Applying Constraint-Based Theory to a Complex Aerospace Manufacturing Process

by

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B.S. Mechanical Engineering
Cornell University, 2010

Submitted to the MIT Sloan School of Management and the Department of Mechanical Engineering
in Partial Fulfillment of the Requirements for the Degrees
of
Master of Business Administration
and
Master of Science in Mechanical Engineering
in conjunction with the Leaders for Global Operations Program at the
Massachusetts Institute of Technology
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ABSTRACT

A new airplane model is quickly ramping up in production rates, and in order to achieve the organizational targets and commitments, Flow Days, Unit Hours and Cycle Times must be reduced throughout the entire supply chain. The Continuous Improvement Group (CIG) is an initiative supporting these improvements by applying the Theory of Constraints to identify improvement opportunities and lead teams to implement solutions and make the improvements.

This thesis details the approach of using historical manufacturing data to identify focus areas for analysis and a methodology for analyzing a specific manufacturing process. This analysis and the improvement opportunities identified for several processes in the Final Assembly of the new plane are discussed, as well as the efforts implement solutions to these opportunities. Finally, this thesis also describes the mindsets and organizational characteristics that are necessary in order to make large efficiency improvements in a complex manufacturing process.

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Finally, I’d like to thank my fellow interns from LGO: Esther Mangan, Ellen Ebner, David Feliciano, Ammar Asfour, and Scott Bromley. It was always great to have you as resources to talk to about the many unique challenges in our work environment, and for those of you in Seattle, it was always great to get together outside of work.
NOTE FROM THE AUTHOR

In writing this thesis, I realized that a reader unfamiliar with the challenges and complexities of the aerospace industry may misconstrue the results and get a negative impression of The Boeing Company. I would like to start this thesis by saying that I believe The Boeing Company is a very well run organization and is led by very talented individuals who work extremely hard to deliver the best commercial jets on the market. I spent considerable time on the factory floor, working with mechanics as they assembled these planes and I have the utmost confidence in the quality and safety of every 787 Dreamliner that rolls off the line. Additionally, this thesis will discuss certain cultural aspects of the organization in which I worked – these views are my personal opinion based upon my unique experience and how the organization appeared to me, so these opinions should not be taken as facts.
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1. INTRODUCTION

1.1. Purpose of Project

The thesis investigates the application constraint-based theory to the Final Assembly process of the 787 Dreamliner at the Everett, WA site of The Boeing Company. Specifically, this project is aimed at improving the productivity and efficiency of Final Assembly, as measured by Flow Days, Unit Hours and Cycle Times. This thesis will diagnose and analyze bottlenecks, identify improvement opportunities and discuss solutions to capitalize on those opportunities.

1.2. Problem Statement

The 787 Dreamliner is quickly ramping up in production rates, and in order to achieve the organizational targets and commitments, Flow Days, Unit Hours and Cycle Times must be reduced throughout the entire supply chain. In addition increasing production rates, cost reductions in manufacturing have been slower than expected, and The Boeing Company has accumulated over $25 Billion in losses on the Dreamliner program as of October 2014 (Cameron & Delaney, 2014). The Lean Global Production System (LGPS) is an initiative supporting these productivity and cost improvements through rigorous application of the Theory of Constraints and other improvement tools.

1.3. Project Goals and Approach

The overall goal of this project is to apply constraint-based theory to 787 Final Assembly as a method to identify, diagnose and eliminate the process bottlenecks in order to achieve several top goals for the business unit. Bottleneck identification will be completed using historical manufacturing data, and the bottlenecks will be
analyzed using Overall Process Effectiveness (OPE) to determine the largest drivers of waste in the system. Based on these waste drivers, specific improvement projects will be organized to capture the opportunity and realize the efficiency gains.

1.4. Thesis Overview

This thesis begins by describing the context of the industry and the competitive environment for The Boeing Company and the 787 Dreamliner, as well as exploring the supply chain and manufacturing process for the aircraft. Chapter 3 reviews common “continuous improvement” methodologies as well their applications in the aerospace industry. Chapter 4 discusses the specific methodologies utilized by the 787 Lean Global Production System, and Chapter 5 will show the application of these methods to Final Assembly, including diagnostics, OPE analysis, and problem solving. This thesis will also comment on the structural and cultural aspects of the organization and their impact on continuous improvement efforts such as this project. Finally, this thesis concludes by recommending specific opportunities for future improvement within 787 Final Assembly.
2. BACKGROUND OF THE AEROSPACE INDUSTRY AND 787 DREAMLINER MANUFACTURING

1.5. Background of Commercial Aerospace Industry and Market

The Commercial Aerospace industry is dominated by two main players in the market for large jets, The Boeing Company and Airbus, while smaller regional jets are also offered by companies like Embraer and Bombardier. The industry has been growing steadily - both companies set new records for aircraft deliveries in 2013 - and is poised for future growth with a combined order backlog of over $1 trillion (PwC, 2014). Boeing forecasts that between 2013 and 2033, close to 37,000 new commercial aircraft will be sold (Tinseth, 2014).

The two companies offer aircraft covering a wide spectrum of the market, ranging from the single-aisle 737 and A319 to the multi-level, twin aisle 747-8 and A380 (see Figure 1 below).
1.6. The 787 Dreamliner Program

Boeing officially announced the 787 Dreamliner program in 2002, originally dubbed the “7E7.” The plane was aimed towards the middle market: a plane that carried a smaller load than the 777 but that was capable of flying the same distances, and that was fuel efficient at both short and long ranges (Arkell, 2003). The aircraft implements many technical advances for the industry and as a result is able to use 20-30% percent less fuel and produce 20-30% fewer emissions than similarly sized aircraft (Boeing, 2015). The key technologies enabling these gains are a carbon composite structure for the fuselage and wing, which eliminates tens of thousands of fasteners, and more advanced engines from GE and Rolls-Royce. Three variants of the aircraft will be produced, the 787-8, 787-9 and 787-10, with passenger capacities of 242, 280 and 323, respectively. Final Assembly of the first 787 Dreamliner began in May 2007 and the first 787-8 was delivered to launch partner
All Nippon Airways on September 25, 2011. The 787-9 was first delivered in 2014 and the 787-10 is scheduled for first delivery in 2018 (Boeing, 2015).

1.7. Overview of the Production System and Partner Supply Chain

To accompany a technologically advanced product, Boeing radically redesigned the supply chain for the 787 from that of legacy aircraft. The Dreamliner, at the start of production, was 80% outsourced, compared to 10% at the start of the 737 production (Ip et al, 2014).

Production is spread to over fifty global partners, many of which are shown in Figure 3 below (image obtained from The Boeing Company). The largest parts, such as the wings and fuselage, are delivered by air using a modified 747-400, named the Dreamlifter. The modifications of the Dreamlifter allow Boeing to reduce transport times from 30 days to one day.
This outsourcing was intended to reduce development time and cost, by 33% and 40%, respectively (Denning, 2013). However, development issues delayed first flight by almost 2.5 years (Cohen, 2011) and the delivery schedule has been delayed at least 7 times (Denning, 2013).

Currently the 787 Production System is operating at a rate of 10 planes per month (Boeing, 2014), with two Final assembly lines in Everett, WA and one in Charleston, SC. However, despite production at the highest rate in twin-aisle history, cost reductions are not taking place as quickly as anticipated and Boeing is still losing money on the Dreamliner program (Cameron & Delaney, 2014). In addition an expensive and complex supply chain, the complexity of the product architecture of the 787, as outlined by Jason Chen (2012) in Table 1, may contribute to the slower rate of cost reductions.
<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Implication for Assembly and Scheduling Control</th>
</tr>
</thead>
</table>
| Requires many highly specialized skills (wiring, structures, composite repair, electronics installation) | • Difficult and costly to cross-train workers resulting in workforce inflexibility  
• Long apprentice times to train an expert technician with a high first-pass quality rate |
| Highly interconnected job sequences requiring coordination and de-confliction of trades | • Difficult to prioritize job flows  
• A critical path exists, but may not be meaningful given resource limitations.  
• Knowledge of the complete build is fractured. Very few stakeholders understand the whole build at enough detail to optimize the process |
| High degree of precision and process specifications | • Highly specific tooling, often requiring rigorous in-process quality inspection. Quality deviations and non-conformances require thorough analysis to resolve, often causing significant delays relative to production cycle times. |
| Relatively low volumes and long production times | • Difficult to gain significant experience with specific jobs, and historical job data is inconsistent and difficult to normalize.  
• Difficult to generate control charts. The process changes often (engineering design changes). |
| Thousands of unique and non-interchangeable parts | • Replacement components are expensive and not readily available  
• Lead times for parts can be very long (weeks or months) and workmanship or manufacturing errors can be very expensive and disruptive. |
| Size and physical configuration | • Highly cumbersome or impossible to employ an assembly line with value added in serial steps.  
• Large jigs are required and problematic WIP cannot be taken off-line and placed in a rework pile. A delay can cause jig-lock that delays every station upstream of the problematic aircraft.  
• The aircraft has large components which require heavy equipment to move  
• An aircraft also has tight work zones that act as bottlenecks for parallel work to occur. |
| New or exotic materials requiring advanced processes | • Each defect requires custom analysis to resolve. The existing body of knowledge is scant, resulting in conservative assessments for defect correction. |

**TABLE 1: COMPLEXITY IN 787 PRODUCT ARCHITECTURE**
3. LITERATURE REVIEW

This chapter will serve as an introduction to several “continuous improvement” methodologies, with a specific focus on the use of lean manufacturing in the aerospace industry.

1.8. Lean manufacturing

The origins of lean production trace their roots back to Taiichi Ohno, who concluded that the mass-production techniques that Eiji Toyoda witnessed at Ford’s Rouge plant would never work for Toyota (Womack, Jones & Roos, 48). Ohno experimented relentlessly with new production methods, such as small-batch stamping operations, and with new assembly operations, with teams run by a leader (who participated in the work) rather than a controlling foreman. (Womack, Jones & Roos 55). Ohno recognized the opportunity for improvement in the form of waste, and in its modern incarnation, lean production still focuses on removing waste through rigorous analysis of the value stream. To identify and eliminate waste, or non-value added activities, lean focuses on five fundamental steps: value identification, value stream analysis, flow, pull and perfection (Akbulut-Baily and Motwani, 2012). In this sense, “lean production begins externally with a focus on the customer,” because it is the customer that determines value (Browning and Heath, 2009). During value stream analysis, actions are determined to fall into one three categories, according to Womack and Jones (20):

1. Tasks that add value
2. Tasks that do not add value but are unavoidable with the current production process
3. Tasks that do not add value and can be eliminated

The two different categories of non-value added tasks show up in seven different forms of waste, or muda ("Combing Lean," 2009):

1. Over production
2. Waiting
3. Transportation
4. Inventory
5. Motion
6. Over processing
7. Defects

In the design of a plant, Lean focuses on creating a balanced line, with each step in the process operating at the rate you need to produce in order to meet customer demand ("Combining Lean," 2009).

1.9. Six Sigma

While lean production focuses on removing waste, Six Sigma, another continuous improvement methodology, focuses on reducing variation in products and processes ("Combining Lean," 2009). Six Sigma started at Motorola as a focus on achieving 3.4 defects per million opportunities and relies of statistical process control to build this capability in a process (Akbulut-Baily and Motwani, 2012). Similar to the five steps of lean production, Six Sigma follows a five-step process called DMAIC:

1. Define
2. Measure
3. Analyze
4. Improve
5. Control
In addition to its use as a process improvement tool, Design for Six Sigma (DFSS) has evolved as a method for redesigning or creating new processes in order to meet expectations (“Combining Lean,” 2009).

1.10. Theory of Constraints

The Theory of Constraints (TOC) was introduced by Eli Goldratt and popularized through his book, The Goal (“Combining Lean,” 2009). TOC is a systems-thinking approach to managing an operation, and is based on three assertions, as listed by Chou et al (2012):

1. Each system has a goal and set of necessary conditions that must be satisfied to achieve its goal
2. Overall system performance is more than the sum of the performance of its components
3. Very few factors or constraints (often only one) limit a system’s performance at any given time

This approach is best explained using the chain analogy: any improvement to a chain that does not improve the weakest link does not improve the entire system.

The five-step approach of TOC is described as (“Combining Lean,” 2009):

1. Identify the constraints
2. Decide how to exploit the constraints
3. Subordinate/synchronize everything else to the constraint(s)
4. If needed elevate the system’s constraint
5. If the constraint has been broken go back to step one.

The TOC process and way of thinking have been found in some ways to be more effective than lean manufacturing (Chou et al, 2012). One of the key differences between Lean and TOC is the way each methodology approaches the design of a system. As stated above, Lean focuses on a production system with each step balanced to meet Takt time. A production system designed using TOC does not
focus on a balanced line, but rather focuses on protecting the constraints by surrounding it with protective excess capacity. This ensures that if the non-constraint station were to fail, the constraint can still be run at maximum speed, thus preventing throughput loss. In this sense, TOC focuses on improving and protecting throughput first and foremost (“Combining Lean,” 2009).

1.11. Continuous Improvement in the Aerospace Industry
While Toyota and rest of the automotive industry were the first companies to adopt lean manufacturing, the Aerospace industry has been focusing on implementing lean since the late nineties, but was believed to be 10-15 years behind their predecessors (Crute et al, 2003). However, Browning and Heath (2009) state that lean implementation in the industry has provided mixed results. This may be due to challenges related to the product complexity or a low-volume manufacturing environment. Both Browning & Heath (2009) and Crute et al (2003) mention that a challenge with implementing in the lean across the aerospace industry is the vast differences between plants, and that the methodology must be tailored to fit specific facilities. However, despite these challenges, Crute et al (2003) assert that lean implementation in aerospace is merely different than in automotive, not necessarily any more difficult. Additionally, Hale (2006) offers several examples of successes based on the work of the Lean Aerospace Initiative:

- C-17 unit price decrease of $82M for a net savings of $6.5B
- Atlas launch program lead time reduced from 48.5 months to 18 months
- F-16 wing shop flow time at Hill AFB decreased from 62 days to 27 days
- Northrop Grumman Integrated Systems reduced throughput times by 21% for major systems
At Boeing, Lean and other continuous improvement methodologies have also achieved significant results: it reduced Final Assembly time for the 777 from 71 days in 1998 to 37 days in 2012, and reduced 737 Final Assembly from 20 days to 11 (Mounts, 2012)
4. METHODOLOGY

1.12. Overview of the Continuous Improvement Group

The Continuous Improvement Group (CIG)\(^1\) was created as an initiative in 2012 in order to improve productivity and efficiency throughout the global supply chain for The Boeing Company. CIG is a fusion between Lean, Six Sigma and the Theory of Constraints, and pulls from each of these methodologies where appropriate. Additionally, rather than focusing on "designing" the entire production system, CIG is focused on improving the existing processes in order to drive cost savings through productivity improvements and capital expenditure avoidance. By focusing on the overall system at each site, CIG’s goal is to answer the three critical questions of the Theory of Constraints ("Combining Lean," 2009):

1. What to Change
2. What to Change to
3. How to Cause the Change

In order to answer these three questions, a typical CIG “deployment” follows a reasonably standard improvement process flow, as shown in Figure 4 (Image obtained from The Boeing Company).

---

\(^1\) Actual name has been disguised
1.13. Plant Diagnostic & Bottleneck Identification

The first step in the standard CIG deployment methodology is to identify the key bottlenecks ("constraints" in TOC terminology) using data and facts. In most cases, this is performed by calculating the current cycle time of each cell and comparing it to the desired Takt time. Takt time is traditionally defined as "the rate at which you need to produce to meet customer demand," ("Combining Lean," 2009) and in this case is determined by the stated production rate, in numbers of planes per month. Since Boeing is planning for several rate increases in the future, the current cycle times are compared to both the current rate and the future rates. By visually showing this analysis as in Figure 5 below, it becomes very clear which work cells in a plant need to be improved.
Once the focus areas for improvement have been determined, the next step in the CIG methodology is to identify opportunities for improvement by analyzing the bottlenecks (this corresponds to the "What to Change to" question above). The two main analysis methods that CIG uses are Overall Equipment Effectiveness (OEE) for automated processes and Overall Process Effectiveness (OPE) for manual processes. These two analyses categorize the time spent by a machine or worker into several "loss buckets," and in the process identify the biggest opportunities to reduce these losses. The time categories for the OEE and OPE analyses are summarized in Table 2 below.

<table>
<thead>
<tr>
<th><strong>OEE</strong></th>
<th><strong>OPE</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Planned Downtime</td>
<td>Breaks &amp; Meetings</td>
</tr>
<tr>
<td>Unplanned Downtime</td>
<td>Waiting</td>
</tr>
<tr>
<td>Change-overs</td>
<td>Walking</td>
</tr>
<tr>
<td>Minor stops</td>
<td>Talking</td>
</tr>
</tbody>
</table>

* Table 2: OEE and OPE Time Categories*
OEE is typically calculated using a combination of machine-generated data and in-person observations. OPE, on the other hand, comes entirely from shop-floor observations and short interactions with the front-line workers. Through the process of these analyses, the biggest improvement levers can be identified. More details around the use of OPE in Final Assembly are provided in Section 1.18. An example of the output of an OPE analysis is shown below in Figure 6 (note that “Non-value added Wrench Time” has been replaced by “Process Waste” for internal messaging purposes).

![Figure 6: Example OPE Waterfall](image)

1.15. Prioritizing the top opportunities
An important part of the CIG methodology is to prioritize to the biggest improvements and focus only on the top two or three projects, in order to achieve the best results with limited time, people and resources. The standard method for prioritizing opportunities is to use both Impact and Ease of Implementation, and to plot all of the opportunities on a X-Y axes to determine the highest-impact, easiest-to-achieve opportunities. An example of this chart used by CIG is shown in Figure 7:

![Impact-Ease of Implementation Prioritization Chart]

**FIGURE 7: IMPACT-EASE OF IMPLEMENTATION PRIORITIZATION**

In this example, opportunities 2 and 3 would be the top priorities due to the high impact and ease of implementation. Once the top opportunities have been identified, project teams are assigned to make the improvements by applying the appropriate problem solving/improvement tool.
5. Applying CIG Methodology to Final Assembly

1.16. Identifying bottleneck focus areas

The Final Assembly line at the Boeing facility under consideration is a slightly more complicated system than the facilities where the CIG methodology has been applied in the past. First, this is not a site where one or two workers complete a sequential job at each position as is common in most factories. Many of the crews are different sizes and use different shift schedules. Secondly, unlike many traditional fabrication processes, the work can be “travelled” if it is not completed: an MT can finish the job farther on down the line in most cases. Finally, in addition to travelled work, a lot of the work packages can be done in parallel, even if that is not the initial plan.

As a result of these complexities, a standard Cycle Time to Takt Time comparison doesn’t necessarily tell the complete story. For the initial diagnostic, four different metrics were calculated to be taken into consideration as part of the bottleneck analysis. Each of the following metrics were calculated using data averaged from 10 planes, and only considered certain models so that the data were comparable.

The first metric was Cycle Time, as measured in flow days. As seen in the graph below, Step 5 had the longest flow from start to finish, followed by Step 6 and Step 7.

---

2 There are a few structural that would prevent the plane from moving to the next position if not completed on time, but for the most part, jobs can travel if not complete.

3 A flow day is any day of planned production. Flow day totals do not include any time overtime, weekends or other “unplanned” days of production.
Additionally, these cycle times were compared to the planned cycle times. The difference between actual and planned in this case can serve as a relative metric of inefficiency, since each work package has already taken into account the amount of time a job should take. The same three work packages, Step 5, Step 6 and Step 7, are again highlighted as the main focus areas.

4 All graphs shown in this chapter are true to scale, but numbers and step names have been removed to protect proprietary data.
Since the two cycle time comparisons mentioned above only considered flow days, another logical metric for comparison is total unit hours required to complete each work package. In this case, Step 5 again is the biggest contributor.

However, while Step 5 has nearly double the unit hours of any other work package, it should be noted that it is a larger scope of work: it has more crews working in
parallel than any other MBU. For example, Step 2 has two crews: one for the left and one for the right. Step 5 has six crews working at the same time.

In order to account for the issues above, a “normalized” cycle time metric was used that had previously been developed by the CIG team. This metric normalizes for the differences between headcounts and planned flows in an attempt to make a more accurate comparison between the MBUs if all factors were equivalent. From this analysis, Step 4 has the longest cycle time, followed by Step 5, Step 6 and Step 7, as seen in the figure below.

![Normalized Cycle Times by MBU](image)

**FIGURE 11: NORMALIZED CYCLE TIME BY PROCESS STEP**

Once these four metrics were calculated, each MBU was force-ranked based on its performance for each metric (1 being worst, 8 being the best). Each ranking was then summed for the MBU, and those with the lowest total sum could be considered the worst-performing areas. As seen in the table below, the three MBUs with the lowest scores were Step 5, Step 6 and Step 7.

<table>
<thead>
<tr>
<th>MBU</th>
<th>Actual Flow</th>
<th>Flow over Plan</th>
<th>Unit Hours</th>
<th>Normalized Cycle</th>
<th>Sum of Ranks</th>
<th>Overall Rank</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
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<td></td>
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31
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<th>Step</th>
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<th>7</th>
<th>6</th>
<th>7</th>
<th>26</th>
<th>6</th>
</tr>
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<tr>
<td>Step 2</td>
<td>8</td>
<td>8</td>
<td>7</td>
<td>5</td>
<td>28</td>
<td>7</td>
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<td>Step 3</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>6</td>
<td>18</td>
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<td>Step 4</td>
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<td>5</td>
<td>5</td>
<td>1</td>
<td>16</td>
<td>4</td>
</tr>
<tr>
<td>Step 5</td>
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<td>1</td>
<td>1</td>
<td>2</td>
<td>5</td>
<td>1</td>
</tr>
<tr>
<td>Step 6</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>3</td>
<td>10</td>
<td>2</td>
</tr>
<tr>
<td>Step 7</td>
<td>2</td>
<td>3</td>
<td>3</td>
<td>4</td>
<td>12</td>
<td>3</td>
</tr>
<tr>
<td>Step 8</td>
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<td>8</td>
<td>29</td>
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</tr>
</tbody>
</table>

**FIGURE 12: RANKINGS FOR EACH METRIC BY MBU**
1.17. Overview of Step 5
Step 5, is the MBU that contains all of the work that happens in the passenger deck outside of the cockpit. Wires and other electrical systems, floorboards, galleys, overhead bins, sidewalls, seats, and crew rests are all installed so that the passenger cabin looks like the finished product. The Step 5 MBU spans the entire factory and with several crews and a lot of work, it easy to understand why Step 5 had nearly double the average unit hours as the other MBUs. However, despite the elevated planned hours, the Step 5 MBU still exceeded the plan by a significantly higher margin than any of the other MBUs (see Figure 10). In order to understand the inefficiencies and identify the largest opportunities to improve, the Overall Process Effectiveness (OPE) analysis was conducted as described in Section 1.18.

1.18. Analyzing Step 5
The OPE analysis for Step 5 was performed over the course of several weeks, led by the CIG team with the help of the industrial engineers assigned to the MBU. For both first and second shift, observers were dispatched to watch up to eight mechanics for the first four hours of the shift. The observations started at the crew meeting, where the analyst spoke to the mechanics to inform them of the objectives and procedures for the analysis, in order to get the support of the front-line. Once the crew meetings ended, the analyst would then meet with the team lead, a very experienced mechanic who oversees the crew, to understand the various job assignments and determine the mechanics they would be observing.

From there, the observers began taking data by recording the activity of each mechanic every 15 minutes into a spreadsheet, such as that shown in Figure 13.
Definitions for each of the categories are shown below in Table 3.
<table>
<thead>
<tr>
<th>Category</th>
<th>Definition</th>
<th>Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Breaks/Meetings</td>
<td>Time during the shift where the workforce is not scheduled to work</td>
<td>Morning crew meeting, mid-shift breaks, lunch, Employee Involvement meetings</td>
</tr>
<tr>
<td>Waiting</td>
<td>Time where an employee is in the work cell but prevented from performing value added work</td>
<td>Waiting for tools or parts, waiting for a nearby task to finish</td>
</tr>
<tr>
<td>Walking</td>
<td>Employee is walking within the work cell</td>
<td>Walking to get parts or tools</td>
</tr>
<tr>
<td>Talking</td>
<td>Employee is talking with another worker, including their lead or manager, while not simultaneously performing value added work</td>
<td>Talking with a manager or teammate</td>
</tr>
<tr>
<td>Computer</td>
<td>Employee is performing any activity on a computer or data collection tool</td>
<td>Researching jobs, signing off jobs, checking email, surfing the internet</td>
</tr>
<tr>
<td>Not in Cell</td>
<td>Employee is not observed in the direct work area, but is not on a scheduled break</td>
<td>Bathroom breaks, getting parts from outside the work cell</td>
</tr>
<tr>
<td>NVA Wrench Time</td>
<td>Employee is performing work that does not change the fit, form or function of the Final product</td>
<td>Tool set-up, assisting with a lift, part cleaning, quality checks, any re-work</td>
</tr>
<tr>
<td>VA Wrench Time</td>
<td>Employee is performing work that affects fit, form or function of the Final product</td>
<td>Installing fastener, drilling holes, applying Seal</td>
</tr>
</tbody>
</table>

TABLE 3: DEFINITIONS AND EXAMPLES OF OPE TIME CATEGORIES

In order to differentiate between Value-Added (VA) and Non-Value Added (NVA) “wrench time,” as well as to understand the causes of the other waste categories, the observers spent the time in between the 15 minute data collections to follow up with two to three mechanics. These conversations helped the analyst learn more about the current jobs and also helped to build rapport with the mechanics. Many times, once the mechanics knew the observers, mechanics would take the initiative to go find the observers whenever problems such as rework or missing parts occurred. These details provided valuable information for the analysis that could be used to determine both the size of the opportunities and their relative complexity.

In some cases, the conversations even resulted in rapid problem solving. For example, when one observer heard from a mechanic that a certain set of parts was
kitted incorrectly on a regular basis, they informed the team lead and manager. The manager and lead went to the kitting station and discovered that multiple sizes of the part were stored in a bin meant for only one size, and since this bin was stored at height that couldn’t be easily seen, the person who made the kits simply reached in and grabbed the right quantity. To fix the issue, the bin was moved to a lower shelf and cleaned so that it only contained the proper sizes, and the problem did not occur on future planes.

These observations were conducted from start to finish for each barchart on a specific plane. The data was compiled from the multiple days and shifts to calculate the OPE for each barchart. Additionally, the conversation notes, which were tied to specific data points on the spreadsheet, were used to calculate values for specific opportunities. Figures 14-19 below show the resulting waterfall charts of the OPE analysis for each of the barcharts within Step 5.

5 While the sizes of the waste buckets are accurate relative to one another, they are not accurate relative to the “Effective Time”, “Wrench Time” and “Available Time” bars, which have been edited to protect confidentiality to make the waste buckets easier to view.
FIGURE 14: OPE RESULTS FOR STEP 5.1 BARCHART

FIGURE 15: OPE RESULTS FOR STEP 5.2 BARCHART
FIGURE 16: OPE RESULTS FOR STEP 5.3 BARCHART

FIGURE 17: OPE RESULTS FOR STEP 5.4 BARCHART
FIGURE 18: OPE RESULTS FOR STEP 5.5 BARCHART

FIGURE 19: OPE RESULTS FOR STEP 5.6 BARCHART
The top opportunities were fairly consistent across each of these barcharts. Parts kitting was found to be the largest opportunity in the MBU. Incomplete, inaccurate and even missing kits would frequently result in non-value added activities, such as entering a report with shipside support or even leaving the cell to go find the parts themselves. Another common issue across these barcharts was daily management and communication between the managers and the mechanics: miscommunication often caused inefficiency. Many times, mechanics would be assigned to a job only to learn that they couldn’t work on it because they were held for an upstream task, after they had spent an hour collecting their parts and tools. Additionally, mechanics were often assigned to jobs which they had never performed before, resulting in a significant amount of time spent at the computer researching the procedure.

Due to the organizational structure in the industrial engineering group, each barchart’s opportunities were prioritized separately. For example, the prioritized opportunities for the Step 5.4 barchart are shown in Figure 20.

<table>
<thead>
<tr>
<th>Initial Improvement Levers</th>
<th>Specific Opportunities</th>
</tr>
</thead>
<tbody>
<tr>
<td>DS Familiarity</td>
<td>1) Train MTs on more jobs</td>
</tr>
<tr>
<td></td>
<td>2) SMEs barred on jobs they know well</td>
</tr>
<tr>
<td>Kits</td>
<td>3) Strongback Kits</td>
</tr>
<tr>
<td></td>
<td>4) All other kits</td>
</tr>
<tr>
<td>Parts Readiness &amp; POU</td>
<td>5) Parts staged properly at Point of Use</td>
</tr>
<tr>
<td></td>
<td>6) PSUs ready to install without cataloging</td>
</tr>
<tr>
<td>Daily Management</td>
<td>7) Various smaller workstreams</td>
</tr>
</tbody>
</table>
FIGURE 20: PRIORITIZATION OF STEP 5.4 BARCHART

In this chart, opportunities farthest to the upper right should be the top priority because they are the easiest to implement and the highest impact. In other words, these are the “biggest bang for the buck” opportunities and should be pursued first.

For Step 5.4, the first project to be undertaken was the Part A Kits.

1.19. Part A Kits
The Part A Kits opportunity was identified during the OPE analysis of the Step 5.3 barchart. A Part A kits consist of a large part and the quick-release pins that connect it to the frame. However, during the OPE analysis, these pins were either missing, incorrect, or in the wrong place. If a mechanic didn’t realize the mistake prior to installing one or more of the pins, it would cause delays and backtracking.

Once this issue was prioritized, the first step was to further define and describe the problem by getting more precise data, both from direct observation and through historical data analysis. In the process of getting this data however, several things were discovered:

1. For each of the next two planes, there were at most two issues with these kits
2. A system to monitor kit quality and provide feedback to the supplier did not exist.
3. Records were not kept when mechanics encountered problems with these kits.

Ultimately, with the current data indicating this was not as large an opportunity as originally believed and a lack of historical data, the Part A Kits project was put on hold.

1.20. Additional Step 5 Opportunities
Through the process of digging into the Part A kitting issue, it was clear that the Step 5 Industrial Engineering group would be unable to support any additional improvement projects. Since the group was stretched too thin with competing priorities, the CIG team decided that it would be best to transition focus to a new MBU where there would be more functional support for implementation. The focus shifted to the Step 4 MBU, which consisted of three barcharts: Step 4.1, Step 4.2 and Step 4.3.

1.21. Step 4.1
Step 4.1 work is done inside a confined space, limiting the number of people who can perform the job at a given time and is also a very tedious operation. This step is a requirement for airplane safety.

5.1.1. Analyzing the Step 4.1 work package
Using the same OPE analysis as for Step 5, the Step 4.1 crew was observed for a total of four days. Unlike Step 5, the Step 4.1 work is roughly the same each day, with minor differences based on location and geometry of the work area. This consistency of work allowed for a much shorter observation period to achieve representative results.
The main waste buckets for the Step 4.1 team were Talking, Not in Cell and Process Waste (Non-Value Added Wrench Time). The Breaks & Meetings category was skewed during these observations because there was an extended safety meeting during the observation period that normally wouldn’t have occurred. Within those categories of waste, the three biggest improvement opportunities that were identified were: streamlined morning processes, area set-up, and improved management communication.

5.1.2. Streamlined Morning Processes
The daily process for getting into the confined space would consistently take a long time once the morning crew meeting was over. Prior to entering the confined space, each mechanic had to take several steps to get ready for the day, including:

- Signing into the confined space entry permit to obtain a radio and entry flag
- Picking up and putting on coveralls
- Organizing their work trays and collecting the necessary materials and tools
- Preparing their tools (many mechanics would customize their tool shapes using a hammer in order to better reach certain spots)

The activities mainly contributed to the “Not in Cell” waste category.

5.1.3. Work Area Set-Up
Once a mechanic was ready to enter the confined space, it would often take significant work to set up their working area, often times requiring several trips in and out of the space. Some of the activities included:

- Running the compressed air hose to each mechanic’s location
- Setting up padding and seating (the area was a very uncomfortable place to work, mechanics would try to make it easy as comfortable as possible)

These activities were considered Non-Value Added Wrench Time because they were set-up activities that were necessary to complete the jobs.

5.1.4. Improved Management Communication
This opportunity was created as a bucket for two drivers of inefficiency: team morale and worker productivity. The data that quantified this opportunity came mostly from the “Talking” category.6

5.1.5. Additional Opportunities in Step 4.1

---
6 Additional details have been removed for confidentiality
In addition to identifying several large causes of waste, the observations during the OPE analysis also highlighted an opportunity to improve the value-added portion of the Step 4.1 work. Step 4.1 is not only repetitive, but also seen as an “art,” rather than a scientific process. Based on process improvement experience, task characteristics such as repetition and regarding it as an art often indicate that there is room for improvement, and the combination of the two indicates that there is a significant opportunity to remove some of the “art” in the process by developing a more effective tool or procedure.

1.22. Step 4.2
The Step 4.2 Barchart was also analyzed using OPE. This crew is responsible for installing the systems that traverse the inside of the fuel Tank. The crew begins working once the Step 4.1 team has finished working in the necessary areas. The results of the OPE analysis for the Step 4.2 barchart are shown in Figure 22.
As can be seen from the chart, the Step 4.2 crew had much more Non-Value Added Wrench Time (Process Waste) as well as Waiting. Some of the biggest improvement opportunities were the same as with the Step 4.1 crew: improved management communication and streamlined morning processes could have a significant impact on the productivity of the team. Additionally, this team had significant non-value added wrench time spent preparing and cleaning their parts, and they also were frequently held up due to lack of coordination between groups.

5.1.6. Improved Management Communication
The Step 4 was still a major opportunity to improve the daily management, particularly the crew could be kicked off more quickly in the morning and ensure that they began their tasks in a timely fashion. 

7 Additional details have been removed for confidentiality
5.1.7. Streamlined Morning Processes
The morning processes for the Step 4.2 crew were very similar to those of the Step 4.1 crew. However, because the Step 4.2 crew worked with more parts and tools, they often spent additional time in line at the tool crib or retrieving their parts from the staging area.

5.1.8. Parts Preparation and Cleaning
For certain jobs, the beginning of each shift was usually spent getting parts ready for installation. This required taking the parts out of their packaging, cleaning them to remove any corrosion, marking the parts for proper alignment and attaching the connecting pieces. One job even required the mechanic to clean many individual washers. Once the parts were cleaned and prepped, the mechanic could enter the Tank and install them.

5.1.9. Work Stream Coordination
Step 4.2 is one of the last work packages and is often pushed back due to delays farther upstream. The longer the Step 4.2 team gets delayed, the more they run into problems with work stream coordination, which can cause significant waiting. For example, during the analysis, the entire team was required to put their work on hold for a customer inspection. In another instance, testing delayed several workers’ ability to enter the Tank.

1.23. Step 4 MBU Prioritization
The prioritization matrices for both the Step 4.1 and Step 4.2 barcharts are shown in Figure 23 & Figure 24.
1 Morning Processes
2 Tank Set-up
3 Improved Management Communication
4 New Methods/Tools

Based on conversations with operations and industrial engineering leaders the New Methods/Tools opportunity was chosen as the top opportunity to pursue.

1.24. Step 4.1 Methods and Tools
Developing better methods and tools would add value to Boeing in three ways:

1. Eliminating NVA time spent reshaping the Special Tools
2. Improving the productivity of the VA time by speeding up the process of applying Special Material
3. Improving the morale of the mechanics by showing support from management and the other support functions

The first step in approaching this project was to understand all of the existing stakeholder views surrounding the opportunities. Manufacturing managers (at multiple levels), crew team leads, mechanics, industrial engineers, manufacturing engineers and tooling engineers were all consulted, and their viewpoints are represented in Table 4 below.

<table>
<thead>
<tr>
<th>Stakeholder</th>
<th>Viewpoint</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manufacturing Managers</td>
<td>This would be great - no one has ever worked on this before and it is item #257 on the Workshop list</td>
</tr>
<tr>
<td>Team Leads</td>
<td>Anything you can do to help my guys out would be great. The angled Special Tools would really help us out.</td>
</tr>
<tr>
<td>Mechanics</td>
<td>If you can help us do our job better, that would be great, but we have seen workshop after workshop happen with no changes, so most of us don’t really have any faith that anything will happen</td>
</tr>
<tr>
<td>Industrial Engineers</td>
<td>We don’t have bandwidth to support this at the moment</td>
</tr>
<tr>
<td>Manufacturing Engineers</td>
<td>I remember this being brought up a while ago, you should get the Lean team involved and do a workshop</td>
</tr>
<tr>
<td>Tooling Engineering</td>
<td>We’ve developed countless tools and the mechanics never want to use them. We’ll support where needed, but we don’t think this will go anywhere.</td>
</tr>
</tbody>
</table>

TABLE 4: STAKEHOLDERS FOR THE SPECIAL TOOLS PROJECT

8 Viewpoints are written by the author to capture the perceived feeling and response of each group, and are not paraphrased quotes

9 The “Workshop” is a machine shop in the factory that works on custom built solutions
While this appeared to be an opportunity where SMED could add significant value\textsuperscript{10}, the mechanic’s negative perception of workshops needed to be taken into account. As a result, the initial scope was narrowed to a tool that the team leads had specifically requested: specialized tools that each mechanic was currently custom shaping using a ball-peen hammer.

5.1.10. Problem Description
Additional observations were made to better understand the problem and the specific opportunity for the Special Tools. Many places where Special Material must be applied are hard-to-reach and hard-to-see: the work is often done blindly by feel and then double-checked with a mirror and flashlight. Due to space constraints from the confined space or the size of the mechanic’s body, applying the Special Material would often require many Tool strokes with a straight tool and would frequently result in quality problems and re-work. To make this task easier, mechanics developed their own solution, by bending the stock tool in a way that allowed them to apply an even layer of material using 1-2 strokes instead of 5-7 (or more, depending on rework).

The mechanic transforms the tool in three distinct ways:

1. Bend the tool to approximately 120 degrees
2. Twist the end approximately to 45 degrees
3. Fan out the endpiece, tapered so it is thicker in the center than on the outside

Each Special Tool was made in a pair, one angled such that it would wrap around the left side of the area, and one for the right side.

\textsuperscript{10} SMED stands for Single Minute Exchange of Dies, an improvement tool for speeding up a process
While these Special Tools made the job easier and also saved approximately one minute per cap (before taking into account rework), they also took a lot longer to make since they were not an “off the shelf” tool.

Table 5 below summarizes the time spent by mechanics in creating these Special Tools.

<table>
<thead>
<tr>
<th></th>
<th>Best Mechanic</th>
<th>Average Mechanic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time to make one tool</td>
<td>1 minute</td>
<td>4 minutes</td>
</tr>
<tr>
<td># of tools Required per shift</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>Approx. Yield</td>
<td>75%</td>
<td>50%</td>
</tr>
<tr>
<td>Total Time per mechanic per shift</td>
<td>11 minutes</td>
<td>16 minutes</td>
</tr>
</tbody>
</table>

Certain mechanics on the crew were known for their skill at making these Special Tools, and were often asked to create the additional Special Tools for other mechanics as well. Based on observations, these “best” mechanics could create a Special Tool in 1 minute, while approximately 25% of the Special Tools would need to be thrown out, mostly due to fracturing the connecting piece. Based on further observations and conversations with several mechanics, an average mechanic could complete one Special Tool in approximately 4 minutes, and had a higher scrap rate (approximately 50%). Each pair of Special Tools would be thrown out as the Special Material hardened on the end, so approximately 4 pairs, or 8 Special Tools, are used by one mechanic over the course of one shift.

While 16 minutes per shift may seem small, each crew was large, so over the course of one day, eliminating this step in the Special Material process has a potential to save close to 13 man-hours.
### 5.1.11. Approaching the problem

Three paths were considered as potential approaches to a solution:

1. Develop a jig that could easily mass-produce the customized Special Tools using a “light duty” worker.
2. Work with the manufacturer to create the custom geometry and purchase in bulk.
3. Create a new, reusable tool that accomplishes the same task in an easy way.

Table 6 below summarizes the advantages and challenges of each of these paths.

<table>
<thead>
<tr>
<th>Path</th>
<th>Advantages</th>
<th>Challenges</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Mass-produce in-house</strong></td>
<td>• Only produce as many as needed</td>
<td>• Lack of resources for tool &amp; die making</td>
</tr>
<tr>
<td></td>
<td>• Maintain current supply relationship</td>
<td>• Still requires a Boeing worker to make the Special Tools</td>
</tr>
<tr>
<td></td>
<td>• Easier to modify in the future</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Uses existing materials that have been approved by safety engineers</td>
<td></td>
</tr>
<tr>
<td><strong>Custom Tool from manufacturer</strong></td>
<td>• Utilizes supplier’s manufacturing expertise</td>
<td>• Long lead times (current supplier is located in India)</td>
</tr>
<tr>
<td></td>
<td>• Becomes an off-the-shelf tool for the mechanics</td>
<td>• Need to work through layers of purchasing approval</td>
</tr>
<tr>
<td></td>
<td>• Uses existing materials that have been approved by safety engineers</td>
<td></td>
</tr>
<tr>
<td><strong>Create a new tool</strong></td>
<td>• Potential to accomplish the task faster and with higher quality</td>
<td>• Any new tool would need to be certified by the safety engineers</td>
</tr>
<tr>
<td></td>
<td>• Eliminate risk of tools breaking</td>
<td></td>
</tr>
</tbody>
</table>

---

11 A light duty worker is a mechanic who is injured or otherwise displaced from performing their normal function.
The option to create a new tool was eliminated quickly due to the size of the challenges. First and foremost, due the safety-critical nature of the job, the tool would need to be certified by the safety engineering group, a process with an uncertain outcome and which could take months to complete. Additionally, creating a new tool added a unique challenge: adoption. Since the mechanics were already asking for a better way to bend the tools, any solution similar to that would almost surely be adopted. However, a new tool would require significant time to show the mechanics the benefits and train them to use it properly.

With the third option eliminated, the other two options were pursued in parallel. First, a sample set of Special Tools were sent to the manufacturer with an expected lead time for their first prototypes of 3 weeks. Secondly, a special tooling design team, was engaged to explore the possibility of creating a custom jig. After numerous conversations with different types of machinists on-site, this option was eventually eliminated due to a lack of tool- and die-making resources.

When the first samples arrived back from the supplier, the product did not meet expectations: they did not twist the shaft and did not properly fan the endpiece. At the time of this writing, the supplier was working on a second iteration of the Special Tools, with an expected delivery in early 2015.
6. **APPLICATIONS ACROSS THE BROADER ORGANIZATION**

The methodology and process described earlier in this chapter is incredibly applicable across the broader Boeing organization. In particular, there are three main principles of the methodology that could lead to improvements in any part of the business:

1. Use data to get directionally correct and avoid “analysis paralysis”
2. Get on the shop floor, observe the work and talk to the workers
3. Believe that opportunity exists everywhere

1.25. Use data to get directionally correct and avoid “analysis paralysis”

“Analysis Paralysis” commonly refers to a situation where people get too focused on making the perfect decision that they delay acting on any decision. Rather than focus on getting the perfect data set or perfect analysis, a key principle of the LGPS methodology is to get directionally correct, and then take action. While the opposite mindset existed throughout much of Boeing, it is easy to understand why: Boeing is so focused on making safe aircraft that every decision is made only after rigorous analysis. However, in a manufacturing environment, nothing will improve if the organization spends months debating the right place to start. By using the initial analysis to get directionally correct, and then adjusting as new facts present themselves based on root cause problem solving, the organization can achieve far greater and faster results.

1.26. Get on the shop floor, observe the work and talk to the workers

This principle goes hand-in-hand with the first: once a decision is made, it is important to get on the shop floor and observe the work. This mentality is critical for several reasons. First, by physically observing a process, an engineer or
manager can often identify several opportunities for improvement right away. Second, by interacting with the employees who perform the tasks, you learn directly from the “experts” – they have been experiencing the process first hand and likely have a lot to say. Even if they don’t have specific ideas, understanding their mindsets and beliefs about the process can often lead to further opportunity identification. Third, this shows the workers that they are being supported, which can improve morale and ultimately productivity. Finally, it is very difficult to improve any process without first understanding that process. The approach of “going down to the shop floor” is applicable across the organization, whether it is a front-line manager, an industrial engineer or a design engineer.

1.27. Believe that opportunity exists everywhere
This is perhaps the principle from the LGPS methodology that is most applicable everywhere within the organization. One example of this principle standing out within LGPS compared to the broader organization was in the categorization of time. The use of “non-value added wrench time” was often questioned by mechanics and industrial engineers because certain processes like measurements and set-ups had to be completed in order to get the job done. However, if those activities had been categorized as “value-added,” the opportunities to improve them would have never been prioritized.

These three principles are critical to the past success of LGPS and are the reasons the initiative has been so successful in other sites. They are broadly applicable across The Boeing Company, and in many cases contrast the current mindsets in the organization, as discussed the Chapter 7.
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