Tool Selection and Kitting: Technical and Organizational Issues

by

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B.S.E. Mechanical and Aerospace Engineering
Princeton University, 2007

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

Master of Business Administration
and
Master of Science in Mechanical Engineering

In conjunction with the Leaders for Global Operations Program at the
Massachusetts Institute of Technology

June 2013

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Abstract

Boeing South Carolina builds the Boeing 787 Dreamliner, the world's first composite-skinned wide-body jet. This new manufacturing facility is evolving to meet the demands of building this complex aircraft. One of the challenges faced by this site is providing the manufacturing workforce with the best tools for the job in an efficient manner. Two different research streams investigate this high-level problem.

First is a technical investigation into the selection of a cutter (drill bit) for use in drilling Carbon Fiber Reinforced Plastic (CFRP) and titanium stacks found in the door surrounds of the aircraft. It was found that a double margin tungsten carbide (WC) cutter with a 135° point angle and double margin design had superior cost and quality performance as compared to a 118° point angle polycrystalline diamond (PCD) cutter with a single margin design that was previously used. For this specific application, changing to the proposed WC cutter resulted in savings of approximately 66% per airplane in tool costs alone and a 62% reduction in defects.

Second is an investigation into the use of tool kits as a means of providing the manufacturing workforce with commonly needed tools. It was found that kits were not as effective as anticipated in reducing the wasted time from retrieving tools at a central location known as a Tool Crib. To ameliorate this, a series of investigations were conducted, creating analytical tools for identifying shortcomings in the tool kitting distribution system. A team was formed to execute improvements based on the analytical tools developed and achieved a 45% reduction in tools retrieved from outside mechanics' work areas over a 12-week period.

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Acknowledgments

I would like to thank the Boeing Company and MIT's Leaders for Global Operations program for their partnership that made my internship and this thesis possible. Thanks to my thesis advisors, Dan Whitney and Steve Spear for their guidance throughout my internship while they were balancing many other commitments. Thanks to my supervisor, Jeremy Stewart, and project champion, Ray Healy, for sponsoring my internship. Their support was above and beyond that required for my thesis, and because of it, I learned much more than is reflected in this document.

The work discussed in this thesis was dependent on help from many people. I thank George Robbins and Brent Craig for introducing me to positive feed drilling, Dzoan Tran and Ed Hojnacki for supporting our experimentation, and Liliana Hughen for monitoring the impacts of our change on production. I also thank Azhar Shah and Mike Maxfield for putting my suggestions for tool kitting into practice, and teaching me about the implementation challenges that are not reflected in the data. Thanks to the entire Tool Services organization for having me as a team member and teaching me about their operations.

I would also like to thank my fellow students for their support and for always being there to bounce ideas off of. In addition, the LGO alumni at Boeing South Carolina were an invaluable resource to me.

Last, I thank my family. I appreciate my parents' support throughout my busy two years in the LGO program. And thanks to my wife Jessica, who always found a way to visit from another state while going to school, working, and serving the community.

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1 Thesis Introduction

Imagine the challenges of starting up new factories to produce the world's most advanced commercial aircraft in a place where aircraft manufacturing had no prior presence. This is the challenge that the Boeing Company took on with the 787 Dreamliner in Charleston, South Carolina starting in 2005. From the ground up, Boeing needed to build manufacturing facilities, supply chains, and a workforce.

In a broad sense, this thesis will focus on the challenges related to tool selection and usage at Boeing's new location, referred to as Boeing South Carolina (BSC). The examples and information presented are based on a six-month internship working within BSC's Tool Services and Hazardous Materials organization. I examine the following high-level question in further detail, with the aid of examples from my time spent working in the Tool Services and Hazardous Materials organization:

> *How does management ensure that the best tools for the job are made available to mechanics in an efficient way?*

The discussion that follows consists of two streams of investigation, one based on the selection of a "designated" tool – one that is mandated for a specific manufacturing operation – and one based on the efficient use of "undesignated" tools – those that mechanics may choose for the manufacturing operation they are performing. This general classification of tools can be applied to any aircraft manufacturing facility as well as factories in other industries.

One can imagine a case in a variety of manufacturing plants (not only in aerospace) when a worker is free to choose the length or grip size of a screwdriver according to his preferences (undesignated tool) for fastening a cosmetic part. It is more likely for a tool to be undesignated when there are not strict specifications for the operation that the mechanic is performing, and the mechanic can benefit (e.g. ergonomically) from using a preferred tool. However, that same worker may be required to use a specific torque wrench (designated tool) when tightening a safety-critical bolt. Here, there are strict engineering specifications on the manufacturing operation that the company wants to ensure are repeatable with little variation.

At BSC, undesignated tools represent the majority of tools used to build the aircraft, which presents logistical problems associated with selection, storage, packaging, and distribution to mechanics across three shifts. Common hand tools, such as wrenches, pliers, or hammers tend to be undesignated. For these "durable" (reusable) tools, Boeing has chosen to pursue a strategy that distributes tools to mechanics in packages called kits, which are approximately the size of a laptop bag. A small team from Tool Services is devoted to building, distributing, and updating kits based on mechanics' input. The main alternative to obtaining a tool from a kit is retrieving it from a Tool Room (commonly called a "Tool Crib"), where mechanics request tools from attendants.

The goal of durable tool kitting is to eliminate the need for mechanic visits to the Tool Crib for standard work activities so that more of the mechanic's workday can be spent on value-added activities required to build the airplane. My investigation into kitting undesignated tools involves BSC's approach to kitting a new manufacturing operation and aims to provide insights on how to make incremental improvements to kits as the manufacturing site evolves. As will be discussed, there are some organizational and behavioral issues when introducing changes to a manufacturing operation. This research dives into those challenges with the aim of making tool kitting at BSC more effective.

A common designated tool that is investigated in this thesis is a cutting tool (also "cutter"), or a drill bit. In the manufacturing cell studied, the selection of the tool is most important. As one would expect, Boeing has a number of controls in place around selecting designated tools as they are used for precision manufacturing operations. For this reason, once a designated tool is selected, it can be difficult to change – both in terms of costs and resources. My investigation into designated tools provides an example of the organizations and processes involved in changing a designated tool, as well as some technical insights into the challenges associated with drilling stacks (combined layers) of Carbon Fiber Reinforced Plastic (CFRP) and titanium with a single-setting drill.

1.1 Thesis Structure

This thesis is structured into two mainly self-contained sections. The first deals with the selection of a designated cutting tool for drilling some of the holes necessary to assemble the 787's aft door surround structures. The second focuses on improving how mechanics retrieve the undesignated tools they need to perform their work on the airplane. To help orient the reader, some relevant background information on Boeing South Carolina is provided before discussing either research stream. Each section introduces a problem and provides relevant background information, leading to a hypothesis. Then a research methodology is described for testing the hypothesis along with the results obtained. Sections conclude with a summary and further questions generated based on the results. Before presenting the aforementioned sections, a brief background on the Boeing 787 aircraft and the Boeing South Carolina site provides context for the technical and organizational issues in this thesis.

2 Boeing South Carolina

Since both the 787 and the South Carolina site are relatively new to Boeing, an overview of the product and the site history helps set the stage for the forthcoming research. The composite-skinned 787 presents new manufacturing challenges for Boeing, a company that has decades of experience working with aluminum-skinned aircraft. Starting a new aircraft manufacturing site thousands of miles away from another Boeing factory presents not only challenges one would expect, but also opportunities to "start over" by deliberately transferring some established Boeing practices while leaving others behind.

2.1 787 Dreamliner

The 787 Dreamliner is the world's first wide-body commercial aircraft made with a composite-skinned fuselage as opposed to a traditional aluminum-skinned fuselage. Due to their high strength-to-weight ratio, composites are particularly attractive for aerospace applications. Composites, including Carbon Fiber Reinforced Plastic (CFRP) comprise 50% of the aircraft's primary structure by weight (The Boeing Company, 2012), as shown in Figure 1. By achieving a reduced weight, and using advanced engines, the 787 is expected to use 20% less fuel than similarly sized airplanes. Fuel efficiency contributes to the 787's long range – the second-longest range in the Boeing fleet, able to travel 7,650 – 8,500 nautical miles with 210 – 290 passengers. (The Boeing Company, 2012)

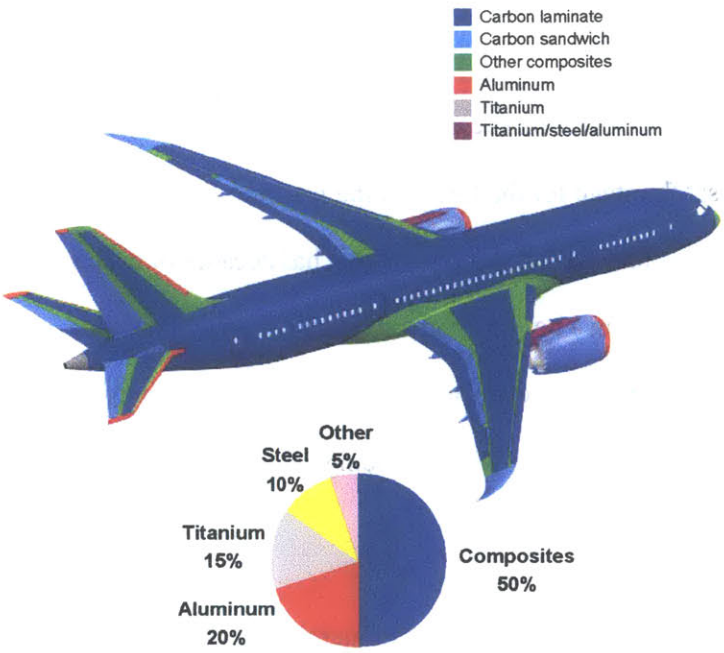

Figure 1: Material Breakdown of 787[1]

To bring the product to market, Boeing set up a sophisticated supply chain that includes partners located in North America, Europe, Asia, and Australia to fabricate major parts of the aircraft. Figure 2 shows where the major parts of the 787 are made. The aircraft is assembled in two final assembly facilities, one in its well-established Everett, WA factory, and the other in a new factory in Charleston, SC. The following Site Background section will provide an overview of the Charleston, SC facility, where this research was conducted.

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[1] Image obtained from the Boeing Company.

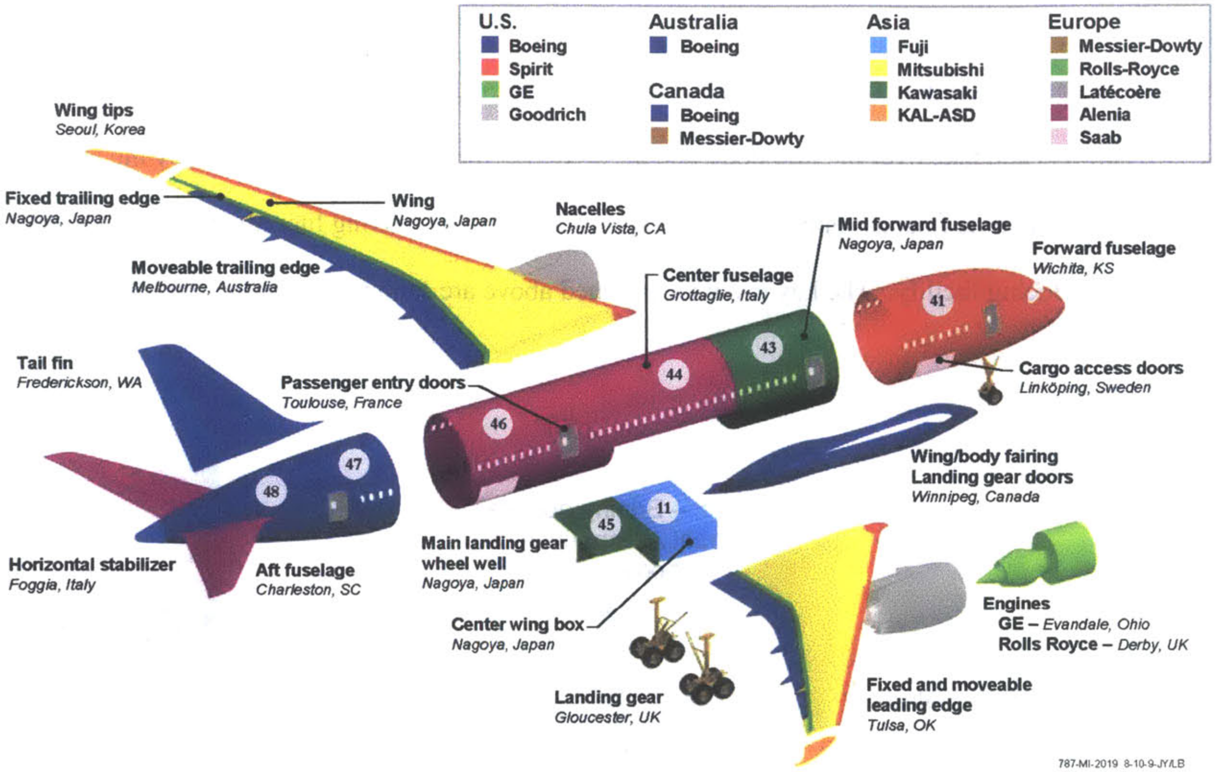

Figure 2: Origins of Major 787 Parts[2]

2.2 Site Background

Of particular importance to understanding Boeing South Carolina (BSC) is an overview of the site and its history. The site's beginnings have had a lasting impact on its organizational structure, political landscape, and cultures throughout the site.

The main production facilities at Boeing South Carolina are aft body (fuselage sections 47 and 48) fabrication and assembly, mid body (fuselage sections 43, 44, 45/11, and 46) assembly, and final assembly. Here, fabrication refers to making fuselage sections from raw material (carbon fibers and plastic resin), and assembly refers to the operations that join the parts of the aircraft together. Assembly includes everything from fuselage sections to wings to interior carpeting. Presently, all of these facilities are owned by Boeing; however, they were originally operated by three different entities. In 2006, the aft body and mid body facilities were opened by Vought and Global Aeronautica respectively. Global

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[2] Image obtained from the Boeing Company.

Aeronautica was a joint venture between Boeing, Vought, and Alenia, an Italian company that fabricates part of the mid body section in Grottaglie, Italy. Over time, Boeing made a strategic decision to buy out these two partners and take over the mid body and aft body facilities, which was finalized by the end of 2009. Boeing opened its final assembly facility in the middle of 2011, having literally built it from the ground up as a Boeing facility. The key events mentioned above are summarized in the timeline in Figure 3.

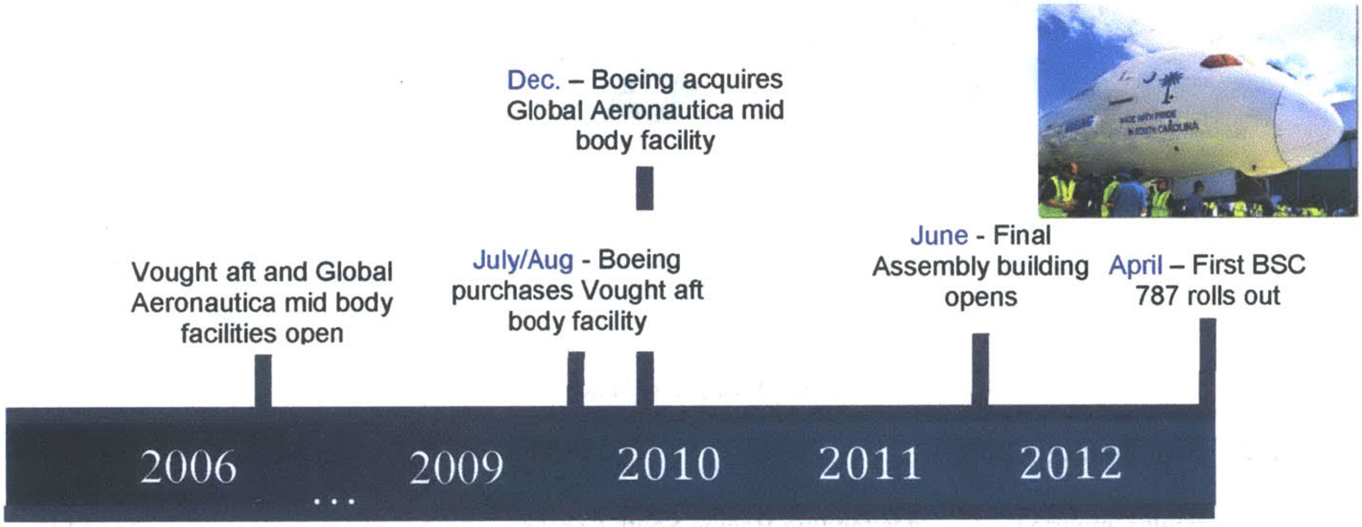

Figure 3: Boeing South Carolina Timeline

Last, it is worth mentioning why Boeing selected Charleston, SC as the location for this new manufacturing site. An important reason Charleston was selected was because South Carolina is a "right to work" state. BSC is currently operated without a union. There were also considerations related to the workforce, tax implications, and labor costs. This site has created some tension with the unionized workforce in the Seattle area, Boeing's primary center for commercial airplane manufacturing (Foust & Bachman, 2009). BSC is the single supplier of assembled mid body and aft body sections to its own final assembly facility and the other in facility Everett, WA. The origins of each facility at BSC help explain differences that still exist today, and these differences will be referred to throughout this thesis.

3 Tool Selection Example: Door Surround Drilling Operations

3.1 Synopsis

A major part of airframe assembly involves drilling holes through the skin and frames, and installing fasteners. While this is well-understood for aluminum-skinned aircraft, which have been produced for decades, it is more challenging for composite-skinned aircraft since carbon fiber reinforced plastic (CFRP) is highly abrasive, which accelerates tool wear, and has a low thermal conductivity, allowing heat to build up during the drilling process. Moreover, when attaching CFRP skin to titanium structures, drilling is more challenging due to the conflicting drill parameters favored by each material.

This chapter focuses on a specific CFRP-titanium "stack-up", or sandwich, that must be drilled in the manufacturing process. There is limited literature on this stack-up and in particular, the thicknesses studied (0.250" CFRP and 0.375" titanium), which are greater than much of the existing studies on these materials.

After reviewing the literature, a controlled experiment is presented, comparing the performance of a double margin tungsten carbide (WC) cutter with a 135° point angle and a 118° polycrystalline diamond cutter. The data show that the WC cutter offers superior performance with respect to cost and quality. After switching to the WC cutter in the manufacturing cell studied, a 62% reduction in production defects was observed. The newly selected tool also offered a savings of 66% over the previous cutter.

3.2 Introduction

The following chapter focuses on the selection of a designated tool for a specific manufacturing process, drilling the "door surrounds" of the aft fuselage section known as the 47 section of the 787. There are two passenger doors, and one cargo door that are part of this manufacturing process.

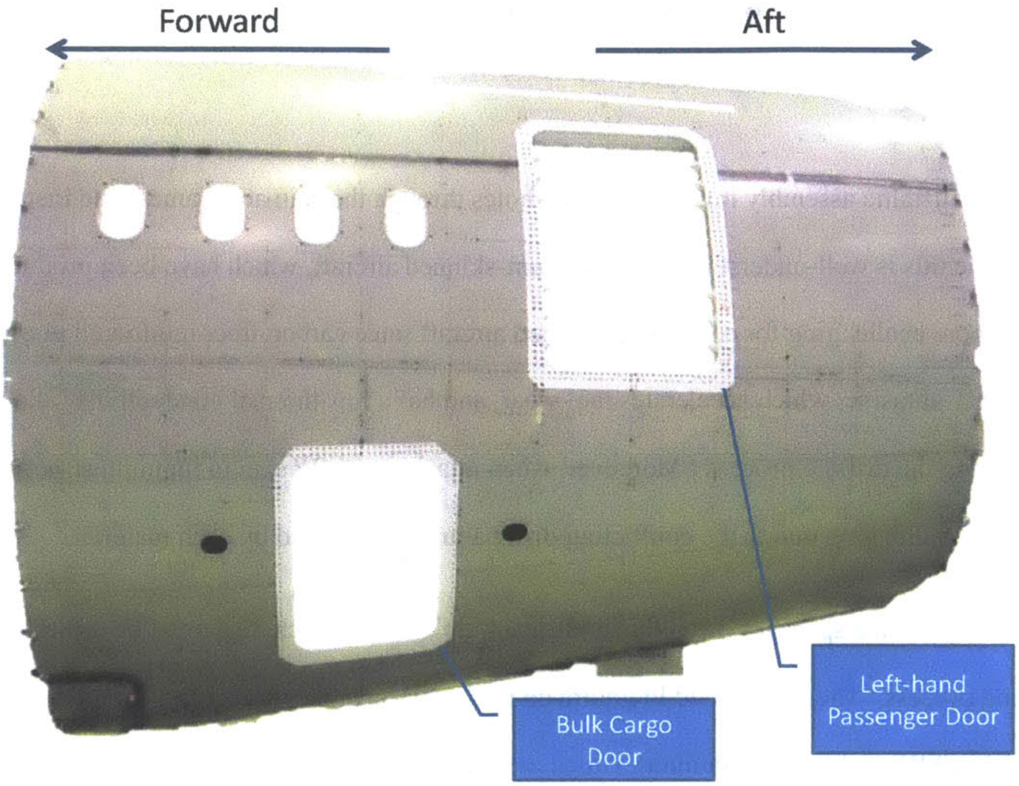

Figure 4: 47 Section Photo

The cargo door and left-hand passenger doors are indicated on the fuselage section in Figure 4 looking from outside the barrel. On the inside of the barrel are titanium structures that must be attached to the Carbon Fiber Reinforced Plastic (CFRP) skin by first drilling through each material in the "stack-up" and then installing a fastener.

The following background section will describe in more detail the door surround work and review the literature on drilling CFRP and titanium. While there is substantial literature on drilling CFRP and titanium separately, limited research has been conducted on drilling CFRP-titanium stacks, which is particularly challenging due to the conflicting drill parameters favored for each material. This research will focus on thicker stack-ups than are in most of the literature, which are important in manufacturing large composite-skinned aircraft.

For Boeing South Carolina, cutting tools or "cutters"[3] represent more than 50% of the cost of tools and consumable materials required to build the aircraft. The purpose of this study was to propose a different cutting tool (drill) for the process that would offer the same or improved quality at a lower cost with the intention of initiating similar improvement initiatives in other manufacturing cells.

The following background section will provide an overview of the production process using the cutting tools, and a literature review of drilling CFRP and titanium. Subsequently, the experimental methods, results, and opportunities for further investigation will be discussed.

3.3 Problem Background and Hypothesis

3.3.1 Door Surround Cell

The 787 door surrounds consist of Carbon Fiber Reinforced Plastic (CFRP) – the skin of the aircraft – and interior structural reinforcement provided mainly by titanium, which is required to reinforce the cut-out in the fuselage for the door. These two materials are commonly paired together on the 787 due to their high strength-to-weight ratio. The titanium structure is attached to the CFRP skin by drilling a series of holes between the two materials and installing fasteners that hold them together. Part of this drilling and fastening occurs in what will be referred to as the "door surround cell". This cell also happens to perform other structural work such as frame installation that is not in scope for this discussion.

Although drilling the door surrounds represents much less than half of the cell's statement of work, which also includes frame installations, this work is very important to the success of the cell and the production system. Many jobs are dependent on the door surround installation being complete and defect-free. One of the reasons this area was chosen for further study was the impact of its quality on downstream work.

Table 1 shows the most common quality issues with the door surround holes and the associated repairs. At a high level, the defects in Table 1 are either damage to the fibers and lamination in CFRP, or an

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[3] The term *cutter* is commonly used in the aerospace industry to refer to what is commonly called a drill bit. *Cutting tool* and *cutter* will be used interchangeably throughout this thesis. *Drill* will be used to refer to the tool that holds the cutter and provides the mechanisms to complete a drilling operation.

improperly shaped/sized hole. Note that the repair times indicated are estimates, and the total duration from diagnosing a quality issue to completing the repair is often much longer due to the various handoffs and required documentation processes. For extreme cases of the elongated, oversized, and volcano defects, engineering analysis may be required before an appropriate repair technique is recommended.

Defect	Common Repair Name	Repair Description	Approximate Repair Time
Fiber Breakout	Sweep, fill, and fair	Sand down, inspect (NDI), apply repair resin, and cure	4-6 hours
[CFRP] Delamination	Sweep, fill, and fair (overlay required)	Sand down, inspect (NDI), apply repair resin, overlay, and cure	8-10 hours
Volcano (extreme breakout condition in CFRP)	Next oversize or	Re-drill the hole to a larger diameter and use a larger fastener	1-2 Hours
	Pot or	Fill the hole with repair resin, cure, and re-drill hole	4-6 Hours
	Sweep, fill, and fair	Sand down, inspect (NDI), apply repair resin and cure	6-8 Hours
Elongated Hole	Next oversize or	Re-drill the hole to a larger diameter and use a larger fastener.	1-2 Hours
	Pot or	Fill the hole with repair resin, cure, and re-drill hole	4-6 Hours
	Pot and Overlay	Fill the hole with repair resin, overlay, cure, and re-drill hole	6-8 Hours
Oversized Hole	Next oversize	Re-drill the hole to a larger diameter and use a larger fastener.	1-2 Hours

Table 1: Common Quality Issues and Associated Repairs

At the time this research was conducted, there was particular concern with the number of breakout/delamination defects occurring since these defects are relatively time consuming to repair compared to a slightly oversized hole. The majority of door surround holes are of nominal sizes 0.3750" and 0.3125". The tolerance for acceptable hole size is from the nominal size up to 0.003" above the nominal size. Figure 5 shows the number of defects per airplane related to the door surrounds, broken out by whether the defect was an oversized hole or a breakout condition. To help understand the relative significance of the defects in Figure 5, there are approximately 100 holes drilled in the door surrounds using the process studied.

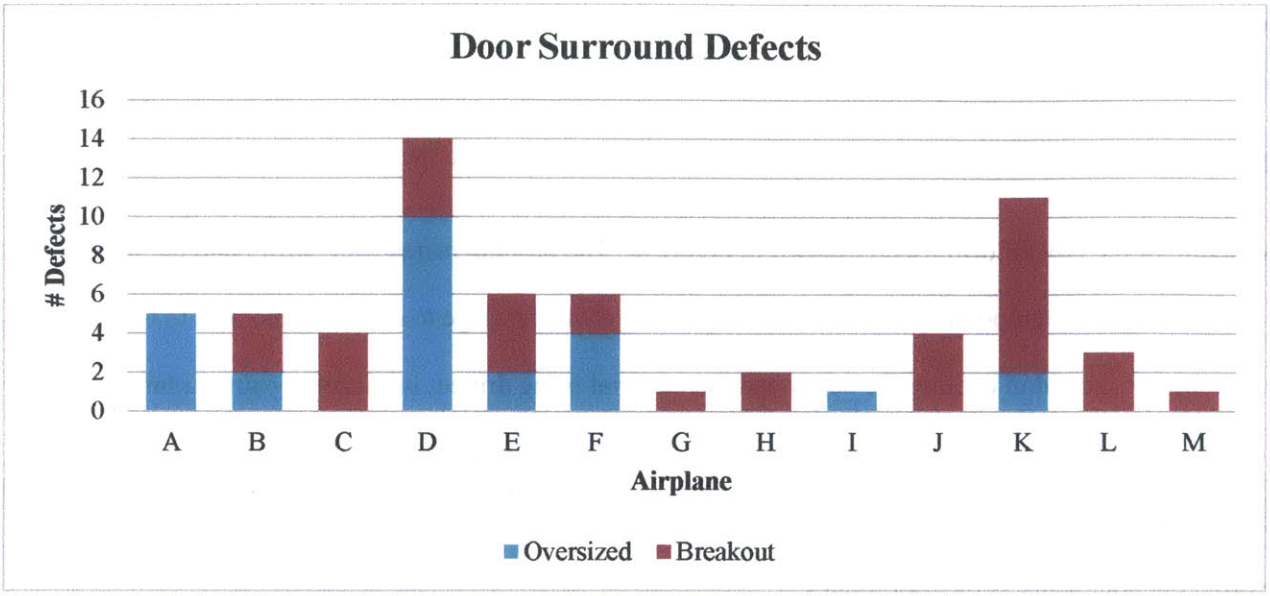

Figure 5: Door Surround Defects Prior to Cutting Tool Change

3.3.2 Initial Drilling Equipment

As summarized by Stewart (2007), there are three general techniques used to drill a stack-up of CFRP and titanium:

1. Drill and Ream[4], which is the process of drilling the hole undersized and then reaming to the final diameter.
2. Peck drilling[5], a process that repeatedly advances the cutting tool (as it rotates) into the material and withdraws it at a preset rate.
3. Positive feed drilling, which is a continuous drilling process in which the cutter is advanced at a preset distance for every revolution of the cutting tool.

For the door surround process, Boeing utilizes "positive feed" drilling equipment, powered by compressed air, which mechanically controls the forward feed rate of the cutting tool and its rotational speed. "One-shot" positive feed drilling has a time savings advantage over the drill and ream process

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[4] A drill and ream process requires drilling a hole undersized first, and then using a cutter called a reamer to enlarge the hole to the desired size. This process can achieve more precise hole sizes than one-shot drilling, but requires more time due to the two drilling operations involved.

[5] Peck drilling requires a special type of drill motor that allows the cutter to repeatedly advance and retract small distances as it rotates.

since it requires only one drilling operation. It also requires less experience than the peck drilling process (Stewart, 2007), which is important for the new workforce at BSC. The drill used maintains one constant speed (revolutions per unit time) and feed rate (distance translated into the material per revolution).

A picture of the type of drill used is shown in Figure 4. The bushing mates with "drill plate jig" (not pictured), which is temporarily affixed to the outer skin of the fuselage to constrain the drill to the desired hole location. To aid in cooling the cutter and the material being drilled, lubricant is pumped through two holes in the cutter tip. A vacuum (not pictured) is used to evacuate chips back through the bushing (via the channels in the cutter called flutes), which helps avoid unintended enlargement of the hole from chips scoring the hole walls as the tool rotates.

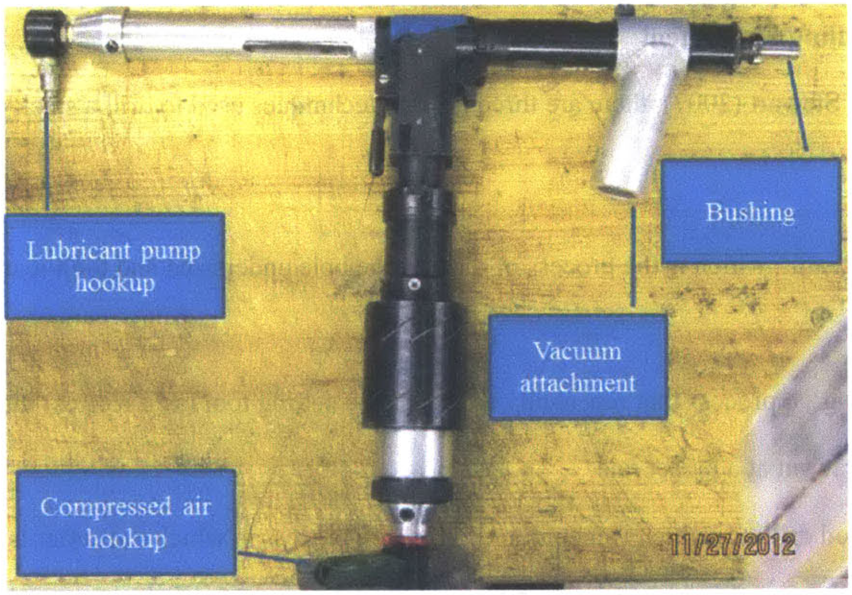

Figure 6: Power Feed Drill

The original cutting tool used for this operation contained a polycrystalline diamond (PCD) coated point, which can be seen as the more sparkling surface near the edge of the cutting tool in Figure 7. Due to its hardness, the diamond coating improves wear resistance when cutting through abrasive materials; however, it also greatly increases the cost of the cutting tool. The following section will discuss the current literature on drilling stack-ups of CFRP and titanium, which will assist in recommending a cutting tool and drilling process for improving quality and reducing cost.

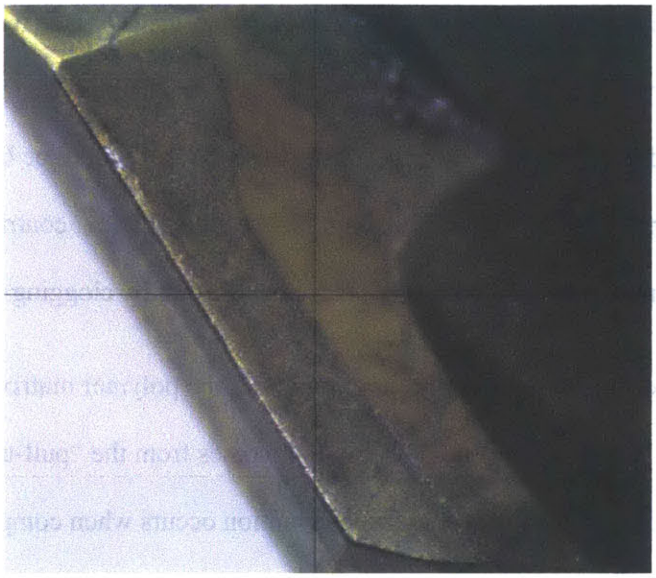

Figure 7: Close-up of Polycrystalline Diamond Coated Cutting Tool

3.3.3 Drilling Carbon Fiber Reinforced Plastic and Titanium

Drilling through layers of CFRP and titanium, commonly referred to as CFRP-titanium "stacks" or "stack-ups", is particularly challenging because CFRP and titanium favor contradictory drilling parameters and different cutting tools. Therefore, selecting drill parameters and cutting tools for these stack-ups involves tradeoffs between hole quality, cost of tooling, and tool life (which affects cost). The following sections will review the literature on drilling CFRP and titanium separately first since much of the literature concentrates on machining the materials individually. Each review will focus on material properties, drilling challenges, common cutting tool materials, and cutting tool wear mechanisms. This section will conclude with a summary of the challenges presented by each material, and what must be addressed when drilling a stack-up of CFRP and titanium.

3.3.3.1 Carbon Fiber Reinforced Plastic (CFRP)

Liu et al. (2011) provide a thorough literature review of drilling composite laminates, including an overview of different composite materials, types of drilling operations, cutting tools, delamination, and tool wear. This section will focus on Carbon Fiber Reinforced Plastic (CFRP) in particular, and the challenges associated with drilling holes in the material.

CFRP consists of carbon fibers and a polymer matrix. A polymer matrix binds the fibers, transferring loads to them and protecting them from environmental degradation (D. Liu, Tang, & Cong, 2011). The fibers provide stiffness and strength; however, they also cause the material to be highly abrasive. CFRP abrasiveness and poor thermal conductivity, which hinders heat dissipation, contribute to rapid tool wear. Additionally, the soft polymer matrix can make the cutting edge dull by clogging. (W. Chen, 1997)

Delamination or breakout occurs when a cutting tool separates the polymer matrix from the fibers near the circumference of the hole. Entry, or peel-up delamination comes from the "pull-up" that occurs when a cutting tool enters the material. Exit, or push-out delamination occurs when composite layers are separated before they are cut upon exiting the material (D. Liu, Tang, & Cong, 2011). Delamination is undesirable both because it results in a larger than desired hole size and weakens the material, making it more susceptible fatigue deterioration (W. Chen, 1997; Gaitonde et al., 2008). Figure 8 shows a cutting tool inducing peel-up and push-out delamination respectively.

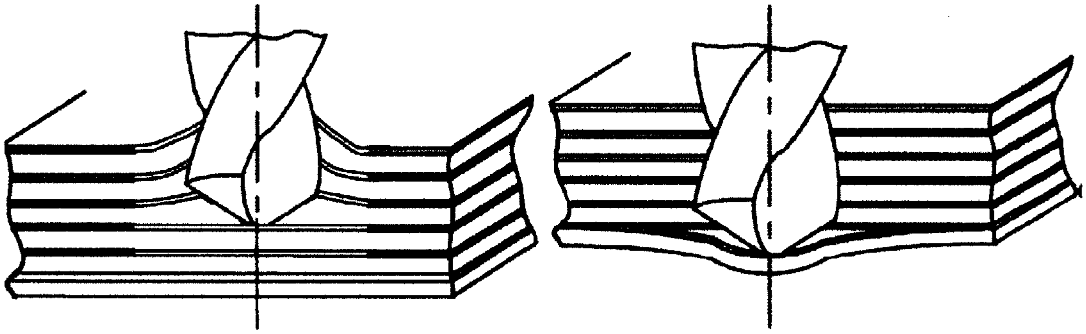

Figure 8: Peel-up delamination (left) and Push-out delamination (right) (D. Liu, Tang, & Cong, 2011)

For the door surround cell, the defect commonly referred to as "breakout" is a result of push-out delamination. Figure 9 is a photograph of an extreme breakout condition from push-out delamination.

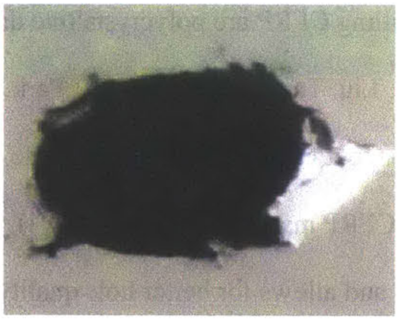

Figure 9: "Breakout" as a result of push-out delamination[6]

Delamination has been found to be dependent on feed rate, cutting speed, and the point angle of the cutting tool (Gaitonde et al., 2008; D. Liu, Tang, & Cong, 2011). The qualitative effects of these factors are summarized in Table 2.

Increase in Factor	Effect on Delamination
Feed Rate	Increase
Speed	Increase / Decrease (woven-ply)
Point Angle	Increase (woven-ply) (Gaitonde et al., 2008) / Decrease (unidirectional GFRP) (Kilickap, 2010)

Table 2: Qualitative Effects of Factors on Delamination (D. Liu, Tang, & Cong, 2011)

Note that for the door surround area, the material is closest to a woven-ply, so the expected relations are that delamination would decrease with increasing cutting speed and decreasing point angle.

Another defect that can occur when drilling CFRP is fiber pull-out. This occurs when some fibers are pulled, instead of being cut, by the cutting tool as it drills through the material (Campbell, 2004).

Optimal drilling parameters for CFRP are relatively high speed and medium/high feed. A higher feed corresponds to less distance traveled (thus less wear) as the cutting edge takes its spiral path down through the hole. Lower feed is usually used to minimize delamination and breakout (Park, Beal, Kim, Kwon, & Lantrip, 2011). Typical parameters are 2,000 to 6,000 rpm with feed rates of 0.001 – 0.003" IPR (inches per revolution) (Campbell, 2004; D. Kim & Ramulu, 2004; Park, Beal, Kim, Kwon, & Lantrip, 2011). As a note, I encountered speeds in excess of 10,000 rpm for drilling CFRP material for controlled manufacturing processes in the industry.

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[6] This photograph is *not* of a hole on the aircraft; it is on a coupon, or testing material.

Common cutting tool materials for drilling CFRP are polycrystalline diamond (PCD), high-speed-steel (HSS), and tungsten carbide (WC) (D. Liu, Tang, & Cong, 2011; Park, Beal, Kim, Kwon, & Lantrip, 2011). PCD cutters are very expensive, but can have a longer tool life due to their hardness, which is helpful when drilling highly abrasive CFRP material (Colligan, 1994). PCD offers reduced wear rates as compared to HSS and carbide cutters, and allows for better hole quality when drilling CFRP alone. The primary wear mechanisms for drilling CFRP are abrasive wear, chipping, and adhesion (D. Liu, Tang, & Cong, 2011; Park, Beal, Kim, Kwon, & Lantrip, 2011).

3.3.3.2 Titanium

Titanium has been an important material to the aerospace industry for decades, and there is more literature on machining titanium than there is on machining CFRP. Despite the research that has already been conducted, titanium remains a difficult material to machine. Zhang et al. (2008) conducted a recent literature review of drilling processes for titanium, discussing cutting force, temperature, tool wear, hole quality, and chip formation. This section will focus on conventional drilling ("twist drilling"), as this is the process that is used in the door surround cell.

The challenges of drilling titanium are summarized by Yang and Liu (1999), and the relevant issues are paraphrased below:

1. *Titanium has a low thermal conductivity. Thus, little heat is dissipated away from the cutting surface via conduction. This problem is pronounced in conventional drilling because the cutting speed diminishes towards the center of the cutting tool, resulting in high cutting forces and heat.*
2. *Titanium chips are very thin since there is a small contact area with the tool (1/3 to 1/2 of that for steel). This causes high stresses on the cutting edge of the tool. Concentrated forces on the cutting edge, high surface friction, and high heat generation may lead to pressure welding and galling, compromising the effectiveness of the cutting tool.*
3. *Titanium's high strength is maintained at machining temperatures, which opposes the plastic deformation needed to form a chip.*
4. *Titanium is reactive at typical cutting temperatures (>500°C). This contributes to hardening as the material is being cut, adversely affecting the tool wear rate.*
5. *Titanium has a low modulus of elasticity, which can cause chatter, deflection, and rubbing problems.*
6. *Titanium has a tendency to ignite due to the high temperatures involved. Sparking is common.*

Challenges 1 and 2 together, result in heat buildup and high stresses, which requires a low cutting speed of approximately 300 – 400 rpm (Campbell, 2004) to limit tool degradation. Higher feed rates (than CFRP) of 0.004 – 0.005 IPR (inches per revolution) are favored to produce thicker chips since thinner cuts allow for more heat concentration and work hardening (Campbell, 2004). Together, these "slow" drilling parameters make it time consuming to drill titanium compared to aluminum or steel. The challenges also lead to high tool wear, making it expensive to drill titanium (Zhang, Churi, Pei, & Treadwell, 2008).

A common defect when drilling any metal is an exit burr, which can compromise structural integrity over time (Sisco, 2003). Exit burrs are raised material around the circumference of the hole where the cutting tool exits. An example of a common way an exit burr can form is shown in Figure 10. There are also interface burrs, which are between two layers in a stack-up, and entrance burrs where the cutting tool enters the first material. Exit burrs are the most significant and the most-studied types of burrs (Stewart, 2007). Dornfeld et al. (1999) demonstrated that the use of liquid coolant is very effective in reducing exit burr size. Coolant also improves tool life (Zhang, Churi, Pei, & Treadwell, 2008). The current equipment used in the door surround process allows for "wet" drilling, or drilling with coolant.

Figure 10: Simulation of Exit Burr Formation (Aurich et al., 2009)

Burr formation is particularly important for "one-up" assembly processes, where the parts being drilled and fastened together are not separated for deburring. There is a significant amount of literature on the study of burr formation, especially exit burrs. Aurich et al. (2009) provide a good overview of burr formation. The door surround assembly process is not a one-up process, and burr formation has not historically been problematic. Therefore, simply understanding what a burr is will be sufficient for the purposes of discussing this research. A trend that is useful to know is that exit burrs generally become higher with tool wear (Aurich et al., 2009). Later, in the results discussion, this relation will be referred to since it is easy to measure exit burr for the purposes of having a rough indicator of tool wear.

Commonly used drill materials for titanium are high-speed-steel (HSS) and tungsten carbide (WC) (Zhang, Churi, Pei, & Treadwell, 2008), often referred to as just "carbide". Zhang et al. (2008) summarized the primary wear mechanisms for drilling titanium in the literature as notching, non-uniform flank wear, crater wear, chipping, and catastrophic failure. Park et al. (2011) found that titanium adhesion was the primary wear mechanism when using a WC cutting tool, and that chipping was the primary wear mechanism when using a PCD tool. Although PCD is generally not the cutting tool material of choice for drilling titanium, it is used to drill CFRP-titanium stacks in some applications, such as in the aft body facility at BSC.

3.3.3.3 Summary: CFRP-Titanium Stacks

As previously mentioned, much of the literature on drilling CFRP and titanium focuses on each material separately; however, some recent studies have investigated composite-metal stack-ups. This section will briefly survey the recent studies and summarize the challenges associated with drilling CFRP and titanium in one shot. For most industrial applications, drilling is started in CFRP first. In the following section, a cutting tool and drilling process will be recommended for the door surround drilling application.

CFRP and titanium are difficult to drill individually, and present additional challenges when drilled in a stack-up. CFRP favors very high speed and low feed while titanium favors a very low speed and higher feed drilling parameters, which is qualitatively depicted in Figure 11.

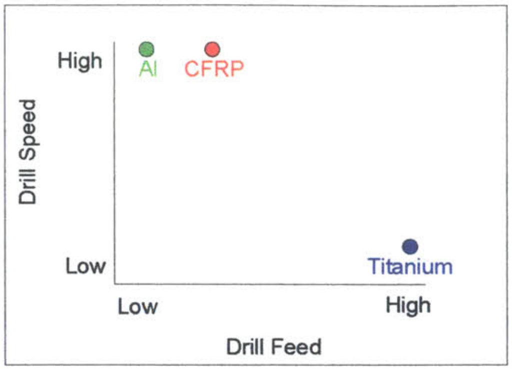

Figure 11: Relative Optimal Settings for Drilling CFRP and Titanium (Stewart, 2007)

In the absence of a drill motor that can change its feed and speed during the drilling process[7], drilling a CFRP-titanium stack-up is a compromise between opposing optimal drilling parameters. Cordell et al. (2005) determined an optimal setting for drilling a composite-titanium stack-up of 465rpm and 0.002 IPR (inches of feed per revolution). This is much closer to the optimal settings for titanium, which agrees with Campbell's (2004) statement that optimal drilling parameters for composite-metal stack-ups are mostly controlled by the metal, the more difficult material to drill.

Additionally, CFRP and titanium cause different types of tool wear, favoring different cutting tool materials. PCD performs well in CFRP due to its superior abrasive wear resistance and has long been the preferred cutting tool material for CFRP. In titanium, WC cutting tools are generally preferred (Park, Beal, Kim, Kwon, & Lantrip, 2011).

Last, the presence of titanium in a stack-up often has an adverse impact on the hole quality of the CFRP. Beal et al. (2011) concluded that there is more vibration when drilling a stack with titanium than when CFRP is drilled alone. This instability contributes to oversized holes. When titanium is the second material in a stack, the evacuation of titanium chips can scratch or erode the surface of the CFRP that has already been drilled. Also, when titanium is being drilled in a stack, the use of coolant is often necessary.

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[7] There is a commercially available computer-controlled drill motor that changes drill feed and speed based on the current thrust force measurement. For CFRP-titanium stack-ups, there is a noticeable increase in thrust force when the cutting tool transitions into titanium, so this technique is effective for such a stack-up. However, the cost of this drilling equipment is significantly higher than a single-setting drill. The door surround cell uses equipment that allows only a single speed and feed rate setting.

In CFRP, coolant can cause a pasty sludge to form in the drill flutes, which can block chips and other debris from exiting.

Kim and Ramulu (2004) conducted a drilling process optimization study for carbide and high speed steel Cobolt (HSS-Co) graphite/bismaleimide–titanium stacks. The stack-up studied was 0.300" Gr/Bi and 0.122" titanium. For comparison, this is approximately half of the CFRP-titanium stack-up thickness found in the door surrounds. Kim and Ramulu (2004) found optimal settings for the carbide cutting tool to be 660 rpm and 0.0055 IPR for this stack. They also concluded that the carbide cutting tool achieved better hole quality and was more economical than the HSS-Co cutter.

Particularly pertinent to this research is Park et al.'s (2011) tool wear study of tungsten carbide (WC) and polycrystalline diamond (PCD) cutting tools in a CFRP-titanium stack. They used a 0.300" CFRP layer and a 0.265" thick Ti-6Al-4V layer. The cutters were 0.375" in diameter, a diameter used by the door surround cell, and had point angles of 135°. Park et al. (2011) used two speed settings for the WC tool: 6000 rpm in CFRP with 800 rpm in titanium, and 2000 rpm in CFRP with 400 rpm in titanium. The PCD tool was used at 2000 rpm in CFRP and 300 rpm in Ti. Feed rates for both tools were 0.003 IPR in CFRP and 0.002 IPR in titanium. They observed that the WC tool undergoes even abrasive wear on the cutting edges from drilling CFRP. In titanium, the WC tool was significantly affected by titanium adhesion to the cutting edge, which was abraded away by the CFRP drilled in the subsequent holes. Titanium adhesion was less severe at the lower speed setting. For the PCD cutting tool, chipping was the main wear mechanism; titanium adhesion was less pronounced compared to the WC tool. The authors noted that the PCD tool produced higher quality holes than WC in CFRP, however, it failed catastrophically on the 73rd hole. It should be noted that catastrophic failures were not uncommon when using PCD cutters on CFRP-titanium stacks in the aft body facility. Cutter failures not only resulted in the loss of a tool, but also a defective hole that would require repair.

Beal et al. (2011) also conducted a study of CFRP-titanium stacks using WC cutters with a 135° point angle. The stack-up studied was 0.297" CFRP and 0.265" of titanium. High and low speed settings were used for comparison. The high speed setting was 6000 rpm in CFRP and 800 rpm in titanium. The low speed setting was 2000 rpm in CFRP and 400 rpm in titanium. Feed rates were 0.003 IPR for CFRP and 0.002 IPR for titanium. Regarding tool wear, they reached conclusions similar to Park et al. (2011). The study also demonstrated that the addition of titanium to a stack-up resulted in larger CFRP hole diameters and delamination in CFRP compared to drilling CFRP alone. Beal et al. (2011) concluded that this was due to vibration when drilling titanium, the evacuation of titanium chips, and titanium adhesion to the cutting edge of the tool. The best hole quality was achieved at the low speed setting, which is consistent with the aforementioned studies.

In summary, CFRP-titanium stacks are challenging to drill due to their material properties, the contradictory drilling parameters and tool materials favored by each material, and the complications associated with vibration and chip evacuation when the materials are stacked. Table 3 summarizes the characteristics and challenges of drilling these materials separately and in stacks.

	CFRP	Titanium
Material properties	• Abrasive, causing high tool wear • Low thermal conductivity limits heat dissipation via conduction • Soft polymer matrix can dull cutting edge by clogging (W. Chen, 1997)	• High tensile strength and work hardening make it difficult to cut • Low thermal conductivity limits heat dissipation via conduction • Affinity to tool materials causes adhesion, which dulls edges • Low modulus of elasticity leads to vibration • Can ignite at machining temperatures (W. Chen, 1997; D. Liu, Tang, & Cong, 2011)
Cutting tool materials	• PCD is preferred for its wear resistance • PCD is brittle, which can lead to chipping and catastrophic failure in titanium (Park, Beal, Kim, Kwon, & Lantrip, 2011) • PCD is expensive (up to four times as much as a similar carbide tool)	• Carbide is more durable in titanium • Carbide wears more quickly in CFRP • Titanium adhesion is more severe for carbide than PCD (Park, Beal, Kim, Kwon, & Lantrip, 2011)
Drilling parameters	• Speed: High (2000 – 10,000 rpm) • Feed: Low (0.001 – 0.003 IPR) (Campbell, 2004; Park, Beal, Kim, Kwon, & Lantrip, 2011)	• Speed: Low (300 – 500rpm) • Feed: Medium (0.004 – 0.005 IPR) (Campbell, 2004)
Heat dissipation and chip removal	• Coolant can form a "sludge" in CFRP that blocks cut material from exiting the hole	• Chips can score the walls of CFRP, enlarging the hole (Beal, Kim, Park, & Kwon, 2011)

Table 3: Summary of Challenges of Drilling CFRP-Titanium Stacks

3.3.4 Review of Current State and Tool Proposal

As stated in the *Initial Drilling Equipment* section, the door surround cell used a PCD cutter at the time this research started. The PCD cutter had a 118° point angle, which is a sharper point than the 135° PCD cutters tested by Park et al. (2011). Figure 12 shows these two different point angles for comparison. Also of note, the original cutter was a single margin design, which means that there is one edge along the "land" (the part of the cutter between the flutes) that anchors the cutter to the material it is cutting, shown in Figure 13 (center)[8]. The cell was experiencing issues with breakout, oversized holes (see Figure 5), and occasional chipping and catastrophic failure of the cutters.

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[8] The rest of the land is of a lower diameter than the margin, providing clearance, which reduces friction during drilling.

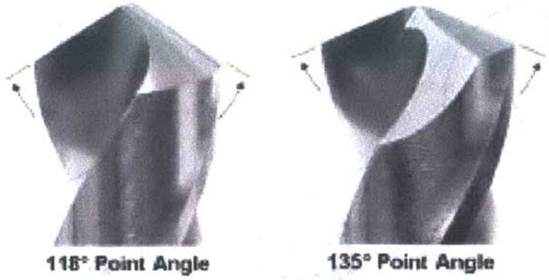

Figure 12: Cutter Point Angle[9]

Holes were being drilled with a single-setting positive feed drill motor and coolant supply using the setup shown in Figure 6. Drill settings were 465 rpm with a feed rate of 0.002 IPR, which is close to the best titanium drill settings tested by Park et al. (2011), Beal et al. (2011), and Cordell et al. (2005). Without the luxury of drilling equipment that can change its feed and speed settings for each material, these settings agreed with the literature since they were closer to the ideal settings for titanium.

While the drill settings were reasonable for the application, based on quality issues, the brittleness of PCD, and additional vibration caused by drilling titanium in a CFRP-titanium stack-up, WC cutters were worth investigating as an alternative. Based on the testing performed by Park et al. (2011) and Beal et al. (2011), as well as recommendations from subject matter experts at the Boeing Company, it was recommended that a WC cutter with a 135° point angle and double margin design be tested for the door surround application[10]. Double margin cutters have two edges along the land that are designed to contact the sides of the hole walls, and this helps with stability during cutting. For comparison, the cross-sections of a no-margin, single margin, and double margin cutter are shown in Figure 13. In addition to the improved durability of the tool in titanium, the WC cutter offers significant cost savings potential, costing 1/4 to 1/3 as much as the original PCD cutter.

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[9] Image obtained from <http://www.vikingdrill.com/Twist_Drill_Term_Face.html>. The cutters shown in this figure are not the cutters used by Boeing South Carolina.

[10] Further information about the cutter design cannot be included because it is proprietary to the Boeing Company.

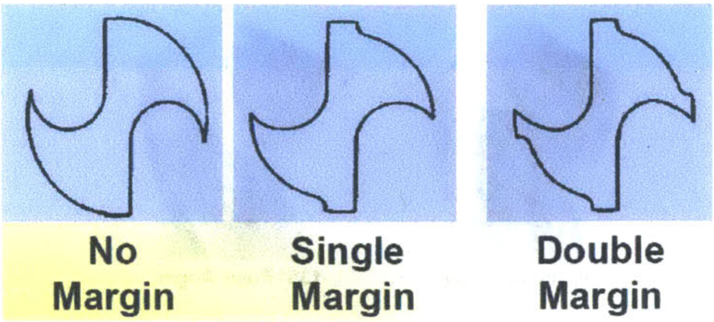

Figure 13: Cutter Cross-Section Indicating Margins[11]

3.3.5 Hypothesis

Based on the literature and expertise within the Boeing Company, it is hypothesized that the proposed carbide cutting tool will produce equal or better quality holes at a significantly lower cost using the same drill settings and equipment.

3.4 Testing Methodology

3.4.1 Initial Experimentation

To gain the support of the Boeing Research & Technology (BR&T) organization for this initiative, some initial testing was performed using the drilling equipment discussed above, and coupons, or rectangular samples of material designed for testing. This initial testing will not be discussed in detail, however, it is mentioned here to demonstrate the importance of providing a strong business case for making a change to existing manufacturing processes. The testing served this purpose of demonstrating that the proposed WC tool showed promise of equal or better performance than the tool that was currently in use and helped justify devoting BR&T resources to the initiative.

This initial testing may not have been necessary at a more established Boeing site. BR&T counterparts from other sites were recommending that BR&T at BSC support the initiative based on their more extensive experience with cutting tools. This situation was an example of how BSC is new and different from other Boeing sites, and that understanding the site's background is important to successfully enact

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[11] Image obtained from <http://www.neme-s.org/2005%20May%20Meeting/drills.pdf>. The cutters shown in this figure bear no relation to the cutters used by Boeing South Carolina.

change. At the time, it was noted that there was no standard followed across all Boeing sites for selecting or qualifying a cutter for a controlled process. During the course of this project, a cross-functional team of experts within Boeing began drafting experimental process guidelines for this purpose.

3.4.2 Final Test Plan

With the support of the BR&T organization, a formal test plan was devised for comparing the performance of the proposed WC tool with the PCD tool in a stack-up designed to simulate the door surround structure. This section will cover the details of the test stack-up, drilling parameters, and experimental procedures.

3.4.2.1 Stack-up

The stack-up used was a 0.250" CFRP coupon from Quatro Composites and a 0.375" Ti-6Al-4V coupon. The CFRP was woven-ply and had a pre-cured strip on the side facing the titanium to best imitate the material used on the airplane. To simulate the worst-case assembly conditions, shims were added between the two coupons to create a 0.009" gap in the stack-up. Figure 14 shows the placement of the shims on the CFRP coupon after it was separated from the titanium coupon after completing testing. While this gap would not be permitted in production manufacturing, BR&T recommended testing under these adverse conditions, which would increase vulnerability to vibration and CFRP breakout.

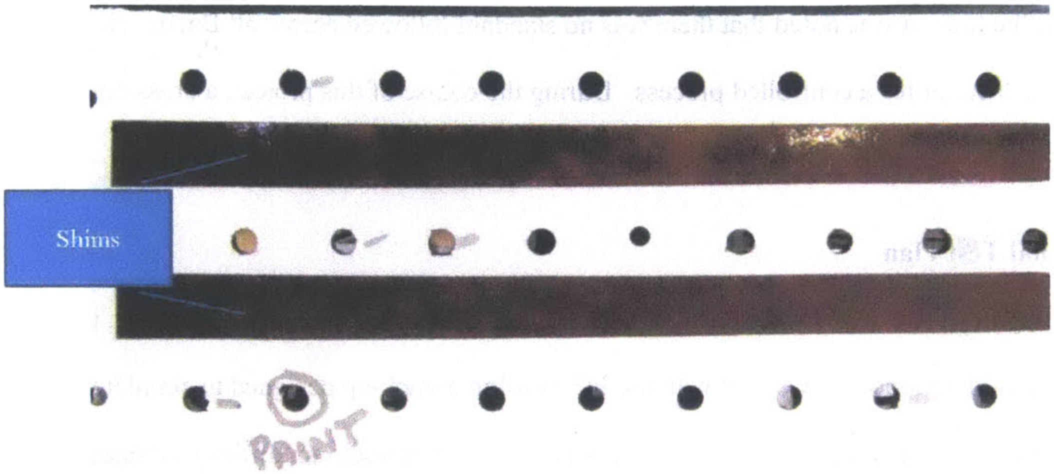

Figure 14: CFRP Coupon with shims to create gap[12]

3.4.2.2 Cutters

For the door surrounds, the majority of the holes are of nominal sizes 0.3750" and 0.3125". Since the initial experimentation was conducted using cutters for the 0.3750" size, this experiment was designed to test cutters for the 0.3125" hole size. Per standard practice, actual cutter sizes were slightly oversized to allow for some cutter wear and prevent undersized holes. The WC cutter was a double margin design with a diameter of 0.3130" and a point angle of 135°. The PCD cutter was a single margin design with a diameter of 0.3133" and a point angle of 118°. Figure 15 shows photographs of the points of the cutters tested. The holes visible in the point are for coolant delivery during drilling.

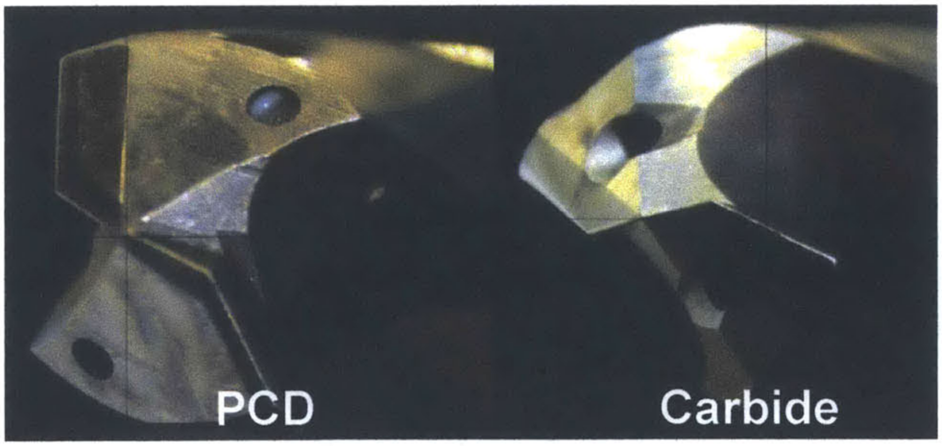

Figure 15: Points of Cutters Tested

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[12] This picture was taken after the CFRP and titanium coupons were separated. The stack-up assembly had a titanium coupon directly on top of the face of the CFRP coupon shown here. Drilling started from the CFRP side of the stack-up.

3.4.2.3 Drilling Parameters

The PCD cutter was tested at one setting and the WC cutter was tested at two settings, shown in Table 4 below. Drills were set up with bushings that allowed for 0.003" clearance with the cutter being used. Suction through the bushing was provided by attaching a vacuum to the attachment shown in Figure 6 to assist in evacuating cut material during drilling. Throughout drilling, coolant was delivered through the coolant holes in the drill points at a rate of 14 mL/min.

Cutter	Speed (rpm)	Feed (IPR)
PCD	465	0.002
WC	380	0.002
WC	465	0.002

Table 4: Test Drilling Parameters

3.4.2.4 Method

Three coupons were drilled with the above stated stack-up and drilling parameters. A drill plate jig was mounted on each coupon that allowed for 27 holes to be drilled. Five 0.25" index holes were drilled with a cutter that was not used for testing. One index hole was drilled in each corner of the coupon, and one at the center of the coupon (five in total). Temporary fasteners were installed in the index holes to constrain the alignment of the drill plate jig and both coupon layers. Red circles in Figure 16 indicate where the index holes were placed. Test holes were drilled in the order indicated in Figure 16.

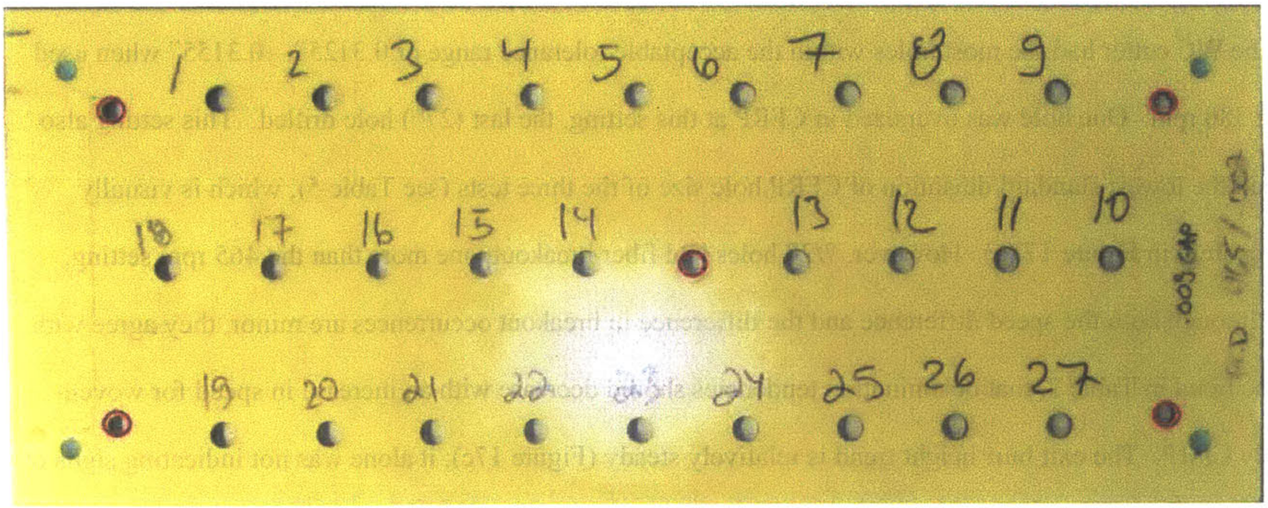


Figure 16: Coupon with Index Holes Circled in Red

As each hole was drilled, a temporary fastener (commonly called a "cleco") was installed to provide adjacent clamp-up for the next hole being drilled. This helps minimize material deflection and vibration, and is consistent with the procedure used in production.

Following the test, the hole diameters were measured at the center of each material using a bore gauge. The titanium exit burr was also measured with burr height gauge. Coupon materials were separated so the CFRP layer could be inspected for breakout and delamination.

3.5 Results and Discussion

3.5.1 Testing Results

There was a clear difference in the performance of each cutter, and a noticeable difference in the results between the two settings used for the WC cutter. Table 5 summarizes the results, characterizing the performance of the cutters at each setting tested in terms of the average hole size, hole size range, hole size standard deviation, percentage of holes within tolerance, and percentage of breakout defects. Figure 17 shows plots of hole size and exit burr height vs. hole number. This section will review the performance of each cutter and drill setting pair tested, and conclude with the recommendation made to the door surround manufacturing operation.

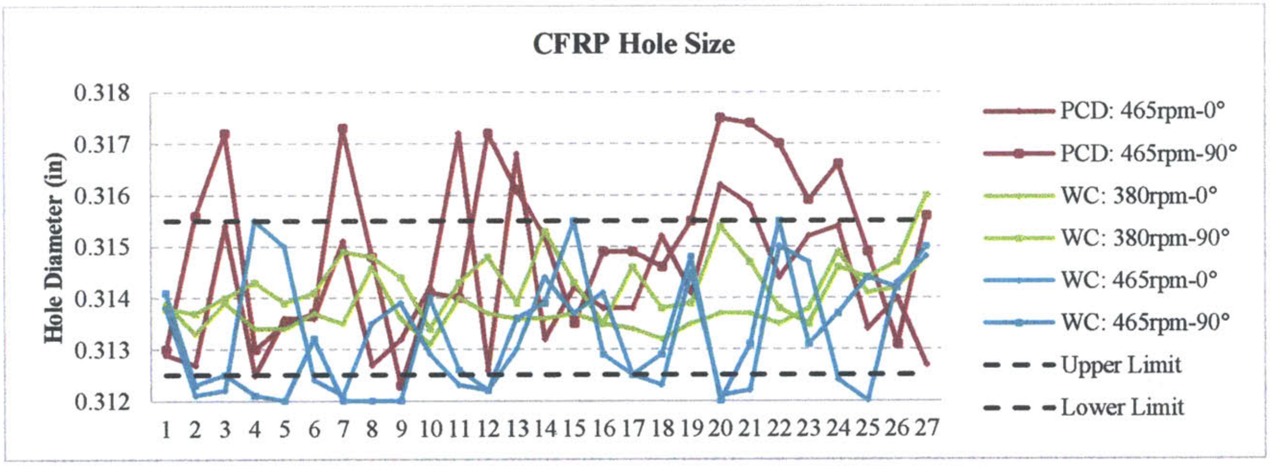
The WC cutter had the most holes within the acceptable tolerance range of 0.3125" - 0.3155" when used at 380 rpm. One hole was oversized in CFRP at this setting, the last (27th) hole drilled. This setting also had the lowest standard deviation of CFRP hole size of the three tests (see Table 5), which is visually apparent in Figure 17 (a). However, 7/27 holes had fiber breakout, one more than the 465 rpm setting. Although both the speed difference and the difference in breakout occurrences are minor, they agree with the trend in Table 2, that delamination tendencies should decrease with an increase in speed for woven-ply CFRP. The exit burr height trend is relatively steady (Figure 17c); it alone was not indicating signs of significant tool wear.

The WC cutter used at 465 rpm had only 44% of the holes fall within the acceptable tolerance range. However, any of the holes that failed were undersized in CFRP by 0.0005" or less. No holes at this setting were oversized, but there were three holes that were marginally passable, measuring 0.3155", the upper limit of the tolerance range. This setting had the best breakout performance, with 6/27 occurrences. It also had the most consistent titanium hole size, with the lowest standard deviation. While this is far from ideal, recall that this test was performed with an unacceptable gap of 0.009" between the CFRP and titanium plates.

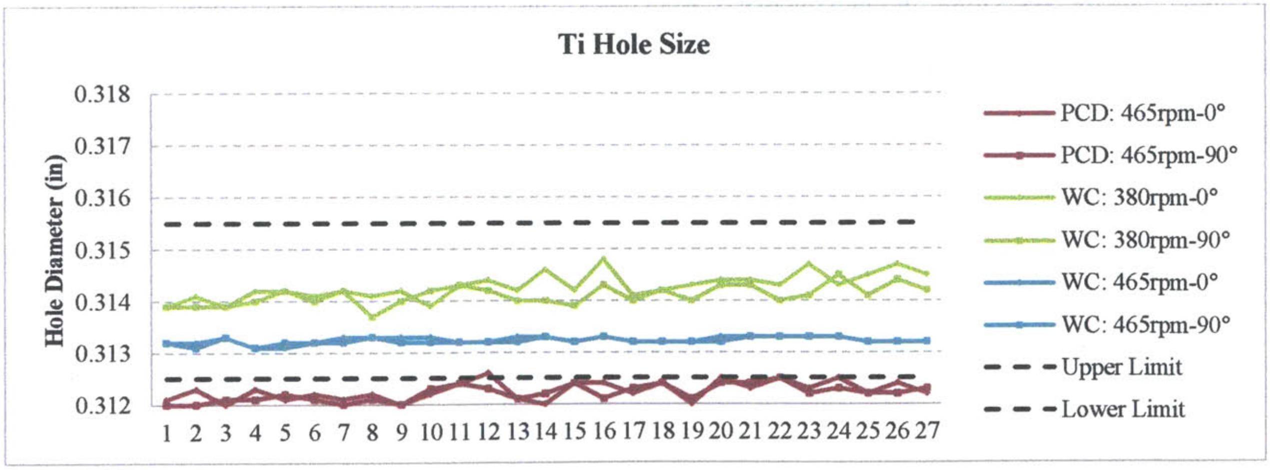
Last, the PCD cutter used at 465 rpm had the poorest performance with respect to hole size, size consistency in CFRP, and breakout. The cutter produced 28% oversized holes in CFRP and 91% undersized holes in titanium. No holes were within the diameter tolerance in both the CFRP and titanium layers. While it cannot be confirmed from the data captured, it is expected that the increased number of oversized holes was partially due to the single margin design, which is more susceptible to vibration than a double margin design. The flute design may have also been less effective in evacuating titanium chips without enlarging the hole in the CFRP. The exit burr height trend starts out high and decreases as more holes are drilled and temporary fasteners are installed. This suggests that the cutter was more susceptible to chatter than the WC cutter. It is inconclusive what caused the undersized holes in titanium. Due to the brittleness of PCD, it is possible that the cutter became chipped on the outer cutting edges, making the diameter of the tool smaller.

	PCD 0.3133": 465 RPM, 0.002 IPR			**WC 0.3130": 380 RPM, 0.002 IPR**			**WC 0.3130": 465 RPM, 0.002 IPR**		
	CFRP	**Ti**	**Exit burr**	**CFRP**	**Ti**	**Exit burr**	**CFRP**	**Ti**	**Exit burr**
Average:	0.3147	0.3122	0.007	0.3140	0.3142	0.007	0.3133	0.3132	0.006
Min:	0.3123	0.3120	0.002	0.313	0.3137	0.003	0.3120	0.3131	0.003
Max:	0.3175	0.3126	0.019	0.3160	0.3148	0.011	0.3155	0.3133	0.009
St Dev:	0.0015	0.0002	0.004	0.0006	0.0002	0.002	0.0011	0.0001	0.002
% Above LL:	98%	9%		100%	100%		44%	100%	
% Below UL:	72%	100%		98%	100%		100%	100%	
% Within Tolerance:	0%			96%			44%		
% Breakout:	41%			26%			22%		

Table 5: Results Summary[13]



(a)



(b)

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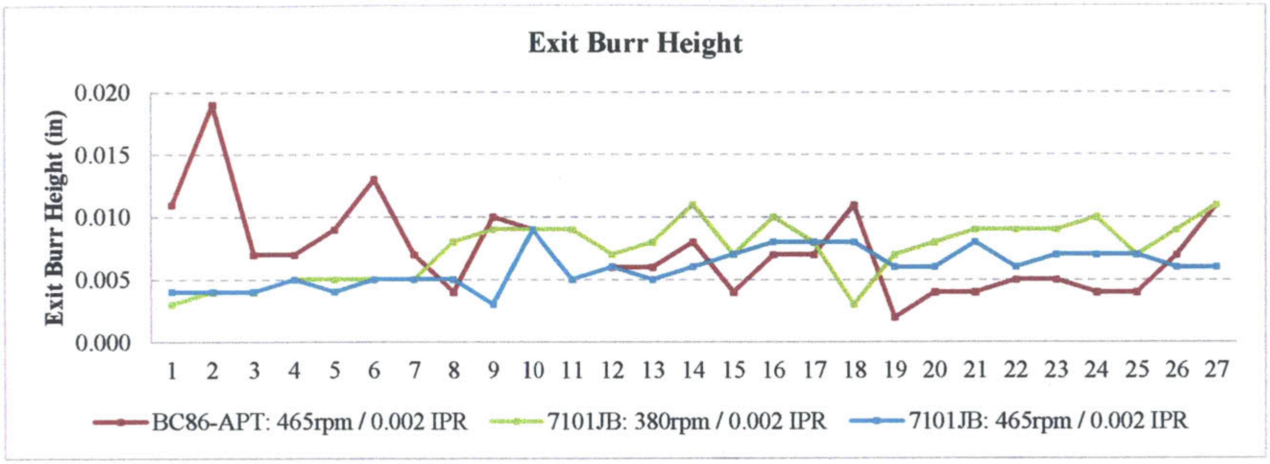
[13] Dimensions are in inches.



(c)

Figure 17: Plotted Results; (a) CFRP Hole Size, (b) Ti Hole Size, (c) Exit Burr Height

After reviewing the results, it was recommended to switch to the proposed WC cutter for its more consistent hole size in CFRP and significantly lower initial purchase price of approximately one quarter that of PCD. Based on the number of slightly undersized CFRP holes at the 465 rpm setting, the author and BR&T recommended using a WC cutter of the same design, but a diameter of 0.3133", which is 0.003" larger than the one used for testing. Furthermore, BR&T recommended using the 465 rpm setting, which was expected to have better performance with respect to breakout, and produced no oversized holes in this test. Actual performance in production was expected to be better than was observed in the test since the gap between the CFRP and titanium materials should always be less than 0.009" based on enforced quality standards.

3.5.2 Quality Impact of Tool Change

After implementing the tool change, there was an opportunity to measure its impact on quality by reviewing the defect information captured in Boeing's production database. It should be noted that in parallel with the tool change, BR&T worked closely with the door surround cell to implement stricter controls around shimming and clamp up to minimize the gaps in stack-ups. This effort undoubtedly also contributed to the positive impact on quality discussed in this section.

Figure 18 shows the number of defects recorded per airplane for the 13 airplanes before the tool change, and the 14 airplanes after the tool change. The green line indicates where the tool change occurred.

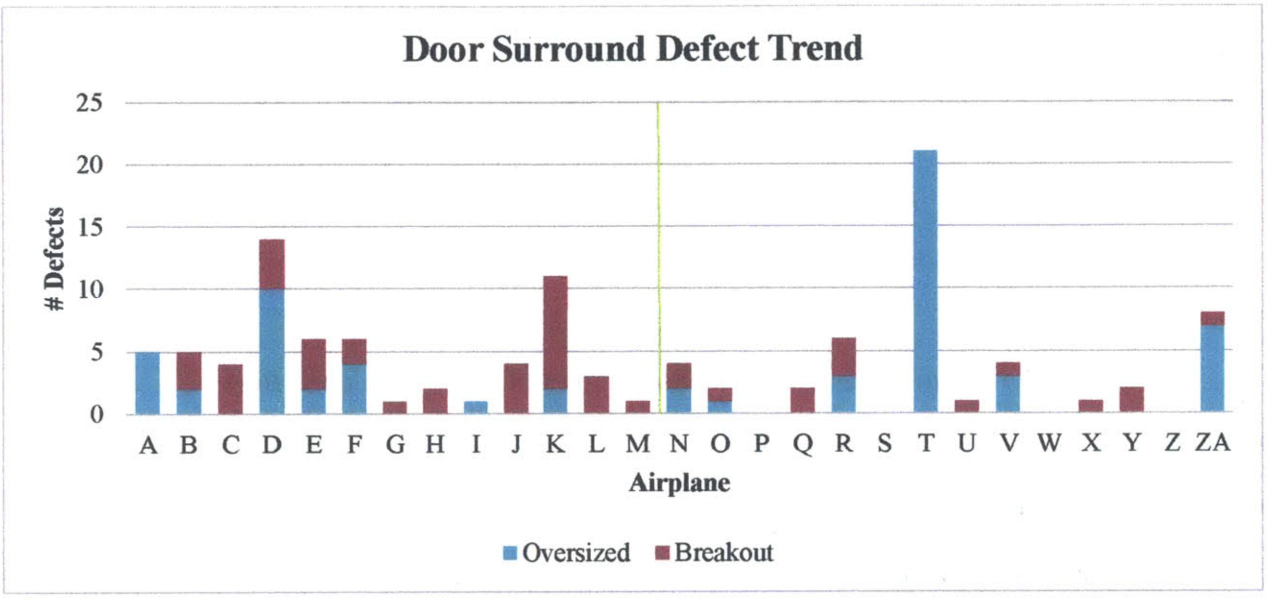


Figure 18: Door Surround Defects Before and After Tool Change

Except for the two outliers, airplanes T and ZA, one can see that the frequency of defects decreased since the tool change. To make a fair comparison, the exclusion of airplanes T and ZA must be justified. For airplane T, it was found that a damaged cutter (containing a chipped chisel edge) was used. Although this may be surprising to the reader, it is actually easy to chip a cutter if it is not handled properly. The cutter may have been chipped when setting up the drill, or if the drill were mishandled when the cutter point was exposed through the end of the bushing. Having a chipped chisel edge, which is at the very tip of the cutter reduces the cutter's ability to advance without deflecting perpendicular to its axis of rotation. Consequently, it makes sense that every defective hole drilled with this cutter was oversized; fortunately no breakout occurred.

A different root cause was discovered for the defects on airplane ZA. It was found that the standard process of cleaning the cutter of chips after each hole was not followed. The mechanics that performed this work were not the mechanics who normally perform the job. All but one defect for this airplane were oversized holes, which can be explained by the presence of additional titanium chips scoring the walls of the CFRP during drilling.

Both of the outliers are examples of the many factors that can go wrong in a complex manufacturing environment that are not accounted for in lab testing conditions. I have great appreciation for the people who work in the Boeing production system and deal with these challenges every day. Having stated that, there is certainly room for improvement to attain tighter control around the manufacturing processes and factors that can impact quality. To reduce the chance of defects due to the condition of the tool it is recommended that the mechanic clears the cutter and bushing of debris between holes and takes a preliminary measurement after each hole. A cutter that results in an oversized hole can be swapped out immediately and inspected for damage. Note that it is not possible to have an in-process test for fiber breakout since it would require stack-up disassembly.

To statistically test whether a difference in quality was achieved by changing to the WC tool and implementing tighter controls around the manufacturing processes, a two sample T-test was used. Excluding the outliers from airplanes T and ZA, there was a 62% reduction in the average number of defects, and a P-value of 0.023, meaning that given the data, it is only 2.3% likely that the average number of defects has *not* decreased since airplane N.

	Total Defects		
	Average	**SD**	**P Value**
Original (PCD) Cutter	4.85	3.89	
Proposed (WC) excluding T and ZA	1.83	2.53	0.023

Table 6: Total Defect Statistics Before and After Tool Change

One of the motivations for the experiment was to evaluate the performance of the proposed cutter with respect to breakout specifically. The same analysis was performed for breakout defects only, and is summarized in Table 7.

	Breakout Defects		
	Average	**SD**	**P Value**
Original Cutter	3.36	2.20	
Proposed excluding T and ZA	1.63	0.74	0.007
Proposed including T and ZA	1.56	0.73	0.024

Table 7: Breakout Defect Statistics Before and After Tool Change

Even with the defect data from airplanes T and ZA, there is a statistically significant reduction in the number of breakout defects observed since the tool change. The average number of breakout defects decreased by over 50%. Referring back to Table 1, breakout defects take 4 – 10 hours of labor to repair, plus the additional overhead required to record defects and determine the appropriate repair. This translates into a significant savings to the production system. Furthermore, perhaps the most important result of this quality improvement is that there are less quality-related delays trickling downstream through the production system.

3.5.3 Cost Impact of Tool Change

While it is not possible to discuss specific costs that would expose proprietary pricing agreements between the Boeing Company and its suppliers, it is possible to provide the aggregate cost savings per airplane in this thesis. To arrive at this cost savings, it was assumed that each cutter is used four times: it is used once new, and reground (or sharpened) three times for additional uses. Due to the expense of the materials used to make these cutters, it is economical for manufacturers to pay to have them reground at a fraction of the cost of buying them new. Typical regrinding costs are about 20 – 40% of the new tool purchase price. Considering the costs involved in buying the cutters new and getting them reground, there is a cost savings of approximately 66% by replacing the PCD cutter with the WC cutter. For the door surround cell, this comes to about $1000 per airplane. Note that this neglects the cost savings impact of the quality improvements mentioned in the previous section, so the total cost savings from this initiative is significantly greater.

3.6 Conclusion

The hypothesis that the proposed tungsten carbide (WC) cutter would produce equal or better quality holes at a lower cost than the previously used polycrystalline diamond (PCD) cutter was correct. However, the WC cutter is not the perfect solution to the manufacturing challenges at hand. Changing the tool does not solve problems rooted in the condition of the parts or tools when they enter the work cell, work standardization and training, or other variables in a manufacturing environment.

Notwithstanding, this research demonstrated that an appropriately-designed WC cutter offers a cost and quality advantage over PCD cutters when drilling CFRP-titanium stacks at a single feed and speed setting. The WC cutter with a 135° point and double margin design outperformed the PCD cutter with a 118° point and single margin design with respect to CFRP hole size and consistency, breakout, and adherence to tolerances in both layers of the stack-up. This was true at both 380 rpm and 465 rpm with a feed rate of 0.002 IPR. It is expected that the improved performance in CFRP hole size was due to better stability of the drill when cutting titanium. Both speed settings appear to be good options for using this cutter in a woven-ply CFRP-titanium stack-up.

Unlike any literature found at the time of writing, this research further validated the performance of the cutter in production manufacturing. The occurrence of breakout defects was reduced by over 50% on the aircraft, and total defects were reduced by over 60% when removing two outliers. In addition to this quality advantage, the use of WC instead of PCD offers approximately 66% savings to the manufacturer when considering the initial purchase cost and the cost of regrinds.

3.7 Further Investigation

There are a number of investigations that can build upon this research project. First, experimentation can be performed to make a tool change in another manufacturing cell that drills a similar stack-up. The cell mentioned uses different drills, ones that can be programmed to change settings for two materials in a stack-up. This would provide an interesting comparison to the single feed and speed experimentation performed in this study. Since the quantity of holes drilled in this manufacturing cell is approximately nine times the number of holes drilled in the door surround cell, the potential cost savings to Boeing is significant. At the time of writing, this experimentation was in progress.

Further experimentation could also be conducted to better characterize the tool life of the newly selected WC cutter. The results of this experiment were not used to establish the expected tool life, or number of holes, that could be drilled in a given stack-up before experiencing an unacceptable degradation in quality. Costs would further be reduced if the maximum number of holes can be increased for each tool[14]. Also on this topic, it would be beneficial to perform a focused study on tool life with respect to the number of times a cutter can be reground. Currently, cutters are reground until they are damaged or fail inspection. A better understanding of the expected number of regrinds would help Boeing better manage its inventory levels of new and reground tools, as well as its suppliers for tool quality.

As a final note, manufacturing time (and thus cost) could be reduced by developing a one-up drilling process for this drilling operation. In a one-up process, the CFRP and titanium layers are not separated for cleaning or inspection after drilling. These processes exist elsewhere at BSC, and would require significantly more experimentation to confirm that acceptable hole quality can be achieved repeatedly, so inspection of the CFRP-titanium interface after holes are drilled would no longer be required.

3.8 Chapter Summary

This chapter focused on the selection of a designated tool used to drill the door surrounds of the 47 section (aft) section of the 787 fuselage, a stack-up of Carbon Fiber Reinforced Plastic (CFRP) and titanium. The study was motivated by quality issues in the door surround cell, and the high cost of the cutting tools used for the work. Both CFRP and titanium are difficult materials to drill individually, and have different optimal drilling parameters and cutting tools. This work explored an effective compromise between the parameters and tools used to drill CFRP and titanium individually that could be applied to

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[14] Specific hole quantity information was intentionally excluded from this thesis as it is proprietary to the Boeing Company.

one-shot drilling in a stack-up. A particular challenge of this the stack-up studied, 0.250" CFRP and 0.375" titanium, is that it is thicker than most found in previous literature.

Based on the improved durability of tungsten carbide (WC) cutters in titanium and lower cost, a WC cutter was proposed to replace the existing polycrystalline diamond (PCD) cutter using a drill process similar to those provided by Park et al. (2011), Beal et al. (2011), and Cordell et al. (2005). Also, a double-margin design was recommended for improved stability in the stack-up.

To gather support for experimentation, initial testing was performed to establish the performance characteristics of the tool and create a business case for comparison testing. At the time, it was noted that experimentation for selecting cutting tools was not standardized across Boeing sites, and a group of experts began working on this during the course of the project.

The experiment tested three cases: the existing PCD cutter at the current drill setting (465 rpm and 0.002 IPR), and the proposed WC cutter at two drill settings. All tests were conducted in a stack of 0.250" woven-ply CFRP and 0.375" titanium, with a 0.009" gap between the materials to provide an adverse condition worse than would be permitted in production. The results showed that the WC cutter performed better than the PCD cutter with respect to CFRP hole size and consistency, breakout, and overall hole tolerance at both settings. A change to the WC cutter was recommended using a speed of 465 rpm and feed of 0.002 IPR. Compared to the cost of purchasing and regrinding the PCD tool, the WC cutter is estimated to save 66%, or approximately $1000 per airplane.

Quality improvements following the tool change were evident. For the 14 airplanes following the tool change, excluding two outliers, there was a 62% reduction in the average number of defects related to the door surround drilling operations that use the WC cutter. Including all outliers, the number of breakout defects decreased by over 50%. Breakout defects typically involve 4 – 10 hours of labor to repair, and oversized holes normally take 1 – 2 hours of labor to repair. This translates to significant cost savings for

Boeing when considering the overhead involved in tracking defects, and the delays induced by defects on dependent work throughout the production system.

4 Durable Tool Kitting

4.1 Synopsis

Supplying the manufacturing workforce with the right tools in an efficient manner is a nontrivial problem with challenges in logistics and organizational behavior. Thousands of mechanics work over three shifts, and each of them may use more than 100 tools for their portion of the build cycle, which lasts multiple days before repeating. This raises challenges in the efficient storage and retrieval of the tools, as well as how to utilize common tools effectively across the workforce.

After reviewing literature on parts kitting and lean manufacturing, I conduct three investigations into the use of tool kits at the Boeing South Carolina (BSC) site as follows:

1. An analysis of the effectiveness of tool kitting in reducing Tool Crib transactions, a more time-consuming way to retrieve tools. The data show that adding tools to kits did not result in a decrease in Tool Crib transactions.
2. An investigation into why mechanics were not using tool kits in a way that reduced or eliminated the need to go to the Tool Crib. Observations and discussions with mechanics were collected and analyzed. For mechanics using the Tool Crib, tool kits tended to be incomplete, insufficient, or incorrect. The root cause of incorrect kits was often an ineffective requirements gathering process. This investigation also illuminated some reasons why tool kits were not meeting mechanics' needs that were not hypothesized.
3. An initiative to address the shortcomings of tool kits identified in the previous investigation by setting up a continuous improvement team. The team was set up to make proactive improvements to tool kits based on Tool Crib transaction data, which could be used to continuously monitor progress. Over the first 12 weeks, the continuous improvement team achieved a 45% reduction in tools retrieved from Tool Crib, outperforming other areas of the site that were not part of the initiative.

4.2 Introduction

This chapter focuses on making incremental improvements to kits, which are mainly composed of undesignated durable (reusable) tools. As these tools are needed by many mechanics and often for more than one job, there are logistical problems associated with selection, storage, packaging, and distribution of these tools to mechanics across three shifts. The original method for distributing undesignated tools was through Tool Rooms (commonly called "Tool Cribs"), where mechanics request tools from the available inventory. Boeing has chosen to pursue a strategy that distributes tools to mechanics in packages called kits, most of which are approximately the size of a laptop bag, as shown in Figure 19. These kits are stored "plane-side", near the mechanic's point of use. The main objective of this strategy is to reduce the "non-value-added" time it takes mechanics to retrieve the tools needed to perform their work.

Figure 19: Tool Kit

BSC also uses toolboxes to store durable tools near the mechanic's point of use. For the purposes of this study, the use of a kit or a toolbox to store tools on the factory floor will be considered functionally equivalent. Although toolboxes contain individual tools that are not in a package that can be transported to the airplane, mechanics can use "containment trays" to carry all of the necessary tools with them. While this may be slightly less convenient than an ideally designed kit, this difference will be ignored. Both kits and toolboxes are provided to mechanics with the goals of eliminating the need to retrieve tools from a Tool Crib and making it more convenient to complete work.

Much of the research to date involving kitting has been a result of the "lean manufacturing" movement and focuses on kitting parts rather than tools. There have also been some studies focused on the inventory management challenges associated with tool kits used by repair technicians (Vliegen, Kleingeld, & van Houtum, 2010). However, the available literature lacks an approach to implementing tool kits and improving them in a large scale, low volume production facility like BSC. This research will touch on implementing kits, but will focus more on adoption challenges and how to improve the effectiveness of tool kits.

The discussion that follows is a series of investigations into problems involving plane-side durable tools. After providing background on tool control and distribution practices at BSC, I review the relevant literature. The first investigation is into the initial state, the effectiveness of kits at BSC as they were upon the start of the project. Then I look into how kits are being utilized and why they are being ineffective in eliminating the waste associated with retrieving tools from a Tool Crib. Last I discuss the formation of a continuous improvement team that uses the analysis developed in the first two investigations to make targeted improvements to kits. The discussion concludes with a reflection on the most effective strategies that were employed, and additional improvement opportunities that BSC can pursue.

4.3 Background

This section will cover some appropriate background information specific to BSC on how tools are controlled and distributed to orient the reader on the rules associated with distributing tools. After reviewing this site-specific information, current literature on kitting and lean improvements will be reviewed as it relates to BSC, or a large scale, low volume manufacturing facility.

4.3.1 Tool Control and Distribution at Boeing South Carolina

Before discussing the forthcoming investigations into kitting at BSC, it is important to understand the basic concept of tool control. For Boeing Commercial Airplanes (BCA), tool control is taken very seriously to ensure that no tools are inadvertently misplaced on an aircraft, which can create a potential hazard for the customer. Boeing's tool control processes are audited by the Federal Aviation Administration (FAA), and Boeing's right to produce aircraft is contingent on compliance with these processes.

Put simply, tool control is a process of tracking the location or status of a tool. For durable tools, this involves checking tools out for use, and subsequently checking them back in to a location when the tool is no longer being used. Due to the expectation of one-time use, consumable items are "issued" (checked out) at the time of use, but are not tracked any further.

To implement tool control, Boeing uses a computerized system called CribMaster[15], which essentially tracks the location and status (checked in or checked out) of every tool. Each durable tool contains a unique serial ID for tracking purposes. When a durable tool is checked out of a Tool Crib, CribMaster records who is using that tool and requires that the exact tool is returned by the end of the workday.

For the case of kits or toolboxes, the contained tools are permanently assigned to a specific manufacturing cell. The workers in each cell are responsible for tracking who has what kit or tool, and ensuring that all are returned to their storage location in complete form at the end of the shift. Kits are usually kept in storage cages (see Figure 20), containing a sign out sheet or board. For toolboxes, tracking is usually accomplished by an ID card system, where mechanics can place ID cards in place of the tool that they are using. Also, some cells have toolboxes that are capable of electronically interfacing with CribMaster.

Consumable items (e.g. gloves and undesignated cutters) are issued on a regular basis to "Point of Use" (POU) stations in cells throughout the factory. This provides similar convenience to kitting for consumable items as compared to obtaining them from a Tool Crib. The focus of the forthcoming investigations will be on durable tools only.

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[15] Produced and sold by WinWare Inc.

Figure 20: Tool Kit Cage

4.3.2 Kitting Team

A small team from BSC Tool Services is devoted to building, distributing, and updating kits based on mechanics' input. The process begins with members of the team gathering requirements from the mechanics for whom they are building kits. BSC uses an off-site third party logistics partner to pick tools from available inventory and assemble them into customized kits. The kitting team also handles update requests for kits. Over the course of this project, the Tool Services organization was working towards more cross-training as the supply of tools was shifted from Tool Cribs to kits. This meant that Tool Crib attendants were getting involved in updating or improving kits. As the focus of this effort was on making effective improvements to kits, this shift was important. It helped align the organization towards serving mechanics through kits rather than Tool Crib counter service.

4.3.3 Literature on Kitting

Brynzér and Johansson (1995) cite Bozer and McGinnis' (1984) definition of a kit: "a specific collection of components and/or subassemblies that together (i.e., in the same container) and combined with other kits (if any) support one or more assembly operations for a given product". As the reader may infer from the definition, this view of kitting focuses on the materials rather than the tools required for assembly. A key difference between kitting parts or materials required for assembly and kitting tools is that material kits need to be prepared for each unit assembled while durable tool kits are assembled once and only updated if there is a defect (broken tool, wrong tool, or missing tool). Much of the existing literature focuses on kitting parts or materials; however, there are some general takeaways that can be applied to tool kitting.

In a case study regarding kitting parts for an electronics manufacturer, Vujosevic et al. (2008) outline five fundamental issues that can be reduced to the following when considering tool kits:

1. *Insufficient quantity of components*
2. *Excessive quantity of components*
3. *Wrong components*
4. *Incomplete kits*

Examples of these issues will appear later when investigating why some kits are ineffective.

Since many companies consider kitting to be a "lean" practice, it is worth briefly providing context for the lean principles, which were mainly modeled after the Toyota Production System. Corakci (2008) reviews the use of kitting systems through the lens of "lean" production and references Taiichi Ohno's eight wastes:

1. *Overproduction*
2. *Waiting*
3. *Unnecessary movement*
4. *Transporting*
5. *Over-processing / incorrect processing*
6. *Unnecessary Inventory*
7. *Defects*
8. *Untapped Human Potential*

Tool and materials kitting mainly addresses the waste associated with waiting, unnecessary movement, and over-processing by reducing the effort required to obtain and use tools or materials in an assembly operation. For the case of BSC, having an appropriately designed kit near the location where the work is performed eliminates the unnecessary movement required to travel to the Tool Crib, wait in line, and process transactions. In surveying the literature, Corakci (2008) also found that kitting generally had a positive impact on quality.

However, there is often a tradeoff with unnecessary inventory, as recognized by Vliegen et al. (2010). For BSC, the majority of kits are designed for specific jobs to make it convenient for the mechanic to retrieve all the tools he needs at once. However, some tools are common across many jobs, which often results in duplicate inventory across kits. Mechanics in one manufacturing cell must perform many jobs over hours or days before the unit being worked on progresses to the next cell down the line. For this reason, kits for jobs not being worked are idle tool inventory by design.

Spear (2009) offers a different perspective on Toyota, and other "high-velocity" organizations, or those that consistently outperform their competitors. The following capabilities are ingrained in each high-velocity organization.

1. *Specifying design to capture existing knowledge and building in tests to reveal problems*
2. *Swarming and solving problems to build new knowledge*
3. *Sharing new knowledge throughout the organization*
4. *Leading by developing these capabilities*

These capabilities can be applied to kitting. As will be shown in the series of investigations that follow, a key element that was missing from the kitting operation was the first, knowledge capture and tests to reveal problems with kits. These problems tended to fall into one of Vujosevic's (2008) categories listed above. However, due to differences in the nature of BSC's tool kitting as compared to the electronics parts kitting studied by Vujosevic, there are some additional problems that were discovered during this research that relate to the condition of the tools inside kits.

4.4 Kitting Effectiveness: Assessment of the Current State

4.4.1 Problem Introduction

This section focuses on how effective kits are in reducing the time wasted by retrieving tools from a Tool Crib. Therefore, the first and most basic question worth asking is: *Are Tool Crib transactions decreasing in areas where tool kits have been provided?*

4.4.2 Initial State of Kitting at BSC and Boeing Best Practices

Before addressing the question, there is some relevant background information on the maturity of the kitting operation at BSC and other kitting practices at Boeing. As BSC is relatively new, tool kitting has not been completed for all of the standard work performed throughout the site. However, the concept of kitting tools is not new to Boeing, which uses tool kitting in other manufacturing facilities, most notably its 777 and 737 assembly lines. This section will review the state of tool kitting upon the start of the project and also briefly discuss how kitting was implemented at other Boeing sites for the reader's reference.

4.4.2.1 Practices at Other Boeing Sites

Tool kitting at Boeing is established at several of its facilities. While there is some knowledge sharing, each facility or airplane program has had the autonomy to develop its own approaches to kitting. This brief overview will focus on the kitting practices used on the 777 and 737 assembly lines based on the author's site visits to these facilities.

The 777 line uses an approach to durable tool kitting most similar to BSC. Tools are kitted in similar cases and kept in cages as shown in Figure 21. However, some cages are not located in manufacturing cells. Instead, they are located off the line, requiring mechanics to travel further to retrieve their tools. The 777 program has most of its durable tools kitted, but there is still some Tool Crib traffic for consumable items such as cutters. In addition, the 777 program has implemented some kitting for hazmat supplies, parts, and cutters, which is out of scope for this discussion.

Figure 21: 777 Kit Rack

A bit more interesting is the approach to kitting used at the 737 assembly facility, which currently has the highest production rate of any Boeing airplane program, producing more than one airplane per manufacturing day. The 737 plant has achieved a nearly 100% kitted operation. Both durable and consumable tools are staged in carts that function like movable toolboxes shown in Figure 22. Carts are delivered to the appropriate manufacturing cell for each shift and retrieved at the end of the shift. This operation is effective in keeping mechanics at their work station and able to perform their work. Tool Cribs in the 737 plant are rarely used and contain considerably less inventory than Tool Cribs in other airplane programs. While approach to staging and delivering tools reduces the waste associated with mechanics retrieving tools, it also requires additional overhead to prepare, replenish, and deliver kits for each shift. On the other hand, staging and delivering tools reduces the floor space consumed by tools in the mechanics' work areas. Only one shift's tools are stored on the floor at any given time.

Figure 22: 737 Tool Kit Cart

The 737 program did not achieve its level of kitting overnight. As the most established aircraft manufacturing operation in the Boeing fleet, it is clear that the program benefits from decades of experience and well-standardized manufacturing processes. In contrast, the 787 is Boeing's newest model and BSC is Boeing's newest plant. The manufacturing practices are evolving at this time as BSC is developing its workforce, optimizing its build process, and increasing its production rate to meet customer demand. This makes it difficult to design kits exactly "right" the first time around. However, the investigations that follow will show that by making targeted improvements, it is possible to significantly reduce the waste associated with retrieving tools.

4.4.2.2 Initial State of Kitting

As was mentioned in the Site Background section, the aft body, mid body, and final assembly facilities that make up BSC were started by three different companies. The cultures and practices established at each facility are being unified, but differences persisted during the course of this project. A summary of the number of durable tools available to mechanics at the start of the internship is shown in Table 8.

FAD[16]	MID	AFT
23,300	18,900	10,300

Table 8: Durable Tools Available in Kits or Toolboxes at Start of Internship

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[16] FAD represents the Final Assembly facility.

The final assembly facility (FAD), the newest facility, had the most tools available to mechanics outside of the Tool Crib, whether in tool kits or toolboxes. Over the course of the internship, most of the kitting team's effort was expended on the final assembly building. The reason for this was not based on relative priority to the needs throughout the site, but rather strong executive support for kitting in final assembly. Mid body had the second-most amount of tools available to mechanics. Last, the aft body facility had the least tools available to mechanics that were organized in kits, and also received the least attention from the kitting team during and prior to the project.

Each building contained a different number of Tool Cribs. Final assembly had three, mid body had two, and aft body had one. Table 9 shows the number of durable tools, those that could be put in a kit, checked out of Tool Cribs on a typical day at the start of the internship. Note that due to the number of Tool Cribs in each building, the aft Tool Crib handles the most durable requests daily (900). The Tool Cribs in final assembly and mid body handled on average 500 requests per day. As the reader can imagine, the more counter traffic at a Tool Crib, the longer the wait time (waste) will be to retrieve a tool.

FAD	MID	AFT
1580	1090	900

Table 9: Daily Durable Tools Checked Out per Building at Start of Internship

While some site history was previously provided, it is now worth briefly reviewing the history of tool distribution at BSC. At one point, the operation of Tool Cribs was outsourced to a third party. However, Boeing decided to take over this responsibility. Without being able to go into detail, the transition required some changes to tool control and inventory management practices. Implementing these changes was a challenge that persisted during the course of this project to some degree.

The investigations that follow will often rely on Tool Crib transactions to measure the impact of kitting. It is important to know that during the timeframe studied, BSC was increasing its production rate in all three buildings. As one would expect, the number of tools checked out correlates positively (not perfectly) with the production rate. Therefore, if the kitting team did nothing, or had no effect, one would expect to see an increase in the number of durable tools checked out each day as the production rate increases.

4.4.3 Hypothesis

Since one of the goals of using tool kits is to eliminate the need to go to a Tool Crib, the problem statement naturally leads to the basic hypothesis: *The availability of tools in kits or toolboxes results in a reduction in the Tool Crib transactions where they have been provided.*

The hypothesis is implicit in the existence of the kitting team, which was created to reduce the non-value added time required to retrieve tools.

4.4.4 Approach

In order to test the hypothesis, we can use transactional data from CribMaster, the software Boeing uses for managing its tool inventory. When checking out a durable tool, CribMaster records an "issue returnable" transaction. When a tool is checked back in, it records a "return" transaction. For simplicity, we will only look at issue returnable transactions, which correspond to the number of durable tools issued on a particular day. Keep in mind, however, that this is only about half the waste associated with durable Tool Crib transactions. The other half is the time required to return the tool.

This transactional information can be compared to two numbers describing the state of kitting at a point in time. The first is simply the number of tools that are currently available in kits or toolboxes, which I will refer to as *plane-side inventory*, at a particular area or building. The second is the number of tools that were recently transferred (or added) to kits or toolboxes in the same timeframe. One would expect that as tools are made available to mechanics via kits or toolboxes, the number of Tool Crib transactions would decrease.

4.4.5 Results and Discussion

As shown in Figure 23, there is no apparent reduction in the number of durable tools checked out per week in each building over the eight week period shown. Note that the dip seen near May 28th is due to a reduced labor force on the US holiday Memorial Day.

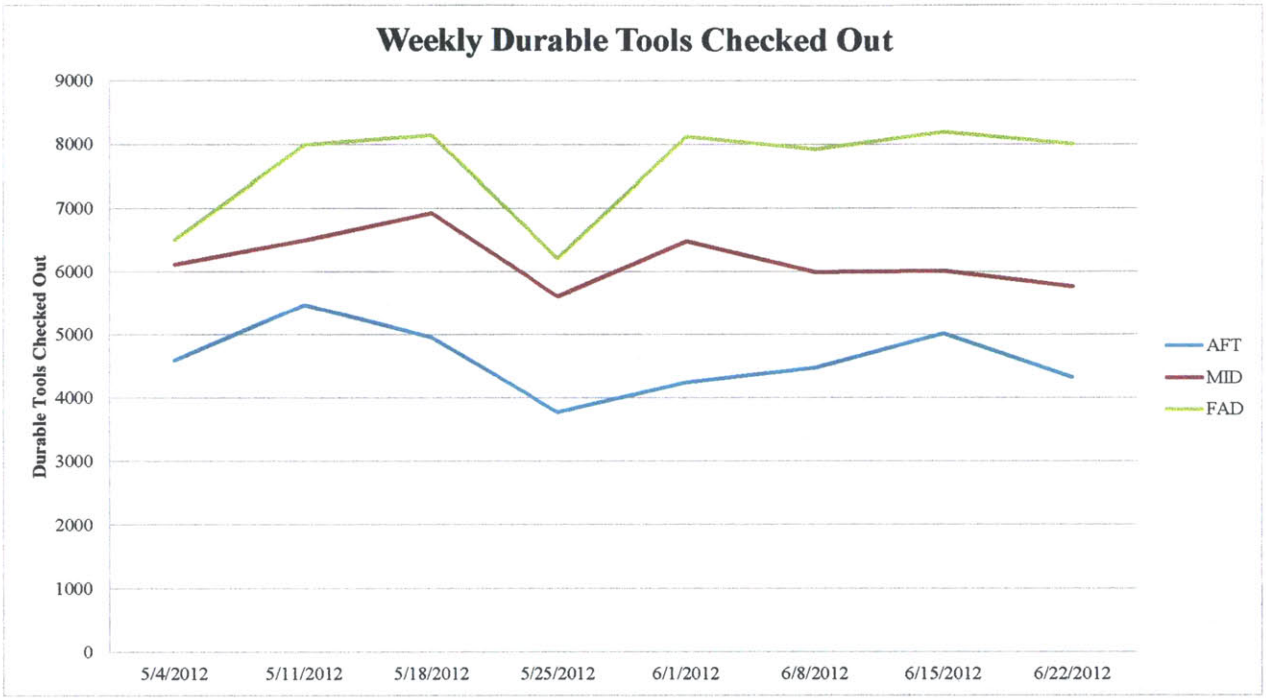

Figure 23: Weekly Durable Tools Checked out by Building

This might lead one to think that the operation could have reached a steady state if there were not a significant number of tools added to the plane-side inventory during this time. Especially for the final assembly building, Figure 24 demonstrates the contrary. Thousands of tools were added to kits or toolboxes during this time. Although some of the transfers shown in Figure 24 are even exchanges for different tools, the number of tools added to plane-side inventory in final assembly is significant over this time period. However, these tools are not being effective in reducing waste as there is no noticeable decrease in the number of durable tools issued from the Tool Cribs in that building. Mid body, which received less tools over this time period, showed a slight decrease in durable issues.

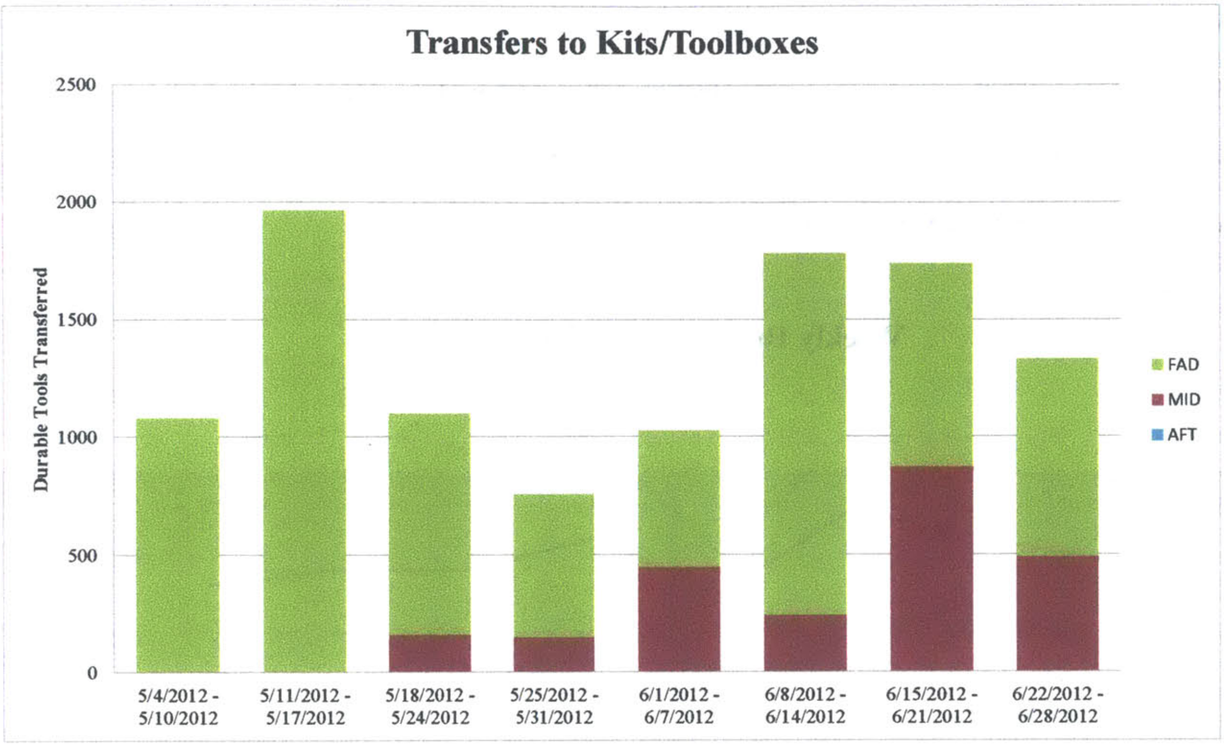

Figure 24: Durable Tool Transfers to Kits/Toolboxes

4.4.6 Conclusions and Next Steps

The results discussed above are puzzling, and show that the hypothesis is incorrect. While one might not expect a one-to-one relationship between the number of tools added to plane-side inventory and the number of tools issued from Tool Cribs, it is surprising to see no decrease in Tool Crib transactions. There is clearly at least one failure mode between the kitting operation and its goal of reducing waste. However, the kitting team was previously unaware of this. Why? The first capability described by Spear (2009) was missing. There were no built-in tests to reveal problems. The information above does reveal a problem, but does not provide sufficient information to reveal the root cause. A next step for further investigation is finding the answers to the following questions: *Are mechanics using their kits in a way that reduces or eliminates the need to go to the Tool Crib? If not, why not?*

4.5 Kit Utilization

4.5.1 Problem Introduction

The previous investigation found that the addition of tools to plane-side inventory (either in kits or toolboxes) did not result in a measureable decrease in Tool Crib transactions for durable tools. This unexpected result leads to an investigation into how kits are being utilized. We seek to answer the questions, *are mechanics using their kits in a way that reduces or eliminates the need to go to the Tool Crib? If not, why not?* These questions brought forth several hypotheses from the kitting team and Tool Services management about why mechanics might not be using tools available plane-side. These hypotheses will be reviewed in the next section with some relevant background.

4.5.2 Hypotheses and Background

Based on section 4.4, it is hypothesized that mechanics are *not* always using their kits or toolboxes in a way that reduces or eliminates the need to go to the Tool Crib. There are multiple hypotheses, based both on logic and experience that were proposed by the author and others in the Tool Services organization to explain why Tool Crib transactions were not decreasing.

1. *Tool Crib break culture* – The most common response to the previously presented data on Tool Crib transactions was that mechanics were accustomed to visiting the Tool Crib and enjoyed using it as a break. It was believed that changing this behavior would require more than just providing the appropriate kits; it required a culture change on the shop floor.
2. *Kitting is incomplete for the area* – Although this hypothesis is functionally equivalent to insufficient tools (hypothesis 4 below), it is called out separately here since the kitting team was well aware of areas that had not received kits yet from the kitting team.
3. *Wrong tools* – This is a logical hypothesis, and in line with Vujosevic et al.'s (2008) issues that can occur with kits. If a mechanic does not have the right tools available in his kit or toolbox, he

still needs to visit the Tool Crib. For the case of wrong tools, there was no built-in test to discover the problem that kits had the wrong tools.

4. *Insufficient tools* – This is another logical hypothesis that is also in line with Vujosevic et al.'s (2008) issues that can occur with kits. In this case, if a manufacturing cell needs more of a particular tool simultaneously than there are in plane-side inventory, some mechanics will need to retrieve the balance from the Tool Crib. As in the previous hypothesis, for the case of insufficient tools, there was no built-in test to discover the problem that areas did not have enough tools. This would be especially problematic for areas where the kitting team thought their job was complete.

4.5.3 Approach

Two approaches were used to investigate why kits were not being used in a way that reduced or eliminated Tool Crib traffic. The first involved data analysis much like in section 4.4.5. The second was a bit more straightforward: ask the mechanics who were using kits or going to the Tool Crib.

It is possible to go a step deeper into the data than was done in section 4.4.5. To verify the answer to the first part of the problem (*are mechanics using their kits in a way that reduces or eliminates the need to go to the Tool Crib?*), it would be useful to know if mechanics are checking out tools that are already available in their area. In order to determine this, Human Resources (HR) data was joined with CribMaster data to identify which mechanics worked in which manufacturing cells. Once a mechanic's work area was identified, any tools checked out by that mechanic could be compared to the plane-side inventory (in kits or toolboxes) at his area. Note that with this information alone, it is not possible to distinguish between a mechanic who went to the Tool Crib because there were *insufficient* tools available at his cell (hypothesis 4) and a mechanic who went to the Tool Crib to take a break (hypothesis 1).

For this reason, and for the opportunity to learn about more possibilities, mechanics were informally asked about how they used their kits, and why they were visiting the Tool Crib. To gather this information, I enlisted the help of the kitting team, who often interacted with the mechanics to specify the design of their kits and update them. I was also fortunate to have the help of Tool Crib leads, who would ask mechanics why the tools they were retrieving were not available to them in a kit or toolbox.

4.5.4 Results and Discussion

As the approach has a data analysis portion and an investigative portion, the results will be discussed in two parts. Using the data first helped direct any investigation done on the factory floor, so the data analysis will be discussed first. Then, insights gained from the factory floor will be used to help explain some of the trends in the data that show kits are not being effectively utilized.

Figure 25 shows an example of the analysis on kit utilization performed for final assembly over a two-week period. While this analysis was performed for the entire site, filtering to final assembly alone provides a representative example and makes the chart much less cumbersome to look at compared to the chart for the whole site. The heights of the bars represent the number of durable tools checked out, and the color of the bars indicates whether the exact tool checked out was available in the area where that mechanic works. The portion of the bar shaded red represents the number of tools that were checked out by mechanics that were also available in a kit or toolbox. In other words, a kit or toolbox contained the specific tool that the mechanic went to the Tool Crib to retrieve. For all manufacturing cells except position 3, more than 50% of tools issued from the Tool Crib fell into this category. This is surprisingly high, and is evidence to support hypotheses 1 and 4 – either that mechanics were going to the crib knowing that the tool was already available to them, or that the tool needed was already in use by another mechanic in the same area.

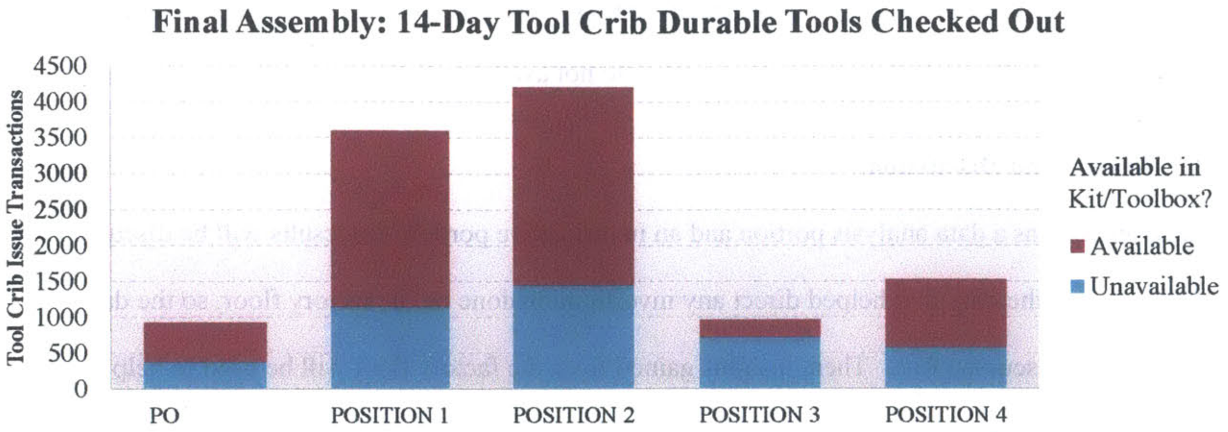

Figure 25: Final Assembly Durable Tools Checked Out and Availability in Kit/Toolbox

The portions of the bars shaded blue indicate tools checked out that were not available in a kit or toolbox. This clearly supports hypothesis 2, that kitting is incomplete for the area, or hypothesis 3, that the wrong tools were provided. Since the kitting team worked to complete specific manufacturing cells before moving forward with other manufacturing cells, it was possible to determine which cells were incomplete and which cells did not have all the right tools even though the team thought kitting was complete.[17]

The approach to analyzing Tool Crib and HR data demonstrated above provides evidence that tool kitting is not achieving its desired effect. However, it has not confirmed the question of exactly why mechanics do not seem to be utilizing kits to their full potential. As discussed in the approach, this was further investigated by informally asking the mechanics in their work cells or as they visited the Tool Crib. The information provided by mechanics was very valuable. In many cases, the Tool Crib break culture hypothesis (1) was incorrect. There was evidence to support the other hypotheses, and also additional explanations that were not previously considered. The reasons *why* mechanics were still visiting the Tool Crib compiled from numerous conversations are summarized below.

- *Insufficient tools* – In some cases, we found that there was an insufficient quantity of a particular tool to meet the needs of a manufacturing cell. Much of the time, the tools that were needed were quite inexpensive and easy to provide.

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[17] One other complication that came up involves "travel teams", which are groups of mechanics who perform non-standard work in multiple cells. Based on the analysis method, it was not possible to conclusively determine what tools these teams had available to them in kits. Travel teams were less likely to have the right tools because they did not always work on the same jobs.

- *Kitting incomplete* – As expected, kitting was not complete for every cell. When questioned, some mechanics would respond that their kit requests had been submitted to the kitting team, but had not yet been fulfilled.
- *Wrong tools* – In the case where kits were available, some mechanics discovered that they were not given the tool they expected. This often traced back to a problem of properly specifying the tools when the original kit request was submitted. For example, mechanics would often handwrite general descriptions of what they wanted in a kit. Often, an item like "pliers" would be written. BSC has multiple types of pliers in inventory, so this request was likely to result in the wrong tool being selected for the kit.
- *Tool only available in Tool Crib* – In very few cases, the "tool" was not something that could easily be put in a kit or a toolbox. An example of this is a two-way radio, which required charging between uses. Charging stations were located in the Tool Crib, so these devices were checked in and out every day unless a customized charging area was set up for a cell.
- *No access* – This reason was not hypothesized and would not be identifiable from the data analyzed. It was found that some teams of mechanics would be territorial about their tools/kits. In some cases, one shift would lock kits in the cages shown in Figure 20, but the key to that cage would not be shared with other shifts. From a management standpoint, this is very inefficient since tool inventory that could be put to use is kept idle while duplicate inventory is retrieved from the Tool Crib, or sometimes a separate kit cage.
- *Broken/dull tools* – This reason was not hypothesized and could not be identified from the data analyzed. Due to the nature of materials or parts kitting, it also did not appear in the list of issues that could occur with kits from Vujosevic et al. (2008). Some tools were wearing out or breaking. Instead of asking the kitting team or a Tool Crib for a replacement to be put in a kit or toolbox, this often resulted in mechanics checking out the same tool from the Tool Crib. Some common items this occurred with were scissors and flashlights. This reason alerted the kitting team to the issue that some mechanics did not know the process used to update a kit or replace a tool. Another issue was that some mechanics chose not to go through the update/replacement process because they felt it was easier to go to the Tool Crib. That behavior could be evidence for the Tool Crib break culture (hypothesis 1).
- *"Didn't know"* – Last, there were some mechanics who claimed not to be aware of the tools that were available in kits or toolboxes at their manufacturing cell. While this may have been true in some cases, we concluded that this was usually a "cover-up" excuse. This type of behavior also supported the Tool Crib break culture hypothesis (1).

4.5.5 Conclusions and Next Steps

This section focused on finding out why the tools in kits and toolboxes did not appear to be fully utilized. The data analysis and subsequent investigations revealed some support for the hypotheses and also shed light on additional reasons why plane-side inventory had not successfully reduced or eliminated the waste associated with using a Tool Crib.

The investigation found that there was support for all four hypotheses: that the tools provided were incomplete, insufficient, or incorrect; and that some mechanics seemed to be using the Tool Crib to take a break from work. However, the latter (hypothesis 1) was less common than hypothesized by Tool Services management. There was often another reason why a mechanic visited the Tool Crib.

Perhaps the most important insight into these hypotheses was the root cause behind an incorrect or incomplete kit. The problem traced back to properly specifying the requirements for the kit. As in the example above, "pliers" is not a sufficient description to provide the right tool to the mechanic given the many types of pliers available. There is a need for a better requirements gathering system to get kits right the first time.

The new reasons discovered for why kits were ineffective were particularly interesting. There were special cases, when the tool (e.g. two-way radio) was only available in the Tool Crib. Addressing this problem requires a customized solution for the tool. There were also challenges getting teams on different shifts to share their tool inventory. This territorial tendency is a bit harder to address and a specific symptom of a broader issue of communication and teaming across shifts. Last, the replacement of broken or worn out tools had a seemingly simple solution, however, the fact that mechanics were ignorant to the process or avoiding it demonstrated the need to make this maintenance activity more seamless to the customer (the mechanic).

While this section identified a number of problems with tool kitting as it is implemented at BSC, it has not proposed a way to resolve them. However, the analytical tools developed in this section help provide Spear's (2009) first capability of high-velocity organizations, a way to capture knowledge of kitting effectiveness and reveal problems. The appropriate next step is to move to developing the second capability, to swarm and solve problems, building knowledge on how to operate in a better way. In the following section, the kitting team's efforts will be directed towards continuous improvement in support of developing this capability.

4.6 Improving Kit Utilization and Fostering Continuous Improvement

4.6.1 Problem Introduction

The previous section focused on how effective kits and tool boxes were at reducing Tool Crib transactions and why existing plane-side tool inventory was not successful in eliminating Tool Crib traffic. Some of the reasons for ineffective kits do not require significant investigation or problem-solving to resolve. This includes cases when a tool is missing for some reason (e.g. incomplete kit, wrong tool, or insufficient quantity). On the other hand, several problems surfaced that do require problem solving between the kitting team and the mechanic customers. The sharing or access issue across shifts may require collaboration with factory floor management. Broken tools may require additional attention to determine the root cause. And there is certainly no black-and-white solution to changing the Tool Crib break culture.

The focus of this section is how to set up a continuous improvement system within the kitting team that will tackle both the issues that do not require significant problem-solving and those that do. In doing this, I aim to develop within the kitting team Spear's (2009) second capability to swarm and solve problems, building knowledge on how to operate in a better way. What follows is an approach on how I aligned the team to this goal and the results they achieved.

4.6.2 Background

In *Dynamic Manufacturing*, Hayes, Wheelwright, and Clark (1988) argue that "continual learning and improving" is critical to the success of manufacturing organizations. This is consistent with Spear's (2009) four capabilities of high-velocity organizations, where building knowledge is a central theme. So, how are learning organizations or teams built?

In pursuit of answering this question, I ask a more fundamental question: *what motivates people to do well at their jobs?* A brief survey of the organizational and behavioral psychology literature reveals some insight into what aspects of a job motivate people. In proposing the Job Characteristics Model, Hackman and Lawler (1971), surveyed previous literature on motivation, finding that there are three general characteristics of motivating jobs:

1. *The job must allow a worker to feel personally responsible for a meaningful portion of his work.*
2. *The job must provide outcomes which are intrinsically meaningful or otherwise experienced as worthwhile to the individual.*
3. *The job must provide feedback about what is accomplished.*

Hackman and Lawler (1971) argue that these characteristics are captured in Turner and Lawrence's (1965) four "core" dimensions: variety, task identity, autonomy, and feedback. In addition, how strongly an individual responds to these characteristics depends on his own desire to grow. While it may not be possible to affect an individual's desire to grow in the short term, the general characteristics of motivating jobs can be used to help design work for a continuous improvement team.

On considering the three general characteristics of motivating jobs above, two of the three are within management's control. The first, allowing the employee to feel personally responsible for his work (autonomy) can certainly be afforded by allowing the employee to make decisions and perform tasks on his own. The second characteristic listed above, that outcomes must be considered worthwhile to the individual, may not be in the immediate control of management. By nature, people have unique interests and preferences that may not easily be changed. However, the problem of matching individuals to their interests would seem to be a duty of management upon hiring an employee. Last, structuring work so that feedback is provided is within management's control. In fact, this is consistent with built-in tests to measure performance, part of Spear's (2009) first capability.

4.6.3 Hypothesis

The hypothesis for this section has two facets, one regarding the formation of a continuous improvement team, and one regarding the results that the team will achieve.

1. By designing a system that allows the kitting team to feel personally responsible for their work and receive regular feedback, the team will provide improvements in a self-sustaining cycle.
2. The areas where this continuous improvement team will focus their efforts will outperform all other areas.

4.6.4 Approach

Now that there are tests available to expose problems with the effectiveness of kits (e.g. Figure 25), the kitting team needs to be engaged in reviewing the information, identifying problems, and formulating solutions to those problems. To begin this effort, I initiated a twice-weekly meeting to train the kitting team on how to use the Tool Crib transactional data I prepared for them. During each meeting the team could review charts and data in a Microsoft Excel spreadsheet, called the SWAT (Special Weapons and Tactics) Team Dashboard, which would assist in answering a number of questions such as the following:

- What tools were most often requested at Tool Cribs for the site, a building, or a specific cell?
- Who checked out those tools and how often?
- Were the tools that were checked out available in nearby kits or toolboxes? If so, how many of those tools are available in the nearby kits or toolboxes?

The team was responsible for taking actions on any issues found or investigating further. Often, countermeasures could be agreed upon during the meeting. Before each meeting the transactional data would be refreshed, allowing the team to see the impact of any countermeasures that were implemented.

The continuous improvement team focused on the mid body facility at BSC. This meant that the other two buildings had "business as usual" operations, which conveniently serve as controls in this pilot experiment. I named the team the SWAT (Special Weapons and Tactics) Team, professing that the team's special weapons and tactics were the data they now had available and the improvements they were able to deliver for mechanics. By framing the team's work in this light, I hoped to make their work meaningful and convey that they were able to make measurable positive impacts to the manufacturing operations.

4.6.5 Results and Discussion

As the hypothesis was given in two parts, this section is organized to first discuss the formation of the team and their engagement in continuous improvement, and then discuss the results they achieved backed by data analysis.

4.6.5.1 Forming the SWAT Team

As stated in the approach, I initiated twice weekly meetings for the SWAT team. The first two meetings were mainly spent guiding the group through the data and reports I prepared for their use. Since the team had varied skills in Excel and with data analysis, I spent some time coaching and training.

I also set a structure for the meeting where we would review any past countermeasures that were assigned and recent trends in Tool Crib traffic. Once the team established a cadence, meetings started with a sense of anticipation for the results that were achieved by past countermeasures. This was in line with the hypothesis and the third characteristic of motivating jobs.

As time progressed, I took a less formal role in running each meeting and coaching the team, encouraging the team members to take charge. Within three weeks, I had one team member take over running the meetings without me, aiming to give the group autonomy in their work. If there were any problems or questions, I was available to them in an advisory role. While I felt the team was in good hands as an autonomous unit, I will let the results in the following section speak for themselves.

4.6.5.2 Better Results with Less Effort

The results that follow are over a relatively short period of 12 weeks from when the SWAT team was formed until my internship concluded. Since the team focused on making improvements in the mid body facility, the other two buildings will be shown for comparison. Results will be shown by first looking at the effort expended by the kitting team in each building, which is best estimated by the number of tools that were transferred (added) to kits or toolboxes. Then the transaction trends will be shown to illustrate the reduction in Tool Crib transactions achieved. Last, a view of Tool Crib transactions normalized by jobs completed will provide a fair measure of progress (by accounting for an increasing manufacturing rate) towards the goal of reducing time wasted by retrieving tools from a Tool Crib.

Figure 26 shows the approximate number of tools added to plane-side inventory by building over the 12-week period since the SWAT Team was formed. As is evident from the graph, the number of tools added to mid body plane-side inventory increased over the period, however as Table 10 indicates, final assembly added the most total tools to its plane-side inventory during this time. This point is brought up for two reasons. First, it shows that the most "effort" in adding tools to plane-side inventory was expended in final assembly even though the SWAT Team was focused on mid body. Second, it is supporting evidence that not all problems associated with tool kits were solved by simply adding more tools (e.g. the access issue between shifts).

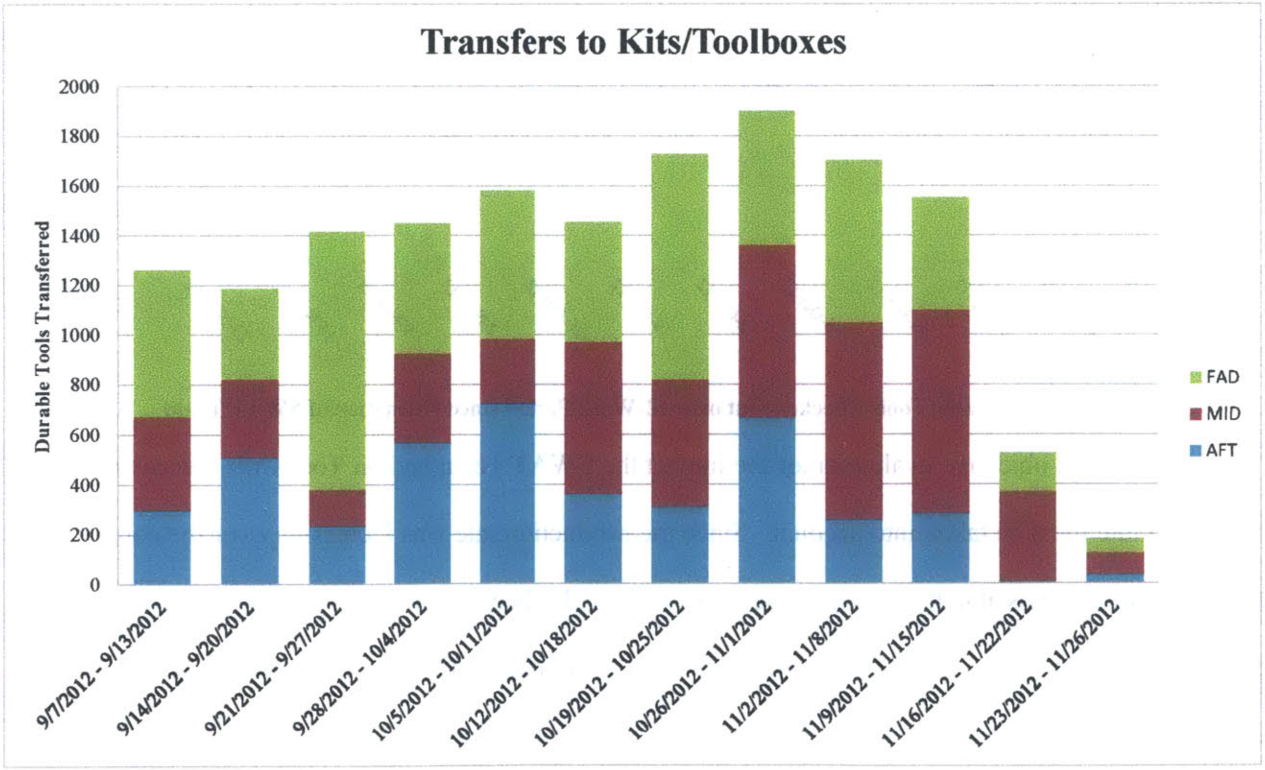

Figure 26: Tools Added to Kits/Toolboxes over 12-Week Period since Formation of SWAT Team

	AFT	MID	FAD
Tools Added	4253	5340	6324
	27%	34%	40%

Table 10: Tools Added to Kits/Toolboxes over 12-Week Period since Formation of SWAT Team

Figure 27 shows the transaction trend for durable tools in each building at the BSC site. Over the 12-week period since the SWAT Team formed, there was a 45% reduction in the number of durable tools checked out per day for mid body. This is more than twice the reduction that final assembly achieved during the same period (22%). With these results, it is evident that the SWAT Team's improvement initiatives delivered more value with less effort.

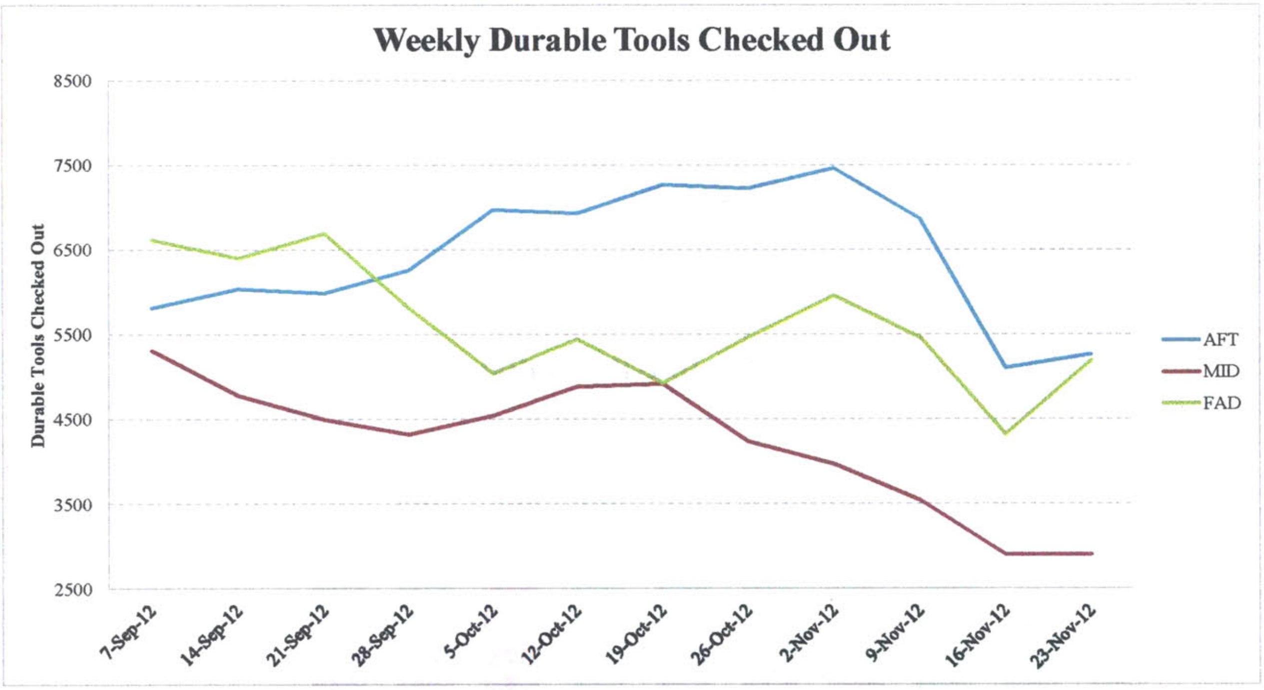

Figure 27: Durable Tools Checked Out over 12-Week Period since Formation of SWAT Team

To provide a more objective evaluation of the impact the SWAT Team had on Tool Crib transactions, the production rate must be taken into account. Since the production rate was increasing over the course of the internship, it is possible that the increase in the total tools checked out per day in the aft body building (observed above in Figure 27 over part of the period) was proportionally less than the corresponding increase in production rate. In other words, the factory could be doing more work per trip to the Tool

Crib. By normalizing for production rate, we will get a better sense of how much more efficient the operation became with respect to retrieving tools.

To normalize for production rate, one can divide tools checked out by the jobs completed daily for each building. This will be referred to as the *normalized tools checked out* metric. A job is a set of one or more manufacturing tasks that mechanics must complete in order to build the airplane. Note that due to the different origins of each building, jobs are defined differently; the amount of work or time it takes to complete a job is different for each building. There is also a wide range of the number of tools required to complete a job. This makes it unfair to compare the normalized tools checked out metric between buildings. However, it is useful to look at the *trend* of the metric over time within each building since each is repeating the same jobs in a multi-day cycle.

Figure 28 shows the normalized tools checked out metric trend for each building. Aft body shows a stable metric, meaning that the production rate increases were nearly perfectly correlated with the number of tools checked out. Mid body and final assembly both show improvements over this time period.

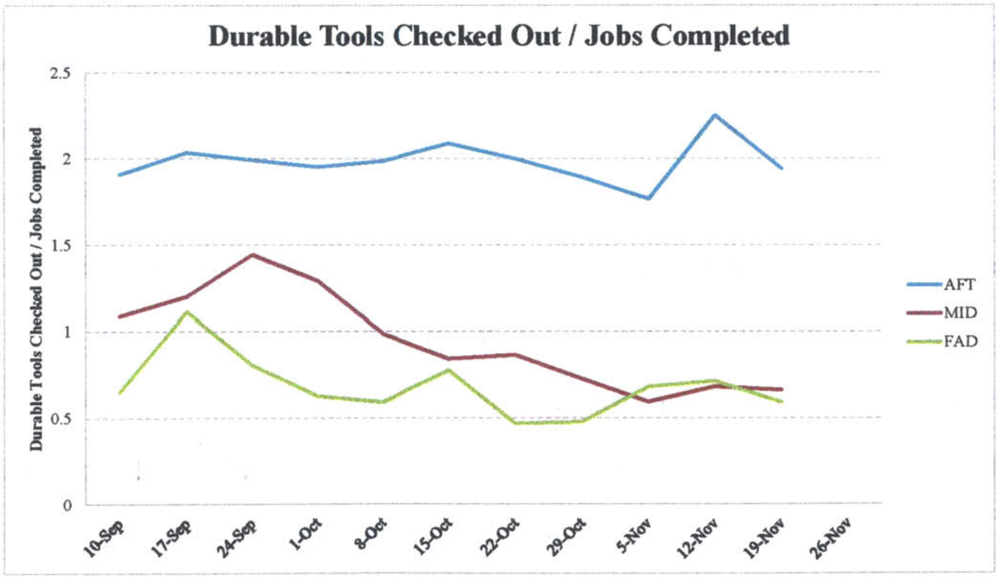

Figure 28: Durable Tools Checked Out/Jobs Completed over 12-Week Period since Formation of SWAT Team[18]

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[18] Due to the lack of job completion data available during the week of the US holiday of thanksgiving, the last week in the graph has an undefined metric. This week is left on the graph for the sake of consistency with Figure 27.

Table 11 shows the percentage change in the normalized tools checked out metric from the week the SWAT Team formed to the 11th following week (one week before the US Thanksgiving holiday). As one might expect based on the number of tools added to plane-side inventory (Figure 26), the two buildings with the most tools added had the greatest percentage improvement over this period. However, mid body achieved more than four times the improvement than final assembly even though fewer tools were added to its kits or toolboxes. This shows the effectiveness of the SWAT Team in prioritizing the most impactful issues and addressing them.

	AFT	**MID**	**FAD**
% Change	1.7%	-39.2%	-9.1%

Table 11: Percentage Change in Normalized Tools Checked Out Metric for Each Building

4.6.6 Conclusions and Next Steps

The SWAT Team was formed to be a continuous improvement team that would serve the factory by helping reduce the waste associated with how mechanics retrieve the tools they need in order to perform their work. Over the period studied, the team's improvements in the area where they focused (mid body) outpaced the rest of the site.

However, I only consider the team formation a true success if the team sustained their work in pursuit of continuous improvement beyond my tenure in Tool Services and Hazmat at BSC. Therefore, it is still premature to judge if the hypothesis was correct; that by designing a system that allows the kitting team to feel personally responsible for their work and receive regular feedback on their work, the team will provide improvements in a self-sustaining cycle. One factor not considered in the hypothesis became apparent near by the end of the internship. Management sometimes prioritized other tasks for the kitting team that reduced the time available for continuous improvement efforts. This is understandable given the dynamic manufacturing environment at BSC but was overlooked when hypothesizing that properly motivating the team would be the key to a virtuous cycle of continuous improvement.

When considering next steps, it is worth revisiting Spear's (2009) four capabilities. Recall that this section focused on implementing the second capability, to swarm and solve problems. However, the third and fourth capabilities have not yet been ingrained in the culture. The third capability would be the next logical step, to share the knowledge and practices learned from making improvements in mid body with the rest of the site. Getting the organization to the point where leadership develops these capabilities throughout the organization, the fourth capability, is a much bigger undertaking. My hope is that the SWAT Team will continue to be motivated by the virtuous cycle of continuous improvement, and show others what they have learned.

4.7 Chapter Summary

This chapter focused on investigating the effectiveness of durable tool kitting in reducing waste, and addressing shortcomings in tool kits by setting up a continuous improvement team. Parallels were drawn from the literature on materials and parts kitting to tool kitting, and previous tool kitting operations at Boeing were reviewed. By analyzing Tool Crib transactional data, it was possible to determine that kits were not as effective as anticipated in reducing the waste associated with retrieving tools from the Tool Crib. Further data analysis and in-person investigations led to the discovery of various root causes for ineffective kits, some of which were not hypothesized.

In response to discovering these issues, and now having the data available to continue discovering issues, I formed a team whose purpose was to make continuous improvements to existing kits. To motivate the team, I designed work such that the team would have autonomy and regular feedback on their progress. After 12 weeks of the team working part-time on this initiative, Tool Crib transactions were reduced by 45% in the mid body facility, outperforming the other two buildings at BSC, where kitting operations were unchanged. The team was able to deliver improvements at a faster rate and with less effort compared to the other buildings.

5 Conclusion

This thesis began with the high level question:

> *How does management ensure that the best tools for the job are made available to mechanics in an efficient way?*

I examined two specific areas of this question during my six-month tenure with Boeing South Carolina's (BSC) Tool Services and Hazmat organization. The first was the selection of a better designated tool (one that is mandated for a specific operation) for drilling the door surrounds in the aft section of the 787. This investigation went into detail on the challenges of drilling Carbon Fiber Reinforced Plastic (CFRP) and titanium stacks, with particular relevance to the aerospace industry. The study found that a double-margin tungsten carbide (WC) cutter with a 135° point angle and double margin design had superior cost and quality performance as compared to a 118° point angle polycrystalline diamond (PCD) cutter with a single margin design. Unlike existing literature on machining stacks of CFRP and titanium, this study showed both experimental results and actual quality results from production manufacturing. For this specific application, changing to the proposed WC cutter resulted in savings of approximately 66% or $1000 per airplane in tool costs alone and a 62% reduction in defects.

The second stream of research looked at serving the manufacturing operations more broadly, with durable tool kits for undesignated tools (those that can be chosen by the mechanic). Tool kits were implemented with the goal of reducing the time it took mechanics to retrieve their tools. It was found that existing kits were not being as effective as intended, but significant improvements could be achieved with the proper approach. By designing a system to detect and troubleshoot problems with existing kits, it was possible to empower a team to greatly improve the effectiveness of kitting in reducing the waste associated with retrieving items from a Tool Crib. The improvement process was designed to give the team ownership of their work and regularly review their impact on operations, which motivated the team to continue. Improvements were piloted in the mid body facility, which achieved a 45% reduction in the number of tools checked out of a Tool Crib over 12 weeks, more than twice that of the second-best facility on the site. Although the implementation of this improvement process was specific to Boeing South Carolina, the approach can be applied at other large scale, low volume manufacturing facilities.

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