Optimization of Shake Inspections

by

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B.S. Mechanical Engineering, Purdue University, 2006

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

Masters of Business Administration
and
Master of Science in Mechanical Engineering

In conjunction with the Leaders for Global Operations Program at the

Massachusetts Institute of Technology
June 2011

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ABSTRACT

The Boeing 737 program has recently announced an increase in the production rate from 31.5 airplanes per month to 35 airplanes per month. Throughout the production value stream, opportunities to improve quality and reduce flow time are being thoroughly investigated. This thesis contributes to the investigation by focusing on improving the inspection process through a prototype computer data collection tool and the formation of a corrective action team.

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Acknowledgements

I would like to thank the many people at the Boeing Company who welcomed me into their organization, answered my questions, and helped me along they way. While everyone I met contributed to my experience, the following people should be noted for their over and above efforts: Lindsay Anderson, Dave Shineman, Glen Kanenwisher, George Thompson, Ron Mudwilder, Clayton Girard, Jim Brown, Agnes, Al, Don, and John.

I also want to thank my thesis advisors Dan Whitney and Roy Welsch. Their combined ability to ask me the right question at the right time was fundamental in my success at Boeing.

My appreciation also goes to all of those who supported me in my MIT LGO endeavor – Mom, Dad, David, Laura and the rest of my family; my mentors and friends Tom Gospel and Larry Coan; my Purdue Friends, my Indianapolis Friends, my new Seattle Friends, and my LGO Classmates. Thank you all.

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Author's Note: In this thesis, all mentions of rework refer to very low impact items that have very little risk to the safety of flight. More significant rework with higher impact is not included in any of the observations, data, or analysis.

1 Introduction

The Boeing Company assembles the Boeing 737 Commercial Aircraft at the Renton, Washington facility at a rate of 31.5 planes per month. Continued strong demand for the 737 and a significant backlog of orders has driven the decision to increase the production rate to 35 planes per month.

The entire 737 production value stream, from suppliers to delivery, is actively preparing for the rate increase scheduled to occur early in 2012. Every opportunity for improvement will need to be evaluated and selectively pursued in order to meet the goal of increasing the production rate. This thesis serves as a small portion of this value stream-wide evaluation and action to increase production rates.

This thesis will explore the process for making incremental quality improvements through collecting normally undocumented rework data found during the inspection process and establishing a team to analyze and feedback the collected data to drive quality improvements and reduce flow time.

1.1 Problem Statement

Manufacturing an airplane involves a very complex system in which millions of parts must come together at the right time and in the right order to produce a quality airplane that meets the production schedule. Unfortunately, in a realistic world, the parts are not always on time nor are they assembled perfectly.

The high risk of catastrophe presented by aviation products results in a strong need for high quality production. Due to this need for high quality, Boeing inspects the airplanes several times during assembly and throughout the value stream.

Inspections occur as part of each individual assembly operation. Each assembly process performed by the operations organization is then approved by the quality assurance organization.

Individual assembly steps are grouped by proximity into larger distinguishable areas of the finished airplane called sections. These larger sections are inspected before the plane leaves the factory during what is called a Shake Inspection. There are about 80 different Shake Inspection work orders that occur in the factory. When combined, the 80 Shake Inspections cover the entire airplane.

After assembly and the Shake Inspections, the plane then travels out to the flight line where it is prepared for the first flight. The same sections are inspected once again before the first flight in what are called Air-Worthiness Inspections. There are fewer Air-Worthiness Inspections than Shake Inspection, but each Air-Worthiness Inspection covers a larger portion of the airplane, thus the entire airplane is once again inspected under a formal work order. When the plane lands from its first flight, all of the sections are inspected one last time during what is called an Intermediate Inspection.

The multiple inspections that occur on the same sections of the aircraft can be correlated to James T. Reason's Swiss Cheese Model of Human Error (Reason).

Reason's model as adapted in Figure 1-1relates to safety related accidents in the work place.

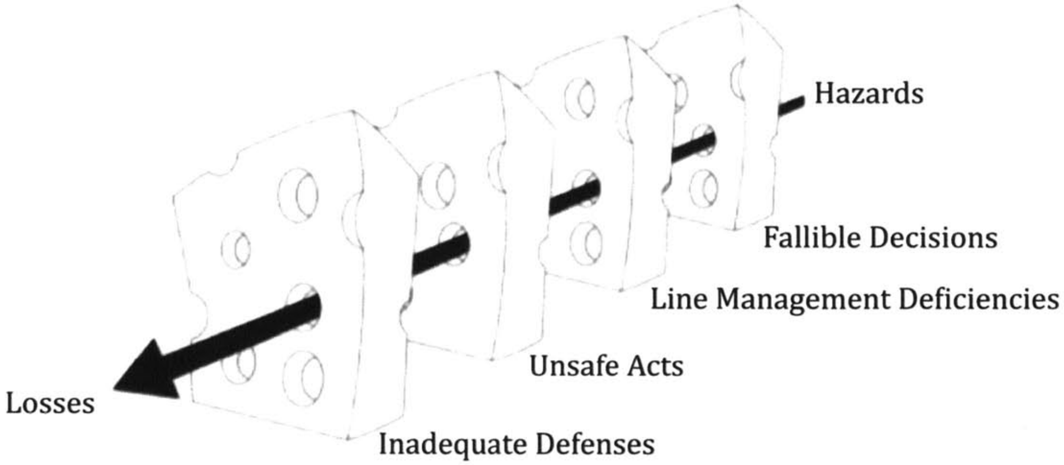

Figure 1-1 Reason's Swiss Cheese Model of Human Error

The Swiss Cheese model shows several layers of defense between hazards and the losses they might cause. Each layer of defense is not perfect, thus the holes in Swiss Cheese represent the hazards that slip through a layer of defense. When holes in all of the layers of defense align, a loss occurs.

The Swiss Cheese model can adapted and applied to the redundant inspections of airplanes. Instead of focusing on the prevention of human accidents as in Reason's model, this following adaptation of the Swiss Cheese will focus on layers of inspections designed to identify rework. The adapted model can be seen in Figure 1-2

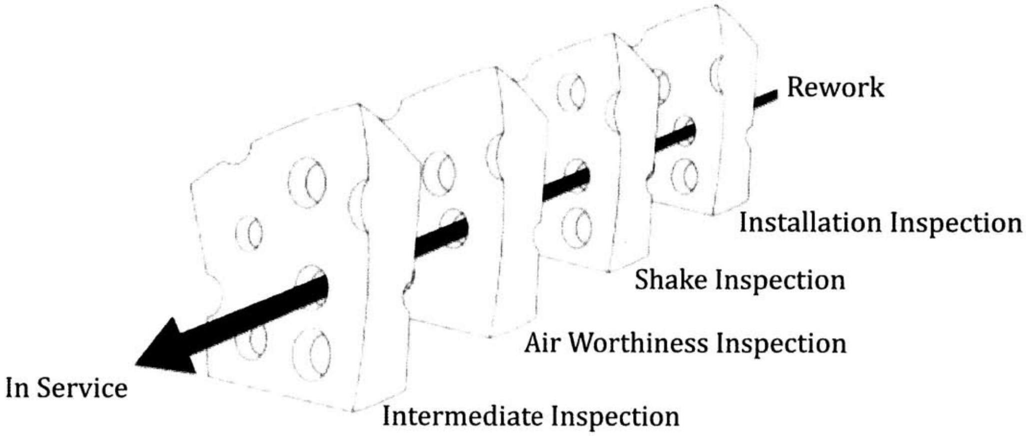

Figure 1-2: Swiss Cheese Model of Redundant Inspections

In this model, each layer of defense is an inspection. The inspections are trying to prevent any rework from occurring when the plane is in service due to the high cost of the rework when planes must be grounded. Just as in Reason's model of human error, each inspection is not perfect, thus holes exist in the layers. When these holes align, costly rework must occur on in-service airplanes.

The redundant inspections are very effective at eliminating rework from occurring while planes are in-service, but they are certainly not an example of lean manufacturing. Reducing the number of inspections without compromising the quality of airplanes will help decrease flow time to accommodate higher production rates.

This thesis is based on a project to lean out the inspection process found in the 737 production line. Elimination of the redundant inspections is the ultimate goal, however the scope of this project is limited, thus the interim goal is to improve the quality of the airplanes as found at the inspections. Improving quality will reduce the perceived need for redundant inspections, thus progressing toward elimination of inspections.

Unfortunately, based on observation and database searches, data representing the actual quality of the airplanes at the inspection points is not accurate. This inaccuracy comes from the low level nature of much of the rework that occurs. According to the FAA approved quality system at Boeing, the low level rework does not require documentation, thus a method for efficiently collecting this low level rework data will also be developed and discussed in this thesis.

1.2 Hypothesis

This thesis proposes documenting low-level rework activity and utilizing a team to analyze and communicate the rework data will improve quality and subsequently reduce flow time in the production of the 737 airplane. Additionally, some of the layers of inspection as identified in the Swiss Cheese model do not add value to the airplane. Collecting detailed inspection rework data will help to reveal the true value added at each inspection while also revealing sources of rework generation for continuous improvement.

1.3 Purpose of Study

The purpose of this study is to develop a repeatable process to be utilized on individual inspection work orders for driving quality improvements to facilitate the elimination of redundant inspections in the future. Once established, this standard process can be used on other inspections to continuously drive quality improvement. The improved quality will help reduce flow time on individual inspections to free up resources for the projected higher production rates. Looking forward, the information gathered in this quality improvement effort will be instrumental in eliminating a layer in the inspection process while maintaining Boeing's reputation for high quality airplanes.

2 Background and Context

2.1 The Boeing Company

The Boeing Company is the largest aircraft manufacturer in the world with five business segments: Boeing Commercial Airplanes, Boeing Military Aircraft, Network and Space Systems, Global Services and Support, and Boeing Capital Corporation. Boeing's developments are not limited to aircraft and include cyber security, clean energy technology, and biofuels.

Approaching its 100th year anniversary, the Boeing Company has established the 2016 Vision as "People Working Together as a Global Enterprise for Aerospace Leadership". Boeing will make strategic decisions and investments to continue its aerospace legacy into the next century.

2.2 Boeing Commercial Airplanes

Commercial airplanes currently in production at Boeing include the single isle 737 and the twin aisle 747, 767, 777, and 787. Final assembly of Boeing commercial airplanes currently occurs in two Seattle area facilities, Renton and Everett, with another facility coming online in Charleston, South Carolina in the near future. The Renton facility builds the smaller 737 while the Everett facility builds the remaining larger planes in the largest building in the world. The developing Charleston facility will also build twin aisle planes initially focusing on the new 787 and expanding to other planes further down the road.

While many of the Boeing planes of the same model appear to be identical except for the paint, very few are the same. The planes are highly customized to the customer specifications. Customization includes various options such as high efficiency winglets, flight deck configurations, and cabin configurations. The vast number of options results in high variability in production to the point where it is often said that no two planes are exactly alike. The high mix of airplane configurations combined with the high complexity of the airplane product itself creates a significant challenge for production.

2.3 Boeing 737 Program

The Boeing 737 is the most successful aircraft in history. The plane is now on the 3rd generation of design with over 7000 airplanes ordered in its 40-year history. A consistent list of backorders has provided stability to the production system. This stability has proven beneficial, as the concept of Lean Manufacturing from the automotive industry has slowly penetrated the aerospace industry, the 737 program has been a leading adopter of the lean principles at the Boeing Company.

One of the most significant improvements to the assembly of the 737 was the introduction of the moving assembly line. The moving line represents the 737 program's single largest lean manufacturing change. Previously, planes were pulled off to both the sides of the high bay factory into individual work cells for assembly operations to occur. Each night the planes would be shuffled around to the next work cell for the next day of activity. This method represented a lot of wasted time moving planes between the various cells and significant amounts of work in process inventory.

The new moving line greatly reduces the inventory of in work airplanes by lining them up nose to tail and pulling them through the factory. The individual assembly jobs are rescheduled to maximize the efficiency of work to fit the entire assembly sequence into 8 days reducing overall final assembly Work In Process from 29 planes to 14 planes. Additionally, implementing feeder lines, or short subassembly productions lines helps to move much of the assembly work off of the space constrained airplane and into other parts of the factory.

The 737 moving line has served as a production model for the rest of Boeing Commercial Airplanes, resulting in significant changes on the 777 and 767 production lines.

The 737 program continues to utilize lean principles to drive operation improvements. Due to the current large backorder of 737 planes, many customers cannot get a plane when they need it, creating inefficiencies in their operations or driving customers to look at other manufacturers for airplanes. Boeing has announced rate increases to better meet the customer demand.

The rate increases represent a significant challenge for the production system. The entire value stream must be prepared for the rate increases for the endeavor to be successful.

2.3.1 737 Value Stream

The Boeing 737 Final Assembly Value Stream consists of three physical locations: the Factory, Preflight, and the Delivery Center as represented below in Figure 2-1.

Figure 2-1: The Boeing 737 Value Stream

Factory

The 737 factory primarily consists of Wings Assembly and Final Assembly. There are many other component factories, both external and internal to Boeing, which supply parts to these factories, but will not be included in the scope of this thesis. Wings are assembled and delivered to Final Assembly where the entire airplane is assembled. While the airplanes are in final assembly, Shake Inspections are conducted before the fully assembled airplanes are then transported to Pre-Flight.

Pre-Flight

Pre-Flight is where the assembled airplanes are prepared for their first flight. This includes fueling the plane, running the engines, functional testing, calibrating and preparing the avionics, and conducting Air-Worthiness Inspections (AWI's) prior to the first flight.

This is the first time the airplane is fully assembled and turned on, thus often times certain airplane-system wide issues are first discovered at Pre-Flight during functional testing. Resolving these newly found issues frequently causes production flow disruptions due to the difficulty in predicting what issues will be found and how long it will take to fix them. Once the airplanes have been fully inspected and all functional testing is complete, the airplanes are test flown by Boeing pilots. Airplanes on test flights land at the Commercial Delivery Center (CDC), a different facility than where they took off.

Commercial Delivery Center (CDC)

The CDC is where airplanes land after their first test flight. After landing, the airplanes are inspected one last time during an Intermediate Inspection. The delivery work then begins by adding final touches, cleaning the airplane, and completing any open work orders before allowing the customer to conduct the first test flight.

Frequently the customer identifies many issues that need to be resolved before they will accept the airplane. Once again, consistent production is greatly disrupted by issue resolution, to an even greater extent than at preflight once again due to the difficulty in predicting the issues and how long it will take to fix the issues. Ultimately, the airplane is delivered to the customer who then flies the airplane away making room for the next airplane.

2.4 Literature Review

Lean manufacturing, a concept developed from the book *The Machine That Changed the World*, consists of the constant pursuit of eliminating waste from a production system. Taiichi Ohno, the founder of the Toyota Production System, commonly categorizes wastes in a manufacturing environment as:

1. Transportation
2. Inventory
3. Motion
4. Waiting
5. Over Production
6. Over Processing
7. Defects

The constant pursuit of eliminating waste was first focused on in Toyota automobile factories in Japan. As Womack points out in his book, the adoption of lean manufacturing will eventually extend beyond the automobile industry into all industries[1]. It is often believed that the Aerospace industry is about 10-15 years behind the automotive industry in implementing Lean manufacturing principles[2].

2.4.1 Lean in Aerospace

Lean principles have been in place in the automotive industry since the mid 1960's. According to Crute in the article "Implementing Lean in Aerospace – Challenging the Assumptions and Understanding the Challenges" three major factors helped build a need for lean in the aerospace industry. These factors include:

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[1] James P. Womack, Daniel T. Jones and Daniel Roos, The Machine That Changed the World (New York: Free Press, 1990).

[2] V Crute, et al., "Implementing Lean in aerospace - challenging the assumptions and understanding the challenges," TECHNOVATION 23.12 (2003): 917-928 .

- Post Cold War Reduction in defense procurement budgets
- Sudden Airline passenger demand drop at the end of the Gulf War after periods of unprecedented high aircraft orders
- Industrial Globalization causing organizations to rethink their structure

Traditionally long lead times due to inflexible production systems combined with these conditions pushed aerospace companies to implement lean principles to reduce inventory, cut costs, and increase productivity. Looking into the future, lean implementation will become more critical for Boeing as new competition arises from European, Chinese and Canadian aerospace companies.

2.4.2 Rework Cycle

As described in the problem statement, the major focus area of this thesis is the inspection process at Boeing. Inspections are where much of the rework is found and performed, thererfore understanding the Rework Cycle helps to understand the system. As described by Sterman, rework cycles can present a significant resource sink as the "uncovering of errors takes time and resources"[3].

Understanding the resources involved in uncovering incomplete or improperly completed tasks and feeding the information back to the task source can make significant gains in the production system.

2.4.3 Process Improvements

When improving a process it is critical to elevate the importance of improvement to an attention getting level. According to Steven Spear, high velocity organizations

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[3] John D Sterman, Business Dynamics: Systems Thinking and Modeling for a Complex World (Boston: McGraw-Hill Higher Education, 200).

swarm a problem to quickly solve it to build new knowledge. By swarming the problems the importance of fixing the problem immediately increases due to the fact that significant resources are tied up. Additionally, the attention brought by the swarm helps to gather attention and raise additional awareness to those nearby. The large amount of resources helps to quickly solve the problem and learn from the problem to help prevent it from happening again[4].

2.5 Chapter Summary

This chapter discussed the high level structure and history of the Boeing Company and the 737 Final Assembly Value stream. The literature review provided samples of understanding that can be applied to the production system. It is important to understand that Lean manufacturing is relatively new to the aerospace industry and therefore significant cultural inertia may initially resists the adoption of lean techniques. When looking at inspections, the rework cycle introduced by identifying items for rework can become a large sink of time and resources. When problems are identified, they should be swarmed to prevent the problem from reoccurring.

3 Current State

Currently there are approximately 109 different inspections that take place during the production of a Boeing 737 airplane. Eighty of these final inspections are the Shake Inspections that occur during the Factory. The remaining 29 inspections occur at Preflight in the form of Air-Worthiness Inspections and one final inspection that occurs at the Commercial Delivery Center. As seen in the figure below, the

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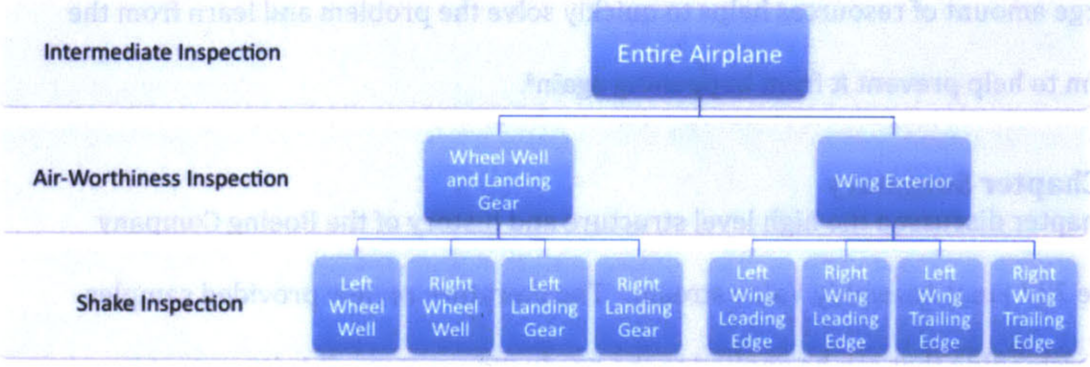
[4] Steven J Spear, Chasing The Rabbit (New York: McGraw-Hill, 2009).

plane is broken into additional less refined areas for inspection as airplanes move down the value stream. For example, the are 80 Shake Inspections in the Factory, 29 Air-Worthiness Inspection at Pre-Flight, and 1 Intermediate Inspection at the Delivery Center. An example of how the inspections consolidate is shown in Figure 3-1. Looking specifically at the wheel wells and landing gear, it is noted that there are many more Shake Inspections than Air-Worthiness, culminating to one final Intermediate Inspection.



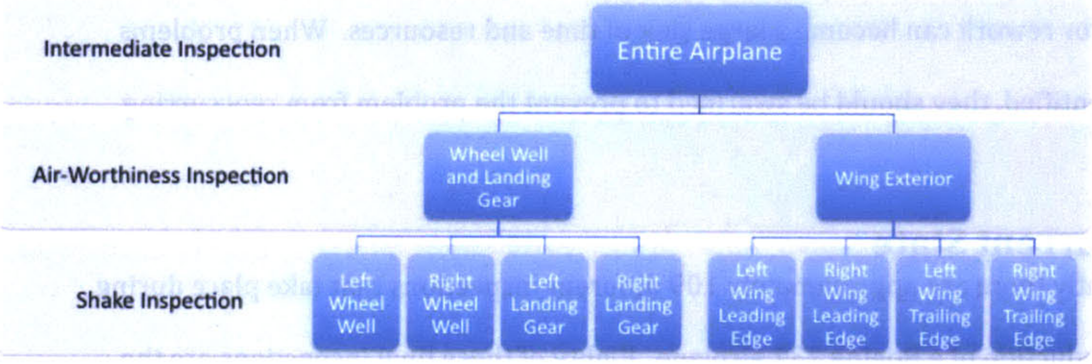


Figure 3-1: Sample of Airplane Area Mapping Between Different Inspections

When looking at the three inspections, Shake Inspection, Air-Worthiness Inspections, and Shake Inspection, the Shake Inspections represent the largest source of waste. Shake Inspections, which occur in the factory, are not only the most numerous in count, but also take the longest. Many of the inspections require an individual's entire 8 hour shift to complete. In other words, it is someone's entire job to perform a Shake Inspection, and there are 80 Shake Inspections on every airplane. These inspections are the source of the most rework in the factory and this rework is often not fully documented. This rework and the time it takes to perform is the true source of waste associated with Shake Inspections. Higher quality airplanes would reduce the amount of time reworking the airplane, and consistent zero rework performance will provide the evidence to eliminate the inspection.

Additionally, there are redundant inspections of the same section or area that occur along the value stream. For almost every section of the airplane there is at least one Shake Inspection in the factory, a corresponding Air-Worthiness Inspection at Preflight, and a final Intermediate Inspection at the Delivery Center. Depending on the section of the airplane, it can have up to five formal stand-alone inspections along the value stream.

3.1 Inspection Overview

As mentioned previously, there are several redundant inspections in the airplane production process. These inspections are similar in that they are looking for rework that needs to be performed in order to bring the airplane back into engineering drawing specification. The inspections are not similar in where they are done or how they are performed. The inspections take place in each of the three physical locations of the value stream, representing the silo-ed nature of the value stream that would be beneficial to overcome. The following sections will look at each of the inspections in greater detail.

3.1.1 Factory Shake Inspection

There are 80 different Shake Inspections in the factory. Each shake covers a portion of the airplane and all 80 of the shakes combined will cover the entire airplane. In some cases, more than one Shake Inspection in the factory will inspect the same section of the airplane; One inspection would occur part of the way through the build process with the other inspection at the end of the build process. The reason for multiple Shake Inspections on the same section of the airplane is unclear and mostly attributed to an artifact of previous decisions.

As seen in Figure 3-2, the Shake Inspection for a specific area of the airplane starts with a Pre-Shake where a mechanic prepares the designated area for the Quality Assurance (QA) inspection. The QA inspection consists of three different inspectors who thoroughly look over the zone and identify and document items that need to be reworked.

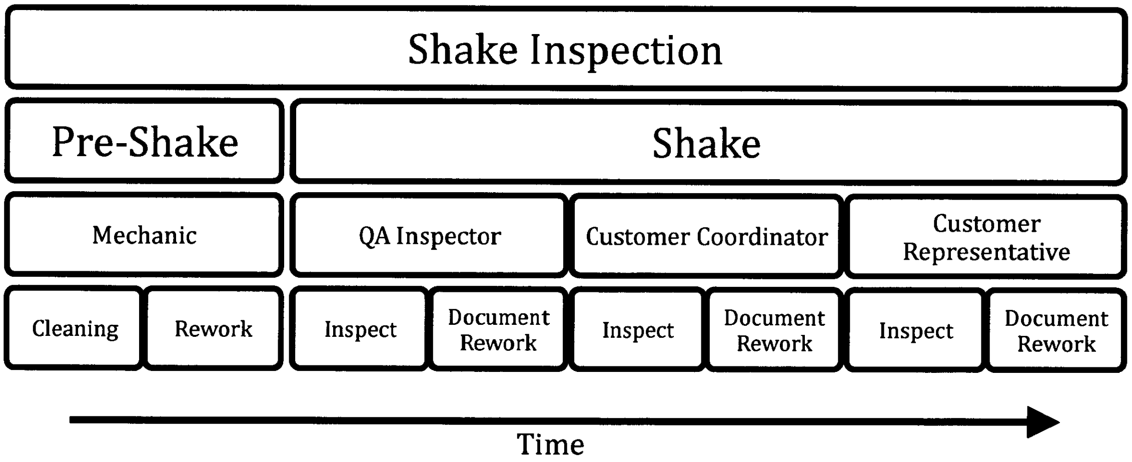


Figure 3-2: Breakdown of a Shake Inspection over Time

Pre-Shake

The preparation of the area for inspection consists of the mechanic thoroughly cleaning the area and identifying and performing rework.

The cleaning consists of wiping off various dripped fluids, removing foreign objects and debris (FOD), cleaning out drill shavings, and removing paint protective covers unused nut plates, and ground caps left on by previous work orders.

After cleaning, the mechanic then typically applies corrosive inhibiting compound (CIC) to the places where it was removed during previous installation jobs, reworking the areas as needed. Finally, the mechanic carefully inspects the zone looking for assembly conditions that are not to specification. Conditions found by the mechanic or inspector that are not to drawing specification fall into two categories:

1. Conditions that can be reworked to the drawing specification with the skills of the mechanic
2. Conditions that require trained skills beyond the mechanic's to be reworked to the drawing specification

The mechanic can typically do most of the rework necessary to bring the airplane back to drawing specification, however sometimes he or she cannot. At that point a non-conformance record (NCR) is written which contains the details of the condition and requests the needed skill sets to correct the condition. This NCR is written by the QA organization and requires a QA representative to complete. Rework that falls within the skills of the mechanic typically consists of adding wire ties to wire bundles, repositioning components that are in contact and should not be in contact, touching up scratched paint, and tightening fasteners and other electrical connectors. Based on observations, all of the initial rework done by the mechanic is not documented. Documenting this rework would require a QA representative to write what Boeing calls a pickup, a category of rework consisting of very low level items. Thus the extra effort of calling over a QA representative for every small act of rework is not put forth mostly due to the additional time required. Schedule pressure prevents this rework from being documented. The mechanic spends upwards of 4 hours completing the Pre-Shake. The benefit of documenting this rework will be covered in a later section.

Shake

Once the mechanic finishes the pre-shake, he or she puts the job up for QA approval. A QA inspector arrives to review the zone designated by the Shake Inspection work order. The QA inspector carefully looks over the zone and indicates with blue tape any conditions in need of rework. The mechanic then comes back and reworks the conditions flagged by the QA inspector. Once the QA inspector approves the rework performed by the mechanic, the Shake Inspection area is put up for Customer Coordinator approval. The blue tape represents pickups, or documented rework, that should occur in an ideal system, but due to the low level nature and time pressure, the rework designated by the blue tape is not documented.

The Customer Coordinator represents the Customer Quality Service (CQS) organization. These are Boeing employees who coordinate with the customer to ensure customer needs and requests are met. In the realm of Shake Inspections, the Customer Coordinators make sure the area designated by the Shake Inspection work order is ready for the actual live customer to review. The Customer Coordinator inspects the area and designates conditions needing rework with red tape. The mechanic then reworks the conditions. After Customer Coordinator approval, the Shake Inspection is put up for Customer Representative Approval.

The Customer Representative can be either an individual who works for the customer airline or a Boeing employee who has been designated by the customer to represent the customer. The Customer Representative inspects the area as designated by the Shake Inspection work order, once again identifying conditions for rework with red tape and approving the rework done by the mechanic. The Customer Representative is looking for issues that the specific airline is having in service. For example, if they prefer to have extra corrosive inhibiting compound (CIC) because they find adding extra prevents service related delays, the Customer Representative will carefully inspect for CIC and perhaps request more to be applied during the Shake Inspection. When the Customer Representative is satisfied, the job is considered complete and the airplane is ready for the next step.

In summary, a single Shake Inspection in the factory consists of a mechanic cleaning and performing rework followed by three different approval inspections. Even within the individual Shake Inspection process, there are redundant inspections when the same area is inspected by three different QA inspectors after the mechanic performs several hours of rework during the Pre-Shake.

3.1.2 Pre-Flight Air-Worthiness Inspections

The Air-Worthiness Inspections occur at the Preflight facility and are somewhat different than the Shakes Inspections in the factory. There are 29 Air-Worthiness inspections and each inspection covers a larger portion of the airplane. When combined, all 29 Air-Worthiness Inspections cover the entire airplane. For example, during the Shake Inspections the wheel wells receive a separate inspection from the landing gear whereas they are combined into a single Air-Worthiness Inspection at Pre-Flight.

The Air-Worthiness Inspection process is also different from the Shake Inspection process, not only in terms of physical location in the value stream but also the general operational process. As described above, Shake Inspections start with a mechanic who cleans and reworks the area followed by a QA inspection. On the other hand, Air-Worthiness Inspections start with a QA inspector who looks over the area under review. The QA inspector marks any problems that he or she finds with blue tape and then documents the problems in the Boeing NCM database, as seen in Figure 3-3.

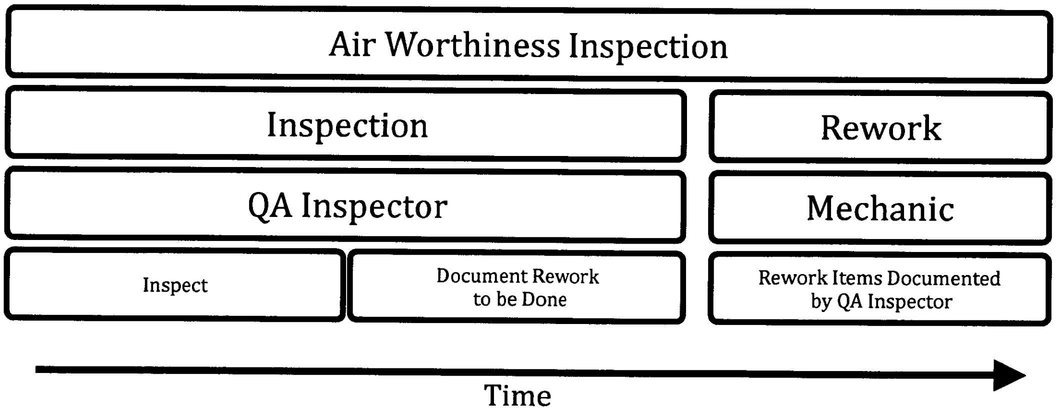


Figure 3-3: Breakdown of an Air-Worthiness Inspection Over Time

The documented items are automatically issued to a mechanic for rework. Once the mechanic finishes the rework, the inspector checks for quality. If everything is acceptable then the Air-Worthiness Inspection is complete. There are no customer inspectors during an Air-Worthiness Inspection.

3.1.3 Commercial Delivery Center Intermediate Inspection

The Intermediate Inspection occurs after the airplane lands from its first flight. The process is identical to the Air-Worthiness process at Pre-Flight where a QA inspects the area, identifying rework items for a mechanic to then come and repair.

3.2 Undocumented Rework

As mentioned in the description of the Factory Shake Inspection, much of the rework that occurs during the Pre-Shake is not documented. The following will show the opportunity missed by not documenting the rework. A Rework Documentation Stock and Flow Diagram will assist in this explanation.

Rework Documentation Stock and Flow Diagram

As airplanes are assembled, rework is generated at a given rate and is categorized as rework to be completed. During the inspections, the generated rework is identified and completed. The process of completing the rework can be either documented or left undocumented.

The rework documentation is captured by the stock and flow diagram in Figure 3-4. Like all models, there are limitations. Rework that is generated and not found during the inspection process is not accounted for in the model. In reality, the rate at which rework is not found is very low and assumed to be zero for the simplification of this model.

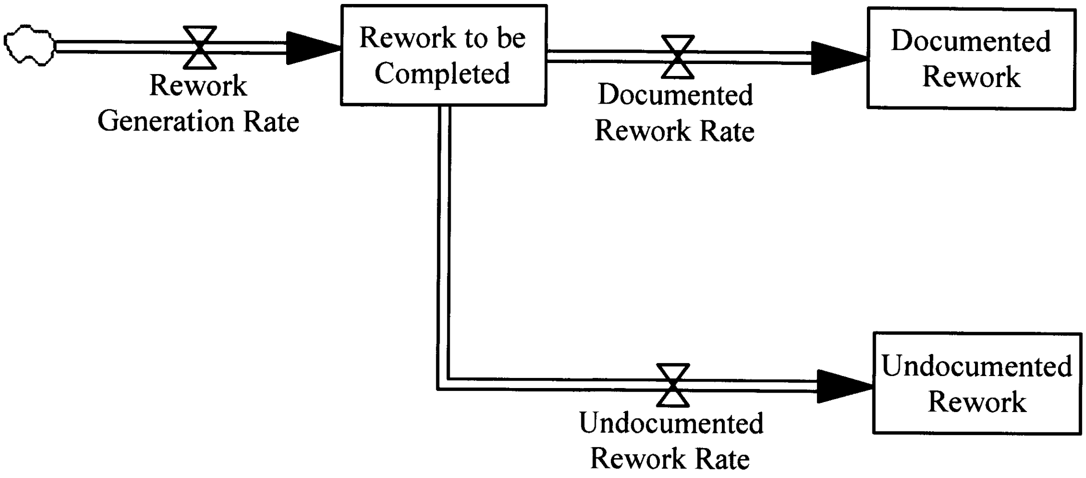


Figure 3-4: Rework Documentation Stock and Flow Diagram

Factory Observations

Based on observations of the inspections, it was found the majority of the rework completed during a Shake Inspection was not documented, while almost all rework completed during Air-Worthiness Inspections and Intermediate inspection was documented.

In the Rework Documentation Stock and Flow Diagram for the Shake Inspections, almost all of the Rework to be Completed flows into in the Undocumented Rework stock as seen by the bold arrows in Figure 3-5.

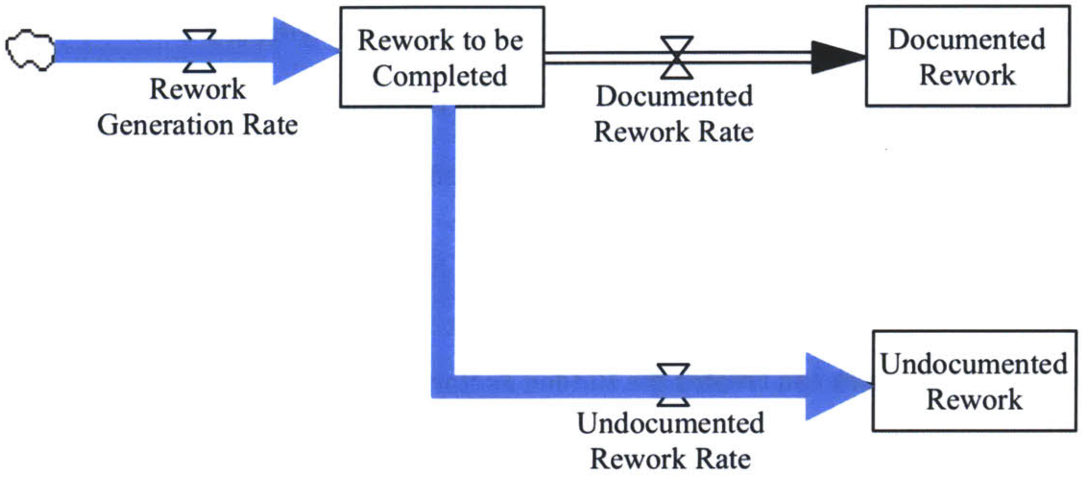


Figure 3-5: Shake Inspection Stock and Flow Diagram

Air-Worthiness Inspection and Intermediate Inspection Rework Stock and Flow Diagrams are the opposite with almost all of the Rework to be Completed flowing into the Documented Rework Stock as seen by the bold arrow in Figure 3-6

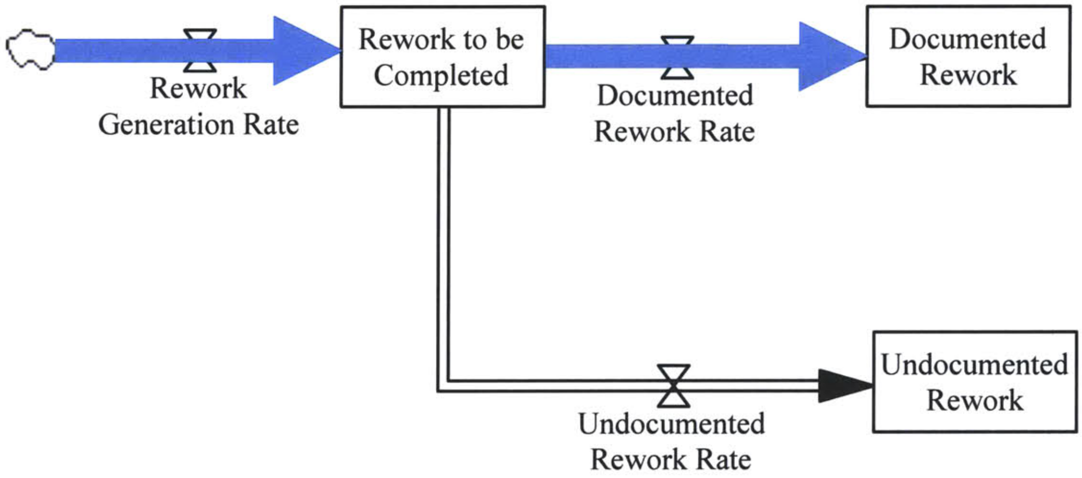


Figure 3-6: Air-Worthiness and Intermediate Inspection Stock and Flow Diagram

The individual items represented by the term undocumented rework are items of very low impact such as adding wire ties, small repainting scratches in paint, slightly loose connectors, reapplying corrosion inhibiting compound, removing unused nut plates and ground covers, and replacing missing torque stripe on hydraulic connectors. The rework performed on the line is within the skills of the mechanic completing the work and brings the plane back into certification specification, which is in complete alignment with FAA requirements.

Hidden Factory

The undocumented rework can creates the Hidden Factory. The undocumented rework activity takes time and resources from value adding production but is not accounted for. No one individual, other than the few mechanics doing the rework, can really understand how much time and resources are spent on rework. This undocumented rework represents a large opportunity for Boeing to better understand their complex production system. By documenting more of the rework, Boeing will better understand the conditions that cause rework and will be able to find solutions to reduce the rework, saving time to help build airplanes faster to meet the increased production rates.

3.3 Customer Specific Rework

The rework activity that occurs during the inspections is not necessarily due to out of specification conditions on the airplane. Some of the rework activity is in anticipation of customer requirements above and beyond the engineering specification of the airplane. For example, some customers prefer the electrical wiring to be tied off closer together than the specification requires. Other customers may prefer to have spotless paint jobs and other customers may prefer to have excessive corrosion inhibiting compound (CIC). As mechanics and inspectors learn their customer's beyond-specification preferences, they adjust the rework to meet these preferences.

This presents significant variability for Boeing production because each customer possesses different beyond-specification requirements. It is noted that accounting for the beyond-specification requirements of each individual customer would be beneficial but is not in the scope of this thesis.

3.4 Chapter Summary

This chapter focused on the current state of inspections along the value stream. It is most noted that there is a significant amount of undocumented rework occurring on the Shake Inspections, which represents the hidden factory using valuable time and resources. Looking forward, the next chapter will explore the future state of inspections.

4 Future State

In an ideal future state no rework would occur during the inspection process and each area of the airplane would only be inspected once. In the case of factory Shake Inspections, there would be no rework done by the mechanic and no rework identified by the QA inspector, customer coordinator, or customer representative. For the Air-Worthiness Inspections that occur at Preflight and Intermediate Inspections that occur at the CDC, there would be no rework identified by the QA inspector. However, given the complexity and variability of the airplanes manufactured by Boeing, this would be very difficult to do.

A more realistic future state for the inspection process would be a reduction of the number of inspections that occur in a particular area. For example, instead of having four inspections for an airplane section, an Installation Inspection, a Shake Inspection, an Air-Worthiness Inspection, and an Intermediate Inspection, there would only be three inspections. The inspections most logical for reduction are the Shake Inspection or the Air-Worthiness inspection, due to their proximity and limited inspection area of the airplane. In addition to the reduction in the number of inspections, all rework found during all inspections would be fully documented.

Due to the limited scope of the internship, an interim ideal state should be established. Given the goals and time constraint of the lean implementation project, a suitable and achievable future state would include the same four inspections with all rework found during the inspection fully documented. The documented rework would then be utilized to drive quality improvements to reduce the amount of rework that occurs during the inspections for an overall reduction of flow time. Beyond the scoped project, when higher quality is built into the airplane rather than inspected in, the data collected through full documentation can be utilized to confidently eliminate one of the inspections bringing the manufacturing system close to the overall ideal state.

4.1 Advantages of documenting all rework

Rework that is not documented is essentially hidden from the entire value stream. In a simple case, the mechanics performing the initial installation work do not realize when they are installing components incorrectly. When their installations are reworked without documentation, the only person who knows the original installation was incorrect is the individual performing the rework. With proper rework documentation, the correction to the original installation can be fed back to the original mechanic eliminating the future need for rework.

Expanding the Rework Documentation Stock and Flow diagram to include this feedback loop can be seen in the Figure 4-1. It can be seen that documenting rework drives the feedback loop ultimately impacting the quality of the airplane. Rework that is not documented has no effect on the quality of the airplanes.

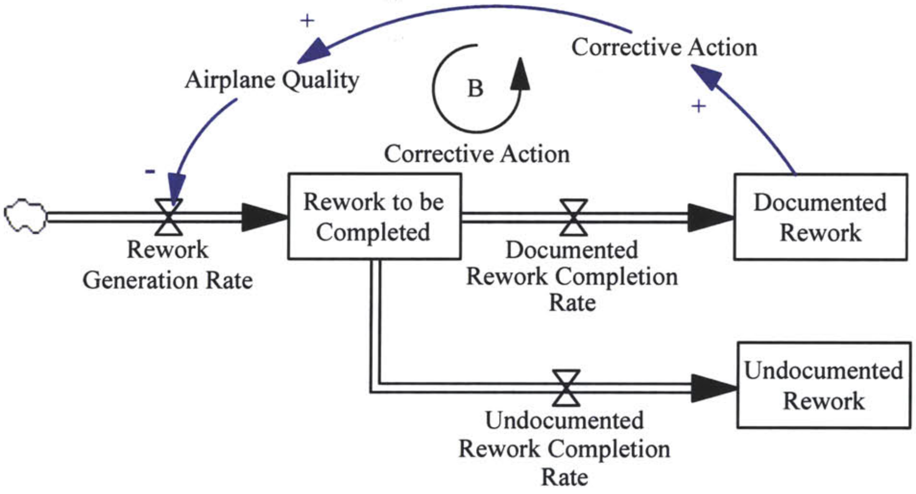


Figure 4-1: Simplified Feedback Loop for Documented Rework

On a larger scale, without consistent documentation of rework there is little or no data to evaluate and support any continuous improvement decisions. For example, the portions of the production system in most need of improvement can be characterized by having the least amount of time to complete the assigned work. Due to the lack of excess time, rework in these areas typically is not documented as this takes additional time. Overall, the result is that the areas in need of attention are overlooked due to the lack of data. Without accurate data to support continuous improvement decisions, the system will stagnate at best and spiral completely out of control at worst.

Thus documenting all rework arms the company with the information necessary to correct rework causing conditions and support larger scale continuous improvement decisions to bring about significant and constant improvement.

4.2 Challenges of documenting rework

When documenting rework, resources quickly become a binding constraint. The rework documentation process takes time. The amount of time spent documenting an individual rework item is directly proportional to the value or quality of the data collected. In other words, more time spent recording a rework item corresponds to a more valuable record to use to drive quality improvements. If very little time is spent recording a rework item then the value of the record is diminished.

For example, documenting 20 items of rework poorly (low quality) may require 20 minutes. Documenting 1 item of rework completely (high quality) may also require the same 20 minutes. You can see an example of the difference of high and low quality rework documentation in the Figure 4-2. The high quality data will be much more useful for driving quality improvements than the low quality data.

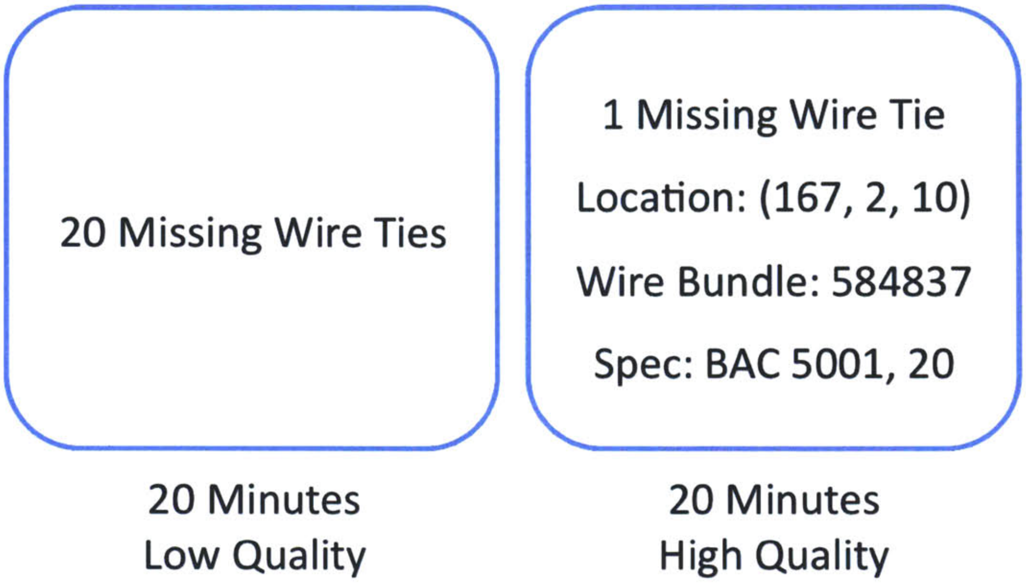


Figure 4-2: High Quality vs Low Quality Data Example

Looking at a larger scale, the area of the graph Figure 4-3 indicates the time it would take to fully document all of the rework that occurs during an inspection. The horizontal axes represents the quality of the documentation record and the vertical axes represents the percentage of rework that is documented. Ideally, all rework would be documented with high quality.

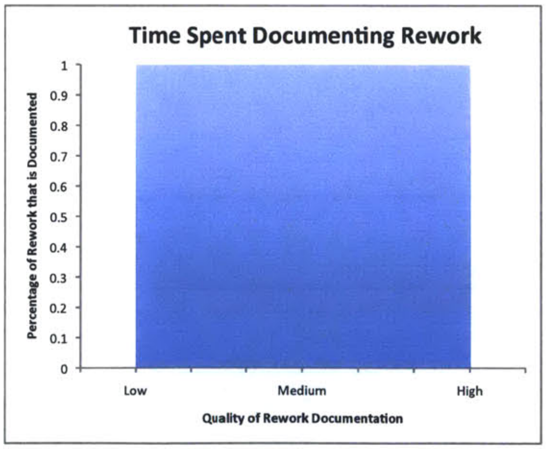


Figure 4-3: Ideal Time Spent Documenting Rework Graph as Indicated by the Area of the Graph

Unfortunately, the system is constrained and does not have the resources to document all of the rework without neglecting other responsibilities. To accommodate the resource constraint the quality of the documentation can be reduced (as indicated by Figure 4-4) the percentage of documented rework can be reduced (as indicated by Figure 4-5), or some combination of the two. In these graphs, the area of the graph represents the time spent on rework.

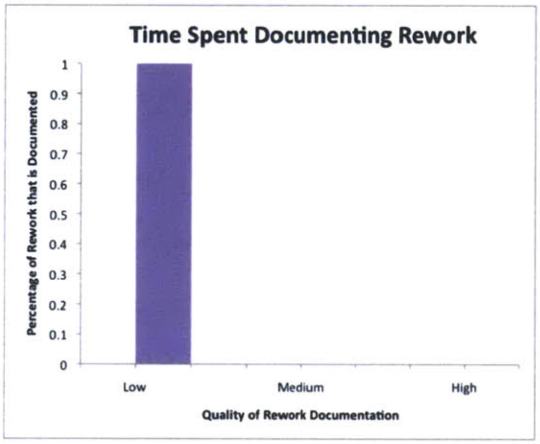


Figure 4-4: Rework Documentation Time Constraint – 100% Documented, Low Quality

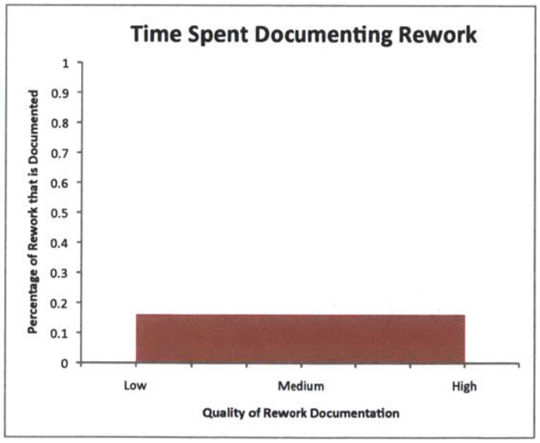


Figure 4-5: Rework Documentation Time Constraint – 15% Documented, High Quality

As seen in the figures, both resource-constrained documentation policies reduce overall time spent, as indicated by the area of the graphs. However, as previously demonstrated in the documentation quality example, higher quality data is preferred. Thus Boeing utilizes the high quality and low percentage documentation policy of rework as represented by the right graph when resources are limited.

Changing the method with which rework items are documented can reduce the limitation of the resource constraint. A new method could more efficiently collect the quantity and quality of data required. As seen in Figure 4-6, the efficiency of the new documentation method would change the scales of the horizontal and vertical axes while maintaining the scale of time (as represented by area) resulting in high quality data collected for 100% of the rework in overall less time than the current method.

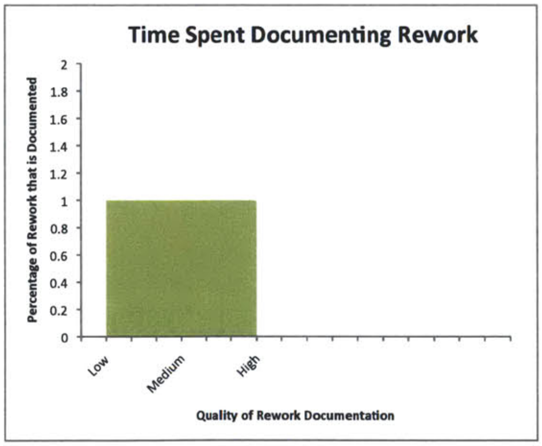


Figure 4-6: More Efficient Time Spent Documenting Rework Graph as Indicated by the Area of the Graph

A new rework documentation method will allow all rework to be documented, filling the stock of Documented Rework in the Rework Documentation Stock and Flow Diagram.

4.3 Corrective Action Resources

As seen in the stock and flow diagram in Figure 4-7, the Documented Rework loop feeds back through the Corrective Action Balancing loop to reduce the rework generation rate. By increasing the Documented Rework through a new, more efficient rework documentation method, the rework generation rate should go down. However, to ensure the rework generation rate reduces, the Corrective Action balancing loop requires resources. More resources dedicated to the corrective action loop will strengthen the impact of the loop resulting in higher quality airplanes.

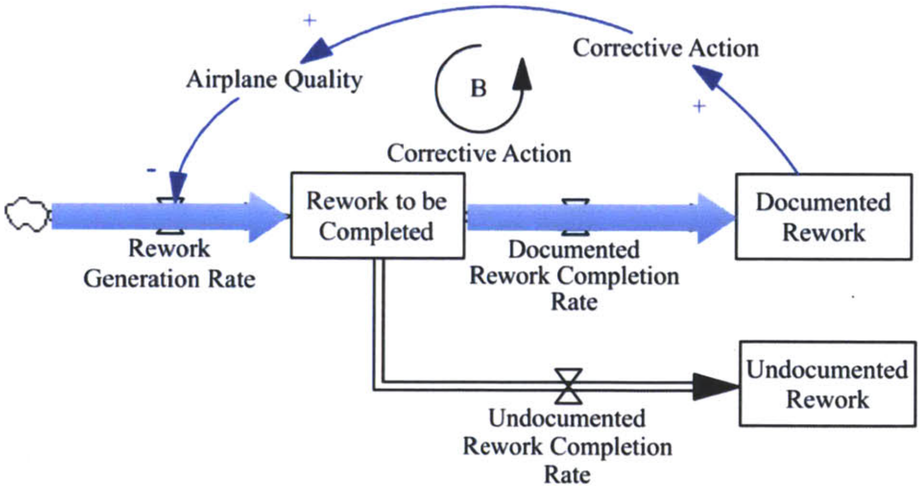


Figure 4-7: Simplified Rework Documentation System Dynamics Model

5 Approach

Boeing is a very large company. When implementing lean principles, the approach is critical for success. In choosing a location to start, it is important to find an area that will provide a significant opportunity for success while also making a significant impact. A successful first step is crucial for building momentum for future similar tasks.

It is also critical to have the right people in the right places to help ensure success. This section will explain the approach to implementing lean principles in the inspection process at Boeing.

5.1 Where to Start

As described in the background section, inspections occur all along the 737 airplane production value stream. Inherent to the Swiss Cheese Model, most of the rework is identified in the first inspections rather than the last inspections. The Shake Inspections in the factory are the first stand alone inspection after the installation inspection. The Shake Inspections are followed by the Air-Worthiness Inspections and the Intermediate Inspections. As the first of a series of inspections, the Shake Inspections identify a much larger volume of rework needing to be completed as seen in the Figure 5-1, which shows the average rework identified per inspection based on observational data in the wheel well section of the airplane.

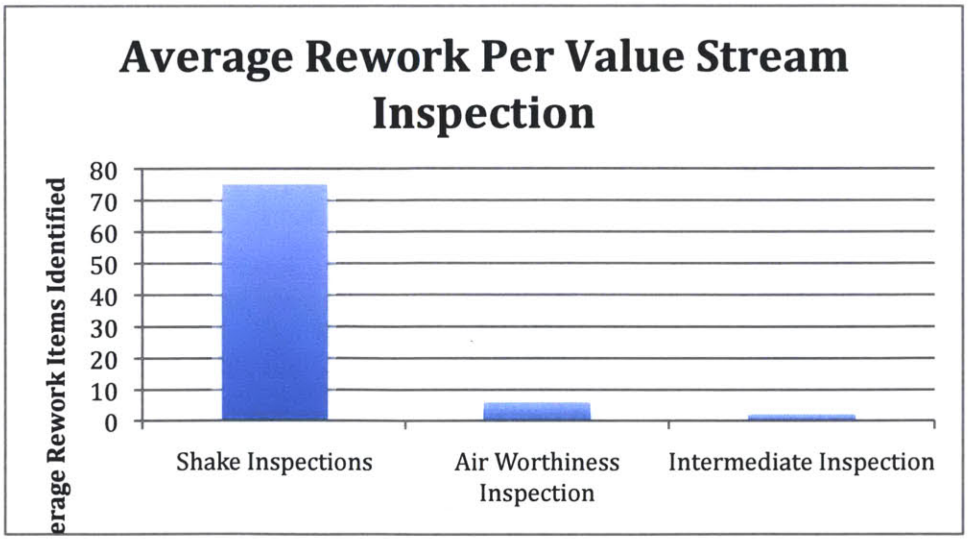


Figure 5-1: Average Rework Per Value Stream Inspection

The larger volume of rework identified during the factory Shake Inspections indicates that focusing on Shake Inspections will provide much more valuable information regarding the health of the production system than the other inspections due to the volume of data points.

It is also noted from observational data and supported by industrial engineering time studies that individual Shake Inspections require more time than other inspections further down the value stream even though they focus on smaller portions of the airplane. Once again, using the wheel well section of the airplane as an example, the time allocated for the wheel well Shake Inspection in the factory is 6.75 hours, while the time allocated for the Wheel Well and Landing Gear Air-Worthiness Inspections is 1.75 hours. Finally, the Intermediate Inspections for the entire airplane is allocated 2.5 hours, but this covers the entire airplane while 80 Shake Inspections at 4 to 8 hours each cover the entire airplane.

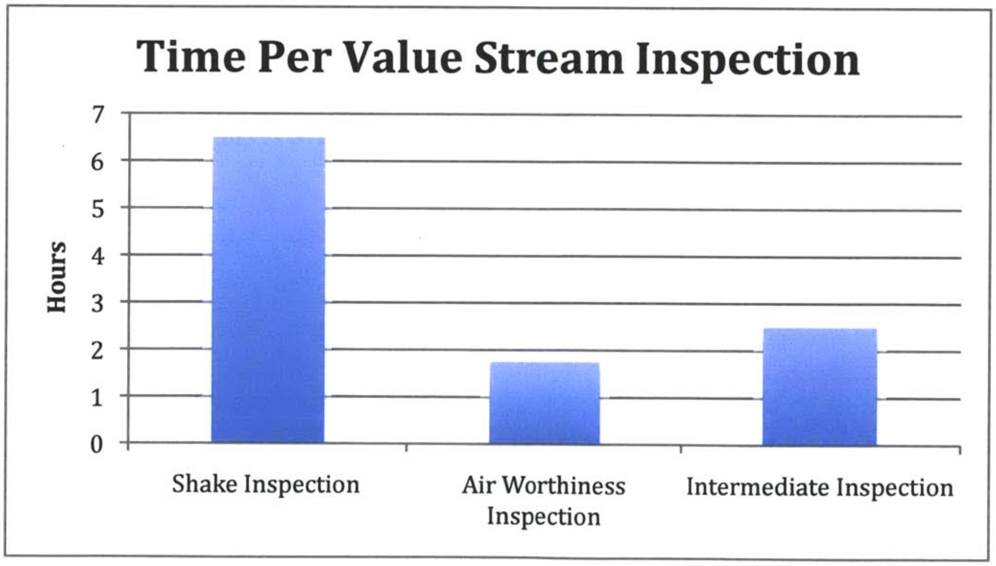


Figure 5-2: Average Time Per Value Stream Inspection

Shake Inspections require more time to finish and identify more rework to be completed, therefore Shake Inspections represent a more significant source of information and waste in the form of rework in the production system. Shake Inspections are a logical choice for the focus of improvement efforts.

There are 80 different Shake Inspections that occur on an airplane. Selecting the individual Shake Inspection to further narrow the focus is best determined using a decision matrix. The decision matrix accounts for many different factors, ultimately attempting to optimize the opportunity for improvement as well as the likelihood of success of the improvement. Specifically, the decision matrix criteria are as follows:

Improvement Opportunity Criteria

These criteria look at the time required for each shake inspection as well as the amount of rework identified during the inspection.

- **Rework Quantity** – This is based on a count of rework identified during the Shake Inspection as found in the Boeing production system NCM database. More rework is given a higher value in the decision matrix because it represents more opportunity for improvement and will produce a greater impact. It is noted that this database was previously identified to be inaccurate when compared to actual activity. While this is true, the database still provides a data point for comparison for initial evaluation.
- **Flow Time** – This is the amount of time allocated for each shake inspection. Longer flow times are giving higher values in the decision matrix because there is more opportunity to reduce flow time thus producing a great impact.

- **Inspection Redundancy** – Some areas of the planes receive more than one Shake Inspection in the factory. Areas of the plane with more than one Shake Inspection represent larger opportunities for reduction and therefore have a high decision matrix value.

Process Reality Criteria

These criteria take into account the reality of the inspections not captured by the improvement opportunity criteria. For example a Shake Inspection that covers a large portion of the airplane should have a larger rework count.

- **Physical Scope** – This is a value assigned based on the physical size of the inspection area relative to other inspections. A larger area is given a smaller value. This will balance the anticipated larger rework and flow time values due to the larger scope as well as discourage selection of an area of the airplane that cannot be entirely observed from a single location to prevent activity from being missed during observation sessions.
- **Number of Workers** – This is associated with the number of workers who perform the Shake Inspection. More workers means there is more activity to keep track of during observations, thus less desirable due to the potential for missed observations and therefore given a lower decision matrix value

Business Structure Criteria

These criteria look at a how the Shake Inspection fits into the larger organization and accounts for the associated advantages and disadvantages.

- **Internal vs. External Supplier** – Many of the Shake Inspection improvements will occur outside of the Shake Inspection process itself, therefore internal suppliers are more advantageous because making changes to improve quality will not require discussions and negotiation with an external supplier. One such example is the fuselage Shake Inspection, which occurs when the fuselage arrives from the supplier. This would be an entirely supplier-based improvement. Accordingly, Shake Inspections that focus on areas with primarily internal suppliers are given a higher decision matrix value than areas with external supplies.

- **Redundancy of Improvement Efforts** – Many other improvement efforts are taking place within Boeing. Areas such as the interior cabin already have a team dedicated to improvements. More efforts to improve that area would be redundant and wasteful therefore areas with existing improvement efforts are given a lower decision matrix value.

Each section of the airplane corresponding to a Shake Inspection will have a determinate value for each criterion. The values are then multiplied together to give an opportunity factor. Higher opportunity factors indicate a more desirable Shake Inspection to utilize as a pilot area for establishing a standard method for improving the Shaking Inspections on a one by one basis. A filled out decision matrix can be found in **Appendix A**.

The decision matrix provides a systematic method for determining the order in which Shake Inspections will be addressed. The priority order of inspections as indicated by the decision matrix is called the Shake Inspection Roadmap and serves as a central guiding document for shake inspection improvement activities. The top 5 Shake Inspections are indicated in Figure 5-3.

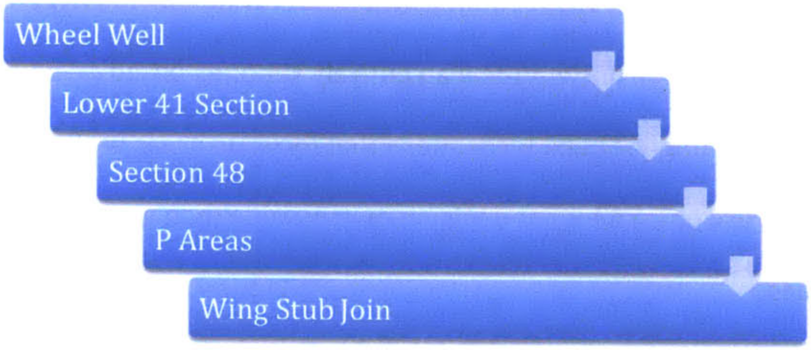


Figure 5-3: Shake Inspection Roadmap

As changes are made to the production system, both internal and external to the Shake Inspection improvement activities, the decision matrix will be reevaluated to see how the changes impact the Roadmap. This allows for the ability to adjust priorities as the production environment evolves over time.

5.2 Chapter Summary

The Shake Inspection Road Map provides the high-level long-term plan for optimizing the Shake Inspections. With the guidance of the high level plan, a standard lower level process for optimization called the Standard Inspection Optimization Work Flow will determine the day to day improvement activity. This process will be defined by the Optimization Team as discussed next and is a standard process that can be applied to all Shake Inspections for optimization. The process includes the coordination of information hand offs along as well as defining roles and responsibilities to ensure a consistent and repeatable method to optimize shakes.

6 Shake Inspection Optimization Team

Implementing lean into the inspection process requires resources. A team must be formed to help drive change. This team will utilize employee knowledge, skills, and contact networks to get information, process data, and develop ideas to help improve the inspection process.

6.1 Background and Motivation

The Factory Field Integration Team consists of General Managers from the three physical locations of the value stream. This is a high level, strategic focused team looking to drive commonality along the value stream and overall improve the production process. The Factory Field Integration team is responsible for improvements in three major areas as defined by the team charter:

- Optimize Final Inspection
- Optimize Installation Sequence
- Optimize Functional Testing

The optimization of a final inspection is intentionally a vague description of the activity driving to an ideal state. This lack of clarity removes the constraints of expectations and provides the ability to take any action necessary to improve the inspection. When applied specifically to Shake Inspections, some Shake Inspections will require a significant amount of standard work implementation while other shake inspections will require re-sequencing of tasks – both activities fall under the concept of optimization.

Optimization as defined by this thesis is to:

- Improve airplane quality found at the Shake Inspection by feeding back rework to the origin of work
- Reduce flow time spent during the Shake Inspection
- Implement Standard Work during the Shake Inspection and on operations that feed into the Shake Inspection
- Re-sequence tasks or events to drive quality improvements and flow reduction

The responsibility of the general managers to improve these three areas as accountable to the Vice Presidents inherently drives support for related activity. Thus putting together a logical well thought plan would get prompt approval from general managers. Team structure as seen in the Figure 6-1 was determined by the management to be optimal to meet the Factory Field Integration team goals.

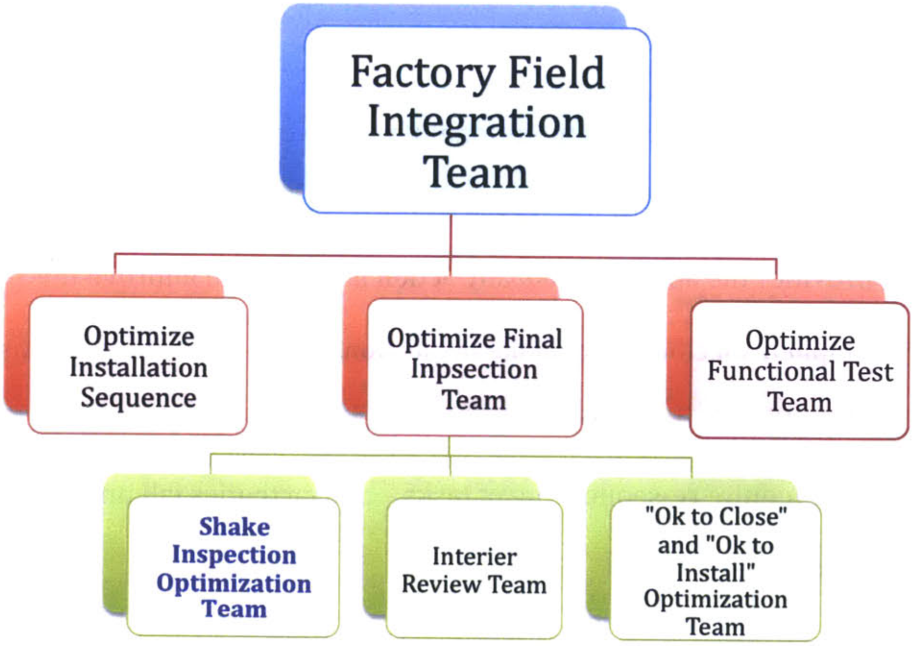


Figure 6-1: Factory Field Integration Sub-Team Structure

The Shake Inspection Optimization team will serve as the lean implementation team for the inspections. The lean team, much like the Factory Field Integration Team, is staffed with cross-functional representation of the entire value stream for several reasons:

1. Ensure that optimization activity does not cause problems outside the area of focus
2. Align the three physical locations of the value stream driving toward more consistent operating procedures
3. Enhance communication along the value stream
4. Gather valuable experience from the entire value stream

This will be a cross-functional team representing manufacturing and quality throughout the value stream. Each physical location will have at least two representatives, one from manufacturing and one from quality. An ideal candidate for these positions:

- Has a positive attitude toward change in the company
- Wants to make a positive impact on production performance
- Is intimately familiar with their designated area
    - Understands day to day processes
    - Has a large network of contacts within the area to easily leverage more detailed knowledge as needed

In addition to representatives from each location, representatives from other key organizations such as Customer Quality Services and Quality Assurance

Investigation will be integrated into the team. While organizations such as these do not directly add value to the airplane through manufacturing, they support the improvement and customer facing side of production and will provide key insights to any process changes the team may make.

6.2 Team Formation, Metrics, Goals, and Deliverables

6.2.1 Formation

Forming the team requires support of management. This support is driven from the Vice President level and reinforced through observational data revealing the hidden factory of rework that is occurring in the inspection process.

With the support of upper management, the General Managers (2nd level supervisors) help identify the key individuals who meet the above criteria to support the lean initiative. The individuals selected for the team are met with individually to explain the lean project and to establish personal buy in for the project. The team consists of 12 individuals representing the breadth of the value stream as well as support organizations such as Quality Engineering and Quality Investigative Reporting.

6.2.2 Team Goals

The team's goal, first and foremost, is to improve quality. This focus on quality is clearly communicated to everyone involved with the project along with a reminder of the need to improve to accommodate increased production rates to prevent any rumors of head reduction from starting.

When determining goals for an improvement team, it is a delicate balance between setting goals that are high enough yet not too high. Goals must be set high enough to motivate members of the team and encourage support of management through the promise of significant return on their resource investment. However, goals cannot be too high as they become unreasonable and seemingly impossible to achieve.

For the Shake Optimization Team, the goals driving their activity are as follows:

- 50% Reduction in Rework Found by the Shake being Optimized
- 50% Reduction in Flow Time of the Shake being Optimized

Through interviews with potential team members, experienced improvement team leaders, and management, these goals reflect an appropriate balance between high enough, but not too high.

6.2.3 Team Metrics

The team goals revolve around rework and flow time. As described in the Current State, much of the rework that occurs during a Shake Inspection is not documented in the Boeing NCM database. Therefore, using the NCM database as a team metric would not reflect the actual performance of the team. Additionally, the actual flow time of the Shake Inspections is not consistently recorded. Therefore, a new method for recording rework and flow time must be implemented. This method can be found in the Rework Documentation Tool Development portion of this thesis.

Utilizing the Rework Documentation Tool, the team establishes baseline data from which improvements will be measured. This baseline current state metric for the Wheel Well is as follows:

- 75 instances of rework
- 6.33 hours of work

6.2.4 Deliverables

The Shake Inspection Optimization Team is responsible to deliver the following to the Factory Field Integration Team:

- Current State and Target Metrics
- Standard Work Flow Process
- Monthly Status Reports

Current State and Target Metrics

The Shake Inspection Optimization Team must provide current state metrics for each Shake Inspection under optimization. The current state metrics are a measure of the Shake Inspection prior to team activity. From the current state metrics, target metrics are calculated based on the team goals. The target metrics are then utilized to identify team progress as improvements begin to take hold.

Standard Work Flow Process

The Shake Inspection Optimization team must document and deliver the standard work flow for optimizing a Shake Inspection to the Factory Field Integration team for approval. This document identifies the generic sequence of action and inclues information hand offs necessary to reach the goals identified for the Shake Optimization Efforts.

Monthly Status Reports

The monthly status reports are to be delivered via the Factory Field Integration meeting. One or more members of the team will present to the Factory Field Integration team the current status, next steps, and where help is needed regarding the team's optimization efforts.

6.2.5 Team Activity

The team's first activity is to establish current state metrics. This is accomplished by documenting the Shake Inspection using the Rework Documentation Tool. While data for the current state metrics are being collected, the team simultaneously works on the standard process workflow.

The standard process workflow is developed primarily from the cross-functional teams deep knowledge of Boeing systems and processes. Working within existing processes is important to establish quick results. Quick results will help motivate everyone on the team through immediate positive feedback from their efforts. This standard process workflow can be found in the next Results section.

The team also looks to expand beyond existing Boeing processes. While the existing processes will be useful for driving quick change that builds motivation for people involved on the team, more innovative ideas must be incorporated to meet the team goals. The team will address these ideas through brainstorming sessions and project management as they apply to each Shake Inspection.

6.2.6 Results

The Shake Inspection Optimization Team has identified the Standard Inspection Work Flow for optimizing a Shake Inspection. This was developed through collaboration with other organizations within Boeing to ensure appropriate and efficient information and responsibility hand offs. The workflow is represented in the Figure 6-2 with functional organizations along the vertical axis, action items and tasks in the boxes, and hand off represented by arrows.

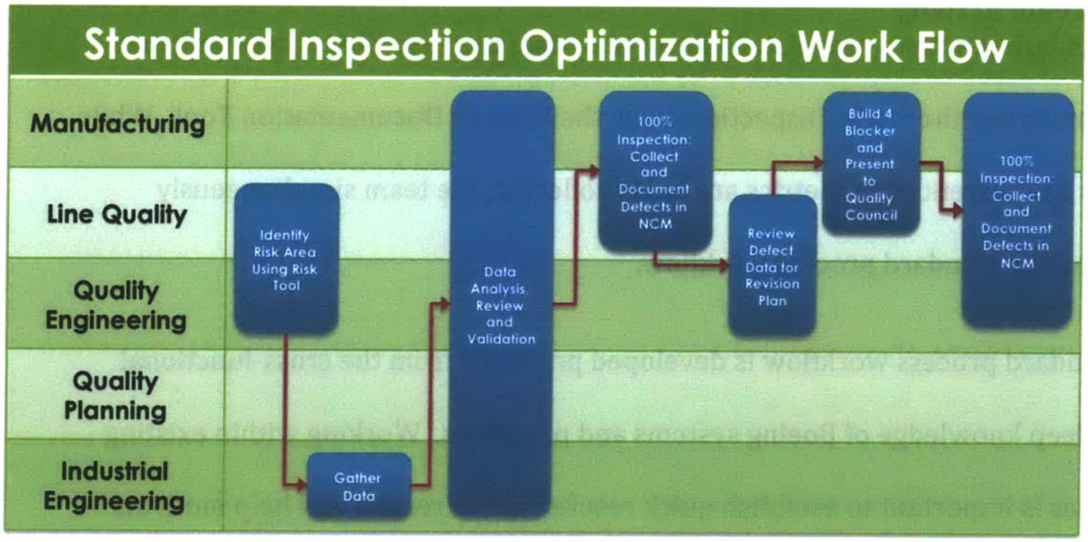


Figure 6-2: Standard Inspection Optimization Work Flow

The team is currently piloting this Standard Work Flow on the Wheel Well Shake Inspection. The Standard Work Flow may be updated going forward based on the results of pilot program scheduled to be complete around April 2011.

7 Rework Documentation Tool Development

This portion of the thesis covers the development of the Rework Documentation Tool. The goal of the Rework Documentation Tool is to develop a tool and method to document all rework with high quality records. The tool will reduce the barrier to data collection by more efficiently gathering the information necessary for quality rework documentation.

The development will focus on building a prototype tool to explore the possibilities for alternative data collection. The prototype will be used to demonstrate capabilities of computer based data collection and explore the possibilities for future production use.

7.1 Go and see

Before any development of the tool can take place, there must be a clear understanding of what the tool needs to accomplish. The first step in development is to go and see where the tool will be used to document rework.

Major observations:

- Large amount of rework occurring – 50 to 100 rework items per wheel well
- Rework falls into a relatively small number of categories with a few sub categories for each category
- Rework location will be very important

7.2 Requirements for tool

Based on observations of the Wheel Well Shake Inspection process and reviewing current data collection practices, the following tool requirements were identified:

- Quick to Use
- Quick to Learn
- Easy to Use
- Implement Standard Work

Quick to Use

The primary requirement for this tool is that it is quick to use. The tool will be used to more quickly document rework than previous methods, making rework less time intensive to document and utilizing resources more efficiently.

Quick to Learn

The tool must be quick to learn. This requirement will help during implementation because there will be less time investment necessary to adopt the new rework documentation process.

Easy to use

The tool must be easy to use. This will be critical in the success of the tool as ease of use correlates to how quickly rework can be documented. A tool that is difficult to use may marginally decrease or even increase rework data collection time. For example a tool with small print that is hard to read or buttons that are easily missed will take more time to document rework than a tool with text that is easy to read and buttons that are easy to select.

Implement Standard Work

Current data collection methods employ limited standard work. Rework or defect descriptions are based on user input. While this allows for flexibility throughout the production system, in a more focused area this can create significant problems. For example, a piece of engineered string-like material used to bundle wires together is called a string tie, a wire tie, a tie wrap, and a twist tie depending on the mechanic.

When searching the data records a search query will show only a portion of the string tie rework. Implementing standard work to consolidate the various names into a single term will increase the value of the collected data as it will be more accurate when filtered.

7.2.1 Type of Data to Be Collected

The goal of the tool is to document rework. The following information must be recorded to provide a high quality rework documentation record.

- Condition Requiring Rework
- Rework Location
- Rework Performed
- Why the Rework was Performed
- Time Study

Condition Requiring Rework

The current condition of the item requiring rework should be documented. This will allow the condition to be recognized in the future for pattern recognition and condition improvement.

Rework Location

Location can be recorded several ways. The traditional method is the three-point coordinate system used to identify any location on the airplane. This system is accurate and useful, but it is not very intuitive or easy to comprehend. Looking for a pattern in a series of three digit locations would be tricky at best. Alternative methods to the three-point coordinate system for locating rework could include visual defect mapping utilizing pictures and diagrams or relative proximity location identifying a point based on what is around that point.

Rework Performed

A clear record of the rework performed to bring the condition back into specification should be captured.

Why the Rework was Performed

The goal of capturing why the rework was performed is to help distinguish rework to bring the condition back into engineering specification from rework to bring the condition beyond the engineering specification at the request of the customer.

Time Study

Collecting time study information will serve as metric performance data. The reduction of flow time at the shake will directly be measured by the time study. This information will also help reveal the largest source of waste in the system.

7.2.2 Data collection Current State

The current method for documenting rework consists of a QA Inspector using a pen and paper to note the rework planeside on the production line regardless of who found the rework. For example, if a mechanic finds rework, in order to document the rework he or she must call over a QA inspector to note the rework on paper. Location is recorded using a three point coordinate system.

Once all of the rework is noted on the paper, the QA inspector then inputs the information into a desktop computer approximately 75 feet away from the point of noting the rework. There are a limited number of computers, which are also used to coordinate all other production activity for the airplanes such as installations, inspection, functional tests, and other work orders. The rework documentation process takes approximately 10 minutes per rework item (not including preparation time or wait time) and is susceptible to failure as jotted down notes are lost, misread, or misremembered before being expanded into more complete documentation on the computer.

7.2.3 Data collection Future State

In an ideal state, anyone should be able to document rework in less than a minute, utilizing standard work for more reliable searchable databases, with visual rework mapping for quick pattern recognition, without the need for multiple transcriptions onto paper and then into a computer database.

7.3 Technology Options and Assessment

There are several technologies that could be utilized to assist in a new rework documentation method. For the purpose of this thesis, the technology analysis will focus on construction of a short term prototype with limited functionality rather than a long term production ready tool.

Technology hardware options for the tool include:

- PDA – Personal Digital Assistant
- iPhone, Blackberry, or other Smart Phone hand held device
- Laptop Computer
- Tablet PC

Due to a readily available tablet PC at the Boeing Company, this technology option was selected for the prototype. It provides a portable interface, long battery life, and runs windows based software, but unfortunately, a stylus is required for touch screen information input rather than a more simple touch screen interface that responds to your finger input. Using the Tablet PC's for prototyping, the project will incur no additional equipment expenditure.

Software options for the tool include:

- Excel
- Access
- C++

Given the availability of the Microsoft Windows based tablet PC, along with the intern's familiarity with Excel, an Excel macro was selected as the software platform to build the Rework Data Collection Tool.

7.4 Build the tool

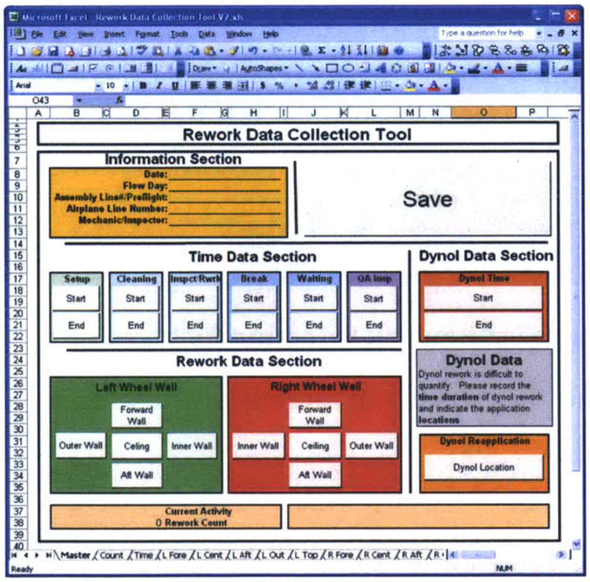
For a given area, there are a lot of rework items, but there are typically just a few conditions that are repeated several times. This provides an opportunity to document the rework quickly by taking advantage of the repetition.

Documenting rework consists of a user selecting a pre-determined original condition, rework activity, and location. Users have the option to type in the documentation information; however selecting the predetermined items is not only faster but also imposes standard work through consistent language when describing conditions. This standard work through menus creates a more reliably searchable database with consistent language allowing for more accurate data analysis and ultimately better decision-making.

Additionally, a particular out of specification condition may have several forms of rework that could bring the condition back into specification but typically there is a more commonly implemented rework activity for the condition. For example, given a tube that has been scratched, the mechanic could repair the scratch by scuffing the area and repainting it, remove and replace the pipe, or call the original installation team to repair the scratch. The most simple and common rework activity would be for the mechanic to scuff and repaint the scratch, and thus this is most commonly accepted as the default repair for a scratch. Commonly accepted rework activities, such as the mechanic scuffing and repainting a scratch, are color coded into the tool allowing the eye to quickly navigate to the default selection. This greatly helps the user confidently document rework at faster rates.

7.4.1 How does the tool collect data

Rework is documented through an intuitive touch screen interface on a tablet PC as seen in Figure 7-1. Anyone can collect the rework data including the mechanic, QA inspector, or industrial engineering. For the purposes of this thesis, we will refer to this individual as the data collector.



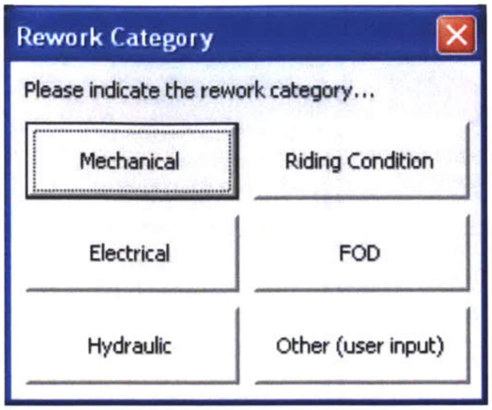
Dynol rework is difficult to quantify. Please record the **time duration** of dynol rework and indicate the application **locations**

Figure 7-1: Rework Data Collection Tool Main Menu

When rework is identified, the data collector selects the general region where the rework is found by clicking on the appropriate button. For example, this could be the forward wall of the wheel well, in which the data collector would click "Forward Wall". Upon selection of the region, a detailed picture of the actual region of the aircraft then appears as seen in Figure 7-2. The data collector clicks on the specific location of the rework. An arrow indicating the specific location appears with a corresponding identification number. The number next to the arrow relates the specific location of rework to a database record of the detail information regarding the specific rework activity.

Figure 7-2 Rework Selection Picture

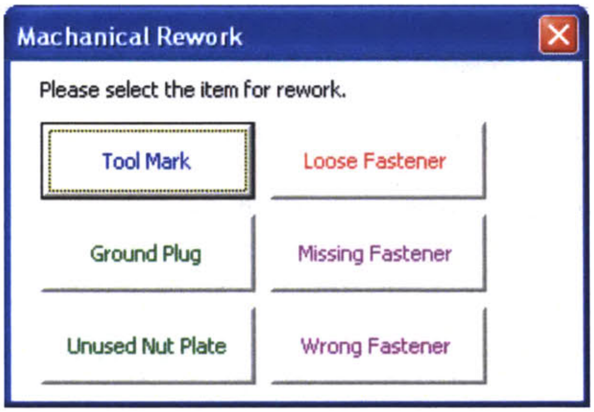
Once the location is selected, the category of rework is then selected via a menu that appears as seen in Figure 7-3. After the data collect selects a category, the arrow indicating the location of the rework changes color to visually reflect the category selection. The result is a color coded visual map of rework with numbers corresponding to more detailed data in a database.



Please indicate the rework category...

Figure 7-3: Rework Category Menu

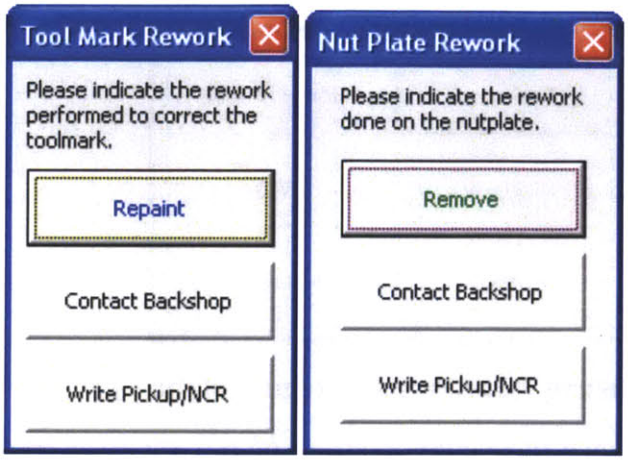
Within each rework category, the condition requiring rework is selected via another menu that appears after the data collector selects the rework category. An example of this menu can be seen in Figure 7-4.



Please select the item for rework.

Figure 7-4: Rework Condition Menu

Next the data collector selects the rework activity for the condition requiring rework. Default rework activity for a condition is color coded to match for more quick documentation. For example, the default rework activity for a tool mark is to repaint (as indicated by blue text in the menus) while the default activity for a ground plug or unused nut plate is to remove it (as indicated by green text in the menus). An example of this color coding can be seen in Figure 7-5.



Please indicate the rework performed to correct the toolmark.

Please indicate the rework done on the nutplate.

Figure 7-5: Rework Activity Selection Menus

7.5 Test the Tool

The tool was tested during production to record in real time the rework that occurred. There were three phases to testing the tool.

Phase 1 - Lab Testing

The first round of testing occurred during the development and coding process and was performed by the intern who wrote the data collection tool Visual Basic code. This testing was to ensure that buttons did what they were supposed to and data was recorded as expected. This testing was rather primitive yet exhaustive to ensure that everything would work on the production line.

Phase 2 – Initial On the Line Testing

The first real environment testing was done by the developer on the line. This allowed the developer to identify when the tool did not meet the needs of the production environment and make changes to fulfill those needs. Several days of testing were completed before proceeding to the next round of testing.

Phase 3 – Production Testing

Ultimately, the tool must be able to be used by anyone in the production system, therefore it was given to other individuals for further testing. This process provided incredibly valuable feedback and led to the restructuring of the tool to make it more intuitive for users.

7.6 Results

Results from the rework data collection tool include a documented list of all rework activity, visual location map of all rework activity, and time study of the shake inspection process. An example of the results can be seen in the following figures. Figure 7-6 shows the database records of the details behind the recorded rework. Each record has a number that corresponds to an arrow in the visual rework map as seen in Figure 7-7. Time study data can be extracted and displayed as seen in Figure 7-8.

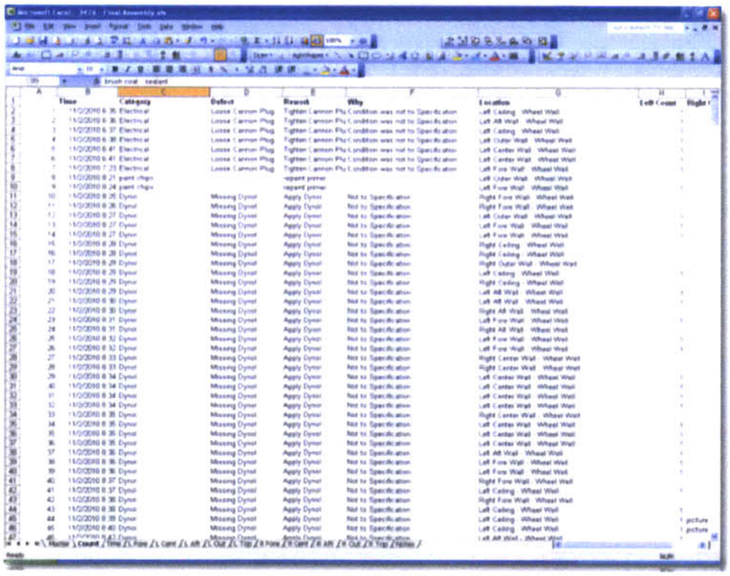
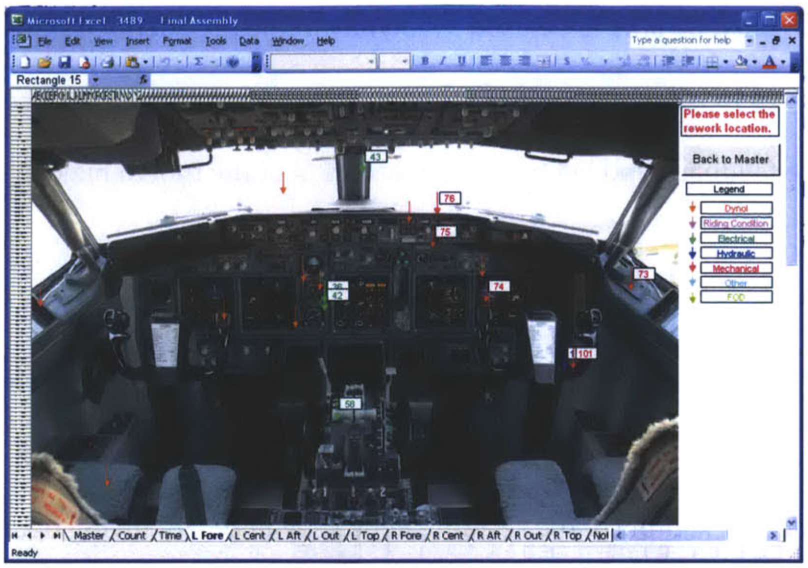


Figure 7-6: List of Rework Activity During Shake Inspection



Please select the rework location.

Figure 7-7: Visual Location Map of Rework Activity during Shake Inspection

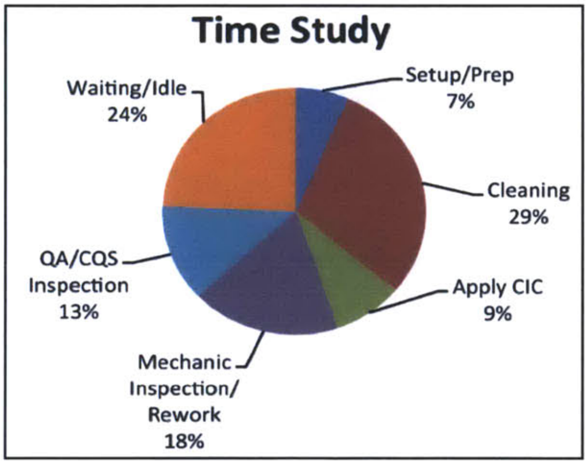
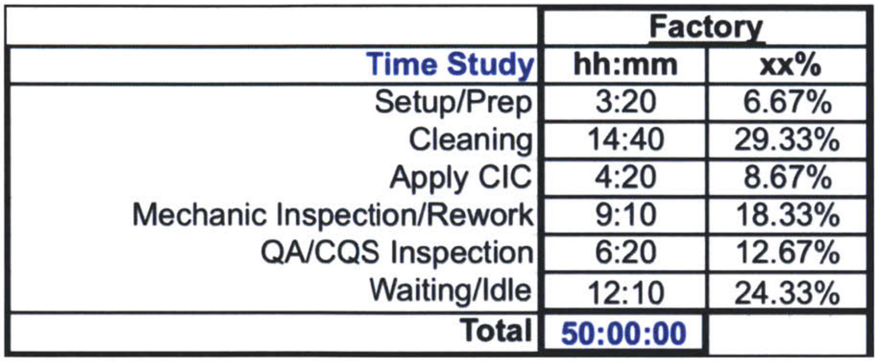


Figure 7-8: Summarized Time Study of Shake Inspections

Figure 7-9 shows the aggregate time study for 8 airplanes worth of observations.



	Factory	
Time Study	hh:mm	xx%
Setup/Prep	3:20	6.67%
Cleaning	14:40	29.33%
Apply CIC	4:20	8.67%
Mechanic Inspection/Rework	9:10	18.33%
QA/CQS Inspection	6:20	12.67%
Waiting/Idle	12:10	24.33%
Total	50:00:00	

Figure 7-9: Aggregate Time Study Data

7.7 Tool Application and Further Development

The current prototype tool, while functional and useful, leaves plenty of room for improvement. Such improvements would include:

- Flexibility – quickly change from one Shake to another
- Integration – integrate into the Boeing Companies NCM database
- Resolution – difficult to select specific locations or areas

These improvements could be incorporated into the tool through the use of professional software developers or off the shelf commercially available software. It would be important for the software tool to integrate with Boeing database systems and procedures.

8 System Dynamics Model

According to Charles Fine, every industry has its own clockspeed, or speed of business. In particular, he notes that "at the slowest end of the clockspeed scale are the manufacturers of aircraft"[5]. Due to the relatively short length of study at the Boeing Company and the slow clockspeed of the aircraft industry, data measuring

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[5] Charles H Fine, <u>Clockspeed</u> (Reading: Perseus Book, 1998).

the impact of the changes implemented by the Shake Inspection Optimization Team is not available. Therefore a detailed system dynamics model of the Shake Inspection process has been developed.

This model focuses on the decision to document rework performed during the Shake Inspection and the decision to increase resources devoted to driving improvements related to the rework found at the shake inspection. As mentioned previously, much of the rework that occurs during a shake is not documented due to the time constraint presented by the production rate. Each time an instance of rework is found, the mechanic makes a decision as to whether or not it should be documented. As a result, only higher impact rework items are documented leaving many of the low level items undocumented. Please note, this is in alignment with the FAA approved quality system at the Boeing Company.

The system dynamics model is constructed using data from the case study of the wheel well Shake Inspection; similar results would be expected in other Shake Inspections.

8.1 Model Formulation

The system dynamics model demonstrates the relationship between production rate, documented rework, corrective action resources, and overall time spent on the non-lean operation of shake inspections. The interesting part about a Shake Inspection is that the work is divided into two organizations within the Boeing Company. The mechanics belong to the manufacturing organization and do the physical work on the airplane. The QA inspectors belong to the quality organization.

They inspect the airplane and document rework that occurs on the airplane. The rework is performed by the mechanics, but documented by the QA inspectors.

Data driving the model formulation has been collected through observational data collection, interviews, production database queries, and observation. Like most models, this model is not perfectly accurate but it provides insights into how the organization works and policy changes that can be made to drive improvements.

8.2 Model Constraints

This model does not include financial estimates because the financial impact depends greatly on the actual rework that is occurring. The model will focus on the number or rework items and assume that each rework item requires the same amount of time to document and repair. This will avoid the need to distinguish between wire ties and scratches in the model.

All improvement activity is grouped into Corrective Action and is given equal impact on production. This does not account for the varying impact that different corrective action items may have. For example, correcting the standard work documentation for a particular installation could have a much smaller impact than re-sequencing tasks, yet both are given the same impact in the model.

The model also does not account for factory production variance. For example, when the factory is backed up and starves the Shake Inspection of work, this lack of productivity is not included in the model.

The model does not account for overtime. All work weeks are a standard 40 hours, thus the backlogs demonstrated by simulations would be much smaller due to overtime adjustments.

8.3 Simulation Results

There are several scenarios the system dynamics model simulates that are important regarding the optimization of a Shake Inspection.

8.3.1 Current State Simulation

The first scenario to present is the Current State of Shake Inspections where everything is in equilibrium. The Production Rate is a consistent 31.5 airplanes per month with a consistent 1.5 airplanes in Shake Inspection process as seen in Figure 8-1and Figure 8-2respectively. While 1.5 airplanes in process seems inaccurate, there are two production lines in the 737 factory with two different production rates. One production line conducts a particular Shake Inspection every day, while the other production line running at half the rate conducts the same Shake Inspection every other day, resulting in an average of 1.5 planes in the Shake Inspection process.

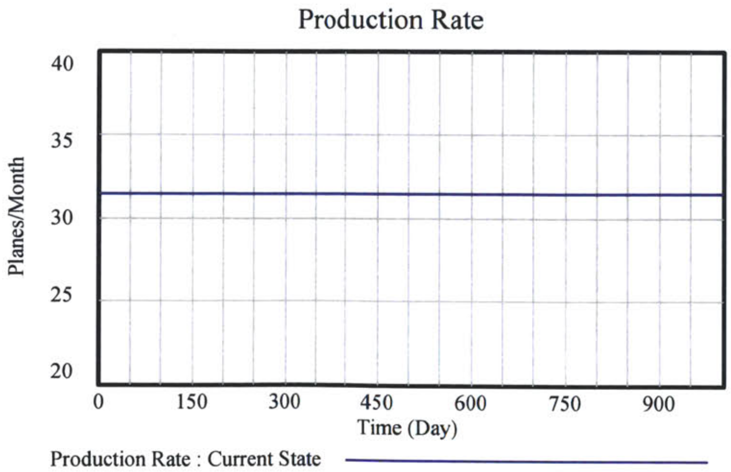


Figure 8-1: Current State Production Rate Over Time

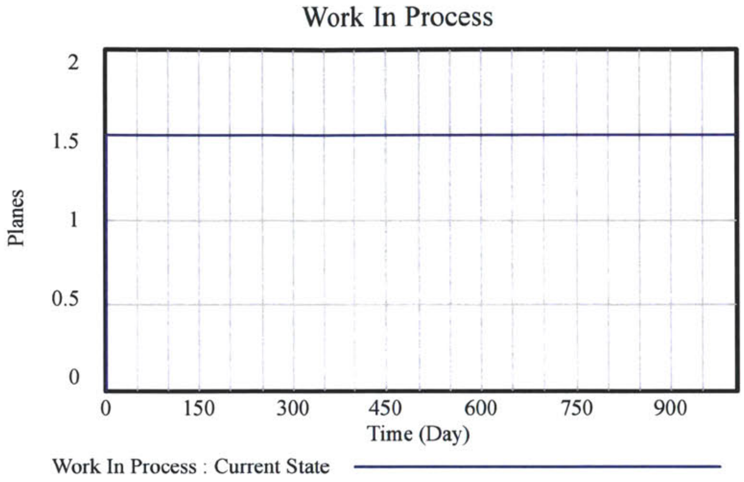


Figure 8-2: Current State Work In Process Over Time

Due to the high volume of Rework found on the airplane and limited amount of time allocated to document it, the Rework Documentation Percentage, or percent of rework that is documented, is a consistent 5.14% as seen in Figure 8-3. Comparing observational data with database data, the estimated 5% rework documentation rate appears to be accurate. The Total Time Spent on a Shake Inspection per Airplane is also consistent at 6.62 hours per airplane as seen in Figure 8-4. This time consists of the Mechanic's Pre-Shake and the QA Inspectors inspection and aligns with observations on the factory floor.

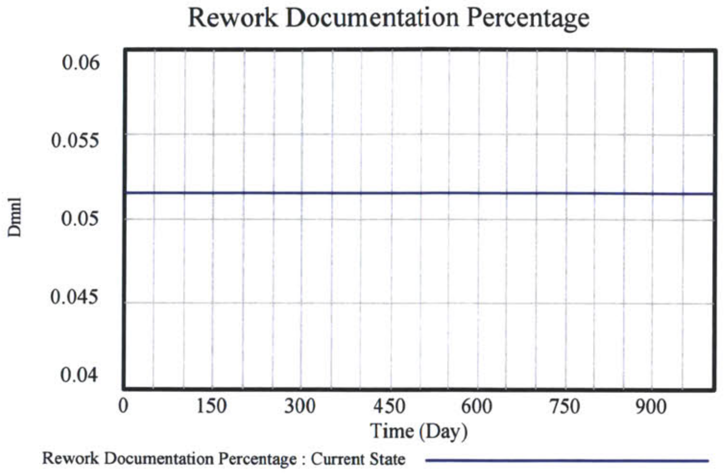


Figure 8-3: Current State Rework Documentation Percentage Over Time

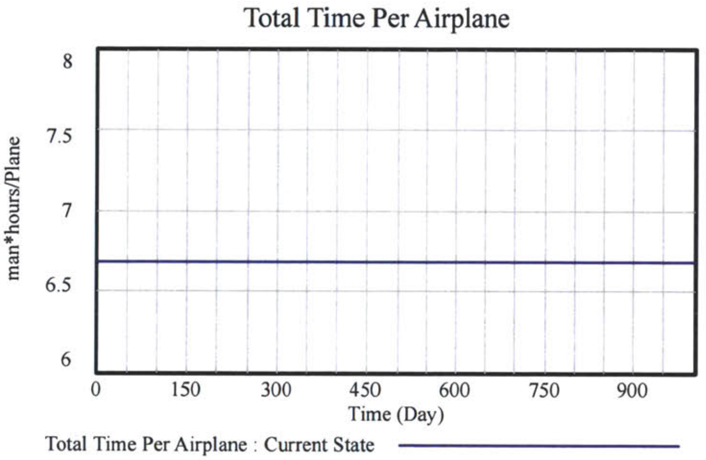


Figure 8-4: Current State Total Time Spent Per Airplane Over Time

It is understood that the Boeing Production system experiences more variability than is shown in this model. For example one plane may have 75 items of rework while another plane may only have 25 items of rework. For the purposes of simulation averages represent reality.

8.3.2 Production Rate Increase Simulation

As mentioned previously, if Boeing were to increase the production rates from 31.5 to 35 planes per month without making any changes to a Shake Inspection, the results would be as follows.

Figure 8-5, shows the Production Rate increasing from 31.5 to 35 airplanes per month 365 days into the simulation. This is in accordance with the projected rate increase in 2012. The first item to note is that the backlog of Airplanes Waiting for the Shake Inspection immediately begins to increase as seen in Figure 8-6. This demonstrates the time constraint very clearly. The current resources committed to the Shake Inspection are just enough to keep up with 31.5 planes per month, however with an increase in rate, a backlog builds quickly.

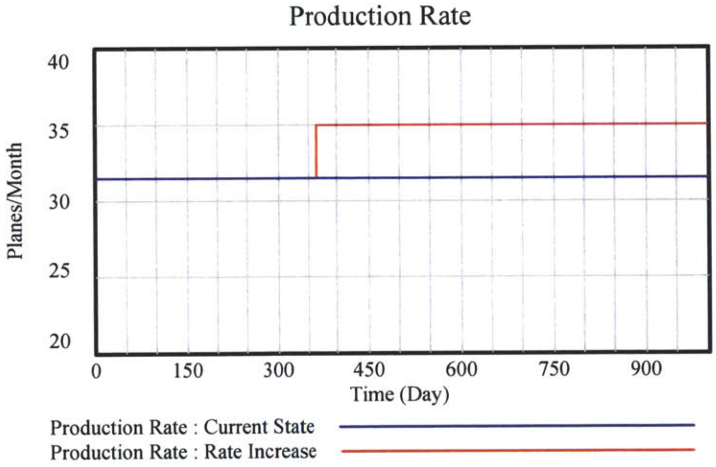


Figure 8-5: Current State and Increased Rate Production Rate Over Time

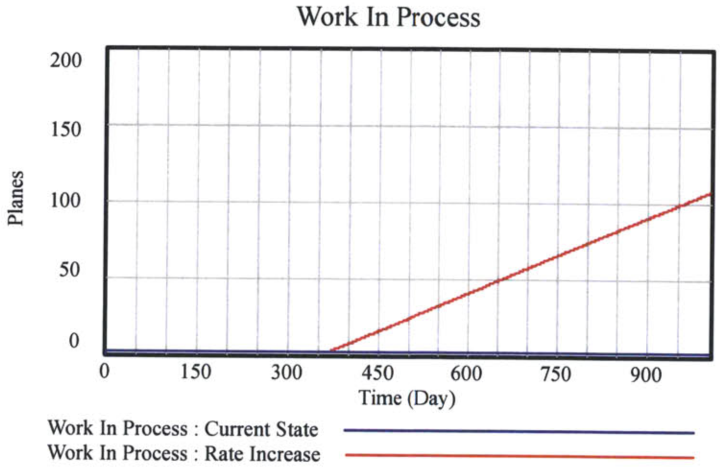


Figure 8-6: Current State and Increased Rate Work In Process Over Time

Additionally, it is noted that due to the increased production rate, there is even less time to document rework, thus the Rework Documentation Percentage drops from 5.14% to 1.0% as seen in Figure 8-7. Finally, the Total Time per Airplane reduces from 6.62 hours per airplane to 6.52 hours per airplane as seen in Figure 8-8. This slight reduction in hours spent per airplane is due to the decreased Rework Documentation Percentage. The same amount of rework is being performed yet less of it is being documented, thus the total time is reduced by the less time spent documenting rework.

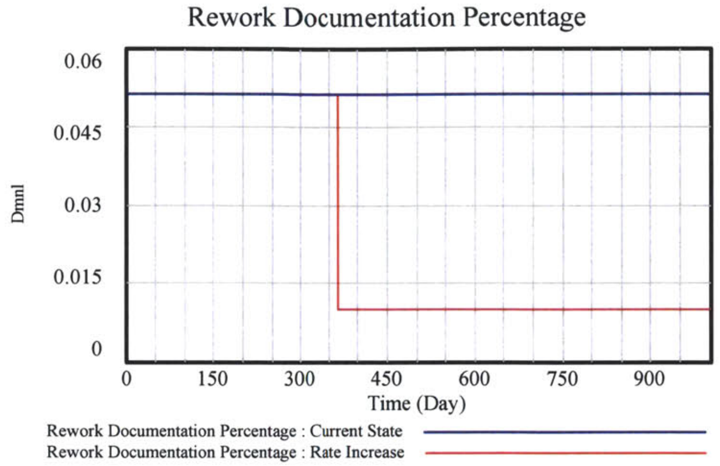


Figure 8-7: Current State and Increased Rate Rework Documentation Percentage Over Time

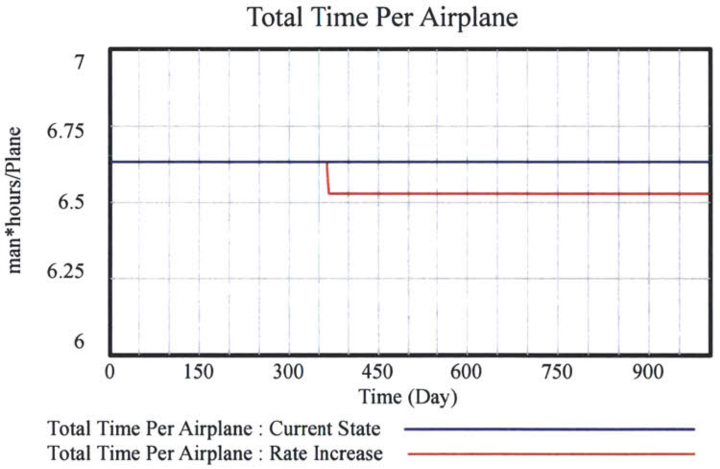


Figure 8-8: Current State and Increased Rate Total Time Per Airplane Over Time

It is clear from the backlog that significant changes must be made to accommodate an increase in production rate.

8.3.3 Shake Inspection Optimization

There are two components driving Shake Inspection optimization. The first component is to utilize the Rework Documentation Tool to document all rework. In addition to documenting the rework, resources in the form of a Shake Optimization Team are dedicated to utilizing the documented rework to drive change.

In the model, the first change will be to increase the Rework Documentation Percentage to 100% from the Current State value of 5.14% as seen in Figure 8-9. Recording the rework alone will not have significant impact on the model. In addition to the Rework Documentation Percentage, the Corrective Action Resources must be increased. An appropriate increase in Corrective Action Resources would be 20 man*hours/week. This would be equivalent to 1 full time employee, or a team of 10 employees each dedicating 2 hours a week. For maximum effect, these changes must be made before the production rate increase. For this model they are implemented 50 days into the simulation. These model modifications combined with the projected rate increase produces the following results.

Like the previous simulation, the Production Rate increases 365 days into the simulation as seen in Figure 8-9. Additionally, the Rework Documentation Percentage is set to 100% after 50 days into the simulation.

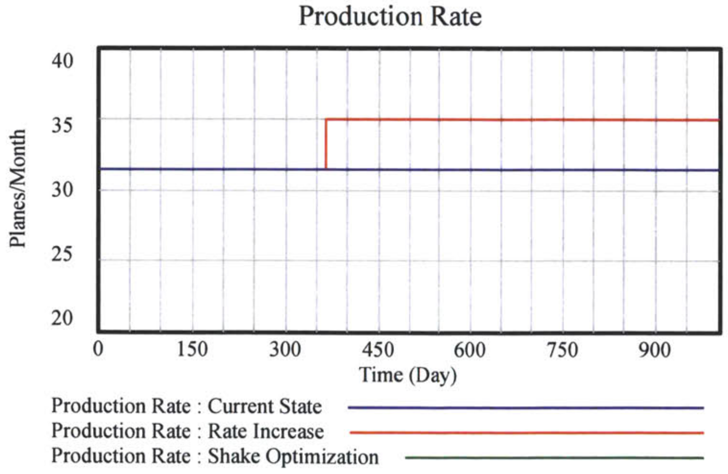


Figure 8-9: Shake Optimization, Rate Increase, and Current State Production Rate Over Time

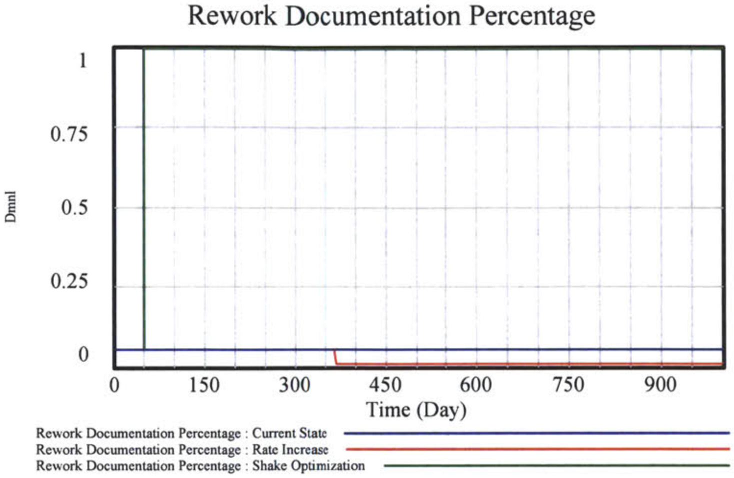


Figure 8-10: Shake Optimization, Rate Increase, and Current State Rework Documentation Percentage Over Time

When looking at the Work In Process, the backlog of airplanes currently in the Shake Inspection Process can be seen to increase and then decrease in Figure 8-11. The simulation shows the backlog approaching 50 airplanes. While this seems wildly large, the simulation does not account for any overtime or employee rotation. In reality, there would be a backlog, but it would never reach 50 planes due to increased overtime and rotating more employees into the Shake Inspection process.

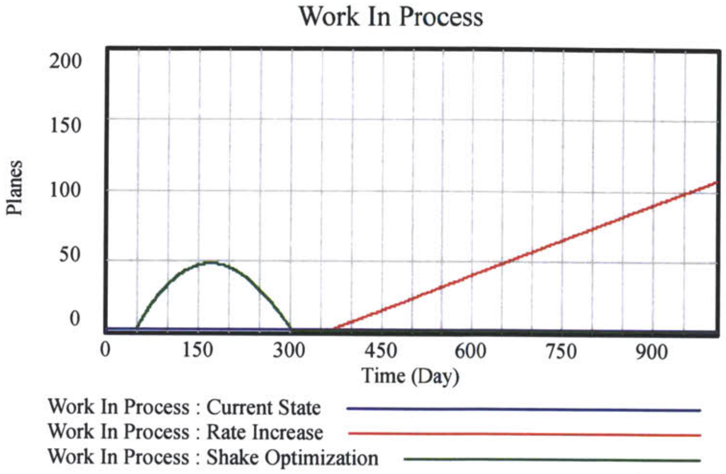


Figure 8-11: Shake Optimization, Rate Increase, and Current State Work In Process Over Time

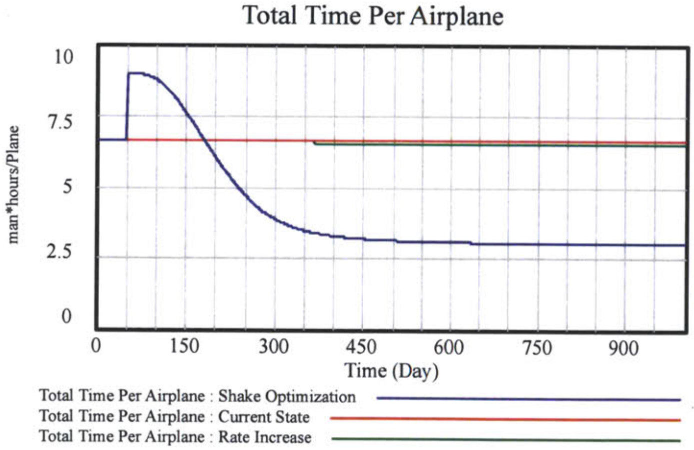


Figure 8-12: Shake Optimization, Rate Increase, and Current State Total Time Spent Per Airplane Over Time

The Total Time Per Airplane is where the benefit of committing resources and additional effort into the Shake Inspection pays off. As seen in Figure 8-12, the Total Time Per Airplane experiences a 'worse before better' scenario. At first, the time increases due to the increased Rework Documentation Percentage and mismatch of resource to demand. However, the feedback loops strengthened by the additional Corrective Action Resources and high Rework Documentation Percentage ultimately drive quality improvements reflected in the reduction of the Average Rework per Airplane. These quality improvements drive the time savings and allow the production rate to increase without serious backlogs. In the model, these improvements are implemented based on the number of people working on the stock of corrective items relative to the number of items in the stock. For example, many people working on a few items will resolve the stock much more quickly than a few people working on many items. In reality, this corrective action will occur through the optimization teams collaboration with the Quality Investigation organization and the manufacturing organization. The optimization team would attend quality focused meetings where found items would be brought forth for discussion, monitoring, and resolution.

An interesting result of the simulation lies in the division of the Total Time per Airplane according to the organization performing the work. The Total Time consists of time spent by a mechanic (also called Shop) reworking items as well as time spent by a QA inspector inspecting and documenting the rework. As shown previously, the Total Time per Airplane relative to the current state is reduced through Shake Inspection optimization efforts however the QA Time Per Airplane actually increases relative to the current state as seen in Figure 8-13. While initially unintuitive, this increase of QA time relative to the current state makes sense. Previously, the QA Inspectors were documenting about 5% of the rework. After the changes, they are documenting 100% of the rework. Even though the rework has been significantly reduced, the amount of rework documented increases requiring more time of the QA Inspector. By implementing the more time efficient data collection tool discussed in chapter 7, the total QA time required would not change due to the increased Rework Documentation Rate. The real time savings comes from the significant reduction in mechanic time spent per airplane as seen in Figure 8-14.

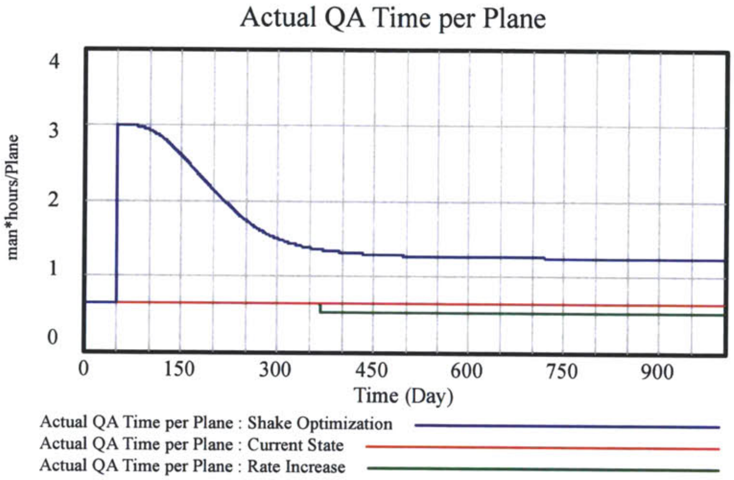


Figure 8-13: Shake Optimization, Rate Increase, and Current State Actual QA Time Spent Per Airplane Over Time

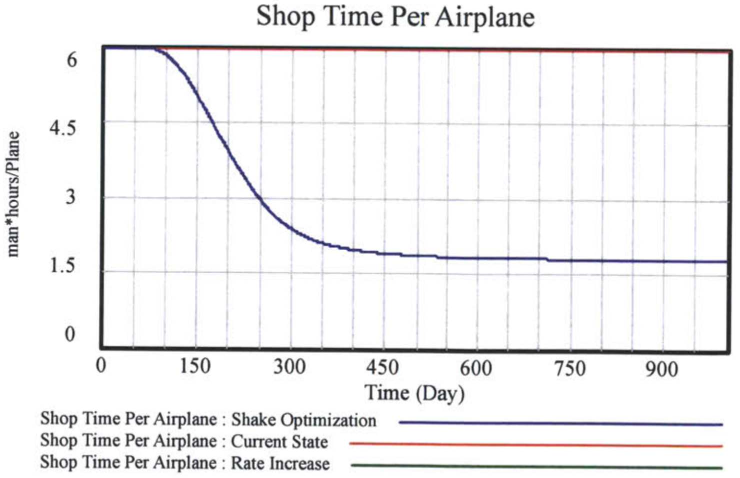


Figure 8-14: Shake Optimization, Rate Increase, and Current State Actual Mechanic Time Spent Per Airplane Over Time

This is an important discovery because it will allow management to allocate resources more accurately before and after the Shake Optimization. Management will best prepare for Shake Optimizations by anticipating this need for more QA Inspection resources due to a higher rate of rework documenting while also understanding that the optimization will free up mechanics to help with other work orders.

8.4 Validation

The simulations show that by documenting 100% of the rework and allocating resources to a Shake Inspection Optimization team, the total time per airplane will be reduced from 6.62 hours to 3.05 hours. Currently the average Wheel Well Shake takes 6.33 hours. By looking at the Wheel Well Shake Inspection time study data collected using the Rework Documentation Tool, it can be seen that by reducing the cleaning, rework, CIC, and idle time through Shake Inspection Optimization Team efforts, the overall time can be reduced by half. The setup/prep, QA inspection, and Mechanic Inspection time cannot be reduced significantly thus making up the majority of the remaining 3 hours of Shake Inspection time.

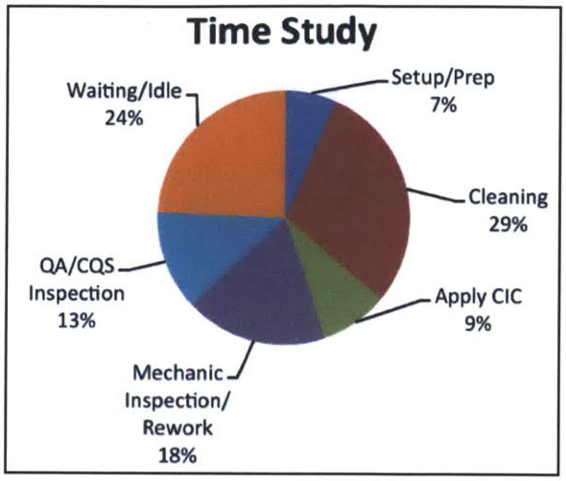


Figure 8-15: Wheel Well Shake Inspection Observational Time Study

The simulation results align with actual Wheel Well Shake Inspection observation data validating the system dynamics model.

9 Business Case

The need to improve Shake Inspections sells itself – given the announced production rate increase, without improvement there will be significant production problems, as demonstrated by the simulation. Overtime and employee rotation will be necessary to keep up with the higher production rates. Every area will be struggling to keep up with the new rates resulting in the inability to rotate employees. This leaves overtime to pick up the slack.

9.1 Process Deployment

The standard Shake Inspection Optimization Process as developed, defined, and demonstrated by the Shake Inspection Optimization team is currently being piloted on the Wheel Well Shake Inspection. The team has a roadmap from the Shake Inspection Decision matrix for future deployment to other Shakes. With success and positive process adjustments from the first Shake Inspections to be optimized, the standard process can be expanded at a larger rate. This will require more resources, but management should understand this is a significant opportunity to prepare for production rate increase.

9.2 Costs

Most of the costs associated with Optimizing the Shake Inspections are in the form of time. It will require the time of the Shake Optimization Team to drive the Shake Inspection improvements. Other costs would include further Rework Data Collection Tool development. Although the cost benefit analysis for this tool is difficult to accurately calculate, many leaders within Boeing are pushing for rework or defect visual mapping capabilities. This software prototype tool is one realization of visual mapping but further flexible capabilities must be built into the tool before production implementation.

9.3 Benefits

As shown through the simulations, by committing a 20 hours per week of improvement team resources, the Optimized Shake Inspection will require 20 hours less per week. This provides a 1:1 return during the Optimization, however after the Shake Inspection Optimization Team moves onto the next Shake Inspection, the time savings really begin to add up. Assuming two Shake Inspection are optimized per year, in the first year there is a 2:1 return on time invested into optimization efforts through the reduction of time required by the Shake Inspections. After two years, this return is 4:1. Long term commitment to improve the shakes will provide the greatest return on improvement efforts.

10 Conclusion

Shake Inspections represent and significant area for process improvement at Boeing. Not only are the Shake Inspections redundant to other inspections, but there is also a lot of time spent on individual inspections and the 80 inspections as a whole. This thesis looked at the impact of spending time to improve an individual Shake Inspection through quality improvements. The next step will be utilizing the data from the quality improvements to support the decision to eliminate appropriate Shake Inspections from the production process.

10.1 Recommendation

Based on the research conducted during the internship and computer simulations it is recommended that Boeing document 100% of the rework that occurs during a Shake Inspection. Ideally, this would be done with a computerize tool allowing visual rework mapping and quick documentation to quickly and efficiently collect the information.

Documenting 100% is the first step to improvement. It provides the information that can be used to make data based decisions to drive improvements. The second step toward optimization is committing resources to a Shake Inspection Optimization team to continue to define and implement a standard optimization process.

10.2 Extensions

Further investigation of implementing a computerized handheld data collection tool should be performed. One significant area for consideration would be the cost of internally developing a computerized Rework Data Collection tool versus purchasing off the shelf software such as the sample found in Quality Engineering called Inspect. This would involve understanding how to better integrate the tool into the existing Boeing databases as well as ensuring the tool is flexible enough for applications throughout the value stream. Other emerging technologies should also be investigated. For example, the low cost netbooks or slate PC such as the iPad could serve as a very good hardware base for a Rework Data Collection tool. Their low cost and finger based touch screen interface could be leveraged effectively in the tool's software.

10.3 Next Steps

The next steps are for the established Shake Inspection Optimization Team to continue their activity on the Wheel Well Shake while also looking forward to the next Shake Inspection. The team also should consistently re-evaluate the decision matrix to ensure system changes are reflected in their roadmap.

Ultimately, the success of the Shake Inspection Optimization team will help the Boeing 737 Program succeed in delivering the popular 737 Airplane at a faster rate to the eager customers.

Works Cited

Crute, V, et al. "Implementing Lean in aerospace - challenging the assumptions and understanding the challenges." TECHNOVATION 23.12 (2003): 917-928 .

Fine, Charles H. Clockspeed. Reading: Perseus Book, 1998.

Reason, James T. The Human Contribution: Unsafe Acts, Accidents and Heroic Recoveries. Burlington: Ashgate Publishing, Ltd, 2008.

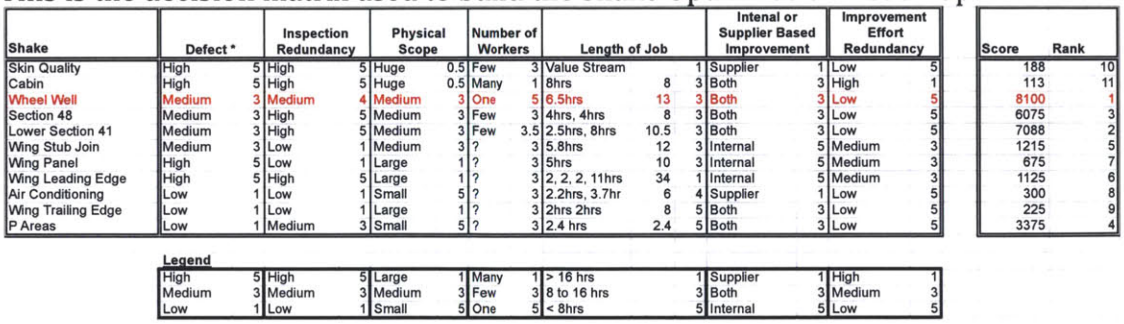
Spear, Steven J. Chasing The Rabbit. New York: McGraw-Hill, 2009.

Sterman, John D. Business Dynamics: Systems Thinkingand Modeling for a Complex World. Boston: McGraw-Hill Higher Education, 200.

Womack, James P., Daniel T. Jones and Daniel Roos. The Machine That Changed the World. New York: Free Press, 1990.

Appendix A

This is the decision matrix used to build the Shake Optimization Roadmap.



Shake	Defect *		Inspection Redundancy		Physical Scope		Number of Workers		Length of Job			Intenal or Supplier Based Improvement		Improvement Effort Redundancy		Score	Rank
Skin Quality	High	5	High	5	Huge	0.5	Few	3	Value Stream		1	Supplier	1	Low	5	188	10
Cabin	High	5	High	5	Huge	0.5	Many	1	8hrs	8	3	Both	3	High	1	113	11
Wheel Well	Medium	3	Medium	4	Medium	3	One	5	6.5hrs	13	3	Both	3	Low	5	8100	1
Section 48	Medium	3	High	5	Medium	3	Few	3	4hrs, 4hrs	8	3	Both	3	Low	5	6075	3
Lower Section 41	Medium	3	High	5	Medium	3	Few	3.5	2.5hrs, 8hrs	10.5	3	Both	3	Low	5	7088	2
Wing Stub Join	Medium	3	Low	1	Medium	3	?	3	5.8hrs	12	3	Internal	5	Medium	3	1215	5
Wing Panel	High	5	Low	1	Large	1	?	3	5hrs	10	3	Internal	5	Medium	3	675	7
Wing Leading Edge	High	5	High	5	Large	1	?	3	2, 2, 2, 11hrs	34	1	Internal	5	Medium	3	1125	6
Air Conditioning	Low	1	Low	1	Small	5	?	3	2.2hrs, 3.7hr	6	4	Supplier	1	Low	5	300	8
Wing Trailing Edge	Low	1	Low	1	Large	1	?	3	2hrs 2hrs	8	5	Both	3	Low	5	225	9
P Areas	Low	1	Medium	3	Small	5	?	3	2.4 hrs	2.4	5	Both	3	Low	5	3375	4

Legend

High	5	High	5	Large	1	Many	1	> 16 hrs	1	Supplier	1	High	1
Medium	3	Medium	3	Medium	3	Few	3	8 to 16 hrs	3	Both	3	Medium	3
Low	1	Low	1	Small	5	One	5	< 8hrs	5	Internal	5	Low	5

Appendix B

Shake Inspection System Dynamics Model