

Lean Principles in an Aircraft Assembly Process

By

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

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and
Master of Science in Mechanical Engineering

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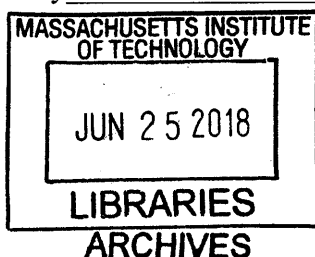
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ABSTRACT

A universal imperative of most manufacturing firms is to lower cost, increase production rate, and deliver exceptional quality for every product. The manufacturing firm that springs to mind as the standard bearer for all three is Toyota and the generalized lean manufacturing method known as the Toyota Production System. The literature on what lean manufacturing is and how to do it is vast. This thesis first contributes to that cache of lean literature an example of one aerospace company's interpretation of lean and how it is defined in assembly production design. In other words, this thesis tests the claim that lean principles can be incorporated in the design of an aircraft assembly process to achieve the lean goals of producing a perfect product with zero waste at the rate at which a customer demands it.

The thesis covers a seven-month research period at an aircraft assembly factory and is broken into three phases. The first phase presents research on an existing lean transformation initiative in the factory and measures its success at achieving lean goals. This evaluation determines that the as-designed system does meet the goals of lean to continuously improve and eliminate waste but also exposes problems to other sub-systems in the factory. Phase I identified several improvement candidates for deeper study, and the rest of the thesis considers one of these opportunities, specifically on the material delivery system.

The second part of the thesis focuses on a root cause analysis of the problems associated with the material delivery system at meeting lean goals. The resulting question is what changes to the material delivery system are required to further these goals. The company was already considering several solutions to answer this question; however, the proposed solutions would violate the original design requirements for the system. This hindered the ability to make improvements.

The third part of this thesis examines the redefinition of the design requirements that embody lean principles as well as other requirements imposed on the system. This allows for new solutions to be evaluated against the design requirements and a final recommendation is proposed.

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ACRONYMS

SOI – Standard Operating Instruction

MPRF - Manufactured Parts Request Facilitator

MIC – Material Integration Center

AGV – Automated Guided Vehicle

POU – Point-of-Use

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1 INTRODUCTION

If given the option, nearly any manufacturing firm would enthusiastically implement a system that would increase production speed, lower costs, and eliminate defects without the need for debate. However, an adage is that between speed, cost, and quality a company must choose two. That mindset shifted when Toyota developed a novel production system and continuous improvement process that delivered improvements to all three. Companies around the world have sought to incorporate the lessons of Toyota in all aspects of operation ever since.

1.1 BACKGROUND OF THE PROJECT

The aerospace industry is no exception. The Boeing Company for nearly three decades has attempted to emulate lean practices in all its production processes. One notable success was in incorporating a lean principle of creating a sense of the visual flow of value in the production process. In a major shift, Boeing adjusted where final assembly activities occurred in the factory. The plane is the value Boeing creates and the challenge was to make it flow through the factory. In the previous assembly process, airplanes remained in a fixed position as mechanics traveled to each in-process airplane to perform all activities for final assembly. In the new method, mechanics remained in a fixed position and performed specific operations to the airplane as it moved through the factory.

However, a rapidly growing commercial aviation market and intensifying competition with Airbus amplifies the sense of urgency to model the aircraft assembly process even more closely to the Toyota Production System. “What Would Toyota Do?” is a literal question often uttered by executives during routine walks of the manufacturing floor.

As a response to this pressure, one aircraft final assembly factory, Factory A, underwent a lean transformation initiative, *Future Factory Vision (FFV)*, to incorporate all known lean principles into its aircraft assembly process. A multi-disciplinary team designed a system of several lean tactics to apply to the current production process that presumably embodied these lean principles. These tactics were deployed and implemented as a total system to achieve the explicit goals of seeing a continuous rate of reduction in mechanic hours until zero waste in the process could be identified and no defects occurred. The beginning of a seven-month research project and this thesis happens after the implementation of the original lean implementation initiative was complete. I was tasked to understand the current use of lean tactics in the factory and recommend future improvements.

1.2 PROJECT MOTIVATION

The goal of Factory A is to reduce the hours required to assemble an aircraft by mechanics, *airplane unit hours*, so that it can reduce unit costs but more importantly have the option of increasing rate to keep up with demand. The goals of the factory align with the goals of lean which is to enable speed, reduce costs, and improve quality (which for Factory A defects are a direct cost). Lean as a set of guiding principles achieves these goals through continuous improvement of the production process and the elimination of waste from the production process.

Therefore, the goal of the project was to reduce airplane unit hours by applying lean principles. The specific deliverables of the project were an assessment of the current state of waste in the production process, identification of root causes to recurring problems, and a recommendation for changes to the Future Factory Vision.

The goal of the thesis is to test the hypothesis that application of lean principles in aerospace results in a reduction of airplane unit hours. In doing so, the thesis focuses on increasing the understanding of the general problem of translating lean principles into the design requirements for a production system and process.

1.3 PROJECT APPROACH

To achieve the goals of the project and the goals of the thesis the project approach is the same. The project is broken down into three phases. The first phase focuses on an assessment of Factory A's lean initiative impact on the reduction of unit hours through waste reduction. This assessment uses factory data of the number of hours required to build an airplane and time studies of the process to identify a percentage of time spent on wasted activities. This study then becomes the baseline measurements for the next phase of the project.

The goal of the second phase of the project is to identify the root causes of problems identified in the first phase. A result of the first phase was that there were many problems, so the focus was explicitly spent on problems associated with the material delivery system. I developed a fault tree and validate known causes through multiple analyses. I studied the operational performance of the material handlers to understand their process capability and the sources of waste in the subsystem process; this study was similar to what had been done previously for the airplane mechanics.

The third phase of the project is to define what to do next. I treat the implementation of lean as a design challenge and use traditional approaches to develop a method of evaluating multiple solutions against the lean principles they are meant to embody. I used an immersive interview technique as outlined in IDEO's human-centered design to inform a stakeholder analysis and the resulting design

requirements. The requirement for the material delivery system is that it follows lean principles, but the stakeholder analysis uncovers other requirements of the system that have not yet been explicitly defined. The analyses and the learning from the first two phases culminates into design requirements for the system. Using these design requirements, I evaluate the baseline system and potential solutions. I use a Pugh analysis to look at a suite of solution options in changing the material delivery system and identify the most promising solutions.

Each of these phases is described in more detail in chapters 2 through 4 respectively, with chapter 5 detailing conclusions and areas for future study.

1.4 GENERAL BACKGROUND INFORMATION ON FACTORY A.

Factory A is responsible for the final assembly of large aircraft. Five positions perform the final assembly operations in the factory, where the primary structure flows through each position. The Primary structure is any major part such as the wings, fuselage, tail-cone, and vertical and horizontal wings. Each position is then a microcosm of the factory where job requests, known as Standard Operating Instructions (SOIs), flow through the position. The materials and tools needed to complete the SOI constitute a critical material flow through each position from an incomplete to complete state. Figure 1 shows a visual representation of the high-level assembly process and the flows in and out of each position.

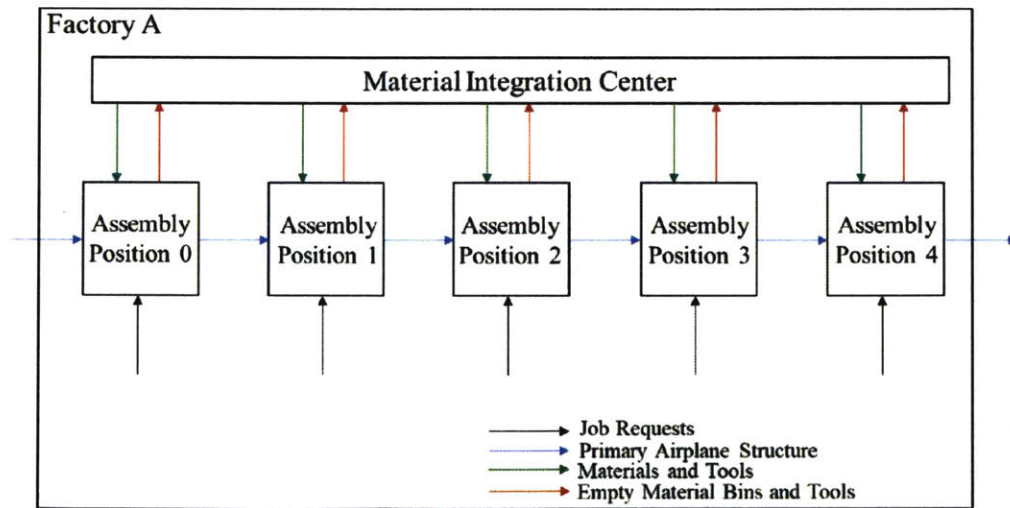


Figure 1: Factory A High-Level Aircraft Assembly Process

The initial implementation of the FFV (Future Factory Vision) was on Position 0, particularly on the work activities (the statement of work) of joining the tail-cone, vertical stabilizer, horizontal stabilizer,

and the end section of the fuselage together. The activities required to complete this statement of work are to

- Drill and Deburr
- Seal and Install Fastener
- Torque, and Tighten
- Clean and Paint

This area was chosen as the area to study because as the first position it was not prone to schedule fluctuations caused by the preceding position. However, Position 0 did experience delays due to external suppliers. The results in chapter 2 will also highlight these sources of variation through the waste analysis of each job. As the first test position of FFV implementation, significant focus and capacity were devoted to the area to incorporate the tactics of the FFV more than any other position.

1.5 LITERATURE REVIEW

What is lean? James Womack, Daniel T. Jones, and Daniel Roos are responsible for the name when they first wrote about the Toyota Production System in “The Machine that Changed the World.”[1] Today, a quick search of “lean manufacturing” in Google Scholar will result in over 860 thousand results. However, for this thesis, it is essential to define the meaning of lean principles for Factory A explicitly.

Jeffrey Liker does this in the “The Toyota Way” by summarizing TPS into fourteen executive principles. The 14 principles are the most recognizable sources for Factory A’s lean tactic strategy. Table 1 shows these fourteen principles.

Principles of the Toyota Production System	
Section I: Long-Term Philosophy	
Principle 1	Base your management decisions on a long-term philosophy, even at the expense of short-term financial goals.
Section II: The Right Process Will Produce the Right Results	
Principle 2	Create continuous process flow to bring problems to the surface.
Principle 3	Use “pull” systems to avoid overproduction.
Principle 4	Level out the workload (heijunka). (Work like the tortoise, not the hare.)
Principle 5	Build a culture of stopping to fix problems, to get quality right the first time.
Principle 6	Standardized tasks are the foundation for continuous improvement and employee empowerment.
Principle 7	Use visual control so no problems are hidden
Principle 8	Use only reliable, thoroughly tested technology that serves your people and processes.
Section III: Add Value to the Organization by Developing Your People and Partners	
Principle 9	Grow leaders who thoroughly understand the work, live the philosophy, and teach it to others.
Principle 10	Develop exceptional people and teams who follow your company’s philosophy.
Principle 11	Respect your extended network of partners and suppliers by challenging them and helping them improve.
Section IV: Continuously Solving Root Problems Drives Organizational Learning	
Principle 12	Go and see for yourself to thoroughly understand the situation (genchi genbutsu).
Principle 13	Make decisions slowly by consensus, thoroughly considering all options, implement decisions rapidly.
Principle 14	Becoming a learning organization through relentless reflection (hansai) and continuous improvement (kaizan).

Table 1: Liker's 14 Executive Principles of the Toyota Production System[2, pp. 36–40]

These 14 Principles take a more elemental structure in the Toyota House, which embodies these principles to create the structure of a production system. Liker notes that the goal of Toyota’s Production System is to produce a product with the Best Quality, Shortest Lead Time, Lowest Cost, and high Safety and Morale. Safety and Morale is not always explicitly stated but it is held as the highest priorities. Figure 2 shows the Toyota Production System, which closely resembles the house structure of Factory A’s Production System.

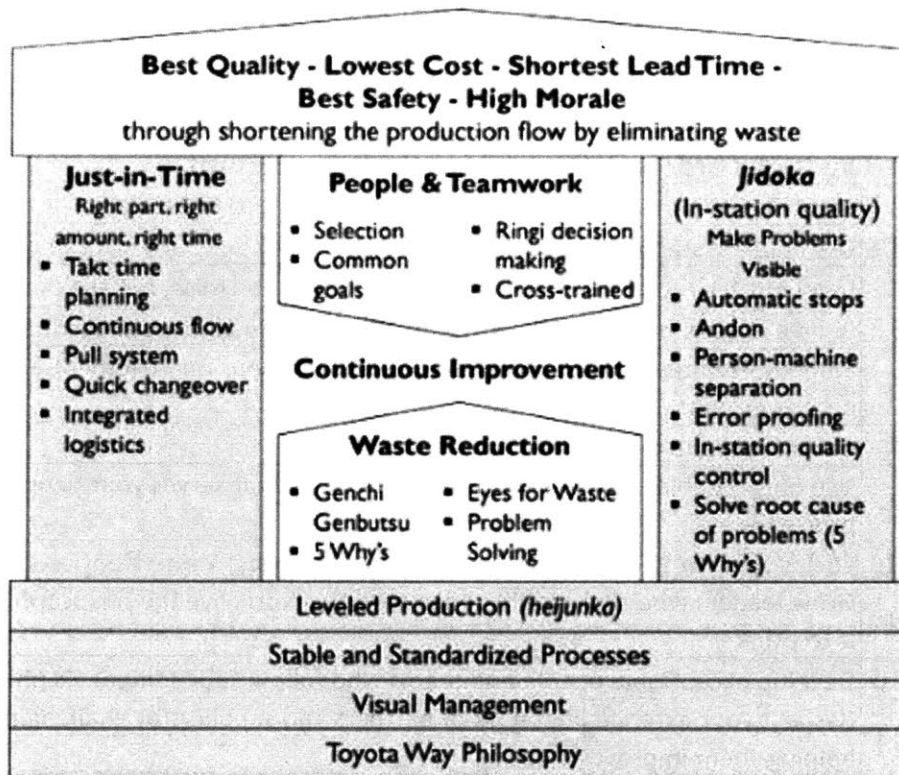


Figure 2: Toyota Production System Tools and Structure[2, p. 33]

Factory A's current lean practices are not a mirror image of Liker's description of the Toyota Production System, but the FFV attempts to bring the two into closer alignment. In testing whether the use of these principles result in the factory goals of reduced hours, the principle and tactics being tested more align with Liker's interpretation of them.

Spear and Bowen offer a different framework in their paper of "Decoding the DNA of the Toyota Production System," where they detail four rules required of any production process. Table 2 lists the four rules of any production rules based on Toyota.

Four Rules to Any Production Process	
1	All work shall be highly specified as to content, sequence, timing, and outcome.
2	Every customer-supplier connection must be direct and there must be an unambiguous yes-or-no way to send requests and receive responses.
3	The pathway for every product and service must be simple and direct.
4	Any improvement must be made in accordance with the scientific method, under the guidance of a teacher, at the lowest possible level in the organization.

Table 2: Spear's 4 Rules of the Toyota Production System for any Production Process[3]

Spear and Bowen's take on the Toyota Production System offers less direction into what the actual elements of a production process are, but their work boils down the essence of what Toyota does. They argue that the tools that Toyota uses, such as the Kanban system, are considered countermeasures to meet these fundamental rules. The commonality between Spear and Bowen's and Liker's principles is the emphasis on continuous learning. The current state of Factory A's FFV does not explicitly reflect Spear and Bowen's principles, but I will incorporate this framework in Chapter 4 when reimagining a new material delivery system.

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2 PHASE 1: FACTORY A'S FFV

At the start of the project, a lean transformation team and the mechanics of P0 had implemented many of the elements of the future factory vision. There was evidence that a reduction in the hours had occurred, and implementation efforts had moved on from Position 0 to other areas in the factory. However, there was also evidence that the rate of reduction in hours was beginning to slow short of the intended goal state. The first goal of this project was to test that a lean transformation had occurred in the P0 area using the prescribed tactics. The lack of reliable, relevant, or sufficiently detailed data was an issue, so the second goal was to provide source data to do further studies. Future studies and initiatives can use this data as a launching point.

Phase 1 Goals:

1. To answer the question, did the implementation of the FFV result in faster, cheaper, better quality product as evidenced by the continuous reduction of hours and elimination of waste in the process?
2. Collect data in a sufficiently detailed manner to test the lean transformation, but also provide data for future studies
3. Hypothesize future areas of improvement and provide the baseline level of improvement to be gained.

The rest of the chapter will detail the results and methods of achieving each of these goals. The main result is that the FFV had significant gaps in achieving the lean state that it is aspiring to, where 34% of the mechanic's time per job was contributing to value-added activities in comparison to the 85% target goal. However, there was a reason to believe that the lean transformation did generate continuous improvement activity. There was confidence in continuing to answer the question of how to further refine the lean transformation. I identified that the material delivery and integration was a high source of non-value added and waste activity. The study estimates improvements to the material integration and delivery system could recover approximately 11.3% of the time per job per mechanic.

2.1 THE IDEAL FACTORY IN A FACTORY

Factory A produces airplanes during a 15-day cycle time and 3-day takt time. Every three days, the plane moves from each position. Figure 1, in Section 1.4 shows the high-level view of the airplane flow through the factory. Within each of these positions, there is "mini-factory" where several operations occur. Figure 3 shows more links between different groups within the factory that all support the completion of a work-package. A work package for a team is made up of several SOI's. Several core engineering support groups produce the necessary information and documents needed by both the

Material Integration Center (MIC) and the mechanics in Position 0. The MIC’s primary responsibility is to manage the flow of materials in and out of the factory from several sources of suppliers and integrate these materials into one physical location for easy retrieval by the mechanic. The mechanics within Position 0 are responsible for executing the assembly tasks required for the build of the airplane. The Line Side Control Center is a problem resolution center. While in a perfect scenario the role of the line side control center would not be required, it is reasonable to assume problems do arise and the line side control center exists to facilitate problem resolution of issues that occur during the build.

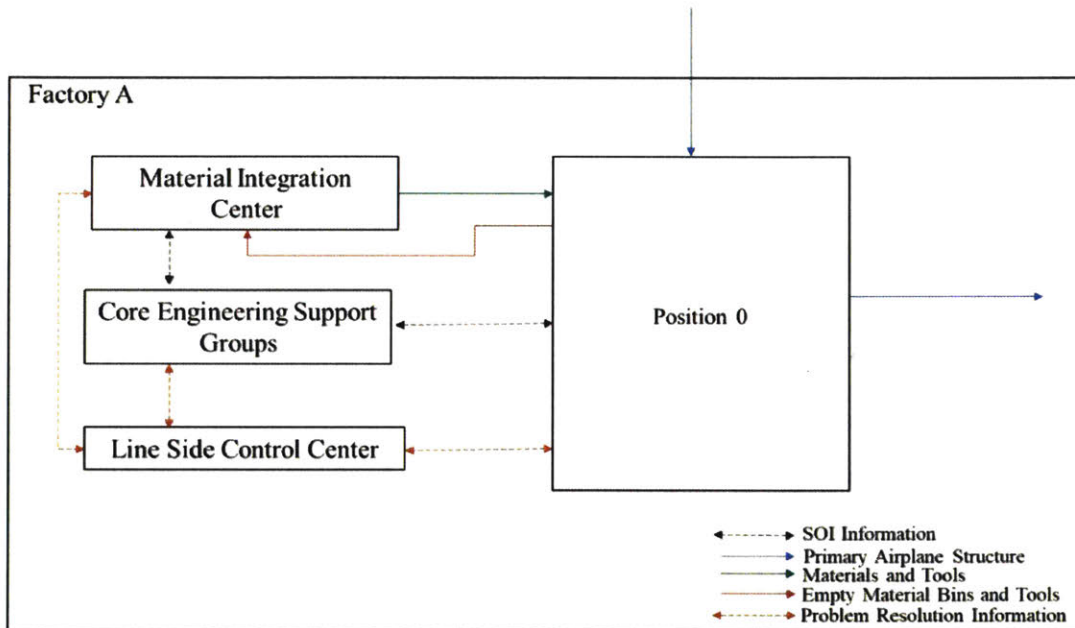


Figure 3: Position Operations in Factory A

Like the “flow” of the airplane through the factory, there is a “flow” of SOI’s through the position. The flow of SOI’s is information and multiple parts and materials that are integrated into the airplane. To understand this, Figure 4 shows the steps required to take a job from an un-finished to complete state. The information flow for how to complete a job starts with the Core Engineering Support Groups. Manufacturing Engineers first translate job requirements provided by Design Engineers into the “how-to-assemble” steps, materials lists, level of quality requirements, and documentation requirements for the mechanic. Depending on the position, each plane can have variable instructions due to varying customer requirements. P0’s work package was mostly standard between two configuration types and over 95% of the jobs did not change plane to plane. They also provide information for any mandatory sequencing of jobs and an estimate of how long each job should take. Manufacturing Engineers input this data into large data platforms. Industrial engineers can then access this information to determine the “fire-order” for the build. The actual issue of the order for specific parts is dependent on the lead time

required. External suppliers are then responsible for delivering the parts to specification in the pre-determined window. Three days before the build the schedule is further refined and frozen. Industrial engineers add start and completion times for each job and assign a mechanic to work with the creation of a “bar chart” or a detailed schedule of the build. Material integration and the mechanics follow this schedule. In the ideal factory, material from external suppliers is received every four hours for the set of jobs that occur in the next four-hour window. Material Integrators integrate the tools, parts, and consumables in one kitted “cart” and deliver two hours’ worth of work every two hours. The mechanic consumes these materials as he or she completes a job every two hours. If a problem does occur or inspections are required, these activities occur within the two-hour time by the responsible party.

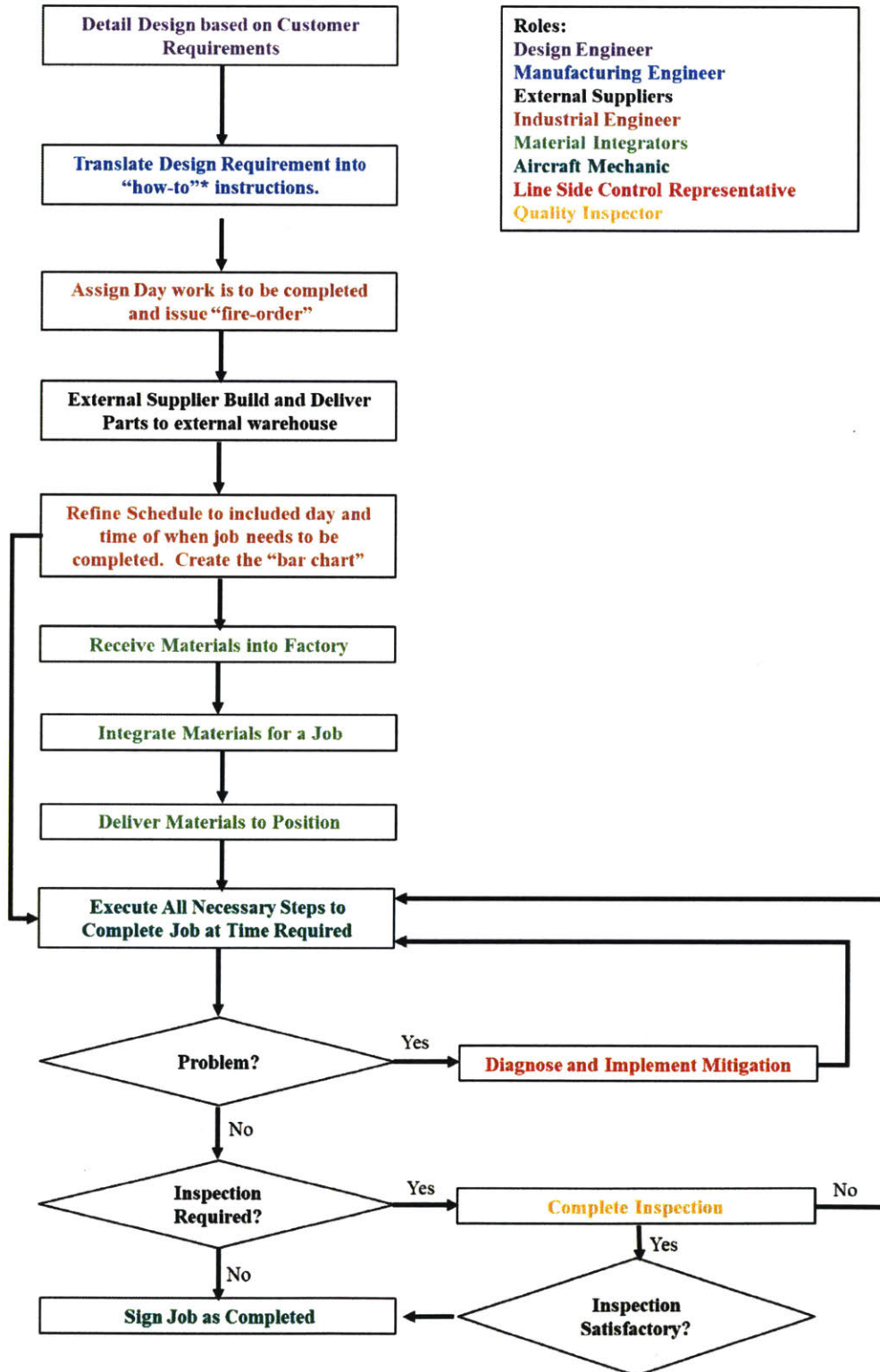


Figure 4: Flow of Job Creation to Completion in the Factory

The Future Factory Vision targets explicitly reducing the number of hours of the mechanics work in “Execute All Necessary Steps to Complete Job at Time Required” step. Figure 5 breaks down the

process even further, to show the steps that are performed only by the mechanic in the ideal factory. After receiving a job assignment from the “bar chart,” the mechanic is to proceed to a computer station where he or she will clock-in to the start of the job. The mechanic will then gather all the necessary materials to do the job. The mechanic then sets up the required jigs and hard tooling to execute the job safely and with the highest quality. The mechanic performs the value-added work, which for Position 0 includes.

- Drill and Deburr
- Seal and Install Fastener
- Torque, and Tighten
- Clean and Paint

After completion of the job, jigs are broken down, and tools and consumable wastes are returned or disposed of. The mechanic will document any measurements that are required and add his digital signature for completion of the job. The goal of the FFV is to ensure that the mechanic is working to a two-hour takt time and spending 85% of the time on value-added work.

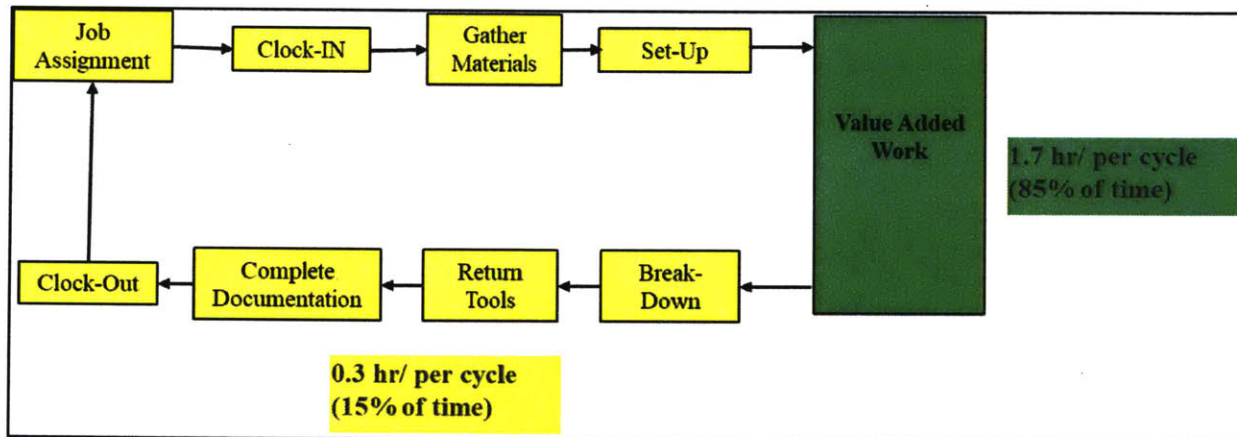


Figure 5: Ideal Mechanic Process to Complete Job

The flow of work presented above represents an idealized state of job start to completion in the Factory. The steps included are the relevant ones impacted by the FFV change. Also, the ideal factory portrays a direct path of how to complete a job; the reality is a much more complicated and iterative process to finish a job. The FFV implementation is not meant to create the ideal factory vision in a single instance, but instead create a system that continually works toward this ideal.

2.2 FACTORY A’S FUTURE FACTORY VISION

To achieve the ideal factory scenario described above, Factory A embarked on a lean transformation initiative that employed ten tactical strategies that aligned with lean principles. Table 3

describes each of the lean tactics in more detail. The table also compares it to Liker's definition of lean principles to directly show where the principles show up in the specific tactics implemented. Liker's Principle 8 and Principle 3 are not directly reflected in Factory A's lean transformation. Principle 8 is to "use only reliable, thoroughly tested technology that serves your people and processes." Before incorporating tactics across the factory, Position 0 was the pilot area for new solutions, which was meant to be the test period for the transformation. Principle 3 is a notable and intentional gap in the lean transformation. Principle 3 is "use "pull" systems to avoid overproduction." Data technology to enable a true pull system is not immediately implementable for a true pull system to work. At the positional level, the material is "pushed" to mechanics every two hours and does not respond to feedback on when mechanics are finishing work.

Lean Tactic		Description	Liker's Principle
1	People	-Developed Leader Standard Work -Trained leaders in lean principles and the use of Leader Standard Work	Principle 9, 10
2	Kaizen Tier Boards	-Messaging board to highlight metrics previous day's metrics -Daily Meetings with mechanics and support of day's goals and improvement -Repository of improvement idea cards and visual slots to show progress on implementing change -Weekly leadership meetings at tier boards to highlight successes	Principle 12, 13, and 14
3	Value Stream Mapping	-Periodic meetings to re-distribute jobs into and out of the position. -Creation of Value Stream teams that consider strategic redistribution of work, and more efficient grouping and layout of work	Principle 1, Principle 11
4	Balance the Line	-Redistributing jobs per shift, an equal number of mechanics across shifts and an equal amount of work per mechanic.	Principle 4
5	Standardized Work	-Rewrote SOI's to capture the best practices to date in the completion of each job. -Rewrote work so that all operations in a job could be performed in less than two-hour time blocks	Principle 6
6	Visual Controls	-Displayed digital metric boards displayed at the line side control center -5S of the work area, with defined positions for all tools (physically marked on the floor) -Eliminated Mechanic toolboxes -Added a color-coded system displayed on material carts that flag the status of a job (To be worked, Work in Progress, Return Cart (Job Finished)).	Principle 7, Principle 2
7	Point of Use	-Marked swim lanes on the floor, for the delivery of kitted materials next to the location of work being performed -Consumable racks moved closer to the aircraft	Principle 4, and 7
8	Feeder Lines	-Redistributed jobs that can run parallel and on a smaller bench away from the main build	Principle 4
9	Line Side Control Centers	-Created Strategic Action Tracker (SAT) System that allows for the input of production problems and tracking of status as it goes through steps to resolution -Co-located critical production support representatives to sit next to production center	Principle 5
10	Moving Line	-The moving line has not been implemented. However, the above tactics are seen as enablers to make a moving line possible	Principle 2

Table 3: Future Factory Vision Lean Transformation Tactics

Completion of implementation of the FFV in the project occurred approximately two months before the start of the project. The FFV focused efforts now on maturing some of the system processes with minor tweaks, but there were no large-scale initiatives. At the start of the project, an opportunity arose to study Position 0 in this quasi-stable state. The only changes expected were the ones that were initiated as a direct result of the continuous learning loop created with the FFV initiative.

The FFV is the collection of tactics that are being tested in the project's time study. The study tests FFV as a whole system, which means that it cannot identify a single tactic within the overall strategy as the single cause of success or failure. Since the study will not conclude with a single cause, phase 2 and phase 3 will dissect a single problem in the overall strategy.

2.3 CURRENT STATE OF P0

To evaluate the current state of Position 0 after FFV implementation, I conducted interviews with the first-line manager of the area, several mechanics, and members of the lean transformation team. What was immediately evident was different stories of the success of the lean transformation. The lean transformation team mostly called the implementation of FFV a success, citing a noticeable reduction in the number of unit hours. While obvious waste in the process existed, the presence of waste was an indication that the transformation was a success because this waste was now visible, and the continuous improvement loop could occur. The first line manager and team leaders of the aircraft mechanics confirmed that there was a reduction in the number of hours but cited three elements of the change that resulted in a time reduction. These included

1. The 5S activities had resulted in a cleaner area
2. A critical tool that was used for many of the SOI's was moved closer to the aircraft, reducing the amount of time spent walking to the tool.
3. Drastic improvements were made to the quality of toolkits, such that missing tools for a job became a rarer occurrence. They added that this wasn't an improvement. The transition proved to be initially problematic and the time to gather tools was getting back to the previous times of when mechanics had their own personally maintained toolboxes.

Furthermore, they noted a lack of support to implement any future changes, so they doubted any substantial transformation had occurred. Looking at the data of the time-period immediately after the majority of FFV change activity had stopped and through the initial interview period, both claims are confirmed. Figure 6, shows normalized aircraft unit hours for the position immediately after the change, which is labeled as airplane unit 1. Looking at 3-plane moving average, it becomes more evident that for

approximately ten aircraft there was a sustained reduction in unit hours. After this, the rate of reduction begins to level off.

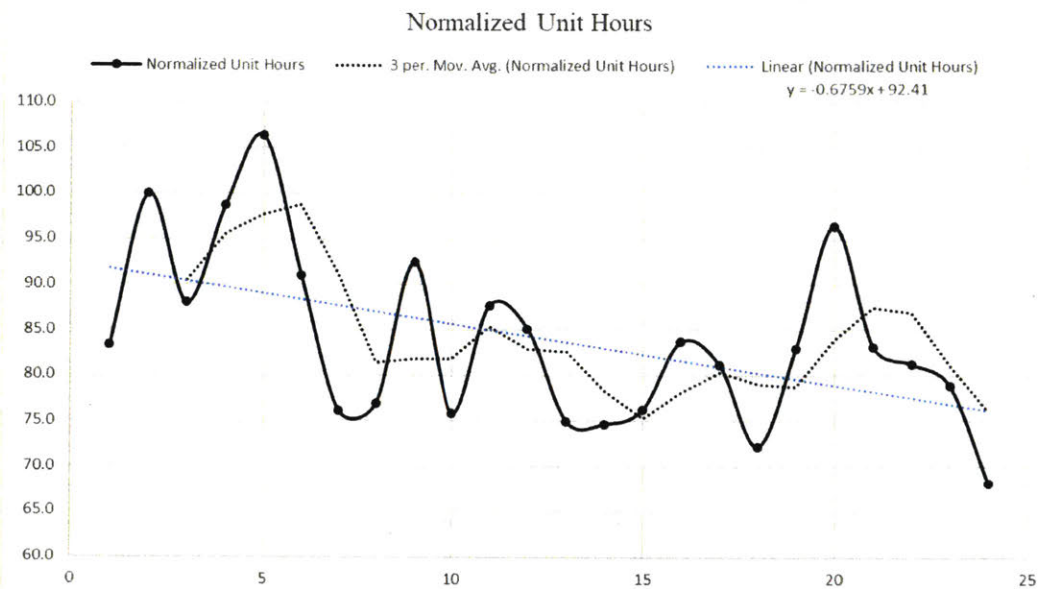


Figure 6: Normalized Aircraft Unit Hours

Even if a downward trend would continue, the normalized rate of reduction of 0.67 unit hours/plane was at 80% of the required rate of reduction to meet year-end targets. Regardless of who was right, everyone agreed that further work needed to be done, but there was no emergent strategy for what should be tackled next. Gathering data on the waste in the system was of immediate interest to the parties involved. While the time study was conducted to test the hypothesis of whether a lean transformation had occurred, the data from the study would be useful in establishing baselines for future improvement endeavors.

2.4 METHOD OF ANALYSIS FOR LEAN TRANSFORMATION EVALUATION

There was a two-part evaluation method to confirm whether the FFV resulted in a lean transformation in the area. As mentioned before the goal of lean is to manufacture a product faster, cheaper, and with better quality; however, the end state will always change to more aggressive goals. Right now, the goal is 85% of the mechanics time is to be spent on value added activity. To test whether a lean transformation occurred, I needed to identify the two required activities of lean, waste reduction and continuous improvement. The first study was a time-observation of mechanics time during a 3-day cycle. This study would take place over the course of 2 months, at which time the second analysis of accumulated time data would be collected to confirm a continued trend in the reduction of unit hours.

2.4.1 Method for Value Time-Study of Mechanic Work

There were two primary goals of this study. First, to confirm the existence of waste in the positional assembly process. The second was to capture detailed data of the types of waste in the assembly process to determine next course of action.

This study involved following five mechanics in their entirety during a 3-day cycle, documenting and timing every activity. One mechanic was followed twice, due to extreme delays in the first observation that caused the mechanic to work different jobs than his usual work. Industrial Engineers routinely perform time studies in Factory A, but they are usually performed on a single SOI. I had a strong hypothesis that waste for jobs largely occurred in between two subsequent jobs and that the traditional time studies would not necessarily capture this because they started when the mechanic was ready to perform the work and did not necessarily capture the set-up time. Some traditional time studies could include this, but I had no idea of knowing which ones did.

I chose mechanics from each shift with different work packages that touched all the major value-added activities performed in the area. For 3-days, I noted the activities of the mechanic and categorized them into value-added, non-value added, and waste activities. Table 4 breaks down the high-level categories of value-added, non-value added, and waste activities noted in the study. Value is defined as anything the customer is willing to pay for, which leads to a definition of value-added as any activity that impacts fit, form, or function of the airplane. Non-Value-Added Activity is defined as steps that are required to be done per the current process. Waste is anything else that is not directly per the process or requires rework to correct a defect. Activities, such as the beginning of shift Team Meeting, Scheduled Breaks, and employee appreciation activities, were all considered to be unavailable time and excluded from calculations in the study.

Value Added Activities	
Drill and Deburr	Activities that impact the fit, form, or function of the aircraft.
Seal and Install Fastener	
Torque, and Tighten	
Clean and Paint	
Non-Value-Added Activity	
Documentation	Clocking In, Clocking Out, Inputting Measurement Data, Inspection Data, Tools Used, Sealant Lot Numbers.
Get Materials	Walking to and from the aircraft to gather any materials from predetermined stations that are required to complete the job.
Set-Up	Putting together specialty tooling, jigs, barriers in order to be able to do the job.
Break-Down	Removing any specialty tooling, jigs, or barriers that are required to complete a job.
Return Materials	Walking to and from aircraft to dispose or recycle consumable materials or return tools or empty parts containers at predetermined locations.
Waste	
Over Transport	Moving materials more than is necessary.
Inventory	Having more material in the work cell than required to do the job.
Excessive Motion	Multiple Trips required to bring in materials, or excessive force required to perform a job.
Waiting	Waiting for inputs or actions from support groups.
Over processing	Doing more than required for a quality product, such as cleaning and recleaning beyond what is necessary.
Defect/Rework	Having to repeat any step more than once to attain required quality.

Table 4: Value Study Activity Definition

I also took down detailed notes to further sub-categorize these activities after the study. A sample of the types of observations and notes taken, are shown Figure 7. Many of the observations occurred in a confined space where hazardous materials were present. Use of a tablet to record observations in this area posed a fire-safety risk. The unit of measure of two minutes introduces an error of approximately 1% to the analysis, but it was used because it was about the time required to take down detailed notes for each activity.

Mechanic		1
Shift		1
Day		1
Time	Activity	Notes
8:00	Get Material	Walking to Swimlane A, Was Found in Swimlane B
8:02	Get Material	Walking to Chemical Storage
8:04	Get Material	Walking to Protective Equipment
8:06	Set-up	Putting on Protective Equipment
8:08	Set-up	Connecting Power Hoses
8:10	Drill	SOI Number (number of holes)

Figure 7: Sample Observation Sheet

2.5 HYPOTHESES OF TIME OBSERVATION

Before conducting this study, I hypothesized that I would find a significant amount of waste in the process. I also hypothesized that a dominant contributor of waste would emerge and could be the focus of the next study. The overall goal of the project was to confirm a lean transformation had occurred, which would be identifiable if there were either no waste in the process or if there was waste in the process continuous improvement activities were still occurring.

2.6 RESULTS OF TIME OBSERVATION

The results of the study did confirm that there was a large amount of waste in the process. The study was not able to conclude a statistically significant dominant source of waste. There were several contributors to the waste and non-value-added activity. Clustering the data into sources of the waste and non-value-added activity identified that activities associated with the material delivery system are a point of interest in improving.

2.6.1 Note about Unit of Measurement in Results

A point of complexity to the definition of jobs is jobs will require multiple mechanics. For this study a job is not equivalent to time per SOI, but rather a time per SOI per mechanic. When measuring the time of an activity, it is SOI/mechanic

2.6.2 Time Observation Valued Added Per SOI Per Mechanic

The study revealed the difference between the ideal flow of work for the mechanic and the actual flow of work in the day. Figure 8 is a visual representation of the actual flow of work as performed by the mechanic. The red boxes labeled, Rework and Delays, are represented as single activities for large instances of delays in the flow, but disruptions can and do occur at nearly all steps. Examples of these disruptions are shown by the red arrows and the percentage of time per activity is shown by the red numbers. Over the course of the study, there was an average of 1 to 2 disruptions per SOI per mechanic that resulted in a delay or rework per job. The yellow boxes represent non-valued added activity and the green box represents the value-added work. The black numbers are the percentage of time spent for each type of non-value added or value-added activity.

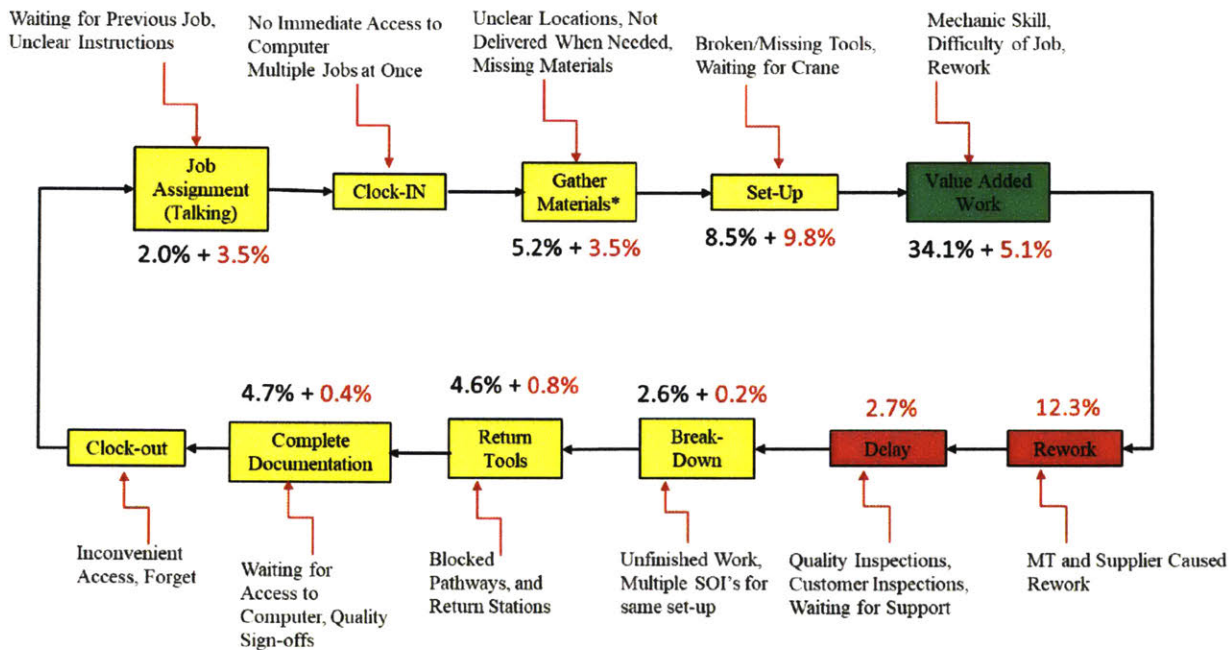


Figure 8: Actual Flow of Job Through Position

Figure 9 shows the time of each job/mechanic, broken down by the types of activities. Value Added activities are represented as one type of activity. The Non-Value-Added activities include talking about job-related topics, the getting and returning of materials, set-up, break down, and documentation. It was often hard to distinguish between clocking in activities and inputting of data, so clocking activities and documentation activities were combined. At this level of categorization, the average SOI/mechanic took 1.2 hrs/SOI/mechanic. The value-added portion of work was 34% of the total time. Non-Value-Added Work and Waste accounted for 28% and 38%, respectively.

Classification of Time of SOI per Mechanic

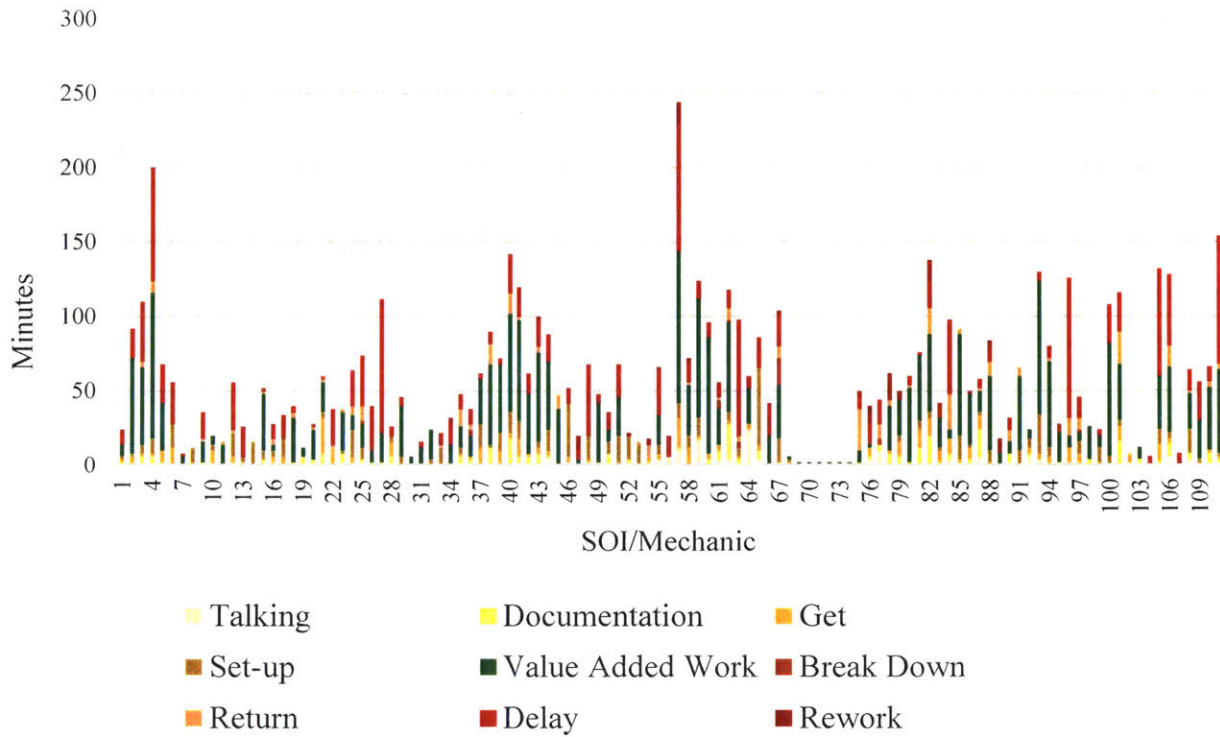


Figure 9: Time Spent on each SOI per Mechanic by Activity

Figure 10 shows the percentage time for each type of activity. What becomes immediately obvious is waste of rework and delays are large contributors to the total time required for a job.

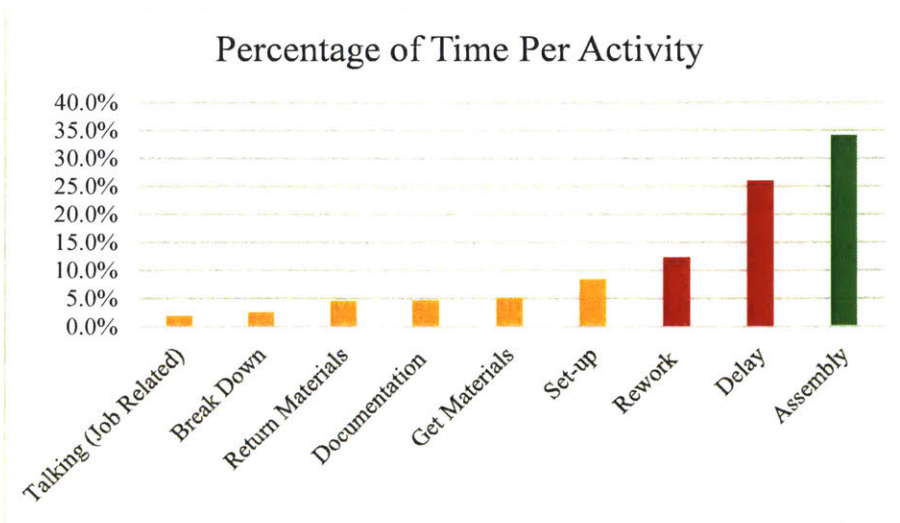


Figure 10: Percentage of Time Per Activity

Figure 11 looks specifically at delays at a more detailed level. This shows that while the total category of delays represents a significant portion of time, the owners of these “delays” are spread amongst many suppliers to the system. The delays could be sub-categorized into 32 different specific categories. Only the first six are shown as the rest of the categories each make up less than 1% of the total time on a job. The main categories of delays are

1. **Schedule Conflicts:** Schedule conflicts arise because the mechanics are unable to work to the bar chart schedule, so “micro” conflicts begin to occur. These include times when a mechanic needs an assist from another mechanic but he or she is required for another job, a mechanic is unable to start a job until the prior job is completed, or the mechanic is unable to start because too many people are in a confined space.
2. **Waiting for crane:** The crane is a shared resource amongst different lines in the factory so delays in any of the other lines have ripple effects downstream.
3. **Waiting for quality:** After a job is finished it is put on to a “call sheet” in which a quality representative will come to inspect the job. The quality group is also a shared resource amongst groups and so when requesting an inspection, the request is put into a queue prior to be completed.
4. **Waiting for line side control:** This refers to waiting for specific problem resolution before being able to proceed on a job.
5. **Extended Break:** Ten minutes are allotted for breaks and this is time extending beyond this. To keep this in perspective, a 1.6% time represents less than 2 minutes of time per job and should be considered as normal and reasonable ramp up times for this type of work. The rest of the 24.4% of captured delays can be attributed to inefficient processes.
6. **Searching for cart:** Materials are delivered to a prescribed location at a specific time. Numerous times mechanics had to search for the cart as it was either hidden or not in the expected location.

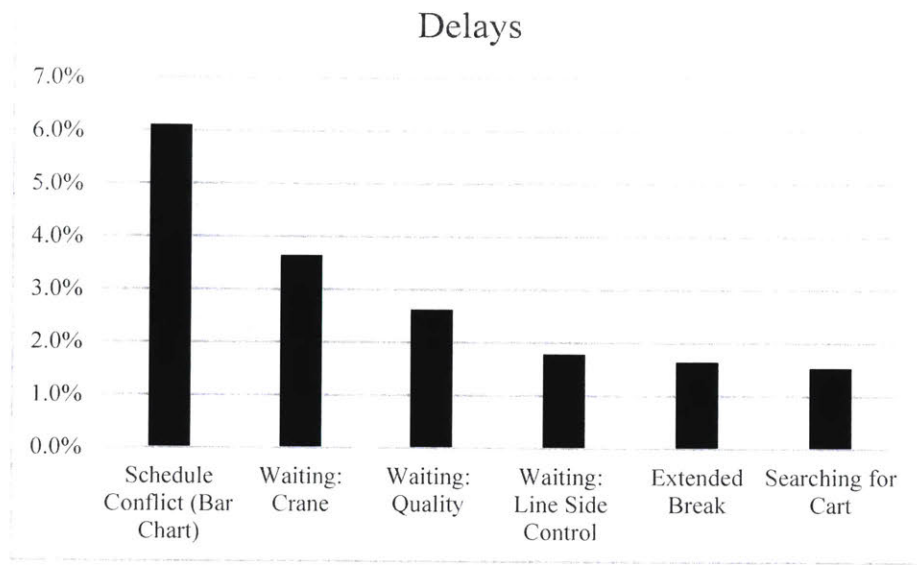


Figure 11: Percentage of Time Per Activity by Delay

2.7 DISCUSSION OF RESULTS

An expected result of this study was that waste in the process would be found. However, what was not expected was the breadth of sources for waste. This means that no dominant source of waste could be identified as any time associated with any one particular-type was below the margin of error for this study (8.6%). However, it does confirm these types of waste exist and the impact is non-zero and so further study is valuable.

2.8 METHOD FOR MEASURING CONTINUOUS IMPROVEMENT

The goal of this study is to confirm whether continuous improvement is occurring over the long-term after FFV was implemented. The main measure is looking at the number of hours required to build this section of the plane.

2.9 HYPOTHESIS FOR MEASURING CONTINUOUS IMPROVEMENT

Shown in Figure 6, the trend in reducing in unit hours had stalled at the start of the project. I hypothesized that this was because a lean transformation had not occurred and there was no sustained continuous improvement activity occurring.

2.10 RESULTS FOR MEASURING CONTINUOUS IMPROVEMENT

At the start of the study it appeared that improvement had leveled off. However, looking at a longer time scale the trend continues. What was interesting to note is that there was a shift in the trend around unit 30. After unit 30, a newly revised standard “bar chart” had been released after collaboration with the mechanics, team leads, and the industrial engineers identified that the original bar chart was not reflective of the optimal sequencing of work. In many ways, this was exactly the kind of idea generation and implementation type activity that the FFV was aiming to inspire.

Figure 12 shows the continued trend of a reduction in unit hours. This is the same chart as Figure 6, with a longer time scale to span the course of the project. What is seen is a reduction of hours which is evidence that learning or continuous improvement is occurring. The shift after Unit 30 though suggests that systemic changes such as a “bar chart reorganization” that impact multiple completions of SOI’s can have a greater impact than a single change to a single SOI.

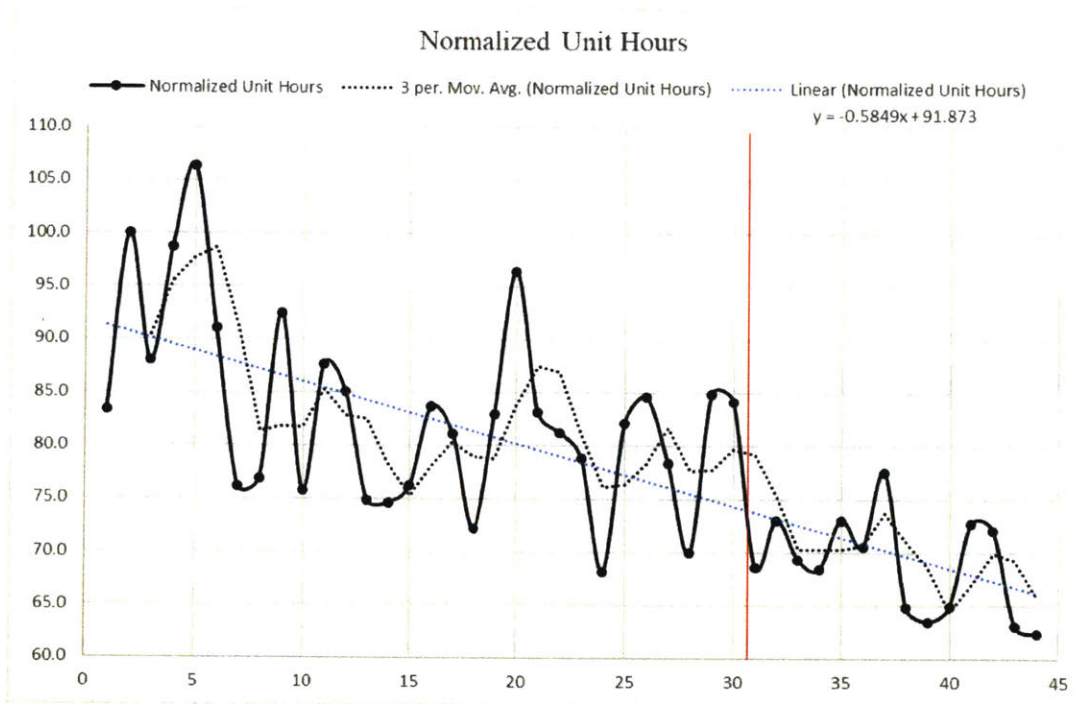


Figure 12: Position 0 Unit Hours

To further illustrate the extent of the change, Figure 13, shows a before and after change in the average number of hours to complete an airplane, after the new bar chart was implemented in the area. Doing a two-sample t-test reveals with 99% confidence that a shift of between 4.00 and 20.43 hours did occur in the normalized hours, with a p-value of 0.001.

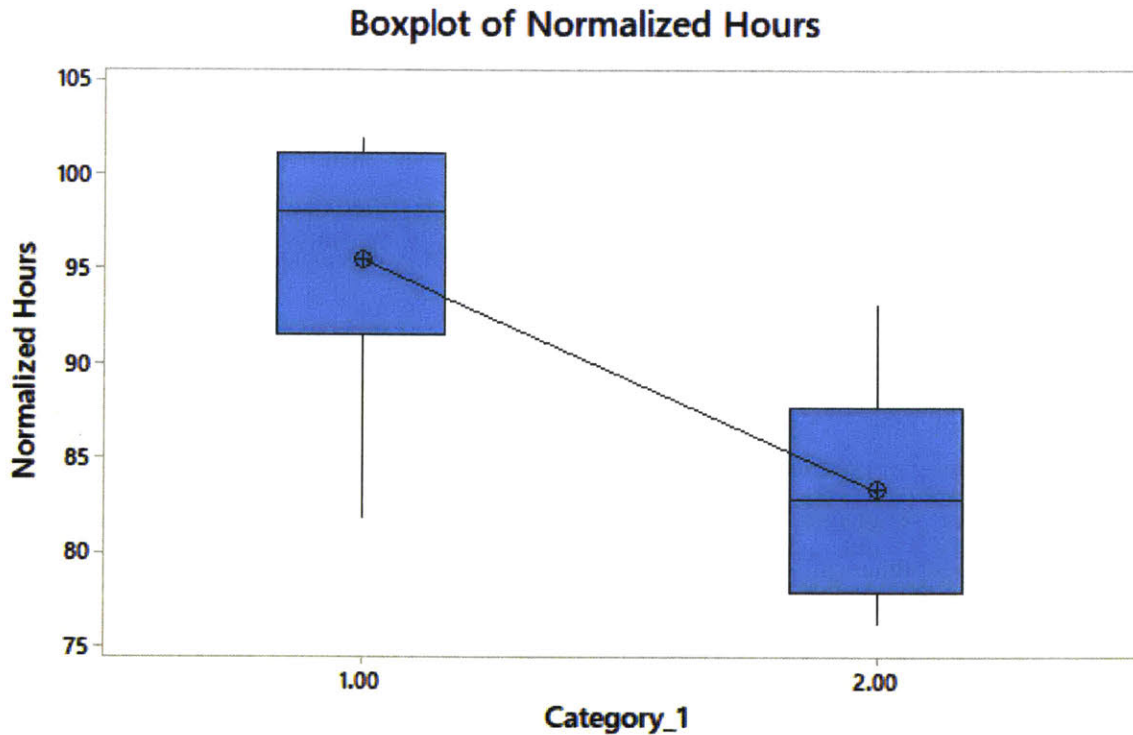


Figure 13: Comparison of Before and After Schedule Update

2.11 DOWN SELECTION TO A SINGLE FOCUS AREA

After understanding the different sources of waste, a single focus area of improvement could be selected, if reframed within the larger context of data. If the data is reframed not by time, but by instance of occurrence per job a different trend emerges. Figure 14 shows the percentage of the observed jobs where a specific type of delay occurred. What emerges is that schedule conflicts, waiting for resolution from line side control and searching for carts do become large impact area in terms of the number of job that are being impacted. The remaining could be evaluated further, but their solution would lie outside the scope of the factory and specifically improvements to the lean initiative.

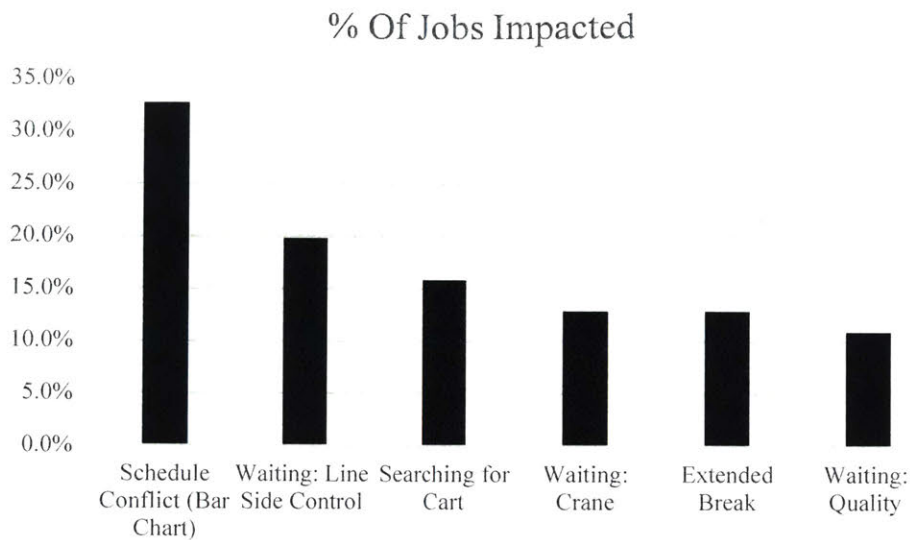


Figure 14: Percentage of Jobs Impacted by Delay

We can further down-select by eliminating schedule conflicts. Schedule conflicts arise because of all the other delays that accumulate during the day. Looking at the resolution times of the line side control would also be worthwhile, as resolution times are 40 hours. Resolution time for the line side control center is the time to close the issue ticket once it is submitted. It can be closed when the issue has been solved. In the case when resolution times are long, mechanics will move on to different work and not wait until the issue ticket has been closed. Looking further into line side control over 50% of the issue tickets for this area were for some aspect of material delivery. Searching for cart became the next choice to dive deeper into. In resolving the problem for searching for cart, though, significant improvements could also be found in the non-value-added activities of getting and returning tools, and in decreasing the number of line side control center issue tickets. Figure 15 shows the base level of improvement expected if focused on the material delivery system. These numbers were calculated from the original time study shown in section 2.6.

Activity	Time per Job
Get Materials	5.2%
Return Materials	4.6%
Searching	1.5%
Total	11.3%

Figure 15: Activities related to Material Delivery

2.12 SUMMARY OF RESULTS OF PHASE I

In conclusion, I can reflect on whether the goals of this phase were met.

Phase 1 Goals:

1. To answer the question, did the implementation of the FFV result in faster, cheaper, better quality product as evidenced by the continuous reduction of hours and elimination of waste in the process?

Yes. Overall the implementation of the FFV did result in continuous improvement in hours; however it is not known if that is from the continuous reduction in waste. The time study revealed that there were system issues of waste that could be targeted for waste reduction. In the follow-up study of looking for a continuous reduction in hours during the same period as the time study, there was evidence of a shift in hours after a single system change to the bar chart. This analysis suggests that targeting system issues will result in greater shifts to line.

2. Collect data in a sufficiently detailed manner to test the lean transformation, but also provide data for future studies.
3. Hypothesize future areas of improvement and provide the baseline level of improvement to be gained.

For goals 2 and 3, I was able to categorize sources of waste and non-valued added activity and recognize that material delivery is a source of opportunity for improvement.

3 PHASE 2: THE MATERIAL DELIVERY SYSTEM

In achieving the lean system with zero waste, I first needed to identify what were the areas of waste. The previous section highlighted that material delivery system resulted in periods where mechanics were searching for material beyond routine collection of necessary items. It also showed that getting and returning materials was still a large contributor to non-valued added activity. This section will first describe the ideal state of how the material delivery system should work in Factory A. It will then dive deeper into the problem of searching, validate these root causes, and provide mitigations to the problems.

3.1 THE IDEAL MATERIAL DELIVERY SYSTEM

Lean principles would suggest material should be delivered to the mechanic at the right place, right time, and in the right quantity. Limitations in the layout and capacity of Factory A cause some deviations to this mandate, but the spirit of the system is meant to be the same. Factory A's system was originally designed to meet this-criteria.

“Deliver tools, standards, and parts by a 2-hour SOI on one kit cart”

Excluded from this system were the primary structure, consumables and specialty tools which required separate plans for delivery. The primary structure was delivered by crane. To limit waste of raw material, consumables were placed in point of use (POU) stations near tools and used a Kanban system to be re-stocked. Specialty tools required an added level of control and were locked in cages near the build area. All other parts and tools were included in this system. Section 3.1.1. details the definitions of materials, and section 3.1.2 details a high level process description of the material delivery system.

3.1.1 Materials Required to do a SOI

For clarity, below are definitions of the types of materials required to complete a job.

Primary Structure: As mentioned before the primary structure is the large structural elements of the place such as an entire wing. These materials require use of the crane system in Factory A. For the purposes of this study this flow of material is handled separately from the rest of the material required to do a job.

Bulk Parts: These are parts of the airplane that are small enough to be pushed by large carts or forklifts but do not require a crane. This part could be something as large as a typical closet or the flaps on the wings. They require carts that are specially made for the dimension of the part.

Small Parts: Specialty parts of the plane that would not be considered standard, but still fit on a standard size cart, which has 21" X 21" surface area.

Standards: Common end item parts, such as nuts, bolts, and screws. They come in kitted SOI specific boxes, where the number of required bolts for sub-operations are slotted in bins within the box.

Dry Consumables: Items that are used in the process of assembling the plane but are not parts for the plane. These are small, disposable or recyclable items. Examples include gauze for cleaning, paint-brushes, gloves, etc. These items are delivered to point of use stations near the main tooling for an assembly build.

Wet Consumables: Sealant, primers, and cleaning chemicals. Depending on temperature requirements these materials are stored in refrigerators or special cabinets near the other dry consumable point of use stations.

Tool-bags: Kitted bags with tools shadow-boxed inside. The shadow box is a visual indication to mechanics of when tools are missing.

Specialty tools: Some tools require a tighter level of control and are expensive to reproduce, so they are kept in special cages. Cages are locked by the team leads and 1st line manager of the mechanics.

3.1.2 Factory A's Material Delivery System

The center of Factory A's operations occurred at the Material Integration Centers (MIC) located throughout the factory. One center was responsible for the integration of parts and tools to Position 0 and four other build teams. The day of the build, Manufactured Parts Request Facilitators (MPRF) receive parts from an external supplier warehouse into the factory, by scanning bar codes and changing the location of the material in an external database system. They place the received parts on shelving for retrieval during the integration step. From there, orders for the two hours block are printed and include two documents. The first is a license plate detailing the "shopping list" of material needed for the job,

and the location where the parts and tools need to be delivered. The second document is an accountability wheel which requires a signature for either the MPRF or mechanic at each location the cart is moved to. These two documents are arranged in an easy to pull filing system before starting the integration step.

After the set of orders are printed, one or two MPRF's begin to integrate each order. The MPRF picks up the two pieces of paper and attaches the license plate and accountability wheel to the cart. The MPRF then picks up a topper, with color coded shift and time block and attaches to the cart. Tool bags are arranged in aisles and the MPRF takes a cart and retrieves the tool bag. Following a u-shaped path, the MPRF then retrieves any small parts and standards that fit on the cart. The MPRF scans the tool-bags and the standards box to update an external database that each item had been picked. The MPRF signs the first box of the accountability wheel and switches the flag on the cart to "Stage for Delivery" as a signal that the integration step was complete. The MPRF then places the cart in a swim-lane dedicated to one of the five places for delivery and retrieves an empty cart to start the process over again.

After all orders were completed, a quality inspection was performed by a different MPRF who did not integrate the carts; therefore at least two MPRF's were required for any integration cycle. If a part or tool is found missing, the MPRF retrieves the required material. The MPRF scans all carts license plates to update the computer system's location of the material to the final delivery destination. When all parts were checked and scanned, the flags are changed to Ready to Work.

A third MPRF then attaches a maximum of 10 carts to a mechanical tug to start the delivery route. The MPRF goes to each location and drops off the required materials in the corresponding swim-lane. Another version is the materials are attached to an Automated Guide Vehicle (AGV), and an MPRF follows the materials to detach into each swim-lane. Along the route any completed work carts are retrieved. The MPRF repeats these steps until all materials for the next two-hour window of work is completed.

In the ideal factory mechanics would have finished the prior two-hour package of work as the MPRF's deliver the next two hours. The MPRF retrieves used carts and brings the carts back to the MIC. Tools bags are scanned to update the location of the tool-bag and placed back on the shelf. Empty standard bins are placed in an empty rack that was delivered back to the external supplier warehouse every day.

The entire process is repeated every two-hours for twenty-four hours. Figure 16 shows a high-level view of this material delivery process.

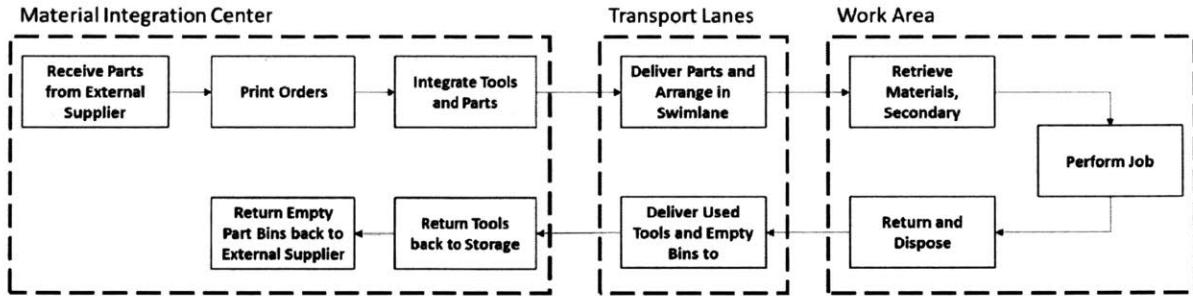


Figure 16: Factory A Material Delivery Process

3.2 THE PROBLEM

As phase 1 of the project revealed, the mechanics incurred several instances where they would have to search for the cart that was being delivered. This searching for a cart accounted for 1.5% of the average time spent performing a job and impacted 15.8% of the jobs being performed. The problem resolution time for any instance was seven minutes. Resolution occurred when the mechanic was able to find the required material and begin the next step of the standard job.

3.3 ROOT-CAUSE ANALYSIS

During the original observation of the mechanics, there appeared to be several causes for the condition of searching for a cart. A few observations revealed the cart was delivered to the wrong location. Another observation resulted in the mechanic checking the computer log to see if or when the cart had been “delivered”, but only to find that it was on route. In another instance, the cart had not been integrated yet and the mechanic had to go to the MIC to get it. Another still, the cart had been delivered to the proper location at the schedule time, but the confusion and disorganization of the carts in the swimlane made it hard to identify. All these instances were collated into a fault tree, shown in Figure 17. The root causes for each of the conditions terminated with (1) final destinations were not assigned to the carts and the MPRF incorrectly chose swim lanes along the route, (2) the delivery of the carts did not match the actual consumption of materials by the mechanics leading to back-up of materials and (3) there was a lack of capacity in the MIC to delivery carts on time.

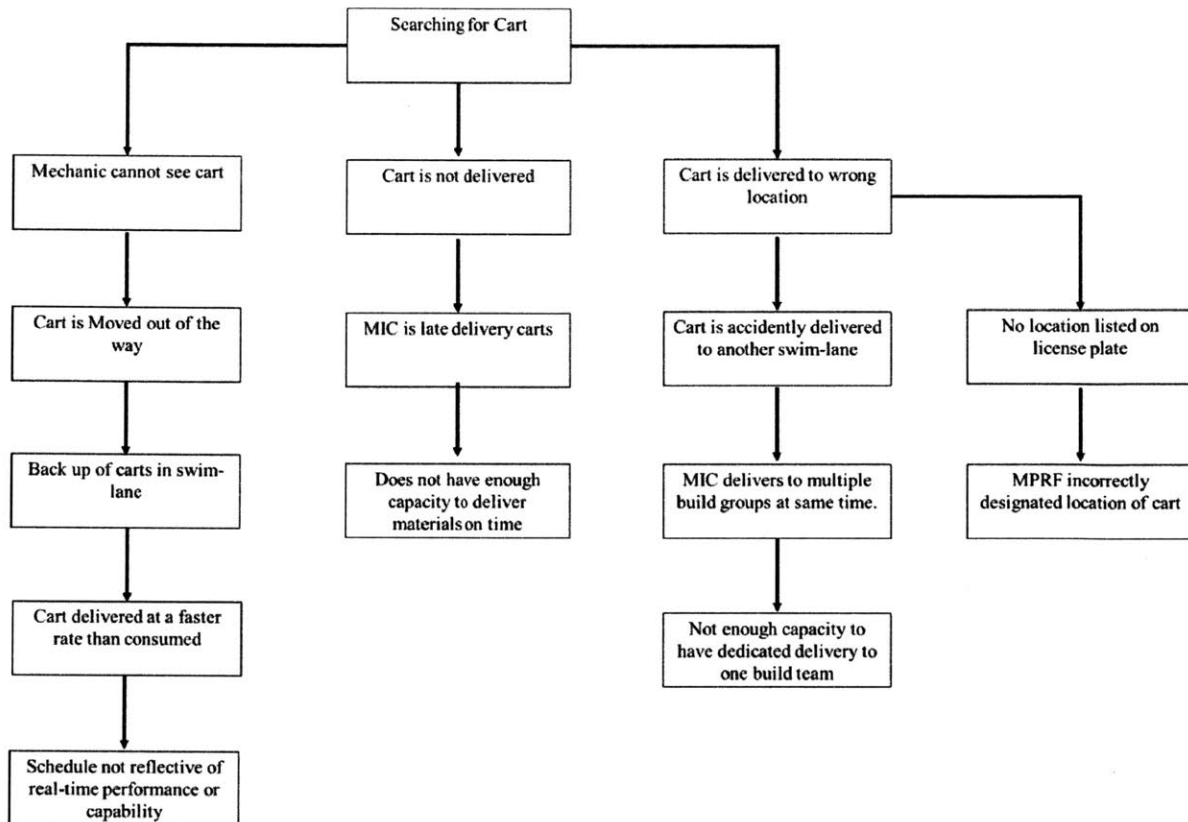


Figure 17: Searching for Carts Fault Tree

3.4 VALIDATION OF LOCATION AS A ROOT CAUSE

The most direct reason why mechanics were searching for carts is the carts were delivered to the wrong location. To confirm this source of error in the system, I performed an audit of the location tags see if carts were properly marked. This was followed by observations of the MPRF's as they delivered carts to the area.

3.4.1 Result

In the first audit of the area, thirteen out of 61 carts were either missing a location identifier on the license plate or had the wrong location listed for where the work was performed. A second audit of a different build area was performed and eleven out of 22 carts were missing a location identifier. Without the proper identifier it would seem like there would be an even higher rate of carts being delivered to the wrong location. A follow-up study of the MPRF's showed that even though a cart could have the wrong label, the job number had enough clarifying information that the MPRF could often deduce where the cart should be or narrow down the options to one or two places. In the case of where the location of the cart

could not be deduced to one single delivery location, the MPRF would deliver the cart alongside the nearest cart neighbor.

A second error mode was discovered during the observation. Even when the location was properly marked, a cart intended for delivery to *swim-lane 1* would end up in delivery *swim-lane 2*. In the description of the ideal process, the MIC delivers to 5 possible locations every two hours. The carts are arranged in corresponding swim lanes to these possible locations back at the MIC, but during delivery they potentially are merged with other swim-lanes to maximize the use of the mechanical tug. For example, if two carts were in *swim lane 1* and five carts were in *swim lane 2*, and three were in *swim lane 3* all would be combined for one delivery. At each delivery location, a mistake can occur when three carts were delivered to the corresponding *swim lane 1* because a cart from *swim lane 2* was accidentally grabbed with the material. Furthermore, the true location of the material would not be captured in the external database because scanning of where the material will be delivered occurs back at the MIC not at the final location.

3.4.2 Possible Mitigations

The correction for an un-labeled cart was simple. There was an existing process at which to update locations for carts. The manufacturing engineer dedicated to the area was able to assign and update all locations in the database at which the data is pulled to generate the license plates of each cart. This is an example of the quick fixes that can immediately result in improvements in the system.

For the second error mode, a simple fix is not immediately obvious. A method to catch the error was in works. A pilot to equip each cart with an RFID tag was in process. This would eliminate the need for the MPRF to scan the location of where the cart would be going. The RFID tag would be able to pinpoint exactly where in the factory the cart is and update the location database real time. This corrects the problem of finding a cart once an error is made but does not eliminate the error itself. The error occurs when combining multiple swim-lanes into a single delivery to maximize the number of carts per delivery cycle. One way to eliminate the error is to only deliver to one swim-lane at a time. Capacity issues with the number of tugs and MPRFS need to be considered to break up delivery to only a single swim-lane .

3.5 VALIDATION OF SCHEDULING ISSUES

Another source of searching for carts was a result of carts backing up. This created a crowded visual field in which it was difficult to see the required cart. This collection of carts would become an obstacle in routine operations and carts would be moved to whatever available space was around, causing confusion. To understand this problem, I created a build-up diagram of the delivered carts against the average time for a SOI and the amount of space available to accommodate the carts.

3.5.1 Result

I created the build-up diagram using available information of the system. The arrival rate of carts is known, as the carts are delivered on a pre-determined schedule. The rate of use is the average time it takes for a mechanic to complete a SOI, which was calculated from the total hourly data. From the observation of the mechanics, I also know that they do not return carts immediately, but rather turn in all tools at the end of the shift. Knowing the input and output of carts in the area, I could calculate how many carts were in the area at any given time. Using the standard dimensions for a cart, I was able to calculate the square footage the carts took up. The space available was calculated as the area around the main tool in which that portion of a build was occurring. The space available changes because for this build position's build process the primary structure must be moved several times to new tools, with varying space constraints. The resulting build-up diagram is shown in Figure 18.

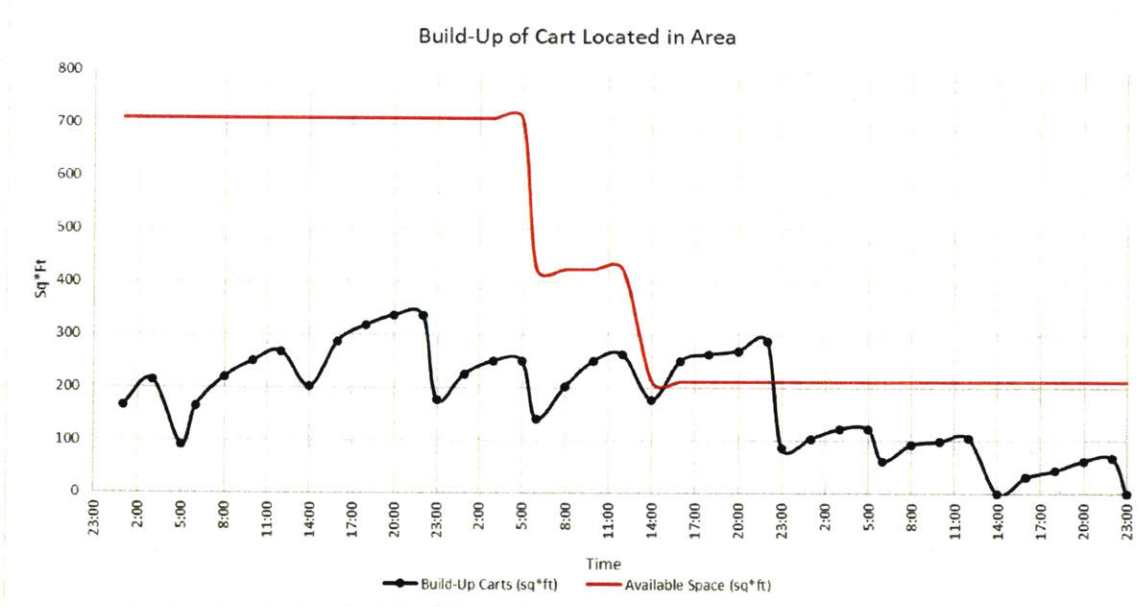


Figure 18: Build-up Diagram of Cart in Position 0 Area

This is a hypothetical outcome based on current average rate of job completion and the standard schedule for delivery. What this figure shows is that on second shift of day 2 of the build, the build-up of carts exceeds the space available, even in an average case. This result matches observations during the time study, where on Day 2, shift 2, time is spent moving carts out of the way to accommodate lifts that are required to complete the build of the job. There is variation to the completion of jobs, so some cycles do not result in this back-up and in other build cycles the back-up of carts is worse. This is still an important result because the original mitigation was to add additional space for carts at the beginning of the 3-day cycle. However, for the first-half of the build cycle there is enough space already to accommodate the carts. More space is required for the latter-half of the build.

3.5.2 Possible Mitigations

Without moving the large tooling to an optimized pattern, no more space can be given for the carts. This is an option and when evaluating the new layout, special consideration should be taken for the need of space in the second-half of the build. However, this change requires at least a year before it can be implemented.

A seemingly obvious short-term solution would be that mechanics return carts as soon as they are finished with a job. This model does not capture the complexity of why the mechanic will choose not to do this. Many of the jobs require being inside a tight position, where ingress and egress is difficult. Because of this mechanics will combine the getting and returning of materials for a few consecutive jobs to minimize the number of times in and out the space. The minimization of time spent searching would need to be weighed against the time saved by not going in and out of the airplane to retrieve and return materials. As the results shown earlier in Figure 15 section 2.11, the time spent on getting and returning materials is 6.5X greater than the time spent searching for carts. The number for getting and returning material would be expected to increase if mechanics returned the tools as soon as every job was finished.

Another short-term solution would involve decreasing the amount of space the carts take-up. This change would require an amendment to the one SOI per cart mandate. The entire work-package for the 2nd shift can be combined to single large shift “cage”. This solution had been implemented before but was changed when the implementation of the lean transformation requiring all SOI’s be on one cart each. This result provides evidence of the effect of systemic clashes in the requirements, that result in waste creation. In the attempt to implement the solution, I came across how binding the original design criteria were on the development of new solutions. This is why in phase 3 of this thesis I develop new design criteria to make explicit all the requirements that have driven design of the lean transformation and generalize these requirements to lean principles such that a broader scope of solutions can be considered.

3.6 VALIDATION OF CAPACITY ISSUES

Paradoxically, while section 3.5 showed the problems of carts being delivered too quickly, there were also occurrences where carts were not delivered fast enough. To dive into why carts are delivered late, I created a process map and measured the time for each step in the process to identify the bottlenecks in the system. First, I needed to perform a similar time study of the mechanics with the MPRF’s. From there I was able to estimate the time it took for integration and delivery activities and identify any bottleneck and capacity issues that might result from demand for delivery.

3.6.1 Result

The results of the time study revealed the bottleneck of the process was the integration step. Also, like the observation with the mechanics there were delays associated with each step, which prolonged the completion of any step. However, most of the delays for the integration step was missing tool-bags that were still located in the mechanics' area because they were not completed or not returned in the previous three-day cycle. This illustrates the additive effect of waste, where one delay ripples down the value chain. Figure 19 shows the results of the time study. Green represents the value-added activity from the perspective of the end customer of the material delivery process. In this process, the customer is the mechanic; therefore, the valued-added activities are integrating materials together and delivering to the mechanics. Represented by the yellow block, the quality check step is a non-value-added activity because it only serves to catch mistakes made at the integration step. The red boxes represent delays in completing the previous step. From this time study, the integration of tools and small parts onto carts and the quality check are the bottleneck of the process.

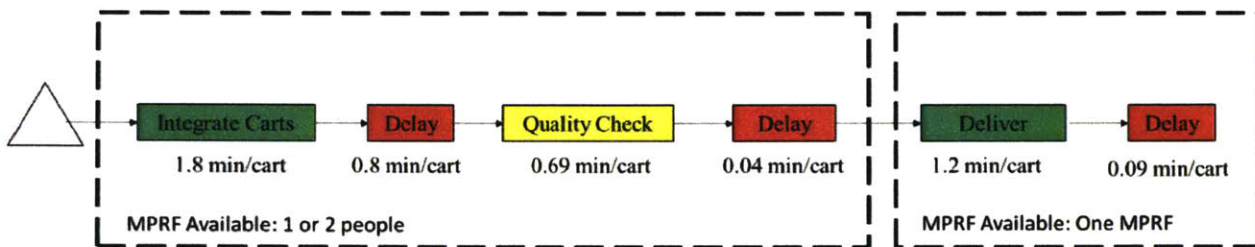


Figure 19: Material Integration and Delivery of Carts

Using this information, I was able to calculate the available capacity at each delivery period and identify any capacity misses of a period. The maximum throughput was calculated from the sum of the average times it takes to integrate carts and perform a quality check, as well as the average delay at each of those steps and how many MPRF's were available per shift. For example, one MPRF could hand-off one cart to be delivered every 3.33 minutes. I assumed that 90 minutes prior to when carts need to be delivered, the integration process started for all the carts. This allowed for 15 minutes of break and 15 minutes of breaking down of returned carts. Two MPRF's are available during first shift, so capacity is highest during first shift which is reflected in the peaks of available capacity in Figure 20. Demand is the number of jobs scheduled to be started within a two-hour period following a scheduled delivery. What becomes immediately obvious is there is not enough capacity to deliver on time in multiple cases for the average time case. Primarily this gap exists at the transition between third shift and 1st shift.

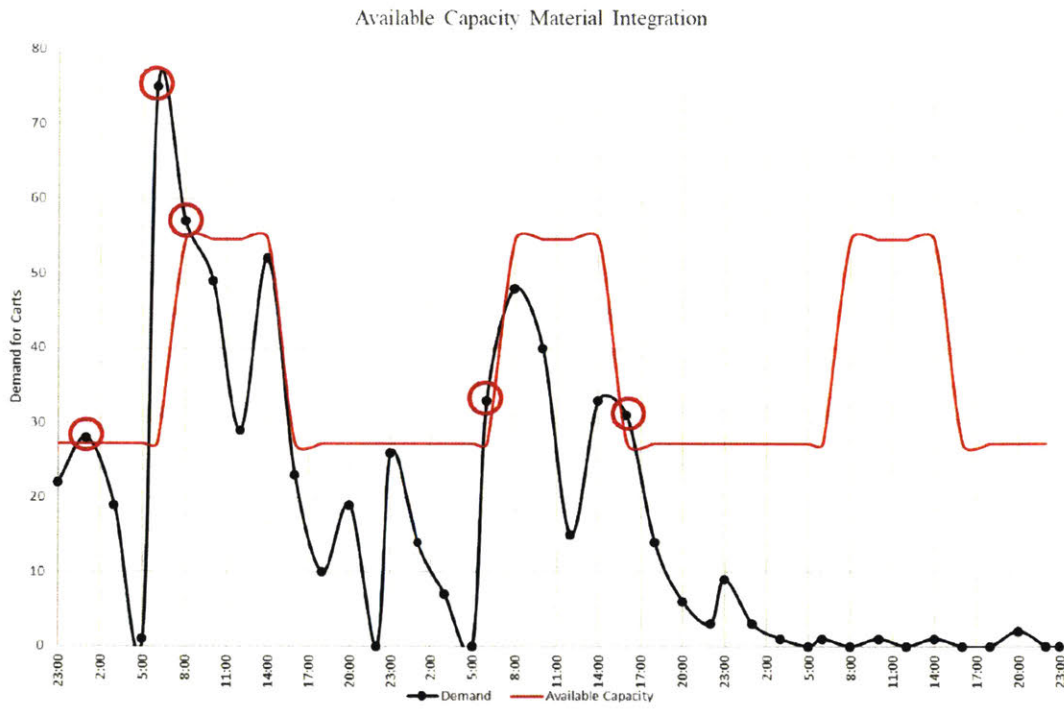


Figure 20: Available Capacity for Material Integration

3.6.2 Possible Mitigations

An obvious first step would be to eliminate the waste in the integration process. This would mean that it takes only 1.8 minutes to integrate the cart. A perfect system would not need a quality check for the cart. However, with the elimination of all waste and the quality check, capacity would still be an issue for at least one instance of delivery. This ideal system is shown in an updated capacity chart of material integration step in Figure 21. There is still a lack of available capacity for the integration step on the day 1 first shift. Either more people need to be hired to address the lack of capacity at this time, or demand needs to be leveled out.

Available Capacity Material Integration

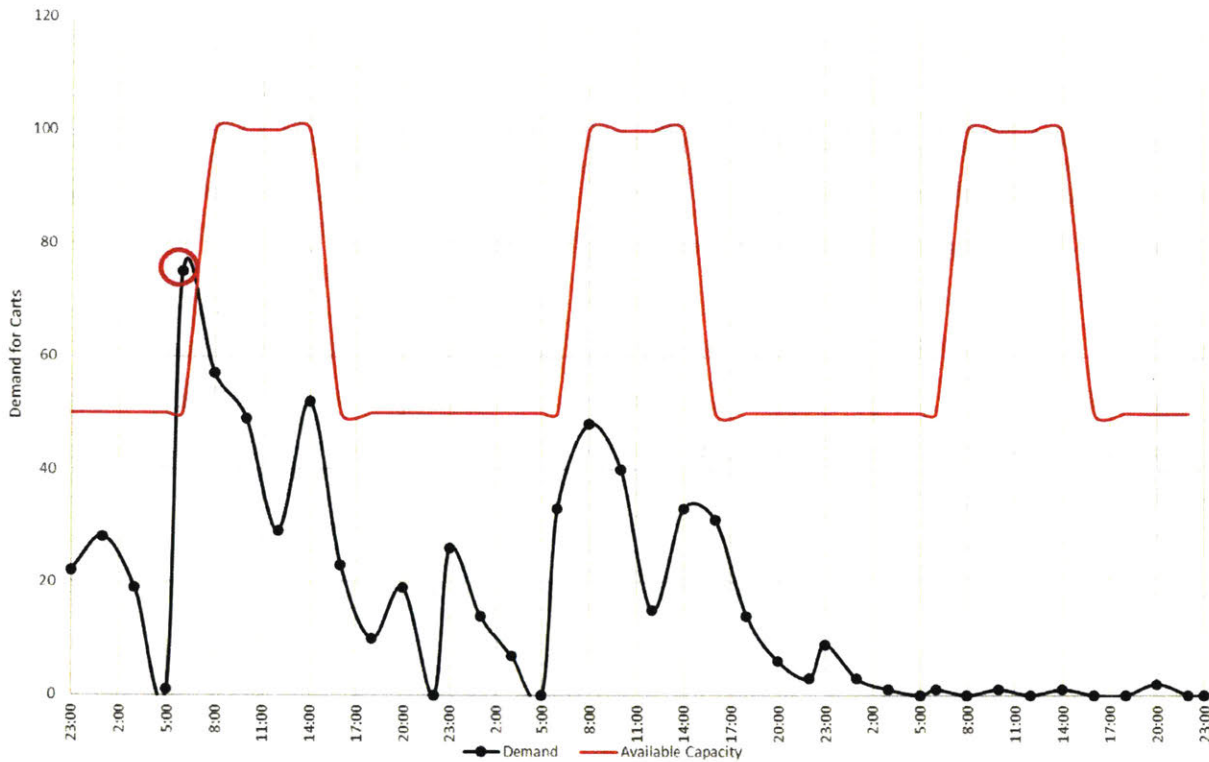


Figure 21: Available Capacity for Material Integration with Delays

The factory could increase capacity by hiring additional MPRF's to perform these jobs, however there is already competing demand for new MPRF's in different areas and this area does not demonstrate the greatest need of the factory. Another solution would be to level out the load by changing the schedule of when carts are needed. However, applying lean principles, the demand is driven by the downstream customer which in this case is the mechanic.

Finally, a fourth solution would be to eliminate some of the demand. It was observed during the time studies that several of the integrated carts do not have parts associated with them. Therefore, the integration is really retrieving and delivering tool bags back and forth and no other integrated materials. An alternate solution would be to leave tool bags at the final work station. Like the mitigation suggested in section 3.5, to apply this solution would directly conflict with the design requirement of one cart per SOI. The original design requirement was a tactical approach to applying lean principles to the system, but it is not a lean principle itself. For this solution to be even considered the underlying design requirements need to be changed.

3.7 SUMMARY

In the investigation of root causes of searching for carts, this section shows systemic problems in the current design of the material integration center that result in capacity issues (time and physical space). However, in attempting to implement mitigations for these types of problems a different problem is discovered. The design requirements are written as such that a constraint is created that eliminates solution options. Specifically, the one cart per one SOI eliminates different types of solutions that may be optimal for the area in the elimination of waste and continued improvement.

The goal of the FFV is not to follow the original design tactics as explicitly written but incorporate lean principles into the assembly process to enable continuous improvement and the elimination of waste. Practically, design requirements are needed to bound solutions. Therefore, the problem remains how to translate lean principles into design requirements that can be implemented in the aircraft assembly process.

4 PHASE 4: DESIGNING MATERIAL DELIVERY TO LEAN PRINCIPLES

The previous section described the root causes for a source of waste, searching for carts. In doing so, I was able to brainstorm possible mitigations to eliminate this type of waste. While pursuing these mitigations, a barrier to eliminating the waste was revealed. The design requirements as written constrained feasible solutions to the problems.

The new problem is how to write lean principles into measurable design requirements that allow viable solutions to be considered

There was also an opportunity to improve the broader system. The larger goal of the lean transformation is to eliminate waste but also minimize the non-value-added time performed by the mechanic. As phase 1 was able to measure, in addition to waste, there is still 28% of non-value-added time per job that is built in to the process. A third of the 28% is gathering and returning materials, which is a step impacted by the design of the material delivery system. The overall target of the lean transformation is to reduce all non-value-added time to 15% per job. Changes to the material delivery system is one lever in which to meet this goal.

The original requirements for the first system was a tactical approach to incorporating the lean principles of just-in-time delivery. There was only one design requirement.

“Deliver tools, standards, and parts by a 2-hour SOI on one kit cart”

In evaluating the current system against this requirement, there are no changes that are required, because it fully meets the requirement. However, future iterations of this system may require violations of this original design requirement to reach the goals of zero waste and minimized non-value-added time. Erin Golden explored changing the design requirements to a more generalized requirement in her LGO thesis, “Determining the Optimal Set of Solutions for Storage and Conveyance of Tools in a Highly Variable Manufacturing Environment.” She identified two goals of the material delivery system from the perspective of the mechanics to be

1. Minimize tool inventory and floor space footprint
2. Maximize mechanic productivity by reducing non-value added time[4, p. 47]

The following section expands on her work and adds to the requirements of the system. These requirements were developed to embody lean principles but also make explicit other requirements of the

system defined by other stakeholders. A human-centered design methodology is used to draw out these requirements. Once requirements are made then the system can be evaluated as an entire system within a broader context because all the stakeholder requirements are built into the evaluation. Also, trade-offs or complements between different solutions sets can be seen. This is shown in the final analysis using a Pugh matrix to evaluate new ideas against the defined requirements.

4.1 METHOD: HUMAN-CENTERED DESIGN

A new trend in design methodology is the use of “design thinking”, user-centric design, or human-centered design. The company IDEO is credited with formalizing and commercializing a design process that aims to keep the end-user at the center of every step. While it has distinct phases, it is a flexible approach to design that draws upon several tactics to inspire more holistic designs that embrace the complexity that is present in most design cases. This method attempts to capture that complexity with the use of empathetic design and rapid iterations and feedback loops to co-create optimal solutions for the people being impacted.

The process involves three phases as follows,

1. Hear: Process of identifying a design challenge, choosing an immersive research method and developing insight to the problem
2. Create: Process of using the insight gained in the first step and translating to into stories, patterns, opportunity areas, and ultimately solutions to iterate on.
3. Deliver: Evaluation of the proposed solutions and plan for the implementation of a new solution.

The result of this process is to take you to the intersections of the three lenses, of desirability, feasibility, and viability, shown below in Figure 22.

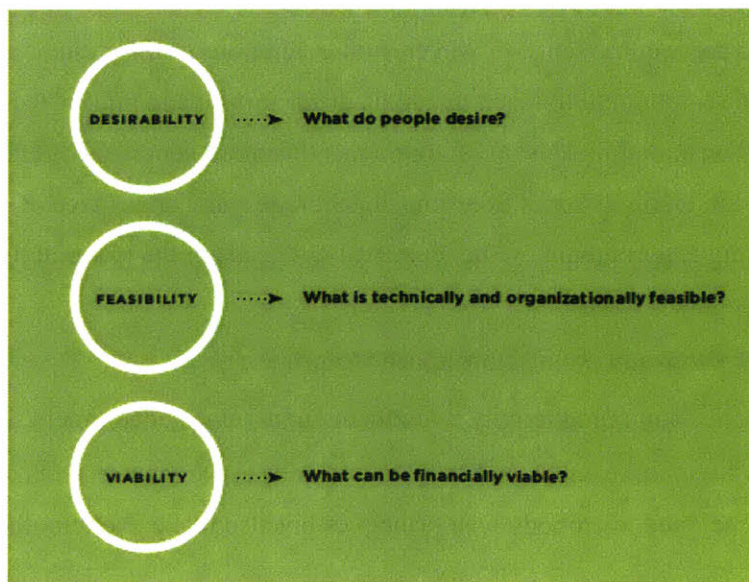


Figure 22: Three Lens of Human-Centered Design[5]

The most unique aspect of IDEO's method is the hear phase. The hear phase requires an immersive approach to interviewing and gathering data about the problem. Immersion means the designer embeds himself or herself in the context at which the design solution will be implemented and see's the problem through the eyes of the end-user. In many ways this also embodies Toyota's principle of *genchi genbutsu* or go and see for yourself to understand the problem. The underlying assumption of both is that important knowledge is conveyed in the experience that is not captured by looking at data removed from the situation.

The rest of the section captures the information using the techniques of human-centered design hear and create steps. The time-studies of both the mechanics and the MPRF's were the same immersive techniques that designers using this method would pursue, with the limitation that I could not perform the work due to union rules. I did follow every and all steps in their respective processes. These time studies also allowed me time to interview the mechanics and MPRF's in the context of where the work is being done and co-imagine new solutions at the very time a problem arose. This was crucial in developing the brainstormed list of new changes to the system. An informal interview approach was also applied to other stakeholders in the system, to gain data on what other implicit requirements were driving the design of the current system and make these explicit in the design requirements.

The results of the interview approaches are framed in two separate analyses, stakeholder analysis and an operation three-lens analysis to draw out the additional requirements of the system. These are then translated into a formal set of design requirements. The current method of delivery materials is evaluated against these design requirements to establish the baseline for comparison with new ideas. Finally, an unweighted Pugh matrix is used to evaluate different ideas for changing the system.

4.2 STAKEHOLDER ANALYSIS

A stakeholder analysis was performed to identify the necessary people impacted and shaping the current material delivery system. The stakeholder analysis was used to identify who will most be impacted and has most influence in the design, in addition to what each stakeholder values in the material delivery system. The stakeholder typology used was to determine the power, legitimacy, and urgency over the system[6]. This is important in assigning relative value of the stakeholder on the material delivery system.

Powerful stakeholders possess a strong ability to impose their will on the system. In the case of the material delivery system, the director of aircraft assembly plant can mandate changes in the system. The mechanics who interact with the system also hold a degree of power as they can utilize work arounds

to a new system put in place. Work arounds develop when inefficient processes are implemented, and mechanics are driven to find faster ad hoc solutions. Production control managers and the associated leadership chain have the explicit responsibility for material management in the factory and so set the process for the system. Senior operations management of the factory also has a powerful position as they are often the communication chain between the director and the mechanics on the floor.

Legitimate stakeholders are those with expressed knowledge or experience of the current state and solutions going forward. The mechanics and 1st line managers are legitimate because they have intimate knowledge of the problems that exist and how a solution is used. Manufacturing and Industrial engineering support groups also have a legitimate claim as they define the contents of the materials and high-level schedule of activities, respectively. There is an internal consultancy group named operational excellence that is responsible for bringing best practices from across the wider enterprise and have expertise in working with multiple programs. Executive leadership, such as directors, of both the factory and production controls have legitimate claims as they have the high-level understanding of the overall business strategy and how a certain process will fit into it.

Urgency occurs when the success or failure of the change is impactful or time-critical in nature. In this case, mechanics, 1st line managers, and senior management of the factory all have urgent claims because ultimately all are responsible for keeping to a production schedule.

Table 5 summarizes the saliency of each of the identified stakeholders. Also included in this table are results from interviews with all the stakeholders to identify goals of the system.

Stakeholder	Power	Legitimacy	Urgency	Does not have...Power, Legitimacy, Urgency	Primary Goals of the Stakeholder
Mechanics	Yes	Yes	Yes		Wants materials to be delivered at the right place, right time, and right quality
Director	Yes	Yes	No	The director has urgency at the total hours level but not at the SOI level	Wants to reduce regular hours and rework hours in the build process and for problems to be visible immediately
Senior Operations Manager	Yes	No	Yes	Senior Operations Manager might not have direct knowledge at the material integration at a single SOI level but have knowledge on the overall work-package.	Wants to maximize time mechanic spends on value added activity
1st Line Operations Manager	No	Yes	Yes	Knows details of material integration at a SOI level, but does not set high level directives	Wants accountability for tools and parts so as not to have to spend additional time tracking parts around the factory
Production Control Manager	Yes	Yes	No	Time to finish a job is not directly tied to success of their job	Wants visibility to the consumption of materials, to aggregate this data and use for inventory management and reduction.
Material Integrators	No	Yes	No	Time to finish a job is not directly tied to success of their job, and take directive from management chain	Wants to be able to deliver materials to the right place, right time, and the right quality
Industrial Engineers	No	Yes	No		Wants to optimize the time mechanic spends on value added activity
Manufacturing Engineers	No	Yes	No		Wants a process that will enable the highest quality of product
Operations Excellence	No	Yes	No		Wants lean principles to be applied in the factory

Table 5: Stakeholder Analysis

As shown in Table 5 many of the goals do align with original lean principles. Conversations with a high level executive reveal part of the intent of the one kit per one SOI mandate is to create a visual representation of the flow and status of jobs in the position. However, a visual representation can be created virtually. Another LGO thesis by David Amiot, explores the virtual moving line concept in his thesis entitled, “Improving Parts Delivery through Data Aggregation, Analysis, and Consumption” in the creation of a dashboard for material integrators to use to identify upcoming orders[7]. Regardless, this type of goal can be included in the design requirements if it is a desired result of the system.

4.3 MATERIAL DELIVERY DESIGN REQUIREMENTS TO LEAN PRINCIPLES

The following design requirements were developed to align with the lean principles that the original FFV is trying to implement. In addition, the goals of stakeholders as revealed in the stakeholder analysis are added. In explicitly defining design requirements for a system, trade studies and conflicts in requirements can be identified. Without this, the different groups can be left to interpret what is most desirable of the system and conflicts can arise. I defined these requirements after interviews with all stakeholders. To validate the requirements, I conducted follow-up interviews to edit and clarify the requirements.

Functional:

1. ***Be safe and ergonomic:*** As the foundation for any lean initiative, safety and people well-being is a top priority.
2. ***Deliver materials to the nearest possible position of where work is performed:*** This requirement specifically seeks to minimize the mechanics non-value-added time associated with the integration and retrieval of materials.
3. ***Deliver the right parts to the right place at the right time with the right identifying labels.*** This requirement directly addresses the issues associated with reliability of the system.

Operational:

4. ***Have method of data collection as to the rate of consumption of materials:*** This is to enable inventory management at an enterprise level.
5. ***Measure and deliver feedback and have control mechanism to resolve issues:*** Feedback is what will enable the continuous improvement loop. This also gets to the requirement of making problems visible, which is the intention of lean when it established flow to a process.

Constraints:

6. *Minimize costs associated with labor, performance, square footage, and maintenance of the system:* From a high-level view of the firm, the function of internal material logistics is necessary; however, it is a cost center.
7. *Design cannot exceed space available in designated work areas.* The current design exceeds available space and this factor has not been an explicit consideration in the past design.

4.4 BASELINE OF CURRENT METHOD

The learnings from the first two phases provide a baseline measure for the new requirements that are defined. A simplified cost model is also developed to weigh the relative costs of the current system. This has not been described in detail yet, and so is described in section 4.4.1.

4.4.1 Cost Model of Current Material Delivery System.

I developed a cost model of the current material delivery system, with data collected from the first two phases. The current costs for the job can be broken down into direct costs per SOI which are incurred for every job, and opportunity costs that, when certain thresh-holds are met, can be eliminated. For example, inventory costs are an opportunity cost but can only be actualized when enough time savings has accumulated that an entire day can be removed from the schedule. Actual cost data cannot be revealed, so numbers are normalized to show the relative costs of each type of cost in the system.

Direct Costs per SOI:

- **Direct Labor:** Non-value-added time at direct labor rate spent by mechanic performing a secondary integration of material step and retrieval from ground to airplane.

$$(\text{Average Time Per Job}) * (\text{Labor Rate}) = \$10.00/\text{SOI}$$

- **Direct Support Labor:** Dedicated system support at support labor rate averaged over time.

$$\begin{aligned} & (1/\text{Average \# Jobs Per Mechanic}) * (\text{Support/Mechanic Ratio}) * (\text{Available Support Hours}) \\ & * (\text{Labor Rate}) = \$1.43/\text{SOI} \end{aligned}$$

- **Cost of error:** The current system results in errors which requires mechanics to go through a mitigation loop to complete the job. This is the percentage of jobs expected to have an error and estimated time for mitigation at the direct labor rate

$$(1-\text{Reliability}) * (\text{Average Resolution Time}) * (\text{Labor Rate}) = \$1.04/\text{SOI}$$

Opportunity Costs:

- **Floor space:** The current system requires dedicated floor space to function. This is an amount of time a single job spends on the floor.

$$(\text{Average Cart Area}) * (\text{Average Number of Carts on the Floor}) * (\text{Opportunity Cost of Floor Space}) = \$0.25/\text{SOI}$$

$$(\text{Average Number of Carts on the Floor}) = (\text{Jobs Behind Schedule}) * (\text{Average Waiting Time})$$

- **Inventory costs:** Inventory costs can only be realized when enough time savings has accumulated to eliminate an entire day worth of inventory. The inventory costs in the supply chain accrue by day not by hour.

$$\$13.08/\text{SOI}$$

In the development of this model, it is interesting to note that the cost of floor space is relatively small in comparison with all other costs. This was not the assumption prior to making this model. This means in the design minimizing floor space does not have to be a dominant design consideration over other possible trades. A design still needs to be within the floor space constraint so that material does not build up in the area.

4.4.2 Summary of the Baseline Evaluation

Results from previously described analyses are used to evaluate the current system against these new requirements. The data from the time studies of both the mechanics and the material handlers are the base data to calculate the baseline for the requirement. This evaluation is summarized in Table 6.

Design Requirements	
Functional Requirements	
1. <i>Be safe and ergonomic</i>	All material kits are designed to be less than 35 lbs and tugs are available to minimize pull effort by the MPRF.
2. <i>Deliver materials to the nearest possible position of where work is performed</i>	Currently carts are delivered at the base of the staircase on large build tooling. Mechanics are required to leave the build tool to retrieve tools. Current time is 9.8% of time/SOI
3. <i>Deliver the right parts to the right place at the right time with the right identifying labels</i>	Current method results in 1.5% of time/SOI spent on searching for carts
Operational Requirements	
4. <i>Have method of data collection as to the rate of consumption of materials</i>	Rate of consumption can be estimated from averaged time data per SOI for a total work package and is currently 2.7 hrs/SOI. Data is not accurate enough for inventory management
5. <i>Measure and deliver feedback and have control mechanism to resolve issues (Make Problems Visible)</i>	The current method requires an issue ticket to be submitted to the Line Side Control Center. The current resolution time for an issue ticket is an average of 40 hours.
Constraints:	
6. <i>Minimize costs associated with labor, performance, square footage, and maintenance of the system</i>	<p>Direct Cost: Direct Labor: \$10.00/SOI Support Labor: \$1.43/SOI Error Penalty: \$1.04/SOI</p> <p>Opportunity Costs: Floor Space: \$0.25/SOI Inventory Costs: \$13.08/SOI</p>
7. <i>Design cannot exceed space available in designated work areas</i>	Space available is time and position dependent. The minimum space available for this area is 212 sq.ft

Table 6: Baseline Evaluation of Material Delivery System

Table 6 is meant to be a tool in which to evaluate new solutions against the current state. This is critical to understanding the benefit or cost that a new solution would bring to the current state.

4.5 BRAINSTORM OF NEW SOLUTIONS

The development of the detailed design requirements is in part to aid in the evaluation of multiple initiatives targeted at improving the overall material delivery system. In working to improve the system, it was discovered that multiple groups and side initiatives had arisen with the broad goal of improving how to deliver material to the airplane mechanics. However, each of these initiatives was being executed in different organizational silos, on different timelines, and with seemingly different end objectives. For example, a pull system was being developed by one group while another group was trying to push carts out at a faster rate. What is also not clear is whether each of these solution options are complements or in competition with each other, or if the solution as designed will work to address known problems. The following is a list of several of the solutions encountered while working to resolve the problem, as well as some that came from interviews with the mechanics and MPRFs.

1. **20 Minute Delivery Cycle (currently being piloted):** Currently, every two hours materials are delivered which allows for standard delivery items and any emergent items to be captured in that two- hour cycle. The 20-minute cycle is really meant to address emergent items. If an emergent item is requested at the beginning of a two-hour cycle, a mechanic might have to wait a full two hours before it would be delivered. In practice this would not happen as the mechanic would walk to the MIC to get what was necessary. With delivery set for every 20 minutes, standard delivery items will not change but emergent items will have a shorter waiting time because the next delivery window should an emergent item occur will at most be 20 minutes.
2. **RFID real-time tracking (currently being piloted):** RFID tags are attached to each cart and can be tracked across the factory. The location of carts is displayed upon a live tracking map.
3. **Pull system from MIC to Work Cell (requesting approval for pilot):** Requires the success of RFID tags. Only four hours-worth of jobs will be stored on the floor at any given time. By moving carts from one swim-lane to an in-work swim-lane, a signal will be generated to deliver the next two hours jobs.
4. **Elevator (initial investigation):** Investment in capital equipment that will elevate large quantities of materials from the production floor to the same level as the aircraft and eliminate need for mechanics to leave the aircraft.
5. **Bar Chart Swim-lanes (currently being piloted):** Right now, work swim-lanes are organized by team and not by mechanic. This initiative adds a level of detail to the delivery of carts as each stream of carts is assigned to a specific mechanic.
6. **Use of Automated Guide Vehicles to delivery materials (pilot):** Carts will be continuously transported on designated paths, eliminating the need for an attendant in the travel path.

- 7. Tools stored on tool and parts delivered:** Transfer of ownership of tools from the material integrators back to the mechanics. Tool bags will remain within the control of the mechanics for each shift over the entire three-day cycle.

The following section will compare each of these potential solutions using a Pugh Matrix. This is to give a relative value of the impact each of the solutions would give to the overall requirements of the system. It is meant to be a tool that can be updated as new solutions present themselves or strategies change.

4.6 PUGH ANALYSIS

A Pugh analysis is an effective way to compare solutions options and discover possible combinations of solutions that improve upon the original design. Table 7 is a Pugh Analysis that shows a summary of the solutions options in Section 4.5 measured against the baseline design for each of the requirements. A five-point measurement scale was used to compare against the baseline.

- -2 much worse
- -1 worse
- 0 same
- +1 better
- +2 much better

A simple sum can be calculated across each solution for total comparison against the baseline. Some versions of Pugh Analysis will weight some design requirements higher than others, however for this case no robust way to determine the hierarchy of requirements was developed and so all requirements were weighted equally. I assigned scores based on interviews with stakeholders about each of the solution options and what requirements were intended to get better with the change.

This Pugh Analysis is meant to be another tool that can help assess future improvements. In a complicated system such as the material delivery system, where there are several stakeholders and competing requirements, this is a simple tool to begin to weigh the relative value of some solutions over others.

Table 7: Pugh Analysis of Potential Solutions

Design Requirements		1. 20 Minute Delivery Cycle	2. RFID real-time tracking	3. Pull system from MIC to Work Cell	4. Elevator	5. Bar Chart Swimlanes	6. Use of Automated Guide Vehicles to delivery materials	7. Tools stored on tool and parts delivered: Transfer of ownership of tools from the material integrators back to the mechanics
Functional Requirements								
1. <i>Be safe and ergonomic</i>	Material Kits <35lbs	0	0	1	1	0	1	1
2. <i>Deliver materials to the nearest possible position of where work is performed</i>	9.8% time/SOI	0	0	0	1	0	0	1
3. <i>Deliver the right parts to the right place at the right time with the right identifying labels</i>	1.5% time/SOI	1	1	1	0	1	0	1
Operational Requirements								
4. <i>Have method of data collection as to the rate of consumption of materials</i>	2.7 hrs/SOI. Poor resolution on single SOI data	0	2	0	0	0	0	-1
5. <i>Measure and deliver feedback and have control mechanism to resolve issues (Make Problems Visible)</i>	LSCC Resolution time 40 hrs/problem	0	2	0	0	1	0	-1
Constraints:								
6. <i>Minimize costs associated with labor, performance, square footage, and maintenance of the system</i>	Direct Cost: Direct Labor: \$10.00/SOI Support Labor: \$1.43/SOI Error Penalty: \$1.04/SOI Opportunity Costs: Floor Space: \$0.25/SOI Inventory Costs: \$13.08/SOI	-1	-2	1	-2	0	-2	1
7. <i>Design cannot exceed space available in designated work areas</i>	Minimum space available for this area is 212 sq.ft	0	0	1	-1	-1	0	1
Total		0	3	4	-1	1	-1	3

4.7 FINAL RECOMMENDATION

From the Pugh Analysis, RFID technology, a pull system, and storing tools permanently on the main build tools are the most impactful solutions to explore for future implementation. The other solutions are low or net-negative impacts. A summary of the results is shown below.

High Impact Solutions:

- RFID real-time tracking (currently being piloted)
- Pull system from MIC to Work Cell (requesting approval for pilot):
- Tools stored on tool and only parts delivered

Low Impact:

- 20 Minute Delivery Cycle (currently being piloted)
- Bar Chart Swim-lanes (currently being piloted)

Net-Negative Impact:

- Elevator (initial investigation)
- Use of Automated Guide Vehicles to delivery materials (pilot)

The RFID technology and pull system are complementary solutions, where the RFID technology can better enable the pull system. In contrast, storing tools on the main tool might conflict with a true pull system, but this is a question that would need to be further explored. RFID technology also directly addresses some of the problems brought up in Chapter 3. RFID technology would allow for an accurate signal of current demand, meaning that demand would level out. The problems associated with not having enough MPRF's at the beginning of the cycle or not enough physical space to hold materials at the end of the cycle could be mitigated by this change, as demand is leveled out.

A more important theme of the Chapter 2 and Chapter 3 was that there were multiple problems that could have multiple acceptable solutions. However, understanding what solution is best requires a systems perspective as there are competing requirements amongst different stakeholders. To understand the trades and the overall benefit of any solution design requirements needed to be defined. Then simple tools, like the Pugh Analysis, can be used to highlight the pros and cons of each solution.

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5 CONCLUSION

The use of lean principles in aerospace setting continues to be a challenge. However lean emphasizes the journey and the challenges with implementation is one step along that journey. This thesis is a snapshot of the latest iteration of lean principles into the aircraft assembly setting. It identifies the successes and shortfalls of the initiative and proposes a methodology of evaluating new solutions to bring systems in closer alignment to lean principles.

The final recommendation for the factory is to focus on developing the use of RFID technology to material delivery in the factory and see if this technology can be used to enable a true pull system of materials to the mechanics.

While much of this thesis focuses on material delivery, Phase 1 of this study highlighted other areas of improvements and subsystem that could be improved. Future studies could include

1. Scheduling of jobs: An interesting conflict arose between how industrial engineers schedule jobs for both the mechanics and material integrators. A possible research question is how industrial engineers develop these schedules.
2. Rework: There is still significant supplier caused rework. It was observed the feedback loop to suppliers about these defects are slow or are never initiated so the problem keeps recurring.
3. Crane Schedule: Waiting for the crane to deliver or move primary structure has a wide impact on an entire build sequence, because often nothing can be worked while waiting for the crane to come.
4. Removing Inspection Steps: In lean culture inspection is considered non-value activity, as quality should be built into the process. Many inspections steps are still required for the completion of SOIs.

Lastly the course of this thesis and project impressed upon me that no technology, or optimized system is a replacement for good leadership and the collaboration of an engaged team. The ideas and successes of the system to date are the result of several people working hard together. The continued success of this team lays heavily on the hard-work put forth by the front-line workers and first line managers. The role of management is to give the best available tools that respect and enable the people who work for them.

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