primarily cultural. New drills that vacuum chips while drilling have been ordered to promote a neater work space.

The wing spans across four stories. Some jobs require the mechanic to alternate between floors, a non-value added task.

3.2 Manpower Organization

Unlike conventional high volume factories, Wing Majors relies primarily on manpower to build and assemble the wing. Machines are highly predictable and operate with a consistent efficiency. Humans, on the other hand, are subject to errors, variable work speeds, and human tendencies described in Boeing's Critical Chain Project Management course. These tendencies include Parkinson's law, which explains that work expands to fill the amount of time given. If a job normally takes twenty minutes to complete and one is given an hour, most people will consume the entire hour rather than finishing early.

The specialized work in Wing Majors requires various certifications. Almost all the work done in the upper panel control code is inside the fuel tanks, which requires special certifications. Once the upper panel is set, all incomplete and behind schedule jobs are converted to "in tank" work. Without the appropriate certifications, mechanics cannot continue to work. A person's physical size also constrains their ability to work inside fuel cells because of the limited access.

In some cases there is an available workforce that cannot complete the required jobs because of the lack of mechanics with the necessary certification.

3.3 Scheduling Processes and Crew Cycling

High level factory scheduling by control code is based on the 777 delivery schedule. Each control code is responsible for scheduling their respective jobs. The inputs to this process are the precedence network, which constrains jobs from starting before the previous job is complete, available workforce, quantity of jobs based on labor hours, and physical space. The output is a schedule by flow day delineating jobs by each mechanic. A commonly used tool to represent the schedule is a bar chart. Introduced by industrial engineer Henry Gantt around 1910, the bar chart is a critical tool at Boeing to show the sequential steps of a large, multi-phase project (Ritz 1990). Figure 5 depicts an example of a bar chart for the lower panel control code.

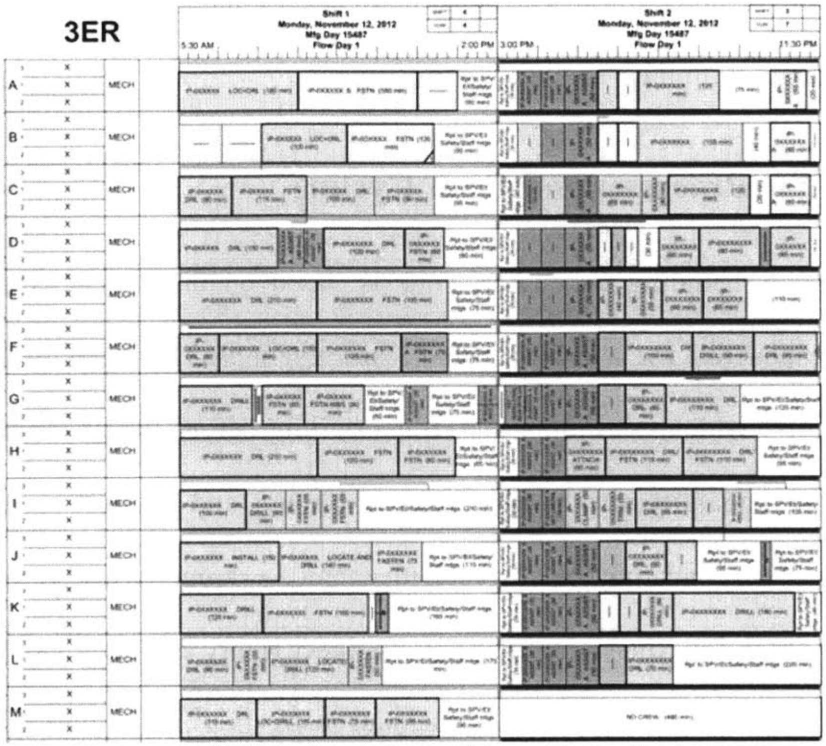


Figure 5: Example of a bar chart. Each individual rectangle represents a job with the length of the rectangle representing the length of time required to complete the job. Each line corresponds to a mechanic.

While the precedence network is an important concept in scheduling, it is not well utilized in Wing Majors. The precedence network, shown in Figure 6, can quickly allow the user to identify which jobs impact others. When a mechanic is absent, the precedence network can help in reassigning the jobs based on the number of other jobs affected. The bar chart, however, has been woven into the culture since the development of the 757 in 1966, making other tools challenging to sustain.

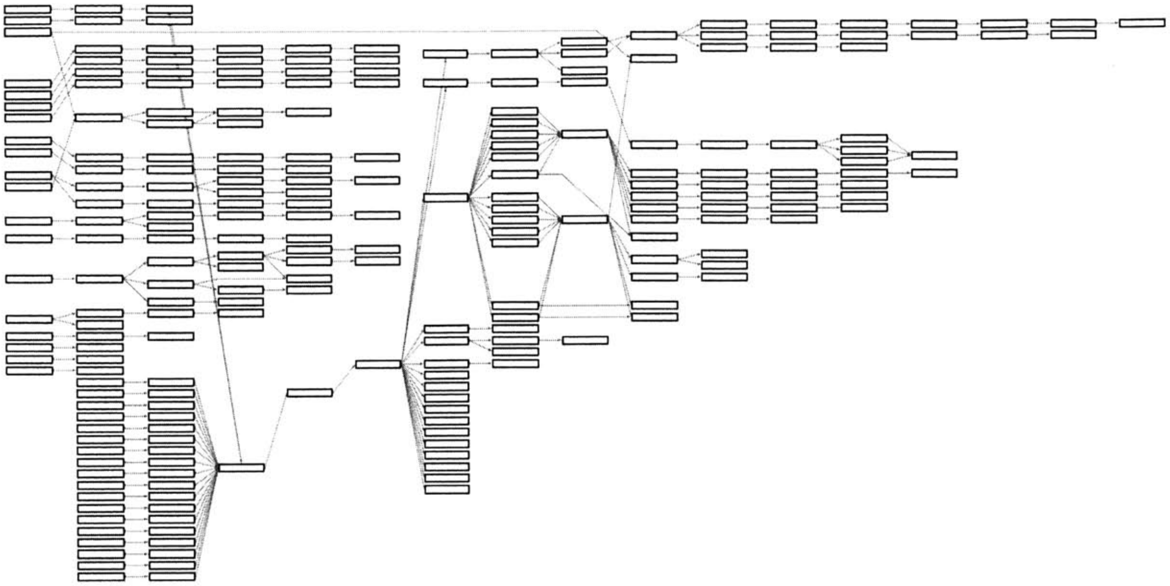


Figure 6: High level view of the precedence network for one control code. Each block represents one job. This network allows the user to quickly identify the critical path and the impact of delays to the system.

The bar chart has several shortcomings including the inability to show resource requirements, relationships between jobs, and the precedence sequence (Oberlender 2014). A close examination of the bar chart will reflect the high level precedence of work. An observer can assume flow day 2 jobs must be accomplished before flow day 3 jobs. However, within a flow day it is difficult to see the relationships between jobs and to understand why there is occasionally no work scheduled. New industrial engineers will adjust the bar chart without understanding its nuances and challenges, potentially disrupting the build sequence.

Crew cycling defines how mechanics are moved from one wing to another and determines which airplane mechanics will work on each day. Individuals are moved to the next wing every other day to every four days although the set of jobs performed usually remains the same. Crews are organized by left and right hand wing though there are several crews that service both. The way mechanics are currently cycled poses several challenges. Because of the 2.5-day rate, there is a "delta day" for the lower panel control code where no work is scheduled every four days. With this cycle, it's difficult to learn a set of jobs well enough to improve because delta days are typically spent completing outstanding work. According to Boeing's learning curve per airplane, shown in Figure 7, increasing cumulative production logarithmically reduces the labor hours required (Jaber 2011). While the learning rate is a function of production rate, predictions for the 2.5-day rate have been inconsistent with actual labor hours. In fact, learning has ceased and labor hours have started to increase on the most recent line numbers. There have been no formal studies that prove that the crew cycling plan and delta day have caused the halt in learning. However, based on interviews with mechanics and team leads, the crew cycling plan and delta day does not facilitate further learning.

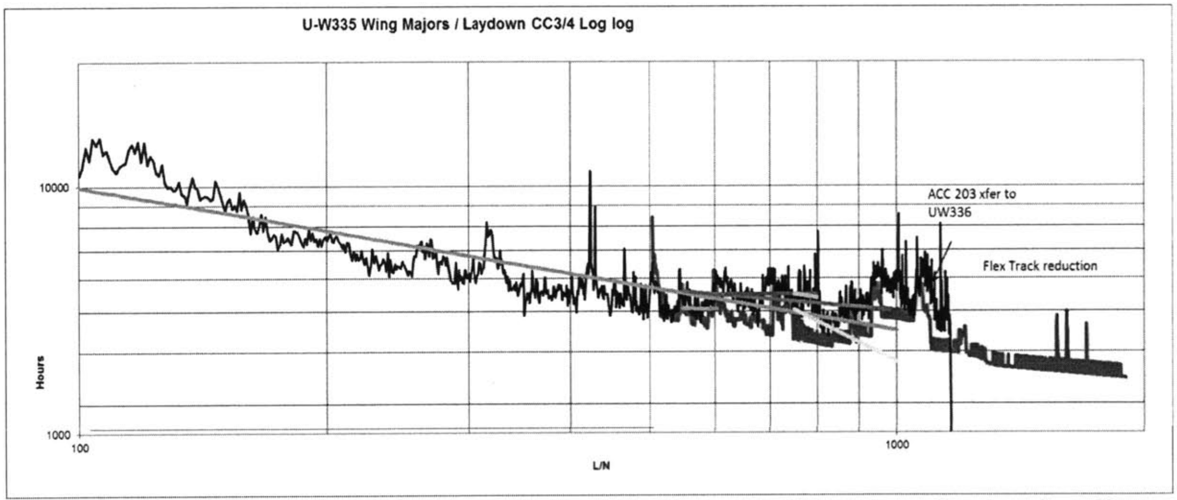


Figure 7: Learning curve on a log-log scale representing actual labor hours per line number. Sharp increases on the learning curve represent a disruption to the build. This may include rate breaks, consolidation of control codes, or reorganization of the shop.

3.4 Support Functions and Stakeholders

There are multiple support groups and stakeholders involved in the assembly of the wing. Table 1 lists these groups and their roles and contribution to the manufacturing process.

Support Function	**Roles and Responsibilities**
Quality Assurance (QA)	• Validates the product is built as designed • Conducts preliminary root cause analysis on defects • Drafts noncompliance report for defects and releases known repairs
Parts Control Organization	• Stages parts and delivers them to Wing Majors
Manufacturing Engineering	• Determines the procedure to carry out each job and how often QA is required to inspect each job
Industrial Engineering	• Determines the duration of time assigned to jobs through time studies and learning curve approximations • Manages the bar chart and crew cycling plan • Develops recovery and contingency plans
Tool Room	• Maintains the tools including drills, motors, and drill bits
Standards	• Prepares fastener kits for individual jobs
Training	• Provides basic training to new mechanics • Provides work place coaches for other mechanics
Tooling	• Maintains the FAJs and attached large indexing tools

Table 1: Wing Majors support functions and their respective roles and responsibilities.

All the above functions do not report directly to manufacturing. Rather, they have a dotted line relationship. This sometimes results in a lack of accountability and service. Manufacturing requires all functions to perform promptly and in sync in order to meet delivery deadlines. For example, when a part is missing from the parts rack, a mechanic must stop work to track it down, expending time that should be used to complete the job. When a drill malfunctions, the mechanic is responsible for returning the tool to the tool room, waiting in line to be seen by the kellermen. When a job is completed and put up to the QA call board, a mechanic will wait upwards of 30 minutes for a 75-minute job because there are not enough QA personnel to handle the requests. In almost all cases, mechanics are responsible for notifying the appropriate functions of issues.

Wing Majors relies heavily on these parties to be successful. The lack of accountability and number of support groups greatly affects the labor hours required to build the wing. While intermittent studies have been done per job to determine the amount of time consumed by non-value added work, there has been no comprehensive analysis to quantify the amount of non-value added time spent in Wing Majors or by control code.

3.5 Defects and Rework

Defects and rework greatly affect the production schedule, often delaying subsequent jobs and causing overtime. While Wing Majors has pushed to improve quality in the past, it has not sustained the gains due to several reasons. There have been no major reforms to new mechanic training. The month long training plan introduces mechanics to basic drilling and fastening but does not expose them to the actual environment or differentiate training based on specific jobs. All the mechanics interviewed acknowledged that the majority of learning was done on the job.

Annual quality plans, which prioritize the initiatives for the year, are developed by managers rather than mechanics. The plans are subsequently equivocal and conceptual in nature, making them difficult to implement. In addition, mechanics are unable to conduct root cause analysis on every defect created due to time constraints and lack of resources. A quality investigator will often provide assistance but not every defect will be examined. If the root cause is identified, it is not usually shared across the control code.

There are currently no incentives to improve quality or harsh consequences for generating defects. By nature of a unionized workforce, financial incentives and other benefits are based on tenure rather than performance. While it is possible to dismiss a mechanic based on his or her quality of work, it is much easier and faster to reassign such mechanic to a less impactful job.

When QA identifies a defect, a standard repair will be issued or stress engineering will be notified to issue a custom repair. A standard repair can be carried out immediately. However, custom repairs require extensive calculation and may require upwards of 6 hours for a 4-hour job. Figure 8 provides a basic flow diagram on how defects are processed. A lack of resources and the complexity of analysis prevent engineering from operating at a similar takt time. In addition to the wait time, the repair is usually done out of sequence, which requires more time because the mechanic must now work around jobs that have proceeded (Hopp 1996).

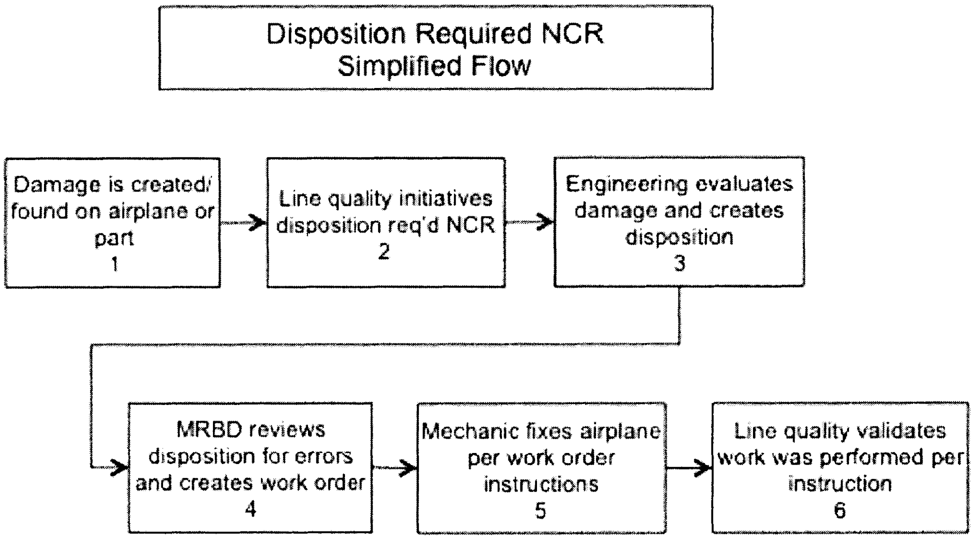


Figure 8: Flow diagram of how defects, also known as Nonconformance Reports (NCRs), are addressed and processed.

3.6 Work Execution and Compliance

Factory schedules operate under the assumption that work will be completed on time. However, when a percentage of the workforce is out sick or on vacation, the schedule is made vulnerable to delays. Wing Majors is able to account for vacation time and sick leave but unexcused absences are much more difficult to plan for. Sick leave can be roughly predicted by historical values. Even unexcused absences can be anticipated based on the time of the year. All absences are referred to as 'labor loss.' The effects of labor loss are mitigated by having additional mechanics called 'overbars.' The ratio between mechanics and overbars is roughly 10:1. That is, a labor loss of 10 percent can be absorbed by the system without delays to the schedule. However, the average labor loss experienced by Wing Majors spans between 10 to 30 percent.

For example, the average labor loss in Wing Majors on Thursday, July 3, 2014 and Monday, July 7, 2014 were 25 percent and 30 percent respectively. Labor loss around holiday weekends is especially high and difficult to mitigate. The labor loss on Tuesday, July 8, 2014 was only 7 percent. Because labor loss fluctuates considerably, it is difficult to plan for and make gains in the schedule. Figure 9 charts the change in labor loss in Wing Majors. Because the average labor loss is roughly 17 percent during the time of my research, is impossible to maintain the build schedule without the use of overtime.

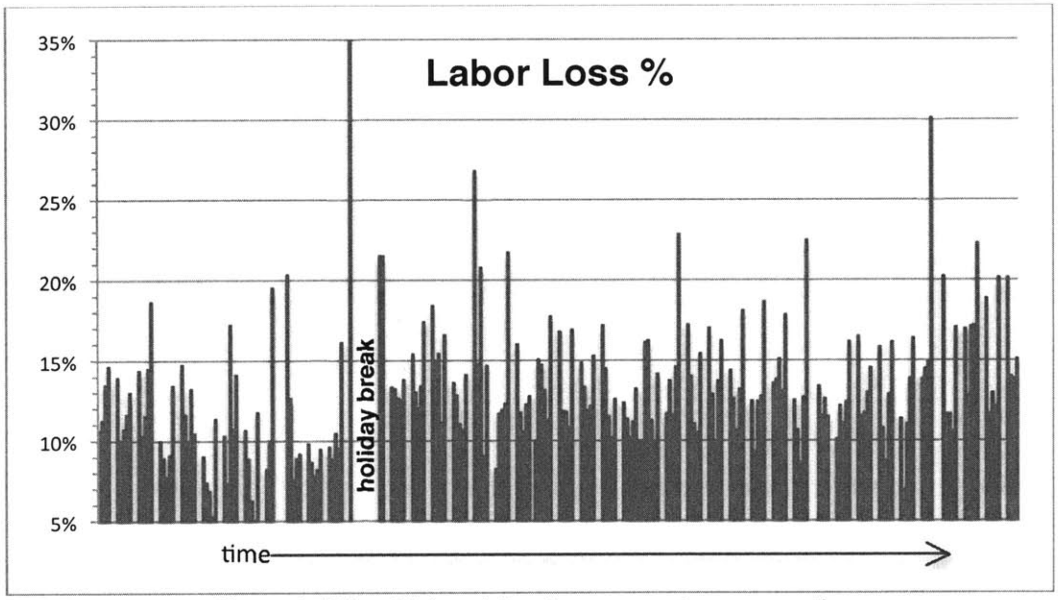


Figure 9: Wing Majors labor loss percentage across time

When a mechanic starts a job, he or she must sign into the work through an online system. This tracks the amount of time spent on each job. The bar chart visually arranges jobs in series rather than parallel. Realistically, however, many jobs can be done faster in parallel, reducing the set-up time and preparation required. For example, one job is to drill and fasten rear spar to ribs 9 through 11 while another is to drill and fasten rear spar to ribs 12 to 15. Rather than taking on the jobs individually, the mechanic may choose to drill through ribs 9 to 15 and then fasten them.

The flaw in the system is revealed when two 4-hour jobs are done in parallel and completed in 7 hours. The mechanic is obligated to sign into both jobs, registering them as requiring 7 hours each rather than 3.5 hours to complete. To address this issue, mechanics are given the flexibility to sign in and out of jobs as necessary. In this scenario, the mechanic must sign out of the first job after drilling ribs 9 to 11 and sign into the second job. After drilling ribs 12 to 15, the mechanic should sign out again only to sign into the previous job to start fastening. For many mechanics, it is difficult to stop in the middle of a task, set down all equipment, and seek the nearest available computer.

The parallel versus series dilemma also affects how managers oversee their crew. If the manager is unaware the mechanic has started on multiple jobs, he or she might express concern over the progress. The performance metric, Cost per Job, is derived from the number of hours logged by the mechanic. Therefore, this metric may show a skewed view of Wing Majors efficiency.

Work compliance refers to the completion of jobs as detailed in the bar chart. The bar chart enforces the work schedule. Jobs that are not in accordance with the schedule are considered out of compliance. Mechanics cannot work ahead of schedule and incomplete jobs of that flow day are therefore out of compliance. This guideline was developed to maintain the precedence network, avoid unnecessary rework, and prevent mechanics from choosing jobs that are easier than others.

Standard work is a very detailed account of how the work can be done most accurately and efficiently. This manufacturing term has been made prominent by the automotive industry where standard work even describes the number of turns required for each screw. Boeing does not apply standard work as rigorously and as a result, there are multiple ways to carry out a job.

3.7 Culture

Culture plays a significant role in any organization and in Wing Majors, it is a source of current state manufacturing issues. Unlike the other sources mentioned, culture is complex in nature, difficult to quantify, and formed over years. Studies have shown that any shift in culture requires at least five years using a consistent message. The area of study focused on effective cultural changes in corporate environments is called Change Management (By 2005).

Wing Majors does not utilize the various communication channels to exchange information. There is a lack of communication between shifts, within and between control codes, and among support functions. For example, email messages are not exchanged to introduce new plans, extol successful completion of projects, or announce retirements and new hires. There is no easily accessible space to hold large meetings, resulting in few all hands meetings by control code or with all Wing Majors. Lastly, there are few visual displays of communication including quality metrics, job completion and status, or line number information on the shop floor. One must log into a computer and navigate through several websites to find the real time build status.

Due to the penalties incurred by Boeing when an airplane is delayed in delivery to the customer, adherence to the master schedule is critical. The delivery schedule takes precedence above other priorities including training, planned maintenance, and reduction in overtime. As a result, the culture values perseverance at all costs rather than self-reflection and problem solving.

Lastly, first line managers are perceived by the mechanics as temporary because there are several management rotation programs that move personnel around. The transient nature of management is often interpreted negatively, making it more challenging for managers to implement and sustain improvements.

This chapter covers extensively the current state manufacturing issues found in Wing Majors that stem from the Fixed Jig Assembly infrastructure, a predominately manpower organization, the scheduling and crew cycling process, the various manufacturing support functions and stakeholders, defects and rework, work execution and compliance, and the culture. Many of these issues are not unfamiliar to Wing Majors, however, they have been amplified with each rate increase. Wing Majors is now challenged to assemble wing structures in spite of these issues at a 2.5-day rate. The catalog of these issues have aided in identifying the process variations discussed in Chapter 4. The objective of this study is to mitigate and eventually eliminate system variations that have a greatest impact to the build process.

Chapter 4

4 Process Variation Impact on Labor Hours

Variations detailed in Chapter 3, Current State Manufacturing Issues, contribute to total labor hours consumed in Wing Majors as they add non-value added time to the process. The mechanic is faced with many variations and disruptions throughout the shift that he or she must troubleshoot, elevate, or resolve. This chapter provides a comprehensive list of high level system variations within the scope of the wing line, focusing on those that are quantifiable. Physical variations in the manufacturing process such as distortion in the panel curvature, the speed in which drills bore out holes, or the nonstandard procedure in which sealant is applied were not taken into consideration for several reasons. These physical variations are immeasurable given the number of distinct jobs in Wing Majors, and there are currently no methods to gauge some of the physical attributes. The focus, therefore, is broad and examines the system variations that contribute to labor hours. To measure a variation's impact on labor hours, a step-wise regression model was created. This chapter aims to address the most challenging process variations with the largest effect on overtime.

4.1 Hypothesis

The null hypothesis is that the identified variations do not affect the total labor hours. This implies that the fluctuation in labor hours is random.

The working hypothesis assumes that actual labor hours are usually greater than the baseline or budget labor hours because mechanics have to contend with system variations such as engineering changes, defects, waiting, and part shortages, which disrupt the process flow and add additional time. Baseline hours is the sum of all jobs within Wing Majors while budget labor hours incorporate some buffer time required for rework.

4.2 Data Collection Methodology

In order to identify and document the variations that occur innately in the manufacturing process, I interviewed and observed first line managers, mechanics, and team leads. Disruptions that lead to non-value-added time, defined as any function that does not physically change the end production, were classified into three categories – labor, support functions, and outside the scope of Wing Majors (Ōno 1988). These categories suggest that Wing Majors has different levels of control over some variations and that the root cause of the variation stems from the mechanics and labor policies, the support functions, or the upstream suppliers. Table 2 lists the variables and identifies those that are measurable.

	Quantitative	Qualitative
Labor	• Work force experience and age • Labor loss • Learning curve • Defects • Travelers • Injuries	• Level of standard work • Crew cycling plan disruptions • Training plans
Support Functions	• Missing kits & standards • Engineering changes • Part shortages • QA response time • Shim production time • Shipside Action Trackers (SAT)	• Tool readiness & maintenance • Level of automation
Outside Wing Majors Scope	• Rate changes	• Upstream (Spars and panels and supplier) • Labor and time-off policies • Tooling infrastructure

Table 2: Quantitative and qualitative variations by labor, support functions, and outside Wing Majors scope.

Of the quantitative variables, the majority is within scope of Wing Majors. Manufacturing can directly affect the variations that result from labor and influence the variations that stem from support functions. In the process of data collection, statistics on average age and experience level of personnel could not be disclosed. Labor loss was challenging to measure because the percentage of mechanics absent is recorded differently across functions. Human resources calculate labor loss by hour as some mechanics clock in for part of the day. Manufacturing deems partial days to be 100% loss because jobs are highly dependent upon each other. In order for the bar chart system to be effective, assigned jobs must be completed on time and in order. Mechanics who cannot complete a full day are taken off their bar and given another task. In addition, labor loss had only recently started to be tracked. With the expansion and implementation of the Family and Medical Leave Act, it has been easier for employees to take time off. Besides personnel and labor loss information, the other quantifiable variables could be accessed through Boeing's comprehensive manufacturing database.

The qualitative variables, such as the level of standard work and level of automation, were not addressed in this paper. Further assessment could be done to quantify these variations through the use of surveys and industry benchmarking, and incorporated into the regression.

4.3 Definition of Variables

Of the quantitative variables listed in Table 2, 11 will be included in the regression. They are the following –

1. **Rate of production** – The program level rate of production is currently 2.5-days. On line number 1074, the rate of production increased from 3-days to 2.5-days. Since line 1074, there have been no changes to the rate. The changes in labor hours associated with this rate break were captured as data collection began with line 996.
2. **Number of defects** – A defect is a job that does not meet drawing requirements and requires corrective action. This variable is a count on the number of defects per line number regardless of severity, location, rework required, or control code. This variable treats all defects equally and only provides the count.
3. **Number of travelers** – A traveler is any job that moves into the subsequent control code incomplete. They can be done without changes to the manufacturing plan but usually require significantly more time to complete because they are done inside the fuel tanks. This variable does not account for how incomplete the job is or why it's incomplete. Travelers in the regression indicate the number of jobs that left Wing Majors incomplete.

Travelers that are completed in a subsequent control code within Wing Majors are not included in this study. Further analysis is required to measure the impact of process variations at each control code.

4. **SAT count** – The shipside action tracker logs a multitude of issues in manufacturing ranging from missing kits to malfunctioning drills. The ship refers to the airplane and shipside support is carried out by the support cell. This variable does not take into consideration the urgency of the issue or the time required to address it. Rather, it counts the number of issues logged on each airplane.

5. **Shortage count and shortage count not related to defects** – Shortage count refers to the number of parts, regardless of size and criticality to the build, missing from each airplane at the time of installation. Parts are absent because they were misplaced in transportation, not ordered on time, or scrapped by manufacturing due to a defect. Missing parts are installed as soon as they are received which spans from same day delivery to several days. Consequently, part shortages create delays in the workflow as well as travelers. This regression considers the total number of part shortages per airplane and those not created by manufacturing defects.

6. **Labor hours predicted by the learning curve** – The industrial engineering group develops and employs learning curves to chart the amount of learning that should occur with each airplane. The learning curves account for changes to the manufacturing process by way of engineering changes or rate breaks as they interrupt learning progress. The learning curves also consider the average attrition of mechanics but do not account for average age and experience of the workforce.

7. **Average QA response time (initiation to acknowledgement to completion)** – This variable calculates the average response time of QA across all jobs in Wing Majors. It is further segmented into the average time from initiation to acknowledgement, acknowledgment to completion, and initiation to completion. When a job is completed, the mechanic is responsible for initiating the request for QA inspection. QA is subsequently responsible for acknowledging the request and completing the inspection.

8. **Average shim production time** – Shims are a necessary component of the wing as part tolerances can lead to nontrivial gaps when parts are assembled. Shims are custom made by machinists in the Everett facility. This variable measures the average production time of shims per airplane, calculated as the total shim production time per line divided by the number of shims. The production time starts when the mechanic submits the request and ends when the machinists complete the order. While the time required to fabricate a shim is not necessarily a delay in the workflow, current production times have been cause for concern in Wing Majors. The shim shop, which services multiple shops in the 777 program, has not increased capacity over the most recent rate break from 3 to 2.5-days. Shim production have steadily increased from an average of 4 hours to 7 hours, pushing the job into the next flow day and potentially causing delays to the schedule.

9. **Number of shims produced/total shim production time** – This variable normalizes the time consumed in shim production by the number of shims produced. Some airplanes require substantially more shims than other airplanes for various reasons including defects, engineering changes, or supplier variation.

10. **Number of engineering (design or manufacturing) changes** – Engineering changes occur when drawing specifications are changed for the purposes of improving performance, reducing cost, or simplifying the assembly. This variable does not consider the extent of the change, effects from its implementation, or degree of success experienced. Only the number of engineering changes per line number is counted.

11. **Model type** – From lines 996 to 1250, four model types were produced – 2F, 2ER, 2LR, and 3ER. Each model differs slightly in the manufacturing process. For example, the panel skin on the 2F is thicker than that on the 3ER. Therefore, drilling through the skin requires more time.

4.4 Analysis of Statistical Regression

The eleven independent variables were used to predict for total labor hours per airplane in the following regression. The variables are not entirely independent from each other. Travelers, for example, sometimes result from prolonged QA response time or part shortages. In order to determine only those significant in predicting labor hours, a stepwise regression was used.

Stepwise regression is a statistical method which scrutinizes each independent variable based on the P-value and through a series of regression steps, provides a best-fit model based on the user's threshold (W. A. Shewhart 1938). The stepwise regression first selects the independent variable with the highest P-value and then calculates the P-value for all remaining independent variables against the regression residual. The model then incorporates the next variable with the highest adjusted P-value and recalculates the P-value for the remaining variables against the updated regression residuals. When the incorporation of a new variable leads to an existing variable's P-value to fall below the user threshold, the new variable will be removed from the model. The stepwise regression will continue this process of incorporation and recalculation until all independent variables that meet the P-value set by the user are included. The user sets two P-values – the threshold to enter and the threshold to remain. The former allows variables to be considered while the latter is the final P-value the model is generated with.

The user can specify the P-value or a minimum Akaike Information Criterion (AIC) or Bayesian Information Criterion (BIC). The AIC is a relative measure of quality of the statistical model for a give set of data. AIC estimates the quality of a model compared to the other possible models and is defined as –

$$AIC = 2k - 2\ln(L)$$

where k is the number of degrees of freedom or parameters to be estimated and L is the maximized value of the likelihood function of the model.

The BIC is another tool for model selection that is closely related to the AIC. The BIC differs in that it has a stronger emphasis on penalizing for the number of parameters used in the model to prevent overfitting the results. It is defined as –

$$BIC = -2\ln(L) + k \cdot \ln(n)$$

where again k is the number of parameters and L is the maximized value of the likelihood function of the model. n is the number of data points in the sample size.

The stepwise regression was carried out with user specified P-value, AIC, and BIC to compare the results.

Correlation

A correlation analysis, summarized in Table 3 below, was done to ensure that the independent variables were not redundant or dependent on each other. It is important to note that part shortages were not included in this analysis. Shortage count was not available before line number 1224 using the current system of replenishing parts. A few significant correlations were observed.

	Total Labor Hours	Overtime Hours	Travelers	Rate	Defects	SAT count	Learning Curve	QA Ave Init to Ack Min	QA Ave Init to Cmpl Min	QA Ave Ack to Cmpl Min	Shim Ave Min
Total Labor Hours	1.0000	0.7669	0.6021	-0.2220	0.4945	0.1491	0.0129	0.0130	-0.0639	-0.0793	-0.1745
Overtime Hours	0.7669	1.0000	0.4329	-0.1267	0.3972	0.1095	0.0390	0.0294	-0.0263	-0.0401	-0.0561
Travelers	0.6021	0.4329	1.0000	-0.1380	0.3742	0.0765	0.0216	0.0905	0.0133	-0.0125	-0.1422
Rate	-0.2220	-0.1267	-0.1380	1.0000	0.0744	0.0546	0.0452	0.2063	0.2096	0.1825	0.4823
Defects	0.4945	0.3972	0.3742	0.0744	1.0000	0.1434	0.1060	0.0710	0.0124	-0.0075	0.0238
SAT count	0.1491	0.1095	0.0765	0.0546	0.1434	1.0000	0.1891	0.0493	0.1199	0.1257	0.0467
Learning Curve	0.0129	0.0390	0.0216	0.0452	0.1060	0.1891	1.0000	-0.0053	0.0310	0.0381	0.0028
QA Ave Init to Ack Min	0.0130	0.0294	0.0905	0.2063	0.0710	0.0493	-0.0053	1.0000	0.6571	0.4621	0.1849
QA Ave Init to Cmpl Min	-0.0639	-0.0263	0.0133	0.2096	0.0124	0.1199	0.0310	0.6571	1.0000	0.9721	0.1914
QA Ave Ack to Cmpl Min	-0.0793	-0.0401	-0.0125	0.1825	-0.0075	0.1257	0.0381	0.4621	0.9721	1.0000	0.1677
Shim Ave Min	-0.1745	-0.0561	-0.1422	0.4823	0.0238	0.0467	0.0028	0.1849	0.1914	0.1677	1.0000

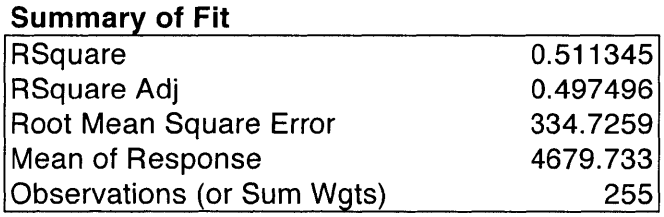
Table 3: Correlation analysis between the independent variables to ensure they are in fact independent.

Total labor hours and overtime hours are correlated by a value of 0.7669 as the latter directly augments the former. Similarly, QA average time from initiation to completion is directly correlated to QA average time from initiation to acknowledgement. Total labor hours and travelers are correlated by a value of 0.6021, which foretells the regression outputs in predicting labor hours. Total labor hours and defects are correlated by a value of 0.4945, which suggests that defects will also be significant in the regression. Defects and travelers are slightly correlated at 0.3742, implying that defects are not the only source of travelers. Both parameters were included in the regression as a result. Interestingly, shim production time and program production rate are correlated by a value of 0.4823. An increase in production rate from 3-days to 2.5-days also reduced the average time of shim production. This may be attributed to the increase in shim shop capacity in preparation for the rate break. Lastly, it's important to note that none of the variables had high negative correlations.

Through the correlation analysis, two variables were removed – QA initiation to acknowledgement time and acknowledgement to completion time because they are redundant. The variable, QA initiation to completion median time, encompasses the issue of long QA wait times and low service levels.

Stepwise Method Comparison

P-value – Using the user defined threshold of 0.25 (probability to enter) and 0.10 (probability to leave) the following model was created.



Summary of Fit

RSquare	0.511345
RSquare Adj	0.497496
Root Mean Square Error	334.7259
Mean of Response	4679.733
Observations (or Sum Wgts)	255

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	7	28959204	4137029	36.9241
Error	247	27674234	112041	**Prob > F**
C. Total	254	56633438		<.0001*

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>ltl
Intercept	–	271.7706	16.11	<.0001*
Travelers	12.448753	1.549461	8.03	<.0001*
Rate	-465.8643	97.03066	-4.80	<.0001*
# Defects	2.1855901	0.375584	5.82	<.0001*
QA Median Init to Cmpl Min	6.5259328	2.499271	2.61	0.0096*

The RSquare and the RSquared Adjusted are close in value, which is common with a large data set. The output of this model implies that four variables – travelers, defects, production rate, and QA response time can explain roughly 50% of the total labor hours. SAT count, engineering changes, and the model 2ER were also cited in the regression output but they were not as statistically significant.

The intercept is the value for which all variables are zero. However, in this analysis, the production rate cannot be zero. While the intercept is not useful for interpretation purposes, is it nonetheless removed for proprietary reasons.

The results of this model establishes the relative importance of the above four variables in predicting for labor hours. The parameter estimates table provides a valuation of labor hours per term or variable. For example, every additional traveler per line number adds 12.4 hours to the total hours. A set of wings with a particularly high number of travelers, regardless of reason or quantity of work, will accumulate labor hours at the rate of 12.4 hours per traveler. An average job requiring two hours when done in position now requires significantly more time when completed out of position. While Wing Majors acknowledges the additional time requirement for travelers, there was no value associated with the additional time prior to this research. Similarly, each additional defect will contribute 2.2 hours to the build as a result of the engineering assessment as required, custom work orders, and rework needed. Most defects can be addressed with standard repairs and only a few require substantial engineering evaluation.

For every additional hour utilized to examine a completed job past the 20 minutes provided for each job according to Quality's Service Level Agreement, 6.5 hours are added to the total labor hours required to build one set of wings. A QA inspection time of roughly ten minutes is incorporated into the manufacturing plan depending on the number of inspections required per job. More often than not, an excess of ten minutes is required to respond to the request and complete the inspection. Mechanics are not necessarily waiting idle for the QA examiner. However, in many cases, jobs cannot start before inspection is complete, often delaying multiple jobs in the chain and generating traveled work.

Production rate is a significant factor in predicting labor hours. An increase in production rate, measured in cycle days, from 4-days to 3-days reduces total labor hours by approximately 466 hours. This is a peculiar point because the quantity of work remains the same after the rate break. The reduction in labor hours can be attributed to faster learning and the cutback of time allotted for jobs by industrial engineering. Faster rates facilitate accelerated learning as mechanics are required to perform the same job more often. In developing the schedule for the rate break, industrial engineers had shaved away some time from each job to anticipate efficiency gains from learning. While rate breaks significantly affect total labor hours, they are infrequent and the 777 program does not foresee any changes until the ramp up of 777X production.

Sensitivity of the significant variables ranges drastically from 2.2 to 466 hours. It is important to note, however, that 2.2 hours are incurred for every defect on the airplane whereas rate changes happen very infrequently. The sensitivities can be normalized through a contribution analysis to represent a more realistic impact to total labor hours. This allows Wing Majors to target the variables with the largest contributions to labor hours, namely travelers and QA response time.

AIC – Using the minimum corrected AIC, the best model was selected given the independent variables.

Summary of Fit

RSquare	0.507359
RSquare Adj	0.49544
Root Mean Square Error	335.4101
Mean of Response	4679.733
Observations (or Sum Wgts)	255

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	6	28733456	4788909	42.5681
Error	248	27899981	112500	**Prob > F**
C. Total	254	56633438		<.0001*

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>ltl
Intercept	–	271.1093	16.28	<.0001*
Travelers	12.488513	1.552374	8.04	<.0001*
Rate	-458.3201	97.08303	-4.72	<.0001*
# Defects	2.2090738	0.375986	5.88	<.0001*
QA Median Init to Cmpl Min	6.3448141	2.501114	2.54	0.0118*
Model 2ER[1-0]	259.56723	140.7761	1.84	0.0664

The regression generated using the minimum AIC method produced very similar results. The

RSquare and RSquare Adjusted remains in the range of 0.49 to 0.51, and the significant variables are also travelers, defects, production rate, and QA response time.

BIC – The stepwise regression was run using the minimal BIC method. The results are shown below.

Summary of Fit

RSquare	0.494798
RSquare Adj	0.486715
Root Mean Square Error	338.2976
Mean of Response	4679.733
Observations (or Sum Wgts)	255

Analysis of Variance

Source	**DF**	**Sum of Squares**	**Mean Square**	**F Ratio**
Model	4	28022123	7005531	61.2129
Error	250	28611315	114445	**Prob > F**
C. Total	254	56633438		<.0001*

Parameter Estimates

Term	**Estimate**	**Std Error**	**t Ratio**	**Prob>|t|**
Intercept	–	267.6506	16.18	<.0001*
Travelers	12.531869	1.545444	8.11	<.0001*
Rate	-455.7129	97.8708	-4.66	<.0001*
# Defects	2.3615437	0.357248	6.61	<.0001*
QA Median Init to Cmpl Min	6.8436086	2.51286	2.72	0.0069*

The RSquare and RSquare Adjusted value using the minimum BIC is slightly lower but still comparable to that of the previous two models. The significant variables continue to be travelers, defects, production rate, and QA response time with similar estimates to that produced by the other methods.

The RSquare Adjusted resides at 0.50 in all three methods of analysis which implies that 50% of factors contributing to labor loss remains unexplained. Eleven variables were incorporated in the regression, however, eight qualitative variables, including level of automation, tool readiness and maintenance, and labor and time-off policies, were not considered. While it is conceivable to translate the qualitative variables into quantitative variables for the purpose of achieving an RSquare closer to one, it is not necessarily practical. If labor and time-off policies were identified as a significant contributor to total labor hours, Wing Majors would take no immediate action. Labor and time-off policies are determined at the corporate and union level rather than by individual shops or programs. In addition, reducing variation by any amount is advantageous to Wing Majors. It would be impossible to eliminate all system variations, as it would require program-wide reforms and major capital investments.

4.5 Implications and Recommendations

This analysis provides Wing Majors with the relative impact of eleven independent variables to total labor hours. The regression output concludes that production rate, travelers, QA response time, and defects have a significant impact on labor hours respectively. The other independent variables were not statistically significant in predicting for labor hours. Because the 777 production rate will not change in the near future, Wing Majors must focus on reducing travelers, defects, and QA response time.

From the correlation analysis, travelers and defects are not completely independent. Travelers are the result of delays and disturbances in the manufacturing process. A stepwise regression was conducted to predict for travelers, the dependent variable, and the following results were produced.

Summary of Fit

RSquare	0.276606
RSquare Adj	0.256105
Root Mean Square Error	13.43819
Mean of Response	31.34902
Observations (or Sum Wgts)	255

Analysis of Variance

Source	**DF**	**Sum of Squares**	**Mean Square**	**F Ratio**
Model	7	17055.485	2436.50	13.4923
Error	247	44604.452	180.58	**Prob > F**
C. Total	254	61659.937		<.0001*

Parameter Estimates

Term	**Estimate**	**Std Error**	**t Ratio**	**Prob>ltl**
Intercept	-7.738945	8.997329	-0.86	0.3905
# Defects	0.070115	0.014305	4.90	<.0001*
QA Median Ack to Cmpl Min	0.9069928	0.220928	4.11	<.0001*
Shim Submit to Complete Min	-0.227026	0.077342	-2.94	0.0036*
Engineering Changes[1-0]	14.201421	6.894227	2.06	0.0405*
Model 2F[1-0]	-3.64937	2.262919	-1.61	0.1081
Model 2ER[1-0]	10.006209	5.601967	1.79	0.0753

With an RSquare Adjusted of 0.277, the model's significant variables are defects and QA response time. The other variables of note are shim production time and the number of engineering changes. This analysis asserts that travelers are indeed dependent on these variables. Therefore, travelers can be reduced by improving quality and QA service levels.

The stepwise regression, which was carried out using three statistical methods, produced identical results in predicting for Wing Majors labor hours. Of the eleven independent variables included in the regression, four proved statistically significant. They are travelers, QA response time, rate changes, and defects. As rate changes occur infrequently, the practical implications of the study converge on reducing travelers, defects, and QA response time which is examined in detail in Chapter 5. A traveler, defined as a job that moves into the next position incomplete, partially results from defects and delays in QA response. Further analysis revealed that defects and delays in QA response account for only 27.7% of work traveled out of Wing Majors. This finding suggests that Wing Majors can influence travelers by means other than improvements in quality and QA service levels.

Chapter 5

5 Recommendations to Mitigate System Variations

The statistical analysis conducted in Chapter 4 identified the system variations that were most significant in influencing the labor hours required per airplane in Wing Majors. The variations were travelers, QA response time, rate changes, and defects. This chapter provides recommendations to mitigate the system variations. As previously mentioned, rate changes occur infrequently and will not be addressed in the mitigation plan. Travelers are the result of disruptions and delays in the manufacturing process. They are due in part to defects and delays in QA response. By addressing quality and QA service levels, travelers will decrease to some extent. This chapter provides recommendations to mitigate the variations that contribute to overtime in Wing Majors.

5.1 Improving Quality

Organizations across every industry seek to ensure quality through robust product design, disciplined inspections, and rigorous training of operators. In Wing Majors, the quality of the work, as defined by the number of defects per line number, is dependent on several factors. In order to impact quality, one has to understand and map the causes of defects. Figure 10 illustrates these casual factors through a fishbone diagram.

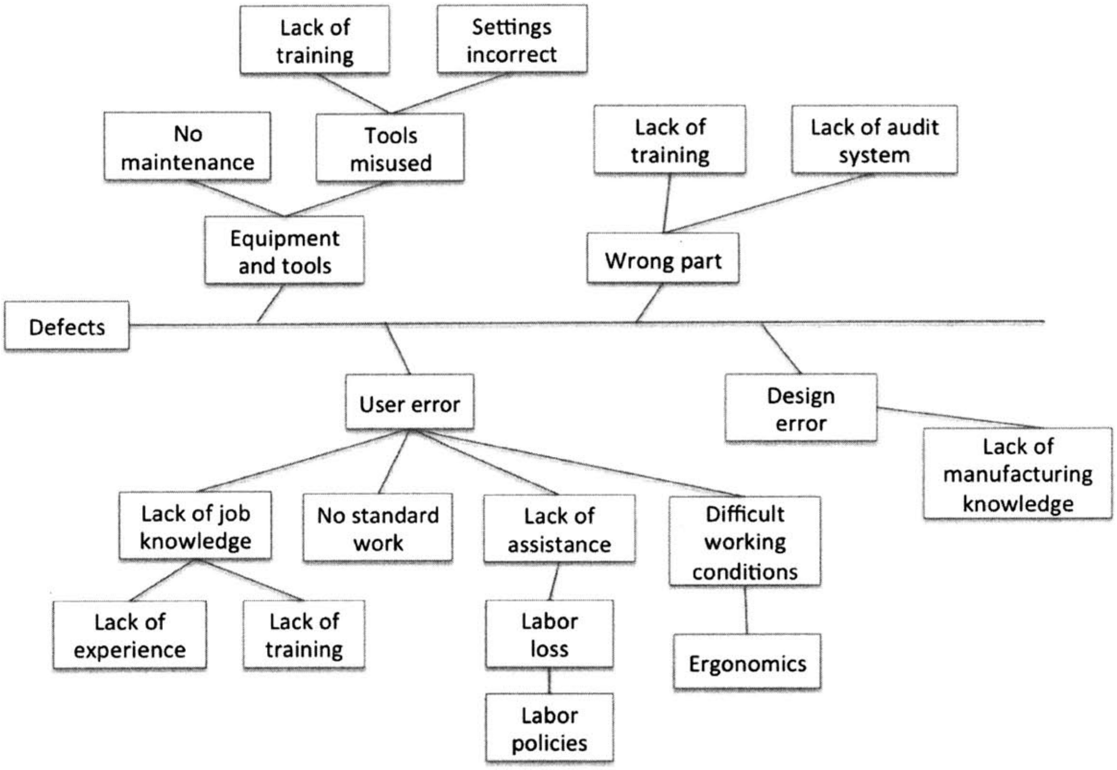


Figure 10: Fishbone diagram delineating the root cases of defects in Wing Majors.

The fishbone diagram provides a starting point to reduce defects. While affecting labor policies and developing a system for standard work are major long term endeavors, Wing Majors can improve quality through immediate changes in mechanic training and the implementation of a preventative maintenance plan for equipment and tools.

5.2 Improving QA Service Levels

The quality function is responsible for providing and abiding by a Service Level Agreement (SLA), which guarantees a response time of 10 minutes. In order to achieve this, the quality function plans for demand and capacity. Very few jobs will be complete and require inspection at the start of the shift while the bulk of jobs will be complete towards the end of the shift. Quality inspectors stagger their start times to better match the demand.

Despite these efforts to uphold the SLA, QA fails to meet the response time of 10 minutes. The average time required from mechanic initiation to QA acknowledgement across all jobs on 255 line numbers is 55 minutes. This occurs because QA is understaffed, overwhelmed with drafting non-conformance reports, and not incentivized to meet the SLA targets. As the quality function is also responsible for writing non-conformance reports if a defect is found, it is important to note that defects in manufacturing negatively affect the QA response time. It is a subtle point to understand that when quality improves, QA personnel will have more bandwidth to inspect jobs, reducing the response time, which in turn diminishes travelers. The interdependencies between these variables are difficult to grasp because they are related in a feedback loop whereas a regression seeks variables that are independent. Additional studies, including a casual loop diagram analysis, should be conducted to examine the relationship between manufacturing defects and QA response time.

There is no robust prioritization scheme for handling inspections. Completed jobs are displayed on a callboard in the order they are finished. Inspectors are able to pick and choose those which are relatively simple to check while leaving difficult examinations for later. Critical path jobs or those that feed into the critical path are not treated differently in the inspection process.

5.3 Labor Loss Implications

As mentioned previously, labor loss is a noteworthy variation in wing production but was not included as a variable in the regression. Calculated per day, labor loss varies greatly between control codes and teams. Aggregated across Wing Majors and line number, the disruptions are made less prominent. Each wing remains in the FAJ for ten days. The left and right wing of each line number do not start the assembly process together but rather begin two days apart. An average of 12 days labor loss data provides a rough approximation of labor loss per line number. With only 79 lines of this approximation, I included labor loss percentage as variable into the regression and the findings were surprising. The new model achieved an RSquare Adjusted of 0.75. Despite the imprecise data, labor loss contributed significantly in predicting for total labor hours. While labor loss has anecdotally always been a large source of variation in wing manufacturing, no analysis had been conducted to prove how disruptive a one percent shift in labor loss could be. Even with aggregated data that did not reflect the daily disruptions, labor loss improved the model's accuracy by roughly 50%. However, the model also estimated that for every additional percent increase in labor loss, labor hours would decrease by 7800 hours. Conceptually, if labor loss were 100%, labor hours expended would be zero. When labor loss is 0%, Wing Majors would experience higher labor hours. Between the two scenarios is an optimal solution where the use of overtime is minimalized while labor loss is kept within the threshold of disruption.

The correlation between labor loss, defects, and travelers were examined, as shown in Table 4, to confirm the suspected causal relationships. Surprisingly, there were no strong correlations between the variables. This is perhaps the result of the aggregated labor loss data. The correlations can be recalculated using daily labor loss values but travelers are only measured by control codes and shops. On any given production day, four sets of wings are being assembled in Wing Majors. It is, therefore, difficult to determine the number of travelers generated on a particular day that remained incomplete when it left Wing Majors.

	Labor Loss	# Code Pages	Travelers
Labor Loss	1.0000	0.0597	0.2526
# Code Pages	0.0597	1.0000	0.2583
Travelers	0.2526	0.2583	1.0000

Table 4: Correlation between labor loss, defects, and travelers.

To improve quality in the short term, mechanic training must be revamped and a preventative maintenance plan for equipment and tools put in place. The issues associated with the lack of standard work and labor loss should be revisited in order to influence long term quality. A robust prioritization scheme for handling inspections and process for identifying critical path jobs are recommended for the Quality function. Preliminary analysis suggests that labor loss is substantial factor in explaining for labor hours. This variable was not included in the analysis described in Chapter 4 due to the lack of higher resolution data. However, it is important to stress for a workshop to reduce labor loss.

Chapter 6

6 Conclusions

My results conclude that four variations in 777 wing manufacturing – travelers, QA response time, rate changes, and defects – account for at least 50% of disruptions that lead to overtime. Chapter 1 discussed the general problem of process variations in manufacturing and the benefits of a controlled manufacturing process. Chapter 2 explored previous research on implementing lean concepts to reduce variation and the tools required for the analysis. In Chapter 3, variations are identified in current state manufacturing issues. In Chapter 4, the methods of analysis were explained and the most critical variations are identified. And Chapter 5 put forth recommendations and mitigation plans to reduce variation. Final conclusions and appropriate next steps for 777 Wing Majors will be discussed in this section.

6.1 Next Steps

Hypothesis testing – To prove the working hypothesis, which asserts that process variations directly affect total labor hours, Wing Majors can drive down travelers and monitor the effects on overtime and jobs behind schedule. My results suggested that for every additional traveler produced, an average of 12.5 labor hours are required to complete the job out of position. The 12.5 hours is not above nominal but rather an aggregation of traveled jobs in various stages of completion. To test this result, Wing Majors can prioritize traveler reduction for at least five line numbers, ensuring no incomplete jobs move into the next shop. While additional resources will be used in this test case for eliminating travelers, we can measure the total effect on the system and prove a savings of labor hours at a rate of at most 12.5 hours per potential traveler. Any savings in labor hours would support the working hypothesis.

Revamp training – To improve quality, mechanic training should be revisited. New mechanic training is currently job agnostic. Once the mechanic learns the basic skills, he or she will usually report to an experienced mechanic for on-the-job training. On-the-job training, however, is not structured and depends heavily on the team, the job, and the availability of the crew. To ensure new mechanics receive the same level of training, Wing Majors must restructure the training process and use it as an avenue to improve quality.

Preventative maintenance – Another aspect of improving quality is tool qualification and maintenance. Devising and implementing a preventative maintenance schedule on all drills and tools will be the next step. While maintenance was not included as a variable in the regression, it is noteworthy in improving quality.

Improve QA response time – Additional studies must be done to better understand why the quality organization cannot meet its service level agreement. My research has shown that any improvements in QA response time are significant. The next step is to conduct root cause analysis to identify the challenges to a faster response time.

Labor loss data – Preliminary analysis has shown that labor loss is a major contributor to total labor hours. In order to prove or disprove this result, more detailed data must be collected on daily labor loss. While labor policies are not easily changed, a more informed view on how the policies affect manufacturing processes is recommended.

6.2 Final Thoughts

Reducing process variations in the form of improved QA response time, quality through a preventative maintenance plan and more rigorous mechanic training, and eliminating travelers are the appropriate next steps. The potential savings of these initiatives amount to 50% of overtime labor hours.

In many organizations including Boeing, external process variations imply a misalignment of priorities and incentives. While support functions are tasked with assisting manufacturing, they are not assessed by how well manufacturing performs. Support functions are not penalized by jobs behind schedule, defects produced, or travelers allowed. Thus, the disconnect between manufacturing and support contributes to the system variations experienced by Wing Majors.

An aligned organization capable of solving problems demonstrates the core principle behind TPS. Having tools like the Andon cord or 5S kits do not affect manufacturing as much as aligned incentives and goals. It is not enough to apply the tools of TPS without applying the mindset at a higher level or realizing that TPS was developed for higher volume line manufacturing. I focused on process variations to shed light on the challenges Wing Majors faces from misaligned support as well as gaps in the internal manufacturing plan.

Chapter 7

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