# Capacity Planning and Change Management in an Aerospace Overhaul Cell

by

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B.S. Mechanical Engineering and Materials Science
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Submitted to the MIT Sloan School of Management and the Department of Mechanical Engineering in Partial Fulfillment of the Requirements for the Degrees of

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*

*Purpose* – This thesis analyzes the transformation of the Small Components Cell in Pratt & Whitney's aftermarket division through lean manufacturing techniques. The thesis focuses on use of a labor capacity planning model, implementation of a new cell layout, and queuing theory. The project was 6.5 months long, running from June through December of 2012.

*Findings* – In Chapter 4, the capacity planning model shows that demand changes significantly affect cell performance but that the product mix in the cell is even more crucial. The model highlights the best workforce allocations based on a given product mix or demand level. This analysis is expanded in a design of experiment that shows improving employee efficiency is the most effective means of expanding the capacity of the Small Components Cell. Four factors (employee efficiency, absenteeism, overtime, and the duration of employee breaks) have a significant effect on the ultimate capacity of the cell. The design of experiment allows the capacity planning model to be a useful predictive tool.

The transformation of the cell into a lean manufacturing flow line requires a significant investment in change management process, including a focus on the logistical details of transformation, continual reinforcement of the vision with the team, and cross-training the workforce. The transformation resulted in a 94% reduction in non-value added part travel, a 72% reduction in flow reversals in the cell, and a 43% reduction in cell exits. Customer satisfaction metrics increase throughout the course of the project as well. Annualized EBIT performance improved by over 40% over the six months of the project, while the costs associated with reworking errors declined by more than 85%. However, on-time delivery of parts to customers failed to meet expectations because of the physical restructuring of the cell and a three month spike in demand which adversely effected cell capacity. Chapter 5 outlines the changes in business metrics, while Chapter 6 discusses recommendations and lessons learned.



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## *Acknowledgements*

This thesis is an attempt to draw conclusions and lessons learned from six and a half months' work at Pratt & Whitney, one of the world's premier aerospace companies. To say that they taught me an incredible amount during that time is a ludicrous understatement.

First and foremost, thanks to General Manager Lori Gillette and Deputy General Manager Craig Thompson for their tireless support and involvement in the project well before I set foot in Hartford. To Dave Beauchesne, Peter Steers, and Mike Franks for their willingness to guide this neophyte of a cell leader through the rigors of meeting customer expectations and managing the Small Components Cell. To Art Speranza, Ed Nelson, and their team, especially Andrew, Dave, and Kevin, for their assistance, patience, and good will in moving and re-installing dozens of pieces of manufacturing equipment in a four-month period.

To Simon Hecht, Bill Mucci, Kevin McMahon, and Chris Bennett for keeping the Small Components Cell on the right path in terms of quality, finances, and technical help. To Frank Hanrahan, Jay Chrzanowski, Henry Long, and David Fothergill for showing me the ropes as a cell leader. Particular thanks to Henry Long and Joe Wrubleski for their daily assistance with everything from union grievances to passing on the lessons learned from their operations experience. To the lady and gentlemen of the Small Components Cell, you have taught me more than I can ever put into words. It was an honor to work with you.

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Finally and most importantly, thanks to my loving wife Renee for putting up with four moves in two years. Your constant encouragement and good-natured support buoyed me when I struggled and highlighted the good times. Both Renee and I wish to express our love to our families for their central role in our lives.

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## *Glossary of Acronyms*

| | Meaning | Description |
|---|---|---|
| ACE | Achieving Competitive Excellence | United Technologies Corporation's overarching lean manufacturing system |
| CLU | Vane Cluster | One of four part families in the Small Components Cell |
| CNC | Computer/Numerical Control | Method for controlling machine tools with a high degree of precision |
| CTSC | Connecticut Stators and Components | The larger business unit of which the Small Components Cell is a part |
| DOE | Design of Experiment | Means of discovering the relative strengths of different variables with minimum resources |
| EBIT | Earnings Before Interest and Taxes | A common means of tracking financial performance; it removes the variable effects of interest and tax rates |
| EH&S | Environmental Health and Safety | An important organization within Pratt & Whitney that ensures employee safety and minimizes environmental impact |
| FAA | Federal Aviation Administration | Regulatory body responsible for all aspects of civil aviation, including repairs to jet engines |
| FPI | Fluorescent Penetrant Inspection | An effective method for locating cracks in metallic structures without destroying the structure itself |
| HPC | High Pressure Compressor | A general term for engine stages prior to combustion, also a part family in Small Components |
| HPT | High Pressure Turbine | A term for power-generating engine stages after combustion, also a part family in Small Components |
| IID | Independent Identically Distributed | Random variables that are mutually independent and have the same probability distribution |
| LPT | Low Pressure Turbine | A term for power-generating engine stages after combustion, also a part family in Small Components |
| MFA | Market Feedback Analysis | The process of collecting extensive performance feedback from customers; the surveys themselves |
| MMP | Material Management Program | System of managing inventory cooperatively between Pratt & Whitney and a customer |
| NDT | Non-Destructive Testing | Quality checks that do not destroy the components |
| OEM | Original Equipment Manufacturer | The company responsible for the initial fabrication of the components or systems |
| OTD | On-Time Delivery | Percentage of time Small Components returns parts on-time to customers |
| SCC | Small Components Cell | Organization at the center of this thesis |
| UTC | United Technologies Corporation | Parent company of Pratt & Whitney |
| WIP | Work-In-Process | Inventory currently moving through the processes or buffers in a defined area |

## *Chapter 1 – Introduction*

### Chapter 1.1 – Problem Statement, Motivation, and Hypothesis

As the high-pitched whine of a jet engine fades, a team of trained technicians approaches the plane for scheduled maintenance. After completely removing the engines from the wings and disassembling them, the parts are sent to designated repair centers for the overhaul work that will permit the engine to operate safely and efficiently for thousands of flight hours.

Within one of those designated repair centers at Pratt & Whitney's East Hartford location, Operations Manager Craig Thompson and General Manager Lori Gillette are concerned. One of the four aftermarket overhaul cells within Gillette's Connecticut Stators and Components (CTSC) business unit is not meeting its business goals. With over $12 million in annual revenue, the Small Components Cell represents a sizable investment for the company. However, on-time delivery performance is not meeting Pratt & Whitney's aggressive targets and the Small Components Cell is not as profitable as it has been in the past. Customer feedback also indicates increasing displeasure with the turnaround time and the perceived value of the services provided. As Thompson and Gillette review the business metrics for the cell, they consider restructuring the cell from a job shop to a flow line to improve the situation, as well as the need to accurately determine the capacity of the mixed-model cell.

The project that emerges from their brainstorming session tests the hypothesis that a lean manufacturing flow line is more efficient than a traditional job shop structure. As a part of this goal, a capacity model of the cell has been created, and a cross-training plan improves the cell's flexibility. This project is equally focused on leadership development through the direct supervision of 20 unionized hourly employees. Motivating the team in the face of significant changes throughout the cell can be a challenge, particularly with the incredible depth of experience that many employees possess. This is frequently the most rewarding component of the project, especially when the team unites to carry out dynamic improvements in month-over-month delivery performance.

### Chapter 1.2 – Research Methodology

Research was primarily conducted through direct interactions with the shop floor and through an analysis of capacity planning challenges faced under similar situations. As a part of the project, a plan for the 70+ pieces of equipment, cabinets, and tools has been developed in accordance with lean manufacturing principles. Capacity planning and variance analyses based on both historical data and studies on current work orders are complete. The new cell layout provides the headcount and equipment needed to efficiently meet customer demand. Additional capital requests have been submitted to eliminate process flow reversals and cell exits wherever possible. An aggressive cross-training plan is in place to ensure that the employees are comfortable with a wide variety of operations throughout the cell. External research focuses on capacity planning models, queuing theory, and variation within aerospace aftermarket organizations.

### Chapter 1.3 – Thesis Outline

Chapter 2 discusses background information on the company, competitors, and customers. Chapter 3 covers the pre-project metrics for the SCC and a brief analysis of the cell through cultural, political, and strategic lenses. Chapter 4 dives into the cell transformation itself, the capacity planning model that was used to develop the floor plans, the implementation of the cell restructuring, and the cross-training plan for the employees. Chapter 5 walks through the data analysis and summarizes key findings. Chapter 6 discusses the conclusions and personal lessons learned.

## *Chapter 2 – Company and Project Context*

This chapter focuses on providing a high-level overview of Pratt & Whitney's company history, the company's role in the aftermarket operations business, and a broader look at Pratt & Whitney's customers and competitors within this marketplace. Chapter 2.4 delves into project context, giving specific insights into the types of parts the Small Component Cell repairs, an overview of the employee skill-sets within the SCC, and the general types of equipment and processes used to overhaul engine components. This allows the reader to more fully understand the situation from both a large-scale industry perspective and to gain additional awareness of the project's specific context.

### Chapter 2.1 – Brief History of Pratt & Whitney

In the early days of powered flight, inventor and airplane enthusiast Frederick Rentschler and engineer George Mead approached their employers at Wright Aeronautical with a plan for a new radial aircraft engine. Citing the declining demand for such products following the end of World War I, Rentschler's aggressive capital plan was denied. Rather than being dissuaded, Rentschler and Mead recognized the opportunity in Wright Aeronautical's decision and began a search for other manufacturers interested in new products. In 1925, the Pratt & Whitney Machine Tool Company of East Hartford, Connecticut extended a loan to Rentschler to develop the air-cooled radial engine dubbed the R-1340 Wasp (Pratt & Whitney, 2008). Utilizing loaned capital and factory space efficiently, Rentschler and Mead completed the design, manufacturing, and testing phases in a mere eight months. The engine easily met the Navy's power and weight requirements, and Pratt & Whitney Aircraft was born. In the developing field, Pratt & Whitney's products quickly gained a reputation for reliable performance, a proud legacy that continues today in the "Dependable Engines" slogan on the company logo.

Figure 1: Pratt & Whitney company logo. Image courtesy of Pratt & Whitney. All rights reserved by Pratt & Whitney and United Technologies Company

The rapidly growing company was soon joined with several others in a spate of mergers and acquisitions driven by the Great Depression. Modern-day companies that were once joined under the umbrella of the United Aircraft and Transport Company include The Boeing Company, United Airlines, Sikorsky Aircraft Corporation, Triumph Aerostructures (Vought), Hamilton-Sundstrand, and Spirit AeroSystems. Following the Air Mail Act of 1934, the combined company was split to preserve the most profitable companies, with Boeing and United Airlines separating from Pratt & Whitney's new parent company, United Aircraft. World War II saw rapid growth in demand for Pratt & Whitney's products, leading to significant advancements in engine technology and increasing factory footprints, primarily near the company's headquarters in East Hartford. From pre-war employment levels of 5,200 employees, Pratt & Whitney saw such large spikes in demand that the company boasted nearly 40,000 staff members by 1943 (Company Histories: Pratt & Whitney, 2012).

In spite of the wartime successes, significant challenges lay ahead. Following postwar cuts, employment dropped to 6,000 as demand ground to a halt. More than 85% of Pratt & Whitney's orders were cancelled at the end of 1945 (Pratt & Whitney History, 2012). Risking his business on the perceived future of jet engines, Rentschler ordered the internal development of a jet engine that could outperform the competition. Pratt & Whitney's eventual solution, the J57, was unveiled in 1952 and produced 13,500 pounds of thrust, far outstripping the competition's engines, which had planned thrust ratings between 4,000 – 7,000 pounds (Ibid). Over 21,000 of these engines were produced, and Pratt & Whitney was once again on solid financial footing (Company Histories: Pratt & Whitney, 2012).

The momentum built during the commercial dawn of the jet age. Pratt & Whitney's products in the newly developed Douglas DC-8 and Boeing 707 answered the call of Pan Am president Juan Trippe for domestically-produced commercial airliners (Ibid). The fact that Pratt & Whitney secured placements on both types of aircraft allowed the company to capture the majority of the jet engine market through the mid-1970s (Pratt & Whitney History, 2012). In conjunction with the success of the J57, which powered the iconic Boeing B-52 Stratofortress, and the J59D, operating on the legendary Boeing 747, Pratt & Whitney began to dominate both the military and commercial facets of engine production. This was particularly beneficial for the company, as it was a time that aircraft and engine technologies were firmly enshrined in the psyche of the country. The company continued to thrive during the Cold War, winning contract after contract on some of the most technologically advanced and well-recognized projects of the time, including the U-2 Dragon Lady and the fastest air-breathing manned aircraft, the SR-71 Blackbird.

Pratt & Whitney's enviable achievements came with a cultural price; a willingness to take on risky projects with customers grown accustomed to success. Serious technical problems plagued the TF30 engines powering the F-111 Aardvark and F-14 Tomcat. These problems were compounded by inter-service disagreements between the U.S. Navy and U.S. Air Force, resulting in work-scope expansions. The final aircraft designs did not meet their original intent, and airframe manufacturers General Dynamics and Grumman cited Pratt & Whitney's engines as the ultimate source of the schedule delays and underperformance (Pratt & Whitney History, 2012). The subsequent F100 engine, which powers the F-15 Eagle and F-16 Fighting Falcon, was a near-disaster for the company in the early stages of development. A test-stand explosion forced Pratt & Whitney into an incredibly costly, self-funded redesign cycle. By the time the company was able to re-introduce the engine, competitor General Electric had successfully petitioned the U.S. Air Force to allow its F110 engine as a second power plant, capturing over 75% of the F100's market (Company Histories: Pratt & Whitney, 2012).

Pratt & Whitney's woes during the 1970s extended to the commercial realm as well. Although the company's products were well-represented on larger commercial aircraft, Pratt & Whitney was phased out of the best-selling Boeing 737 in the 1980s in favor of the General Electric and SNECMA CFM56. Compounding the blow was another loss to the CFM56 on the high-rate Airbus A320 line, though Pratt & Whitney was able to regain portions of the business in the late 1980s by forming a consortium with Rolls-Royce, Japanese Aero Engine Corporation, and MTU Aero Engines (Pratt & Whitney History, 2012).With nearly 13,000 Airbus A320 and Boeing 737 variants in service today and over 6,500 firm orders for the two programs, these on-going product families represent a devastating loss of market share to rivals General Electric and SNECMA.

Today, Pratt & Whitney has nearly 16,000 commercial engines in flight, accruing more than 1 billion flight-hours since their installation (Products, 2008) (Commercial Engines, 2008). In addition to extensive work with domestic defense programs, including the EA-6B Prowler, F-111 Aardvark, F-14 Tomcat, F-15 Eagle, F-16 Fighting Falcon, F-22 Raptor, F-35 Lightning II, B-52 Stratofortress, KC-135 Stratotanker, AWACS, and C-17 Globemaster, Pratt & Whitney provides military engines to 27 international armed services (Military Engines, 2008). Almost 11,000 Pratt & Whitney military jet engines are currently in service (Ibid). As a part of United Technologies Corporation, Pratt & Whitney provided over \$9.0 billion (23.8%) of UTC's \$38.1 billion in revenue in 2009 and reported an operating profit of \$1.3 billion, resulting in an operating margin of 14.6% (Clearwater Corporate Finance, LLP, 2011). Figures 2 through 5 show key information about Pratt & Whitney in relation to other business units within UTC (Ibid).

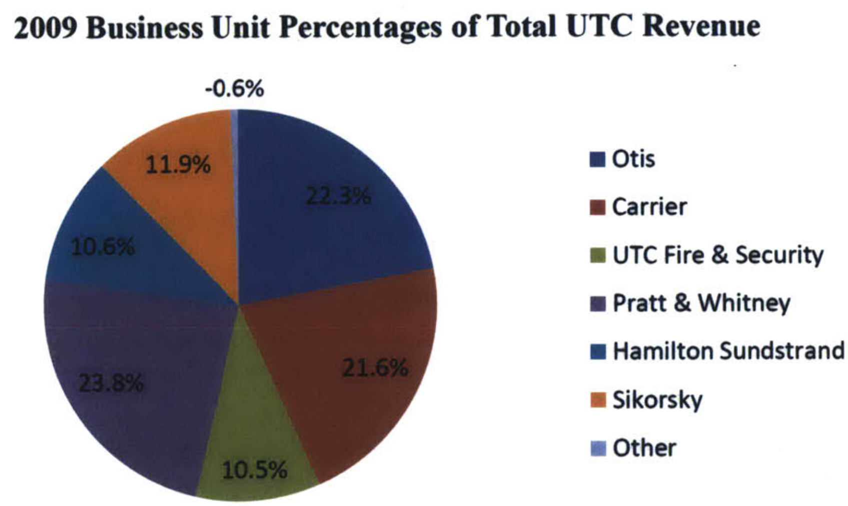



Figure 2: 2009 UTC business unit contributions to company revenue

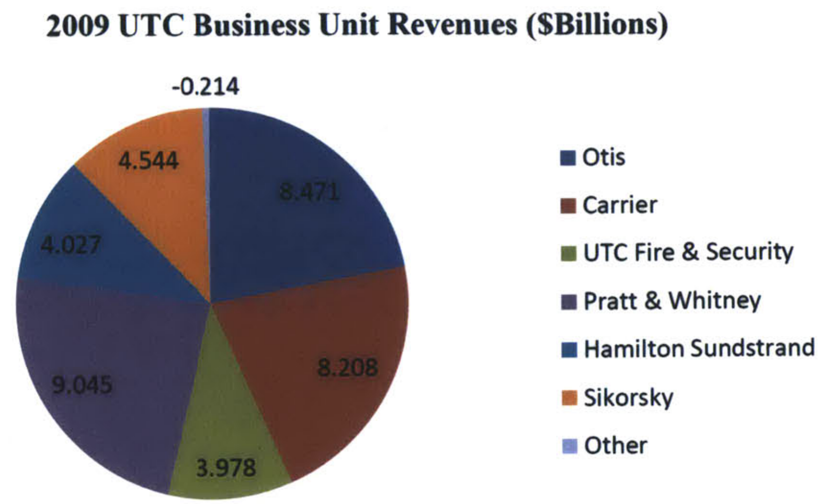



Figure 3: 2009 revenue of all UTC business units

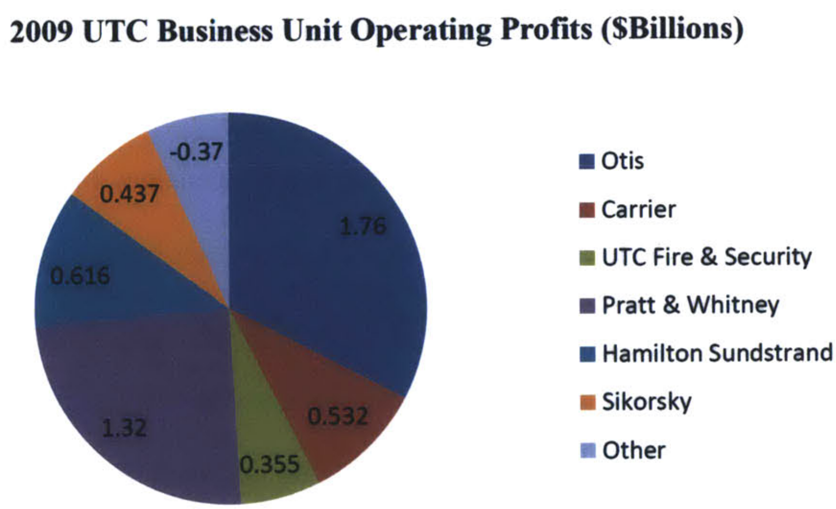



Figure 4: 2009 operating profits of all UTC business units

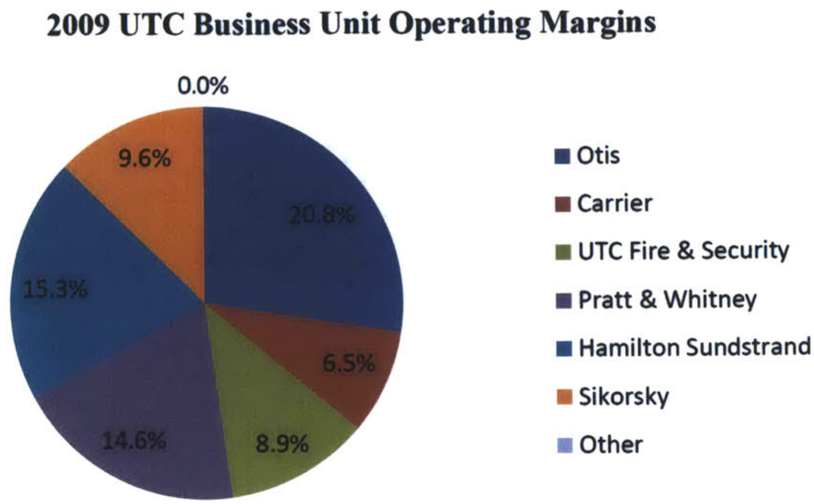



Figure 5: 2009 operating margins of all UTC business units

## Chapter 2.2 – Pratt & Whitney's Role in Aftermarket Operations

Throughout this storied and tumultuous background, Pratt & Whitney has been a significant force in the manufacture of a wide variety of engines and their components. Recognizing that the market for aircraft engines extends far beyond original equipment manufacturing, Pratt & Whitney maintains a strong presence in aftermarket operations as well. The large numbers of Pratt & Whitney commercial and military engines currently in operation provide an expansive market landscape. Additional information on the overhaul market for engines can be found in Chapter 2.3. The company repairs over 1 million engine components per year through a global array of engine service centers (Part and Accessory Repair, 2008). Previously seen as a secondary market to original equipment manufacturing, Pratt & Whitney's role in aftermarket operations is developing in several important ways.

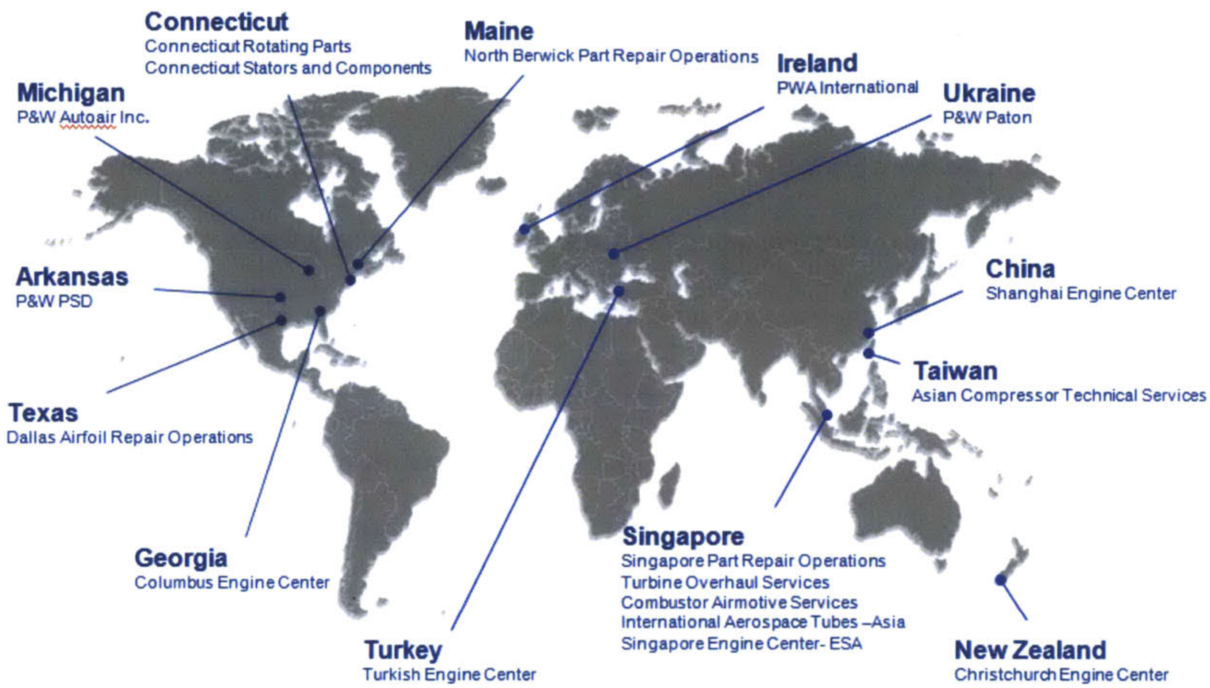



Figure 6: Map of the Pratt & Whitney aftermarket facilities around the world.

One such development is the advent of holistic material management programs (MMPs). Owing to the high capital cost of a new engine and the high operating costs associated with jet engines, many airlines find it economically attractive to allow an outside party to bear the corresponding inventory costs. As a result, Pratt & Whitney has several divisions that interface directly with customers like United Airlines and Delta Air Lines. These MMP organizations facilitate overhauls for the end user, allowing the airlines to reduce their inventory holding costs and permitting Pratt & Whitney to maintain market control over its products. This control is particularly crucial in light of the tendency of engine manufacturers to expand their aftermarket divisions through repairs on competitors' engines. Pratt & Whitney captures market share by doing just that, as the company holds FAA approval to conduct overhauls on General Electric and SNECMA CFM56 engines (Engine Overhaul, 2008). This strategic win is crucial to recapturing a portion of the revenue in the Boeing 737 and Airbus A320 engine market.

Beyond simply maintaining a customer's engines, aftermarket operations have been expanding into the digital age. Pratt & Whitney offers rigorous data analysis of 'on-wing' engines around the world. By comparing critical engine operating parameters to known performance standards, the company can anticipate future maintenance needs and assist customers with pre-emptive overhauls and other services (Engine Health Monitoring, 2008). Known as engine health monitoring, this business strategy benefits the customer through improved on-wing engine efficiencies and more predictable, cost-effective maintenance cycles. Pratt & Whitney benefits through additional 'womb to tomb' control of its products and the ability to more accurately predict its cash flows in a historically cyclic industry. Furthermore, this data collection allows Pratt & Whitney to directly compare in-flight engine data to competitors' products, permitting engineering groups to prioritize improvements for future products and additional repair strategies for existing engines.

These strategies of expanding aftermarket operations are critical to what industry insiders see as the next step of engine manufacturing and service: 'fixed price per engine flight hour' contracts (Anonymous, Personal Interview with Pratt & Whitney Executive, 2012). In this model, the end user leases the engines from the manufacturer for a per-unit-time rate that includes all associated maintenance. This situation benefits both the airlines and Pratt & Whitney by helping to stabilize revenue during the course of a fiscal year. Under current operating conditions, the airlines and Pratt & Whitney see major expenditures and revenue, respectively, only when the engine returns for maintenance. As this situation develops unpredictably, neither company has effective control of large amounts of cash. In an industry with very high capital requirements, these expenses can devastate plans for fleet upgrades, new engine development programs, and other investments.

Over the past decades, Pratt & Whitney's aftermarket operations have developed several reinforcing strategies, from material management programs (MMPs) and engine health monitoring programs to fixed price per engine flight hour contracts. Each step enables Pratt & Whitney to more effectively moderate their cash flows over the duration of the engine's life cycle. Simultaneously, airlines are more thoroughly supported in their efforts to receive high-quality maintenance from the OEM while carrying less of the inventory cost burden.

Figure 7: Overhead picture of the Pratt & Whitney facility in East Hartford, Connecticut. The circled building contains the Global Service Partners (aftermarket) division, including the Connecticut Stators and Components business unit and the Small Components Cell.

**Chapter 2.3 – Competitors and Customers**

After describing Pratt & Whitney's history and role within the aftermarket operations space, this chapter concentrates on understanding the current commercial customers and competitors within that market. Figure 8 outlines the fractional value of new components and systems of an average new aircraft and Figure 9 provides an estimate of the size and breakdown of the 2010 overhaul market (Clearwater Corporate Finance, LLP, 2011).

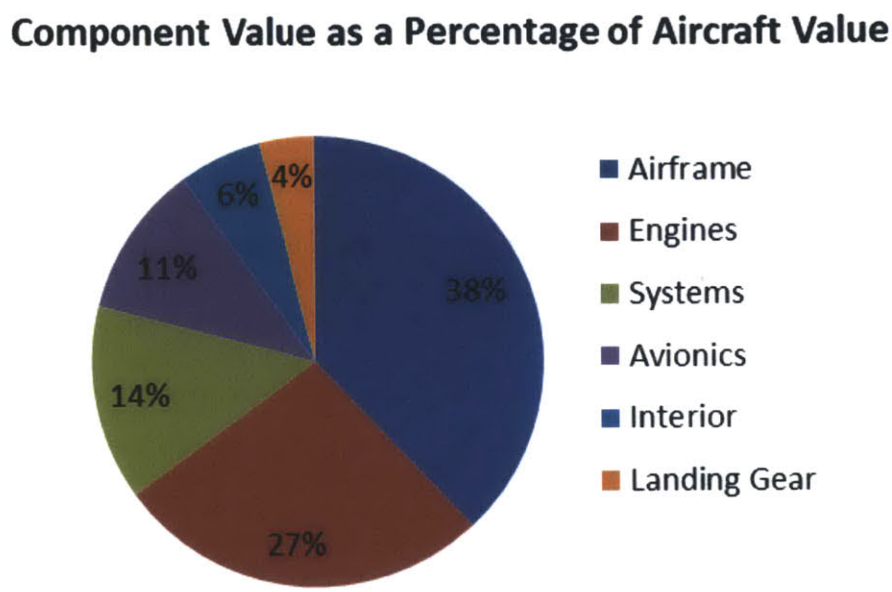



Figure 8: Value added to an aircraft by component (Clearwater Corporate Finance, LLP, 2011).

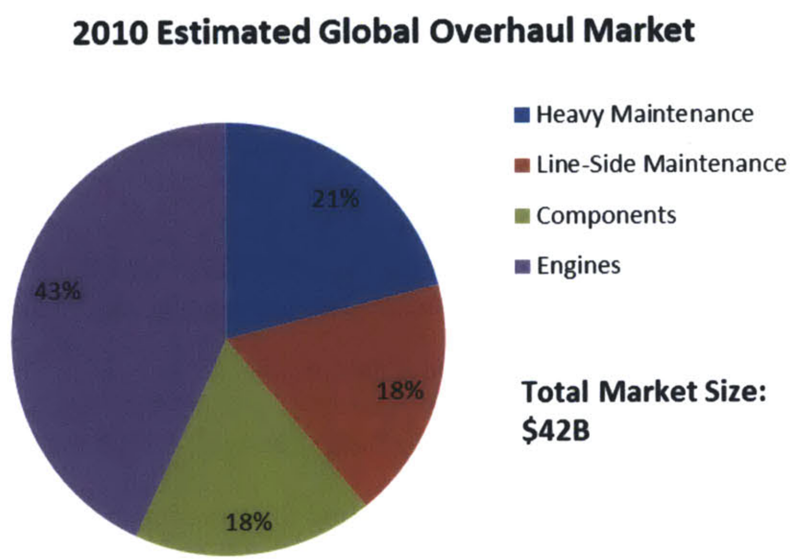



Figure 9: Estimated size of the 2010 aerospace overhaul market with percentages associated with the different types of overhauls performed (Clearwater Corporate Finance, LLP, 2011). Note that 'Line-Side Maintenance' refers to maintenance on the flight line, while 'Heavy Maintenance' refers to repairs performed in a specialized facility that is not on the flight line.

As befits a company with such a rich history, Pratt & Whitney maintains a diversified, global commercial engine customer base that includes the OEMs of the aircraft themselves as well as most major airlines. The company currently boasts 7 different types of commercial jet engines: the V2500, GP7200, PW2000, PW4000 engine family, PW6000, JT8D, JT9D, and the PurePower ® PW1000G Geared Turbofan™ engine (Commercial Engines, 2008). In addition, Pratt & Whitney Canada, a sister division, produces a variety of turbofan, turboprop, and turboshaft engines for business- and commuter-style aircraft (Ibid). Pratt & Whitney's jet engines are found on an astounding array of aircraft, from the smaller regional jets including Mitsubishi's newest regional jet offering, Bombardier regional jets, the Russian Irkut MC-21, and Embraer regional jets to the largest aircraft in the skies: the double-decker Airbus A380 and Boeing 747 (Ibid).

Of course, Pratt & Whitney is not alone in this market space. The company faces serious challengers, including General Electric's Aviation division and Rolls-Royce. When discussing the engine market, this relatively stable triumvirate of engine OEMs is often described as the 'Big Three.' Market position between the Big Three has been fluid, and Pratt & Whitney is currently the smallest of the three in terms of revenue, as shown in Figure 10 (Rolls-Royce, 2011) (General Electric, 2011) (United Technologies Corporation, 2011).

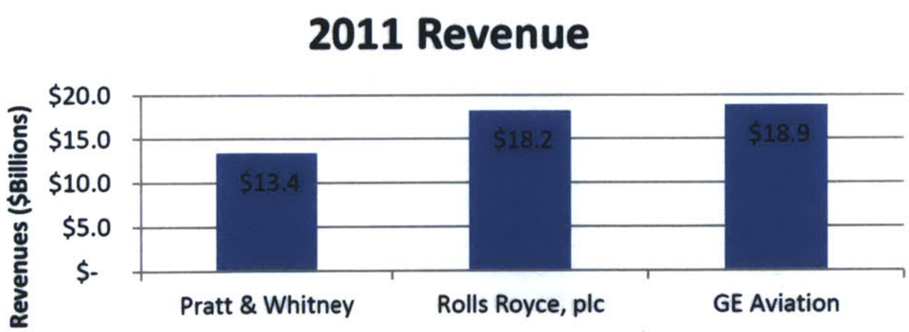



Figure 10: 2011 revenue for the 'Big Three' engine OEMs

In order to mitigate risk and defray the large capital expenditures associated with new engine development and testing, several risk-sharing joint ventures exist. These unions of convenience hold substantial portions of the market share, placing Pratt & Whitney in the interesting position of frequently designing and marketing engines in conjunction with their biggest competitors. Although this model has been stable in recent history, a recent development could begin to re-order the market. The introduction of the Pratt & Whitney PurePower ® PW1000G Geared Turbofan™ engine promises major fuel efficiency improvements and is initially targeted at regional jets and the single-aisle commercial airliner market segment. The engine is the only option or is the primary power plant on the new Mitsubishi and Bombardier regional jets, as well as the Airbus A320neo (new engine option). This represents a particularly vital step towards re-capturing portions of the high-rate regional jet and single-aisle markets that were lost to CFM International and GE Aviation on the earlier versions of the Airbus A320 and Boeing 737 aircraft families.

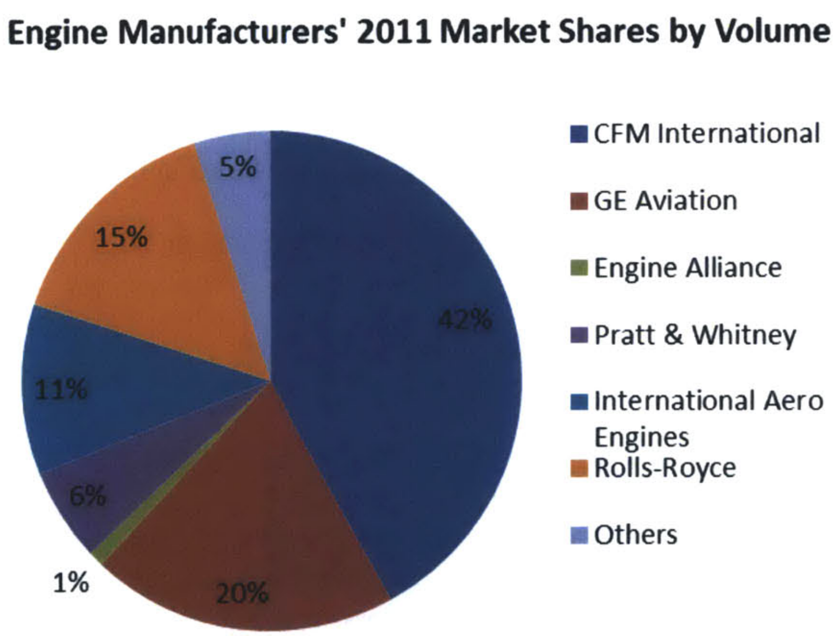



Figure 11: Market shares of the major engine manufacturers by volume (Clearwater Corporate Finance, LLP, 2011). Please note that the Engine Alliance is a joint venture between Pratt & Whitney and General Electric's Aviation division, while International Aero Engines is a joint venture between Pratt & Whitney, Rolls-Royce, Japanese Aero Engine Corporation, and MTU Aero Engines. CFM International is a joint venture between General Electric's Aviation division and French engine manufacturer SNECMA.

Transitioning from new engine manufacturing to overhaul, Pratt & Whitney's aftermarket operations division interfaces directly with the same airframe OEMs, but also serves airlines and their MMP groups directly. Major customers include domestic airlines such as Delta Air Lines, United Airlines, and American Airlines. International relationships make up a large component of the customer landscape as well, including Japan Airlines, Air China, Korean Air, and Emirates among others. As previously mentioned, the airlines' MMP groups represent an important portion of Pratt & Whitney's aftermarket business. When specifically considering the Small Components Cell, the market breakdown is diversified between domestic and international airlines, as shown in Figure 12. A significant portion of the Small Component Cell's business stems from MMP organizations. Because of the proprietary nature of this information, customer names are not shared in conjunction with the volume of their business.

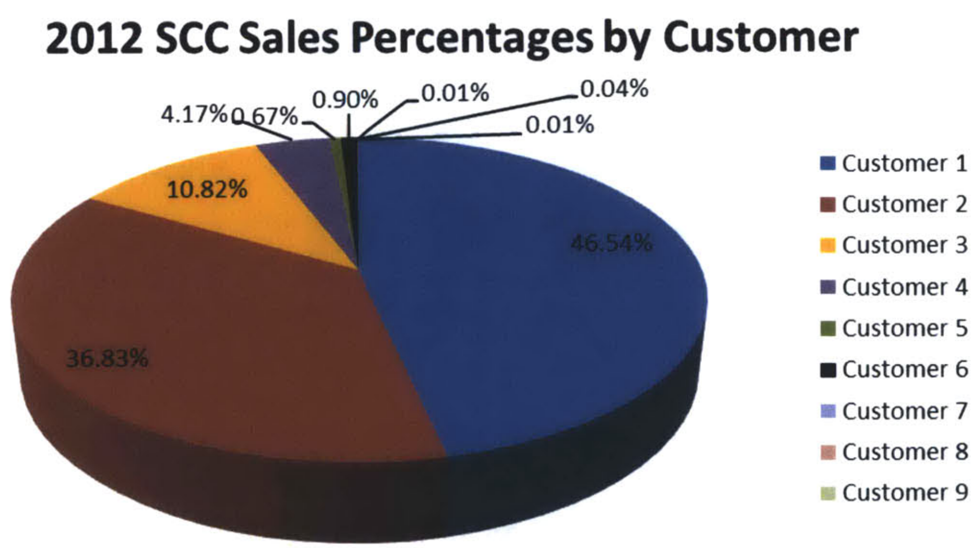



Figure 12: 2012 sales for the Small Components Cell by customer. This is a representation of the Small Components Cell only and is similar, but not identical to, other business units within Pratt & Whitney's aftermarket division.

Looking forward, a 2011 Clearwater report notes global aftermarket revenue of $45.7 billion in 2009 alone, with solid growth expected throughout a 7-year horizon (Clearwater Corporate Finance, LLP, 2011). As Pratt & Whitney plays a major role in all aspects of the engine overhaul markets, this growth estimate bodes well for the company, particularly if the new PurePower ® PW1000G Geared Turbofan™ engine meets performance expectations in the new engine market. In summary, Pratt & Whitney operates in a cyclical industry which is characterized by three dominant market players and a variety of joint ventures with other companies. Competition is fierce and product lifecycles are best measured in decades.

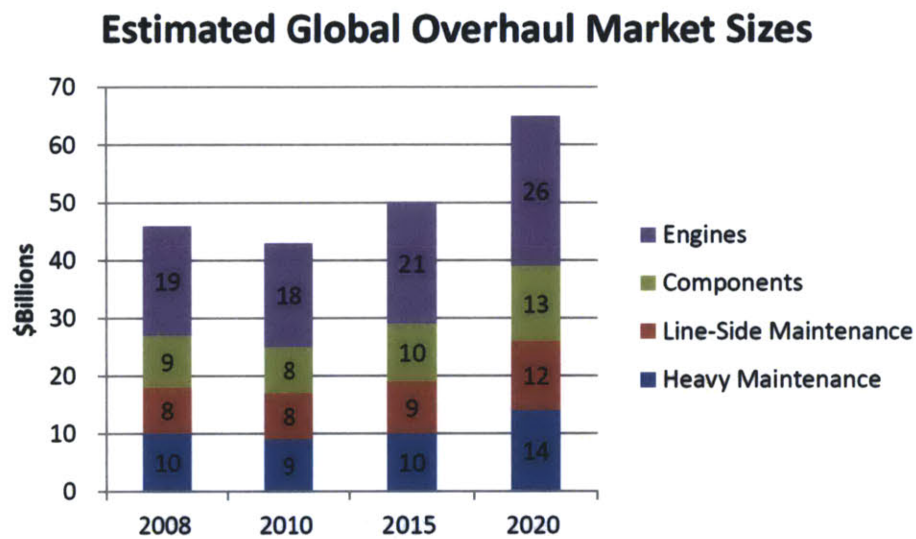



Figure 13: Market sizes and estimates from 2008 through 2020, predicting significant growth in the aerospace overhaul market (Clearwater Corporate Finance, LLP, 2011).

**Chapter 2.4 – An Overview of the Small Components Cell**

Previous chapters discuss Pratt & Whitney's history, its role within the engine overhaul space and the commercial engine marketplace. This chapter focuses solely on the parts repaired by the Small Components Cell, the workforce, the general types of processes used, and the equipment in the cell. One of four overhaul cells within the Connecticut Stators and Components

(CTSC) business unit, the Small Components Cell consists of 20 hourly employees, 1 cell engineer, and 1 cell leader. There are also more than 70 pieces of equipment, including weld booths, CNC milling machines, super-abrasive machines, downdraft blend benches, and inspection stations. From June 6th, 2012 through December 20th, 2012, I was the cell leader for the Small Components Cell. Daily job responsibilities included prioritization of work, meeting the expected operating metrics, supervising the hourly employees, and managing the transformation project described in Chapter 4.

*Chapter 2.4.1 – Part Families and an Introduction to Jet Engines*

The Small Components Cell is a mixed-model cell which focuses on the overhaul of four different part families, each of which contains many unique part numbers. In all, there are nearly three hundred unique part numbers that are repaired within the cell. These components come from the low pressure turbine, high pressure compressor, and high pressure turbine sections of the PW2000, PW4000, and other Pratt & Whitney jet engine products. No military work is performed in the cell. Made from a variety of temperature resistant metallic alloys, most parts are smaller than 6" x 6" x 6" and weigh less than 3 lbs. The parts, however, differ radically in geometry and processing steps between families. Low pressure turbine (LPT) components are primarily thin metallic structures with a bonded 'honeycomb' surface. These parts serve to seal off different stages of the low pressure turbine from one another. High pressure turbine (HPT) duct supports are supporting structures for the various flow lines that snake throughout the engine. High pressure compressor (HPC) shrouds provide airflow and pressure separation between stages of the high pressure turbine stages. Vane clusters (CLU) are the small airfoils that re-direct flow within the engine. Within the Small Components Cell, part families are usually referred to by their three-letter designations: HPCs, LPTs, HPTs, and CLUs. Images of the different part families are below.

Figure 14: Sample pictures of the four different part families. From left are the high pressure turbine (HPT) duct supports and the vane clusters (CLU). The right-most picture shows both the high pressure compressor (HPC) shroud in front of two different types of low pressure turbine (LPT) parts. For proprietary reasons, these images are not to scale and do not represent the full spectrum of geometries within each part family. All rights to these pictures are reserved by Pratt & Whitney and United Technologies Corporation.

Generally, HPCs and CLUs make up the majority of the parts that arrive for repair, with LPTs and HPTs forming the remaining portions of the inventory, as shown in Figure 15. The degree of work performed on each part is driven by four primary factors: the thermal and mechanical wear on the part, the location of the wear, the age of the part in flying hours, and the material. Since many features have tolerances on the order of +/- 0.001 in., extreme care is taken to ensure that the overhaul process itself does not damage the parts or exceed the allowable dimensions.

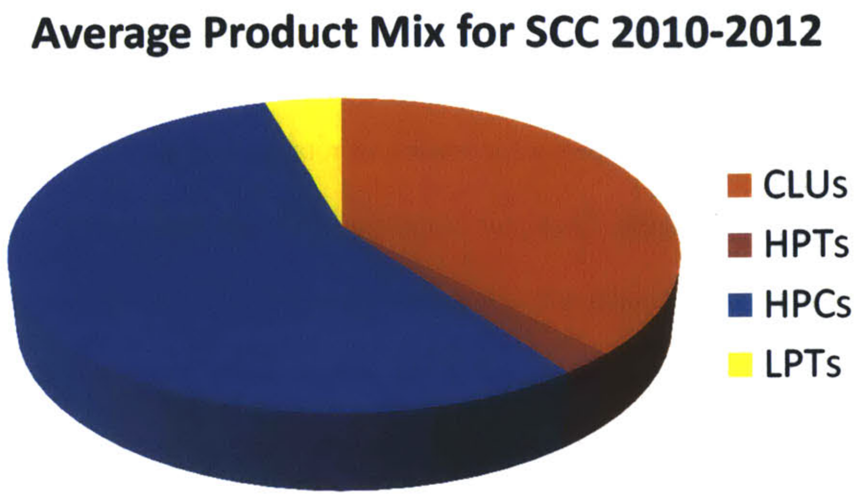



Figure 15: Small Components Cell work volume by part family. For proprietary reasons, these data have been disguised, though the trend is are representative of reality.

Furthermore, because of the long service life of the components and the high degree of precision required, the unit cost of each part is significant. Mistakes have a very large impact on the overall profitability of the business, especially since unserviceable parts require a new and very expensive component to be purchased for the customer. As Ravindran, et al, notes in an analysis of an overhaul center at Tinker Air Force Base, "Parts are overhauled and returned to service for a fraction of the cost of a new part. A major overhaul may cost less than five percent of the cost of a new engine in terms of labor, material, and replaced parts" (Ravindran, Foote, Badiru, Leemis, & Williams, 1989).

Having reviewed the four main part families in the Small Components Cell, the following paragraphs discuss their place within a jet engine. In a high-bypass turbofan engine, the primary components are a central compressor, the combustion chamber, and a power-generating turbine. Upstream of these core components are the iconic fan blades at the inlet of the engine. As air flows through the fan blades, a portion of the flow called bypass air is directed around the core.

The remaining portion of the flow is directed through the core, where all four part families from the Small Components Cell are found.

As air enters the core, it meets a succession of rotating and stationary airfoils in the compressor section of the engine. Each pair of rotating and stationary airfoils is known as an engine 'stage.' Engine components are usually categorized by the stage to which the parts belong. The rotating components force air into the intermediate chambers, increasing the pressure. At the end of the compressor section, atomized fuel is sprayed into the combustion chamber and ignited. The resulting explosion is channeled by the turbine blades through the aft-facing nozzle. This airflow spins the turbine and the front fan blades, providing thrust and electrical power to the aircraft through a mechanically coupled generator.

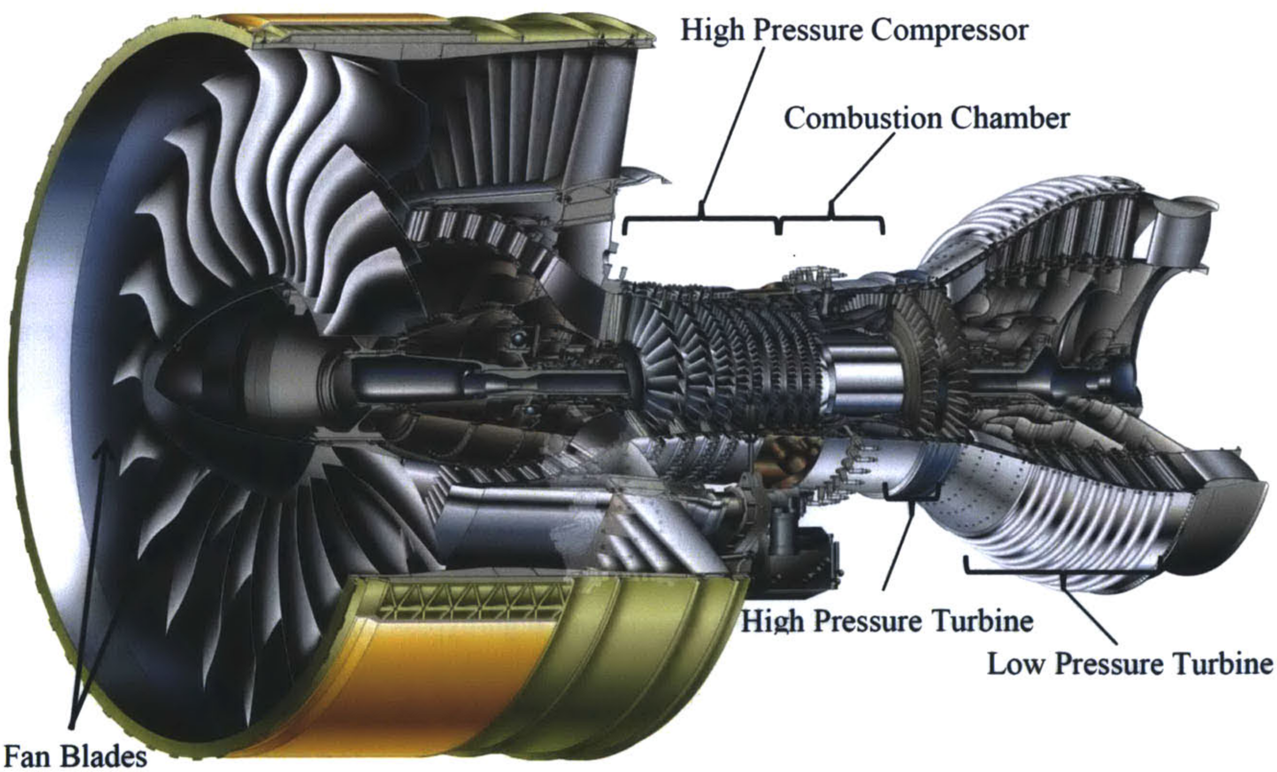



Figure 16: Schematic of a GP7200 turbofan jet engine. Image courtesy of Pratt & Whitney (Pratt & Whitney, 2008).

*Chapter 2.4.2 – Workforce*

The employees have a tremendous amount of skill in their respective functions and a deep understanding of the processes and parts. On average, each of the twenty hourly associates of the Small Components Cell have twenty-seven years of experience, and several employees are nearing or have recently passed the forty-year service mark. Because of the slim margins for error and the critical nature of the engine as a whole, it is crucial to discuss the employees who complete the work as well as the type of work performed within the Small Components Cell. Figures 17 and 18 show several different perspectives of the employees' experience levels. It is important to note that employees are separated by 'occupation codes,' which specifically define the types of roles that they conduct in the cell in accordance with the contract between Pratt & Whitney and IAM District 26, which represents the employees in East Hartford. Employees can only perform work within their occupation code.

The Small Components Cell has employees in five different occupation codes: the machinists (occupation code 176H), surface mechanics (occupation code 344H), welders (occupation code 380H), inspectors (occupation code 400H), and non-destructive inspection technicians (occupation code 464H). One support group, the material handlers/expeditors (occupation code 901H) is important to keep in mind as well. A brief description of the duties of each occupation code is below.

- ***Machinists (176H)***: Machinists focus on operating CNC mills, drill presses, and hand blending processes. In the Small Components Cell, they are also responsible for the upkeep of tooling fixtures and for any required part assembly work.
- ***Surface Mechanics (344H)***: Surface mechanics perform surface preparations such as grit blasting, thermal spray, part cleaning, and etching.

- ***Welders (380H)***: Welders use tungsten inert gas welders or plasma welders. Within the Small Components Cell, this skill is frequently used to add material to ablated or damaged surfaces rather than to join parts.
- ***Inspectors (400H)***: Inspectors are responsible for visually and mechanically confirming that contours, thicknesses, angles, radii, surface finishes, and other critical features are within the acceptable design tolerances.
- ***Non-Destructive Inspection Technicians (464H)***: Non-destructive inspection technicians analyze parts for surface and internal cracking, distortions, and voids. Industry-standard methods include fluorescent penetrant inspection (FPI), ultrasound, and X-ray.
- ***Material Handlers/Expeditors (901H)***: Expeditors are responsible for moving parts across main aisles throughout the facility or between buildings. Since the Small Components Cell was initially separated by an aisle and relies on certain processes outside of the cell, this job code has an important impact on the operation of the cell. There are no expeditors who directly report to the Small Components Cell.

In certain occupation codes, there are 'lead' employees who hold additional responsibilities, including helping to assign work, training other employees, troubleshooting new repair methods, and tackling particularly difficult overhauls. In the Small Components Cell, both leads are machinists with the 176H occupation code.

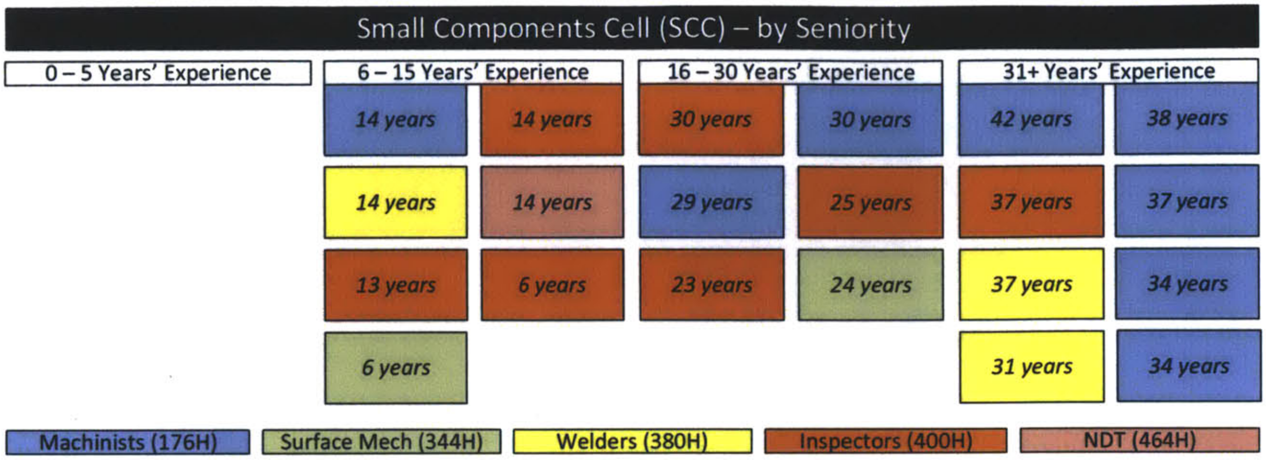



Figure 17: Employee experience within the Small Components Cell, organized by seniority order, with less senior employees on the left and the most senior employees on the right. Color codes represent the different occupation codes, and the key is shown at the bottom of the figure.

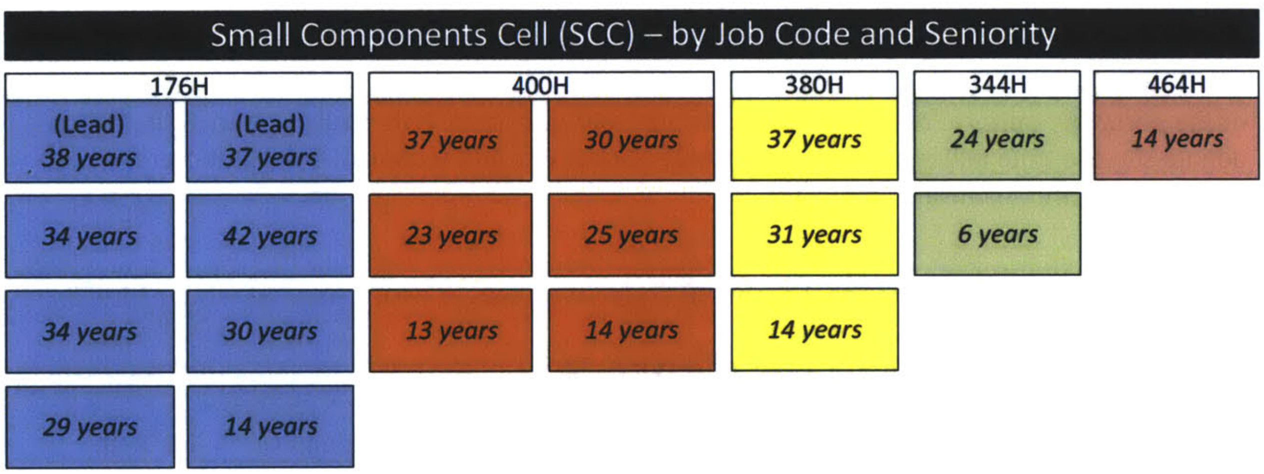



Figure 18: Employee experience within the Small Components Cell, organized by occupation code, with less senior employees lower in their respective occupation code and the most senior employees at the top. Color codes represent the different occupation codes and follow the labeling convention in Figure 17.

The vast majority of the blue Pratt & Whitney badges within the Small Components Cell show the 'eagle wing' emblem, signifying at least 25 years of employment with the company, as seen in Figure 19. Many also sport the coveted gear pattern, signifying that they have at least one patent to their name.


Figure 19: Scanned images of two Pratt & Whitney badges, which are powerful symbols of the company culture. Note the "eagle wings" and gear icon in the badge on the left, which denote service time and a patent, respectively. Longevity and technical contributions are highly prized in the organization.

Overall, the team has more than 490 collective years of experience, of which 51.4% comes from employees with 31+ years of service. 32.3% of the total years of experience are found with employees who have between 16-30 years, and the remaining 16.3% lies with employees who have 6-15 years.

*Chapter 2.4.3 – Working Environment*

This chapter discusses the manner in which work is designed within the Small Components Cell. Employee morale, employee engagement in improvement activities, feedback, and autonomy are crucial to understanding the Small Components Cell more thoroughly. In their groundbreaking work, Richard Hackman and Greg Oldham discuss five key characteristics that benefit employee growth within a working environment: skill variety, task identity, task significance, autonomy, and feedback (Hackman & Oldham, 1976). After briefly defining each key characteristic, a short analysis follows, noting how the Small Components Cell addresses each category. Category definitions are drawn from Hackman and Oldham.

- **Skill Variety**: The degree to which the job requires the application of different skills to complete it. This should not be confused with job complexity; extremely intricate jobs can be based on relatively few skills.
- **Task Identity**: "The degree to which the job requires completion of a 'whole' and identifiable piece of work; that is, doing a job from beginning to end with a visible outcome" (Hackman and Oldham, 257).
- **Task Significance**: A measure of the perceived meaningfulness of the work. If task identity is high, employees feel that the work they are doing has a significant impact on others.
- **Autonomy**: The amount of freedom afforded the employee to choose how to schedule and carry out the work.
- **Feedback**: How effectively the employee receives direct, specific feedback about their job performance.

The following table summarizes how the Small Components Cell fares within each category with a three-part scale (Effective, Average, Ineffective), as well as some brief recommendations for change.

| Key Characteristic | Small Components Cell | Suggested Improvement |
|---|---|---|
| Skill Variety | Ineffective because of constraints on job definitions as noted in Chapter 2.4.2 | Work with the company and union to relax the occupation codes, see Chapters 4.8 and 6.1.3 |
| Task Identity | Effective, as employee roles are clearly defined with tangible results based on stringent tolerances | Expanding job roles would allow employees the opportunity to have a more holistic appreciation of the task |
| Task Significance | Effective. These parts are critical to the safe operation of engines that carry thousands of people per year. | Take employees to the full engine mock-ups regularly to focus the team on the broader goal. |
| Autonomy | Average. The Pratt & Whitney and FAA processing requirements are understandably inflexible. | Use the SCC's transition to a flow line to involve employees in level-loading the cell. |
| Feedback | Effective. Quality standards are frequently checked and all work is traceable to specific employees. | Continue to hold employees accountable for the positive and negative results of their work. |

Table 1: Performance comparison of the SCC to job design criteria.

Working to build upon these solid foundations will benefit the Small Components Cell by improving employee morale. The increased flexibility and employee involvement in lean optimization activities will be of tremendous benefit to the company as well. Chapters 4.8 and 6.1.3 discuss how training can improve employee capabilities. Of course, training and job design are not the only ways to more effectively align employee goals with the company. Pratt & Whitney has an incentive compensation plan for its salaried associates and management team that effectively incentivizes these employees to meet and exceed the business targets that the company establishes. Expanding this program to the hourly associates would be tremendously beneficial in more effectively binding the teams together. This type of hourly incentive compensation plan has already been implemented in several other Pratt & Whitney sites, including locations with IAM-represented employees. A leadership team member notes that "these sites perform better and have achieved bonus payouts consistently" (Anonymous, Personal Interview with Leadership Team Member, 2013).

Current hourly compensation is driven by regular and overtime hours worked, along with incentive bonuses when a union contract is ratified by the membership. Unfortunately, this payment structure can result in some sub-optimal incentives. While overhead costs are applied to parts based on the labor hours for each part, hourly associates may be incentivized to increase labor hours per part owing to their payment structure. As a result, management and hourly employees have diametrically opposed interests in how the work is performed. Aligning these incentives through an hourly compensation plan based on the performance metrics in Chapter 3 would allow all team members to share in the benefits of performance excellence.

Along with Chapter 2.4.2, the reader now has a more thorough understanding of the workforce and environment. The following chapter describes the types of processes and equipment within the Small Components Cell.

*Chapter 2.4.4 – Processes and Equipment*

As briefly described in Chapter 2.4.2 above, the overhaul processes within the Small Components Cell are centered on manual operations. For the purposes of this paper, manual operations are defined as operations which are not controlled through computer-aided or robotic machining, surface preparation, or welding. While there are several CNC systems throughout the cell, the majority of the processes involve manual removal of material through hand-blending, manual welding to add material, or manual applications of surface treatments. In light of the nature of the work, it is important to have highly-skilled, highly-experienced workforce that the

Small Components Cell possesses. Brief descriptions of the different processes and the equipment are below.

- ***CNC Machining***: One of the most difficult processes to implement, CNC machining requires significant capital investment for the equipment, programs, and fixtures to hold the part in place. Once the process has been established, the actual machining operation is relatively simple for a trained machinist. Most of the CNC equipment in the cell is quite versatile.
- ***Hand Machining or Blending***: Although the equipment is simple, including pneumatically-driven grinding disks, sanding wheels, and down-draft booths, the skill level required from the operators is very high, considering the tight tolerances demanded.
- ***Assembly***: Limited manual assembly is performed using basic hand tools.
- ***Welding***: The Small Components Cell has the capability of joining parts or adding material through tungsten inert gas welding or plasma arc welding, both of which use an electric arc to deposit metal onto the working surface. The equipment involved includes the arc welders, a ventilation system, and a protected welding booth.
- ***Oven Cycles***: Parts are frequently heat-treated to either remove stresses within the metal, or to change the grain structure of the metal for advantageous strength or fatigue characteristics. The ovens are usually very high-temperature and frequently require vacuum or inert-gas systems.

- ***Brazing***: A process similar to welding in terms of results, brazing joins components together by melting a filler metal, usually in an oven cycle. The resulting flow and solidification of the liquid metal bonds the parts together.
- ***Part Cleaning***: In order to achieve the best results when welding, brazing, or inspecting the components, parts are frequently cleaned to remove oxidation, discolorations, and contaminants. Commercial-style washers with specific temperature ranges and cleaning solutions are used.
- ***Surface Coating***: Surface treatments are often added to reduce friction between engine components or to restore worn dimensions. They involve either manual application and a baking process or automated application in a ventilated booth.
- ***Inspections***: Inspectors use a variety of gages, fixtures, calipers, and other tools to visually and mechanically confirm that part contours, thicknesses, angles, radii, surface finish, and other critical features are within the acceptable design tolerances.

The preceding chapters describe the history of Pratt & Whitney, the company's role within the aftermarket operations sphere, the market size and competition, and the Small Components Cell. Chapter 3 discusses the pre-project status of the business indicators and the political, cultural, and strategic undercurrents within the Small Components Cell.

# *Chapter 3 – Pre-Project Status and Challenges*

This chapter captures the flavor of the Small Components Cell from both a qualitative and quantitative perspective and discusses the specific business metrics for improvement. Understanding the strategic, political, and cultural landscape of the business unit is instrumental in recognizing which changes will be better received than others. Chapter 3.1 reviews the most important business metrics in the Small Components Cell, covering the state of the business *prior* to the start of the project. Please note that all data within Chapter 3.1 reflect accurate trends within the Small Components Cell but that certain information has been redacted to protect company proprietary data. Chapter 3.2 provides a brief, high-level analysis of the entire CTSC organization from strategic, cultural, and political perspectives.

## Chapter 3.1 – Pre-Project Cell Metrics

### *Chapter 3.1.1 – Market Feedback Analysis*

All businesses need to understand how effectively the customer's needs are being met. Pratt & Whitney uses the term 'Market Feedback Analysis' (MFA) to describe both the process of collecting survey responses from their customers as well as the results themselves. Market surveys are electronically sent to a single point of contact at each customer on a quarterly basis and responses reflect the business performance of the previous quarter. Surveys contain a number of questions answered on a sliding scale. These questions emphasize service times, the technical quality of the repairs, perceived value, customer interactions with Pratt & Whitney, and overall satisfaction. Additional free response questions give customers the opportunity to expand on their rankings but do not directly affect the numerical rating. All responses are weighted equally to return an average score.

An interesting aspect of the surveys involves the perceived values of the rankings themselves. The surveys are distributed to a variety of international customers and certain cultures perceive customer satisfaction differently. A 'Satisfactory' score on the survey indicates marginal customer happiness with certain customers but an ecstatic customer in another case. The Small Components Cell's MFA scores for the first and second quarters of 2012 are shown below in Figure 20. These scores are considered in-line with company expectations and are similar to the overall Connecticut Stators and Components (CTSC) business unit.

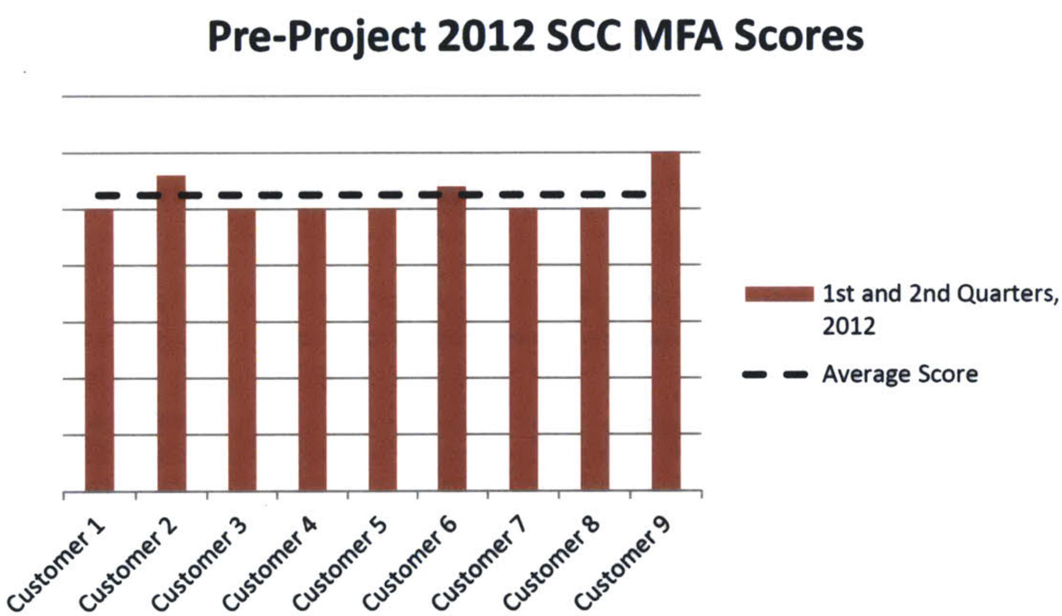



Figure 20: First and second quarter 2012 MFA results for the SCC. The top of the figure is the highest score possible, and the bottom of the figure is the lowest score possible.

*Chapter 3.1.2 – Sales, Costs, and EBIT Performance*

Although customer satisfaction is an excellent indicator of solid or shaky long-term customer relationships, business profitability is a key metric. However, improving profitability alone may conceal fundamental structural concerns if it is accompanied by decreasing sales. With that in mind, this chapter will provide information on sales, cost, and EBIT performance from the Small Components Cell. Since labor costs make up the majority of recurring costs, overtime rates are used as a proxy for trends in cost control. As overhead costs are allocated based on labor hours, this proxy reflects the realities of Pratt & Whitney's cost management strategy. Although this chapter will not discuss overhead costs directly, significant improvements in material management and other recurring costs have recently occurred throughout Pratt & Whitney's aftermarket division (Duncan, 2011).

The first two figures of this chapter show EBIT performance as a percentage of a target for the Small Components Cell and for the Connecticut Stators and Components business unit as a whole. Note that the first six months of 2012 show that both the SCC and CTSC are underperforming their EBIT goals.

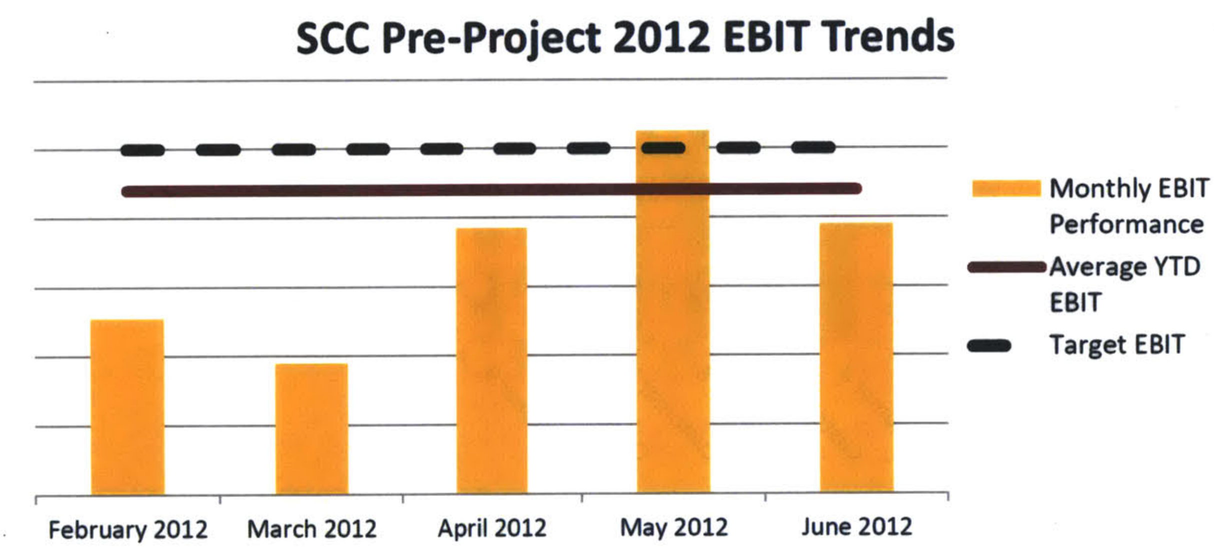



Figure 21: First and second quarter 2012 EBIT performance for the Small Components Cell and average sales data for the SCC from 2011. Please note that January's performance was omitted owing to a large one-time accounting correction that skewed the month's results.

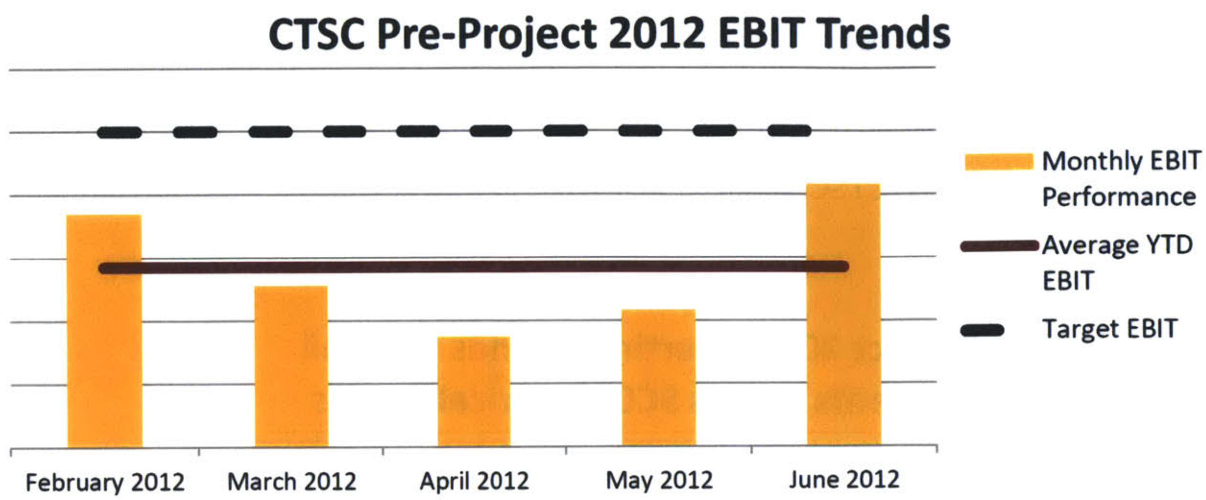



Figure 22: First and second quarter 2012 CTSC EBIT performance business unit as a whole. Please note that January data have been eliminated because of a large one-time accounting correction which skewed the month's performance.

The next figure highlights trends in sales from 2011 and 2012. The first figure has monthly sales information from the first half of 2012 along with an accompanying average for the Small Components Cell only. Note that sales declined significantly more quickly in January – March than did the corresponding overtime rates.

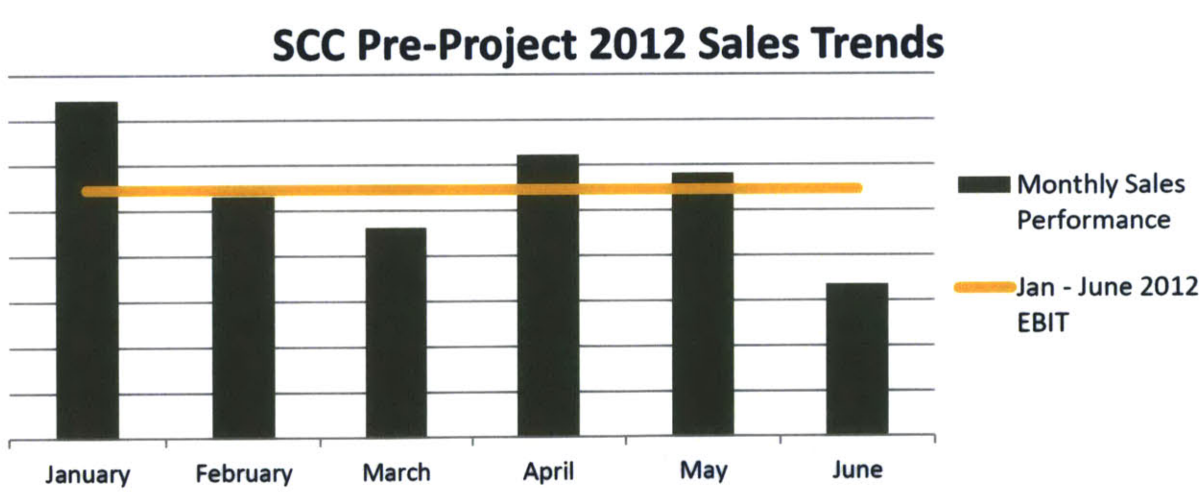



Figure 23: First and second quarter 2012 sales for the Small Components Cell and average sales data for the SCC from 2011.

The next two figures are focused on overtime as a method of cost control. Both show that overtime was down slightly vs. the previous year, but that the other portions of the Connecticut Stators and Components (CTSC) business were reducing their overtime more effectively than the Small Components Cell.

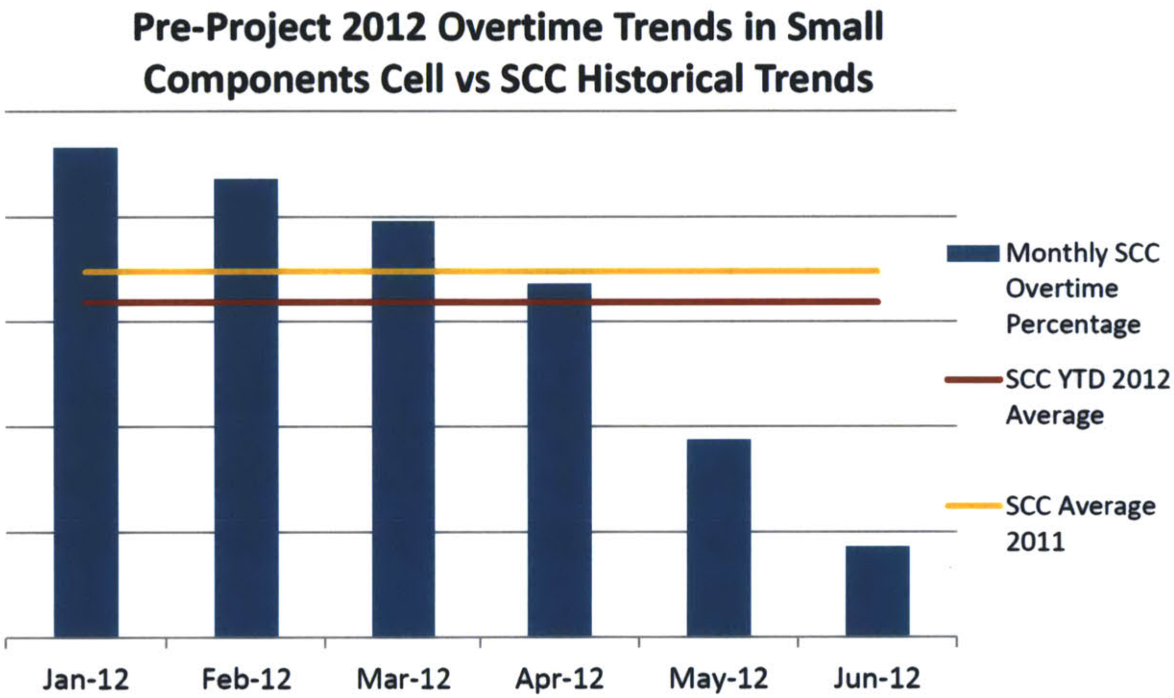



Figure 24: First and second quarter 2012 overtime percentages for the Small Components Cell. The chart is intended to provide a look at the overall trends within the first two quarters of the year prior to the project start, as well as a reference to the 2011 performance of the Small Components Cell.

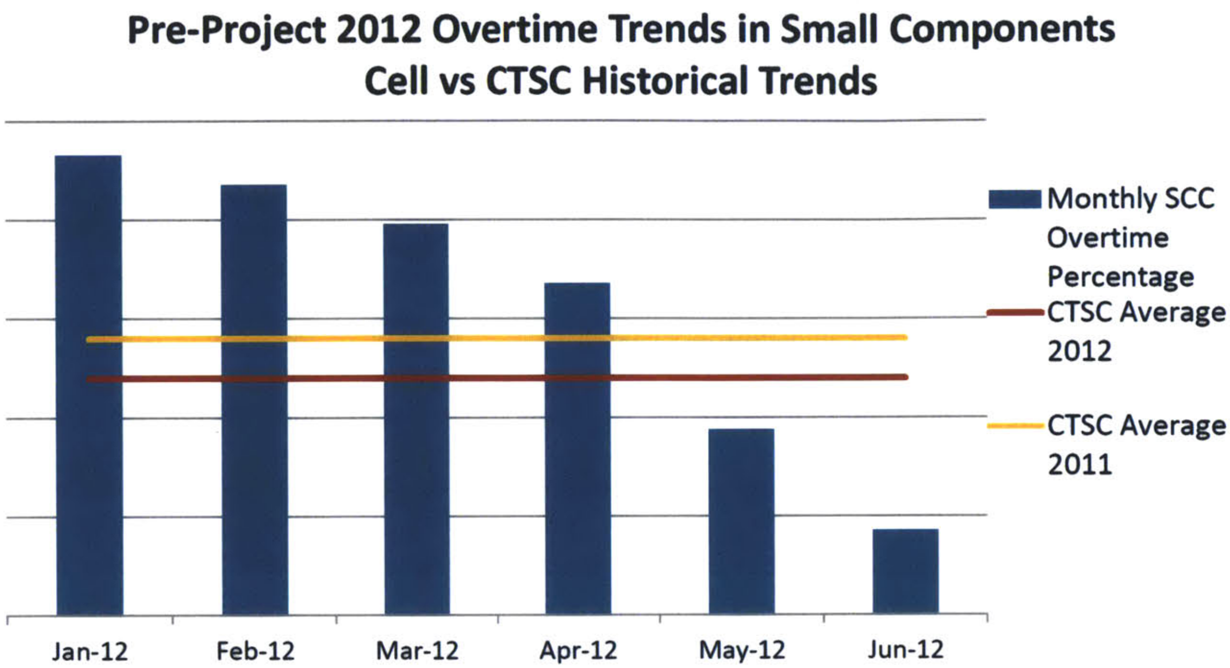



Figure 25: First and second quarter 2012 overtime percentages for the Small Components Cell. The chart examines the overall trends within the first two quarters of the year prior to the project start, while comparing the Small Components Cell to the Connecticut Stators and Components business, of which the SCC is a part.

*Chapter 3.1.3 – On-Time Delivery*

Owing to the capital-intensive nature of airplanes, idle aircraft must return to service as soon as possible to recoup the investment. As a result, the on-time delivery (OTD) of repaired components is critical to the customers. Contracts specify that parts be returned a fixed number of days after they arrive in East Hartford for repair. It is critical to note that the Small Components Cell does not have any control over the incoming demand, as the airlines send hardware in for repair in accordance with their operating level and regulatory requirements.

Traditionally, the Small Components Cell has struggled with on-time delivery, as shown in Figures 26 and 27. Interestingly, Chapter 4 forecasts capacity problems in the cell for a 'normal' product mix and volume level. This suggests that queuing or another factor may be a principle cause of missing on-time delivery targets. Analyses related to queuing and other potential causes are found in Chapters 4 and 6.

On-time delivery percentages are calculated as a fraction of the total number of orders rather than weighting OTD based on sales. As a result, the Small Components Cell's high volume has a disproportionately large impact on the on-time delivery of the overall business unit when compared to the SCC's contribution to sales.

Finally, it is important to note that the large amount of part numbers within the four part families makes carrying a safety stock of parts prohibitively expensive for the Small Components Cell. Several other cells within the Connecticut Stators and Components business unit work with smaller numbers of unique part numbers and smaller order quantities. These cells make effective use of a small rotable inventory pool to fulfill customer needs if circumstances prevent parts from shipping on time.

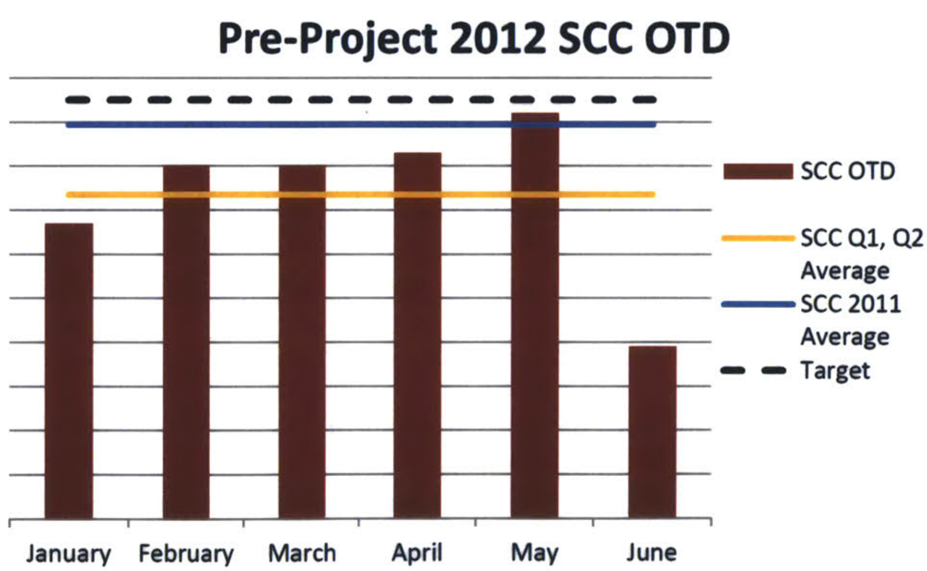



Figure 26: 2012 On-time delivery rates for the Small Components Cell. Note that on-time delivery performance in 2011 was better than the average on-time delivery rates in 2012. Both 2011 and the first half of 2012 fell short of the target on-time delivery performance, shown by the orange dashed line above.

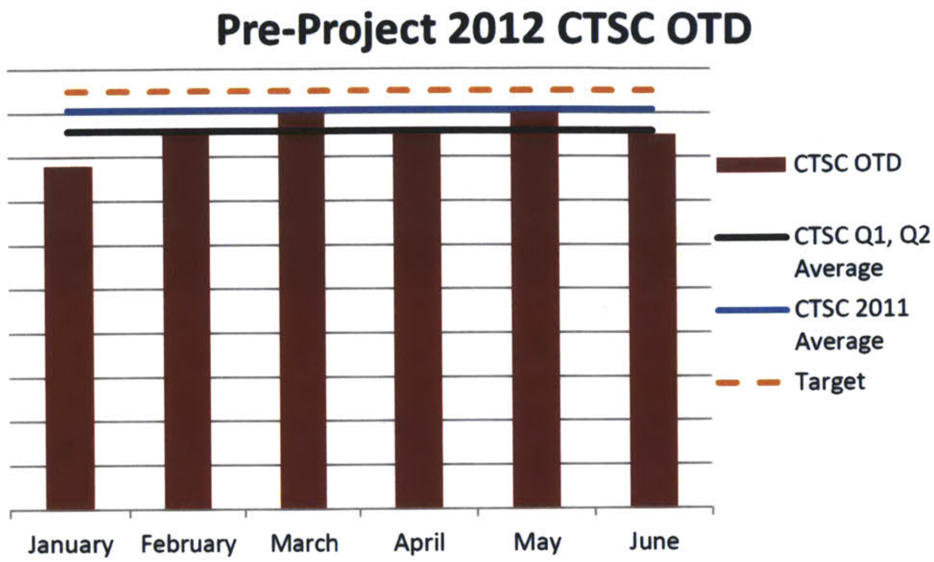



Figure 27: 2012 On-time delivery rates for Connecticut Stators and ComponNote that on-time delivery performance in 2011 was better than the average on-time delivery rates in 2012. Both 2011 and the first half of 2012 fell short of the target on-time delivery performance, shown by the orange dashed line above. The three other cells in CTSC have higher on-time delivery performance on average than the Small Components Cell.

*Chapter 3.1.4 – Cost of Rework*

In the pantheon of critical metrics, cost of rework holds an extremely important place. While on-time delivery, profitability, and customer satisfaction are all vital to the success of the business, quality is king. The cost of rework is a good proxy for a cell's performance to regulatory and technical requirements. Cost of rework is calculated by capturing the cost of repairing or purchasing a part that was damaged by Pratt & Whitney-internal processes. The data are reported as a percentage of the total sales of the cell or business unit, depending on the scope of the report. This metric receives a high level of attention across the business, as errors are expensive and can damage the company's reputation.

Overall, the Small Components Cell has made excellent strides in reducing the cost of rework associated with the cell, as shown in Figure 28 below. Year over year improvements are significant. 2012 shows more than an 85% reduction in the cost of rework compared to 2011.

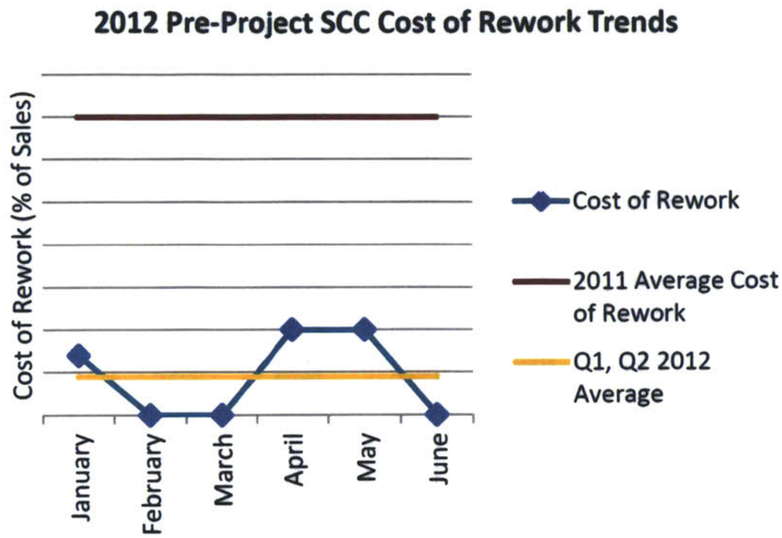



Figure 28: 2012 Cost of rework for the Small Components Cell. Note the large decrease in the cost of rework between 2011 and the first six months of 2012. The Small Components Cell has been well below its cost of rework goals for more than two years.

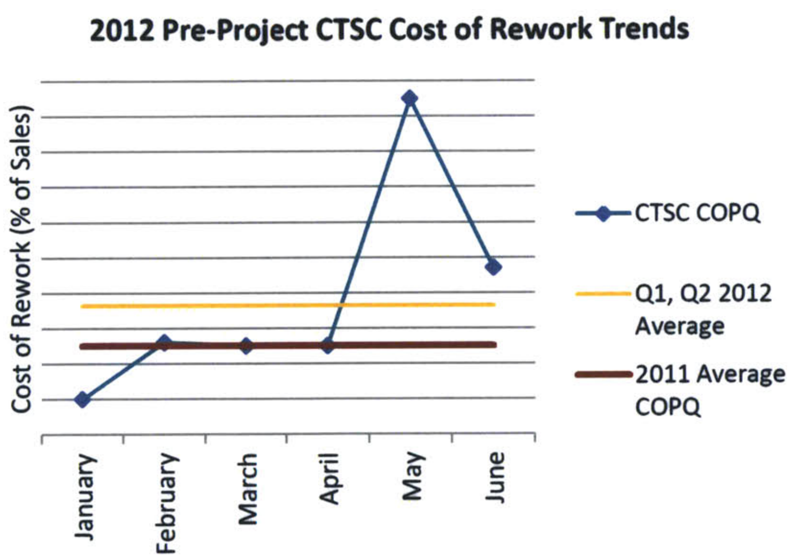



Figure 29: 2012 Cost of rework data for Connecticut Stators and Components. While the business unit enjoyed four excellent months to start the year, errors in May and June have shifted the 2012 average cost of rework above the 2011 average rate.

Having reviewed the crucial business metrics of the Small Components Cell, the following chapter will discuss items that are more difficult to quantify: how strategic, cultural, and political concerns benefit and constrain the project.

### Chapter 3.2 – Political, Cultural, and Strategic Considerations

This chapter will analyze the project at a high level from strategic, cultural, and political perspectives. Strategic considerations analyze how the project aligns with business needs, how the organizational structure aids or hinders the initiative, and how job roles and assignments are designed. The cultural lens highlights situations where the project supports or undermines the organizational norms and perception of the business. The third facet, the political lens, analyzes the relationships, history, and power structure between functional groups within and outside the Small Components Cell.

The over-arching summary of this chapter reflects the fact that, strategically, this project is well-aligned with the business' long-term goals. From a coldly logical standpoint, there are virtually no barriers to the project's implementation and success. The challenges blossom when we view the cultural and political lenses. The changes associated with completely restructuring the cell are often seen as a threat to the routine and a potential imbalance in the power structure of the organization.

#### *Chapter 3.2.1 – Strategic Lens*

The project links neatly with the goals of the overall business. The Small Components Cell is being restructured to improve on-time delivery, profitability, cost of rework, and customer satisfaction metrics. In an effort to increase market share, engines are often sold at a razor-thin margins or a loss, provided that the end user agrees to rely on Pratt & Whitney to service the engines, as described in Chapter 2.2. In these situations, there is significant pressure on the aftermarket division to keep costs low and profits high. Customers are focused on turnaround time above all else, as repaired parts allow the airlines to quickly return an aircraft to profitable use. Focusing on the aforementioned metrics, the project seeks to improve cell performance in concrete ways that will improve business and customer relationships.

Examining the project strictly from the perspective of its effect on business metrics captures only a portion of the full picture, as the organization's influence on the project is important to the project's success or failure. As shown in Figure 30, Pratt & Whitney has a traditional organizational structure. The overhaul process is a uniquely choreographed ballet, with each cell leader, engineer, and employee responsible for very specific steps in the dance. Job functions are strictly defined among hourly employees based on a union contract. This structure generally serves the project well from a strategic perspective, as it clearly defines which groups are responsible for carrying out particular types of work.

However, strict job definitions do have drawbacks in efficiency and flexibility. Expeditors, as described in Chapter 2.4.2, are the only employees who move parts across main aisles, resulting in unnecessarily slow transfers to a shared service, difficulties when retrieving parts from common tool cribs, and delays in reaching the building's shipping well. This is discussed further in the queuing analyses of Chapter 4. Other than this structural misalignment, the defined functional leaders and clear job roles help the project to maintain momentum through direct communication and a reduction in ambiguity. I receive strong support from the General Manager of the business unit, who is also the project sponsor. The project is buoyed by daily status meetings with the project team and weekly staff meetings with the whole leadership group. These coordinating systems effectively reinforce the needs of the project, and the only structural change I recommend is to train employees across the boundaries of the current occupation codes.

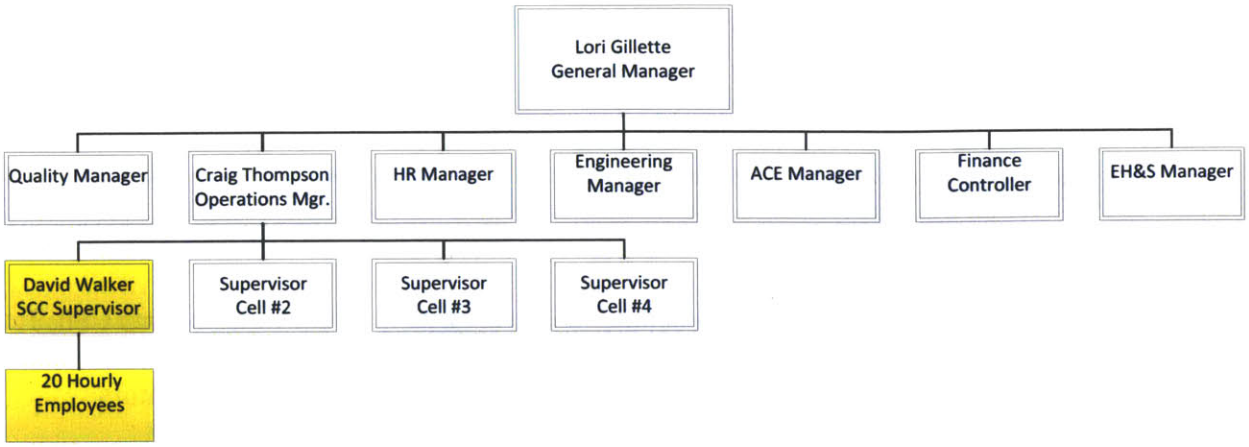



Figure 30: Organizational chart of Connecticut Stators and Components (CTSC). My role and the 20 hourly employees who report directly to me are highlighted in yellow. General Manager Lori Gillette is responsible for over 400 employees.

*Chapter 3.2.2 – Cultural Lens*

Although the project enjoys significant strategic support, cultural elements of Pratt & Whitney are not aligned with the project. Among the hourly employees of the Small Components Cell, there is an *average* of 27 years' experience in Pratt & Whitney's Global Service Partners division. Experience and time-in-service are highly prized. As noted in Chapter 2.4.2, seniority and significant technical contributions are readily visible on employee badges. Contractors are less fortunate, with bright yellow badges marking them as someone from "outside the Pratt & Whitney family," (Anonymous, Personal Interview with SCC Employee, 2012).

With this atmosphere, it is often difficult to gain traction for projects involving a significant amount of change, particularly when that project is led by a comparatively inexperienced outsider. The overt displays of experience and belonging do have practical benefits. It is simple to identify senior employees upon entering an unfamiliar part of the facility. Training is assigned based on seniority, vacation is dependent on time-in-service, senior employees are given the opportunity to accept or refuse furloughs before their less-experienced co-workers, and reductions in force are also conducted based on years of service. Since many important aspects of working life revolve around seniority, it is understandable that it is so prominently presented.

Because of the complex and highly technical nature of the work, coupled with long product lives, structural changes to overhaul cells are normally accomplished over a period of several years. As a result of the 6-month schedule to restructure the Small Components Cell, I have gained a reputation as a "pusher" (Anonymous, Personal Interview with CT Stators Employee, 2012). Time is ironically not always considered of the essence, even when feedback from customers indicates otherwise. With this prevailing culture, a project seeking to implement lean manufacturing principles is often viewed with pessimism. Though the salaried culture is strongly in favor of lean manufacturing, hourly employees sometimes sees "lean" as an excuse for future headcount reductions. ACE, which is UTC's lean operating system, is jokingly meant to stand for "Adios, Connecticut Employees" (Anonymous, Personal Interview with SCC Employee, 2012).

However, the culture is not completely opposed to the project. Interestingly, the basis of the support of several team members stems from the same source as their co-workers' resistance: their long histories at Pratt & Whitney. Rather than seeing the changes to the Small Components Cell as a threat from an inexperienced outsider, several group members perceive the internship as a chance for the business to evolve and remain competitive while operating with a traditionally high-cost workforce. They see the project as a means of strengthening their team. These employees are a powerful cultural pillar in support of the project, and their numbers have fortunately grown throughout the project. Fostering this hourly approval of the project is crucial for the long-term implications of the project. Although the cultural skies are currently overcast, the silver lining does exist.

*Chapter 3.2.3 – Political Lens*

One of the strongest impressions I have of Pratt & Whitney is the stark division of power between the unionized hourly employees and the salaried management. Program and engineering managers are instantly recognizable, an island of khaki slacks, dress shirts, and ties in a sea of union t-shirts, shorts, and tennis shoes. Dress is not all that separates management from the unionized employees. Contract cycles are three years long and negotiations are often contentious. Walkouts and strikes are common, and there are already shop rumors of a strike when the current contract expires on December 31st, 2013 (Anonymous, Personal Interview with SCC Employee, 2012). One leadership team member noted that June through December of 2013 will see bi-weekly marches of hourly employees around the perimeter of the building, accompanied by drums and union flags (Anonymous, Personal Interview with Leadership Team Member, 2012). Of course, there is another side to the story: a court injunction several years ago prevented the company from moving jobs from the Connecticut facility to lower-cost factories in Georgia, Japan, and Singapore (Singer, 2010). Both sides have equivalent amounts of power stemming from different sources. The company's power centers on the managerial and salaried workforces and tends to be very data-driven. The union's power derives from its membership, who rally to an emotional call instead of business metrics.

In the overall scope of company-union relations, however, the restructuring of the Small Components Cell has not spurred any large conflicts, as re-organizations and new work assignments are relatively common. This is a very fortunate situation, as strong opposition to the project would dramatically complicate the internship's overall goals. Conflicts are focused on the day-to-day operations of the cell, with union grievances stemming from the allocation of overtime among the employees, training priorities, and work assignments. The grievance (conflict resolution) process is heavily structured, like job definitions. As a result, conflicts are solved quickly rather than being allowed to fester. A key component in heading off conflict related to the project is keeping the employees up-to-date on the restructuring plan and actively requesting their input in our weekly "Toolbox" meetings. Allowing employees to see and discuss the plan, as well as to suggest changes before implementation strengthens the sense of ownership they have as veteran employees of the area. This is one reason that several employees have started to speak out in support of the project over the past months. Figure 31 reflects the trend of increasing support for the project and decreasing levels of grievances.

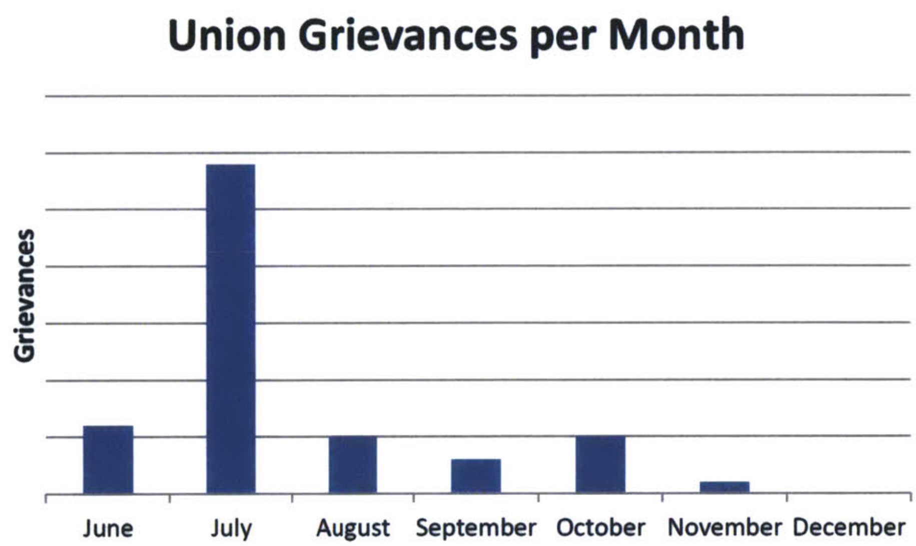



Figure 31: Summary of union grievance activity in the Small Components Cell. Interestingly, work on the restructuring of the Small Components Cell began in earnest in July.

*Chapter 3.2.4 – Summary of Cultural, Political, and Strategic Considerations*

The strategic, cultural, and political perspectives are summarized by the images discussed above: the badges displaying years of service, the highly defined job roles, and the division between the managers and the employees. The highly traditional, hierarchical structure has benefitted the project thanks to the consistent support of the General Manager and Operations Manager of the Aftermarket group. By aligning the project's goals with the strategy and structure of the organization, the restructuring of the Small Component Cell has an excellent chance of success when considered through the strategic lens. Culturally, the speed at which the project moves runs counter to several aspects of Pratt & Whitney's comfort zone. Politically, the project walks a fine line between two opposing camps, each of which wields its power in a unique fashion. Fortunately, the lower-level conflicts that the internship faces are resolved through an agreed-upon grievance process.

With an eye on the future, one particular approach will allow the project to have long-term positive impact on the organization: continuing management's approach of encouraging the hourly and salaried teams to work together to plan significant portions of projects. This provides a tremendous sense of project ownership. Continuing weekly reviews with the hourly employees to foster a sense of cell ownership is crucial. This will ensure that the project becomes a natural part of an employee's 30 years at Pratt & Whitney, rather than the inorganic add-on of an outsider. Successful completion of this project will allow the Connecticut Stators and Components division to take another step towards simultaneously meeting customer needs and improving the company's bottom line.

## *Chapter 4 – Transforming the Small Components Cell*

Chapter 3 highlights the key metrics of the Small Components Cell and discusses the organizational landscape from three different perspectives. At this point, the reader has a better understanding of the concerns that General Manager Lori Gillette and Operations Manager Craig Thompson faced prior to the project start. Chapter 4 describes the approach to overcome these obstacles by answering the following questions:

- Chapter 4.1 – Why attempt to transform the Small Components Cell using lean manufacturing techniques?
- Chapter 4.2 - Does the Small Components Cell have sufficient capacity to meet demand? Under what conditions?
- Chapter 4.3 – Can the capacity planning model of Chapter 4.2 suggest focused opportunities for improvement?
- Chapter 4.4 – Can the Small Components Cell be organized more effectively?
- Chapters 4.5 and 4.6 – What logistical considerations must be tackled before implementing the project? How is the project's timeline organized?
- Chapter 4.7 – What are the qualitative and quantitative benefits of the new cell layout? How does queuing affect the performance of the cell?
- Chapter 4.8 – Moving equipment is only a portion of the change. How can a training plan help the Small Components Cell to more effectively meet demand with a minimum of cost?

Please note that this chapter centers on the development and implementation of the cell transformation, while Chapter 5 will describe the results of the restructuring. While reading this chapter, please keep in mind that the data presented represent the actual trends in the Small Components Cell. However, the actual average processing times, standard deviations, historical demand data, absenteeism, overtime rates, and employee efficiencies have been disguised to remove company proprietary information.

### Chapter 4.1 – Why Use Lean Manufacturing Techniques?

Having reviewed the crucial business metrics of the Small Components Cell in Chapter 3, we see the need for change. Lean manufacturing techniques have generated incredible operational improvements over several decades, primarily in the automotive industry. A holistic approach towards business improvement, lean manufacturing techniques provide the broad-based opportunities for business optimization that the Small Components Cell needs. Womack and Jones note that lean manufacturing provides "great performance advantages that a best-in-class lean manufacturer such as Toyota [has] over typical mass producers" (Womack & Jones, 1996). Automotive manufacturers are not the only companies that can capture the value of lean manufacturing, as the aerospace industry has more recently made strides towards achieving similar performance increases through lean manufacturing (Crute, Ward, Brown, & Graves, 2003). This chapter describes the rationale behind this choice. Lean manufacturing has five central tenets (Womack & Jones, 1996):

1. The endless pursuit of perfection
2. Identify and enhance value-added processes
3. A system in which the customer pulls value from the upstream overhaul center
4. Minimize any interruptions in the repair processes
5. Eliminate or reduce non-value added processes as much as possible

Pratt & Whitney conducted several value stream analyses prior to the start of the project. As a result, this project focuses on the elimination of non-value added processes, the minimization of interruptions during the repair processes, and the development of a customer pull system.

However, before diving in, we should review several common pitfalls associated with lean implementation. The greatest stumbling block involves "managers [who grasped] the power of individual lean techniques… [but] they had stumbled when it came to putting them all together into a coherent business system. That is, they could hit individual notes (and loved how they sounded) but still couldn't play a tune" (Womack & Jones, 1996). Fortunately, Pratt & Whitney's ingrained "Achieving Competitive Excellence" (ACE) culture is a fundamental part of the company. This concern should never be far from our thoughts, but is not an imminent threat.

Other common concerns focus on sufficient physical space and time to improve cell performance (Crute, Ward, Brown, & Graves, 2003). The project timeframe for the transformation of the Small Components Cell is quite brief, as noted in Chapters 3.2.2 and 4.6. This could result in a rushed project with sub-optimal WIP placement or unnecessary queuing. Crute, Ward, and Brown also note that senior management consistency and commitment are crucial to project success. As noted in Chapter 3.2.1, managerial support for a lean transformation of the cell is very strong. Finally, one consistent threat to the successful implementation of lean manufacturing is a firm focus on the product (Crute, Ward, Brown, & Graves, 2003). The project tackles this concern directly. Chapters 4.4 and 4.7 address this danger by designating specific areas within the cell for specific products. This reduces the uncertainties regarding the next repair step and establishes more effective visual control of the products.

The project is well-suited to improving performance through the five central tenets of lean described above. The capacity planning model and floor plans described in Chapters 4.2 through 4.7 examine ways to eliminate non-value added processes, reduce queue times, minimize interruptions in the repair processes, and enhance the value-added processes of the Small Components Cell. Similarly, the flexible training plan in Chapter 4.8 minimizes process interruptions. All the following chapters seek to enhance value-added processes and improve the development of a customer-centric, value pull system. Please see Chapter 5 for a description of how the lean manufacturing transformation impacted the underlying business metrics.

## Chapter 4.2 – Capacity Planning

We must develop a thorough understanding of the capabilities of the equipment and the employees within the cell before transforming the cell. In short, how can we use a capacity planning model to determine if the system can complete the work? This model-based approach is partially inspired by the development of a capacity planning model for Tinker Air Force Base, a U.S. Air Force installation that rebuilt following a serious fire (Ravindran, Foote, Badiru, Leemis, & Williams, 1989). As the authors of the study note, "We developed a large simulation model to aid reconstruction efforts…The new design has decreased material handling…decreased flow times, [and] allowed better management control of part transfers" (Ravindran, et al, pp. 102). The Excel-model approach is similarly inspired by a comparative analysis of an open queuing model between Excel and dedicated factory simulation software (Koo, Moodie, & Talavage, 1994).

### *Chapter 4.2.1 – General Model Development and Assumptions*

This chapter describes the capacity planning model in general terms, while following chapters provide insight into specific applications and assumptions in the Small Components

Cell. Fundamentally, this capacity model determines how many employees, resources, or pieces of equipment are required such that all incoming demand is met:

$$D \leq C$$

Where $D$ is the incoming demand and is given by

$$D = \mu + \epsilon, \text{ where } \epsilon \sim N(0, \sigma^2)$$

μ is the average daily demand for a specific product and is calculated directly from an input. σ is the standard deviation of the daily demand, and is an input as well. The model is developed in Excel, using random number generators to reflect the variability in demand across simulated days. When demand is greater than capacity more than 50% of the simulated days, a threshold is triggered to add additional employees or equipment as necessary. Having defined the demand side of the equation, $C$, the available capacity of the system, is

$$C = f(G, \rho, \tau, J, H)$$

Where $G$ represents employee breaks, $\rho$ is the operating efficiency of the employees or the equipment, and $\tau$ consolidates a variety of time-based inputs, including the number of hours per shift, shifts per day, and working days per month. $J$ is the percentage of overtime, while $H$ is the absenteeism percentage. All arguments of the function are inputs. Symbols are consistent with the definitions in Chapter 4.2.2.

General assumptions are listed below. Extending this general case to the Small Components Cell, Chapter 4.2.2 shows sample input sections and explicitly defines many of the relationships. Chapter 4.2.5 illustrates a case study of labor capacity planning for an average product mix and different levels of demand, while Chapter 4.2.6 discusses equipment capacity planning in the same scenarios. Chapter 4.2.7 discusses a case study of labor capacity planning in the Small Components Cell for a skewed product mix at different demand levels. This iterative model is helpful to forecast potential capacity problems in a variety of situations, but does not provide insight into how to most effectively increase the capacity of the Small Components Cell. Chapter 4.3 discusses how capacity in the Small Components Cell can be most effectively increased.

**General Model Assumptions**

- The model is structured as a buffer – process – buffer – process linear chain from the beginning of the process through the end. This assumption matches the working conditions of nearly every lean manufacturing flow line and prevents processes in the model from conducting out-of-sequence work.
- Utilization rates must be less than 100%.
- Rework is corrected in the same step in which it is found. This prevents the need to simulate dozens of variable return loops within the process. This assumption is aligned with the actual operating processes on the factory floor. An additional implication of this assumption is that the complete output of one process is the complete input of another; no parts are re-routed, lost, or taken out of service. For the purposes of the model, the standard deviation of the process contains the contribution of rework. Since rework is completed in the same process step, employees do not clock off the job to conduct rework, and the rework time is contained within the clocked time and standard deviation. As a result, the standard deviations reflect both the likelihood that rework is required and the duration of the rework itself.
- Although an average and standard deviation of demand is known from historical data, the exact arrival times of this demand is unknown. Work is assumed to arrive as a

series of independent and identically distributed random variables (IID). The IID assumption is valid for "'flexible' manufacturing systems [with] short changeover times from one part type to another" with a "processing time 'stream' [that has] shorter sums of similar times," a situation that is very representative of the many manufacturing flow lines, including the Small Components Cell (Wang & Wilson, 1994).

- For the purposes of the model, queue lengths can be as large as necessary. This is not physically practical but provides an opportunity to determine where large queues may develop during processing. In other words, the system is an open queuing network, with a non-constant number of jobs in the system at any given time (Wang & Wilson, 1994).
- In order to save time during the calculation processes, a simulation of 100 working days is assumed to be sufficiently accurate. This assumption was tested by comparing the differences in results between 100 day simulations and 1000 day simulations and finding negligible differences over a variety of input settings.

### *Chapter 4.2.2 – Pratt & Whitney-Specific Model Development*

While Chapter 4.2.1 provides a general overview of the capacity planning model, the next chapters describe specific applications of this general approach to the Small Components Cell. As discussed in Chapter 2.4.1, the Small Components Cell repairs four different part families, each with several dozen part numbers. The four part families are vane clusters (CLUs), high-pressure turbine duct supports (HPTs), high-pressure compressor honeycomb components (HPCs), and low-pressure turbine seals (LPTs). Part families are usually referred to by their three-letter designations. Please note that each of the four part families has a unique process flow which will not be explicitly stated because of proprietary data. The model itself is a linked series of buffers and processes, as Figure 32 illustrates. The similarities and differences between the various process flows are accounted for in the new cell layout, as shown in Table 12.

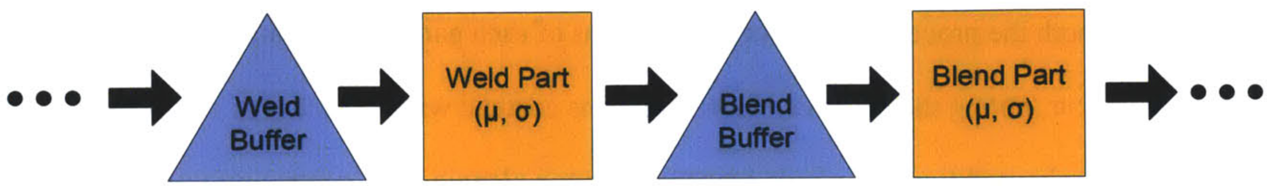



Figure 32: Illustration of capacity planning model, showing buffers (in blue) and processing times (in gold), which are a function of the average processing time ($\mu$) and the standard deviation of the processing time ($\sigma$).

The total processing times for all four part families are summed together according to the occupation codes discussed in Chapter 2.4.2. If the man-hours required to complete the work are less than the available labor time for a given occupation code, the Small Components Cell has sufficient capacity within that occupation code for that simulated day. In the event that the processes require more time than is available within an occupation code, the Small Components Cell has insufficient capacity on that simulated day.

Of course, the model is only as good as the data it is based on. With this in mind, all model data were collected from the 2010 – 2012 timeframe, which has several benefits. First, the information is recent enough that major changes in equipment and technology are not factors. Also, the data are sufficiently large enough that daily demand spikes or localized variations in product mix do not skew the entire set. Finally, within the 2010 – 2012 range, the majority of the group's employees, support personnel, and leadership remained generally stable. Collectively, these data represent thousands of jobs and hundreds of thousands of individual part repairs on every part family within the Small Components Cell. Data have been disguised throughout the chapter, though the figures and charts show accurate trends from the actual data.

The Small Components Cell's resources must accommodate repairs on all four part families at the same time, rather than examining each part family separately. It is also crucial to account for both the processing times and variations of each part family. Daniel, Guide, and Spencer concur, noting that "Remanufacturing firms contend with a number of complicating factors that make traditional methods of manufacturing planning and control impossible unless modifications are made to these traditional tools. The complicating factors include probabilistic routing files, probabilistic material replacement, and highly variable processing times required to perform required repair operations" (Daniel, Guide, & Spencer, 1997). The letters following each bullet refer the reader to a specific section of the associated figures.

**Demand Inputs**: To simulate demand, the annual demands from 2010, 2011, and 2012 are averaged, forming a base annual demand (A). See Figure 33. With a known product mix (B), the volume of each part family is easily determined. Working hours per shift (C) and working days per month (D) are assumed based on knowledge of the performance of the Small Components Cell. Thanks to Pratt & Whitney's Engineering and Customer Service groups, the standard deviations (E) for the demand are also available. Daily demand per part family (F) is defined by

$$Daily\ Demand = \mu + \epsilon, \text{ where } \epsilon \sim N(0, \sigma^2)$$

$\mu$ is developed from the average annual demand according to:

$$\mu = \left(\frac{A}{12}\right)\left(\frac{B}{D}\right)(Volume\ Scaling\ Factor)$$

where A, B, and D are defined above. σ is the standard deviation of the daily demand. The Volume Scaling Factor is a multiplier ranging between 0 and 2 in increments of 0.25 that allows the model to simulate low, average, or high demand periods. An Excel-based random number adjusts the amount of variation in the model based on actual historical demand fluctuation.

| Product Families | Annual Demand | Product Mix | Hours/ Shift | Work days/mo. | μ | σ | Daily Demand |
|---|---|---|---|---|---|---|---|
| CLUs | 1000 | 40.00% | 8 | 20 | 1.666667 | 0.833333 | 0.833333 |
| HPT Ducts | | 3.00% | | | 0.125 | 0.0625 | 0.1875 |
| HPCs | | 50.00% | | | 2.083333 | 1.041667 | 3.125 |
| LPTs | | 7.00% | | | 0.291667 | 0.145833 | 0.4375 |
| | (A) | (B) | (C) | (D) | | (E) | (F) |

Figure 33: Example demand input section of capacity planning model. Note that none of the values shown above reflect actual data from Pratt & Whitney.

The model creates different 'days' by recalculating formulas every time the worksheet is refreshed. With each recalculation, the random number generator yields a different value, simulating a new arriving demand for each simulated day.

**Capacity Inputs and Assumptions**: Calculating the available man-hours or machine availability involves a blend of collected data and variable inputs. Expected time spent on breaks (G), efficiency (ρ), employee absenteeism (H), and overtime rates (J) are all drawn from available information and can be varied to create different scenarios.

| | Breaks (hrs) | ρ (%) | Absenteeism (%) | OT (%) |
|---|---|---|---|---|
| CLUs | 1 | 0.75 | 0.08 | 0.05 |
| HPT Ducts | | | | |
| HPCs | | | | |
| LPTs | | | | |
| | (G) | (ρ) | (H) | (J) |

Figure 34: Capacity Inputs section of the model. Please note the values shown here do not reflect the actual metrics in the Small Components Cell.

With these demand and capacity inputs, the model now simulates the demand for each specific product flowing through the product-specific process-buffer-process chain. The following screenshots are all from the CLU product family as an example. Similar chains exist for the HPCs, HPT Ducts, and LPTs.

| CLU Process Steps | | Arriving Jobs | Process #1 | | Buffer | Process #2 | Buffer | Process #3 | Buffer | Process #4 |
|---|---|---|---|---|---|---|---|---|---|---|
| | Avg. time per job (hrs) | | 1.25 | K | | 2 | | 5 | | 0.5 |
| | Job Std. Deviation (hrs) | | 0.75 | L | | 1 | | 1.5 | | 0.1 |
| | ENG Std Time (hrs) | | 1 | M | | 1.5 | | 4 | | 0.5 |
| | ENG Std Deviation (hrs) | | 0.6 | N | | 0.75 | | 1.2 | | 0.1 |
| CLU | Eng. Avg. jobs per shift | 2.5 | 3.445313 | P | 2.5 | 2.45 | 2.45 | 1.96875 | 1.96875 | 13.78125 |
| | Shifts per day | | 1 | Q | | 1 | | 1 | | 1 |
| | Eng. Avg. jobs per day | | 3.445313 | R | | 2.45 | | 1.96875 | | 13.78125 |
| | Eng. Avg. man-hours required | | 5.333333 | S | | 7.5 | | 16.98667 | | 1.3125 |

Figure 35: Example processes of the CLU part family portion of the model. Note that these values are fictionalized. Also note that Process #2 and Process #3 are forced examples of bottlenecks, as these processes can only complete 2.45 and 1.96 jobs per day, respectively, while demand is 2.5 jobs/day.

The "Arriving Jobs" of each part family are calculated from the Demand Inputs section (shown in Figure 33). Each process has an average time per job (K), the standard deviation of that time (L), the engineering standard time (M), and the engineering standard deviation (N). K and L are clocked times drawn from actual employee-generated time records, while M and N are engineering standard times drawn from time studies conducted by Engineering. The differences between clocked times and engineering standard times are discussed more thoroughly below. The engineering average jobs per shift (P) is simply the total number of hours in a shift (C) divided by the engineering standard time for the process (M). The number of shifts per day (Q) can be set individually for each process, as management may elect to implement a partial second- or third-shift. Engineering average jobs per day (R) calculates the number of jobs completed in a day (possibly involving multiple shifts). Engineering average man-hours (S) is:

$$S = M + \frac{N(Random\ Number\ Generator)(Jobs\ in\ Buffer)}{\rho}$$

where ρ is the efficiency from the Capacity Inputs section (Figure 34). The Random Number Generator serves the same function as above, but is a separate calculation to prevent demand variations and process variations from being artificially linked.

**Clocked Times (K,L) vs. Engineering Standard Times (M,N)**: The model assumes that engineering standard times are more accurate representations of processing times than clocked times. Clocked times are the processing times recorded automatically by a computerized system when employees scan a barcode to record their labor hours. Engineering standard times are generated by the engineering staff as an estimate of the ideal processing time needed to complete specific operations.

**Engineering Time Standard Deviations (N)**: When engineering times are generated, the staff does not create standard deviations for those times. As a result, the model assumes that the standard deviations for the engineering times exist in the same proportion as the ratio between the engineering and actual times. In other words,

$$\sigma_{Engineering\ Standard\ Time} = \sigma_{Clocked\ Time}\left(\frac{\mu_{Engineering\ Standard\ Time}}{\mu_{Clocked\ Time}}\right)$$

All standard deviations, clocked processing times, and engineering standard times are specific to each part and each machine. For example, an HPC and an LPT that are processed on the same machine have unique clocked processing times, engineering standard times, and standard deviations.

Now that the model reflects both demand variability and process variability, it must track the requirements on the cell's equipment and personnel against the cell's capacity. This is accomplished through a summation sheet, as shown in Figure 36 All engineering average man-hours (S from Figure 35) that machinists are responsible for are summed across all four part families and compared to the machinists' available working time. These steps are repeated for the surface mechanics, NDT technician, inspectors, and welders.

| Daily Man-Hour Requirements by Occ Code | CLU | HPT Ducts | HPCs | LPTs | Daily Total | Current Capacity |
|---|---|---|---|---|---|---|
| **176H (machinists)** | 3 | 1 | 10 | 25 | 39 | 40.572 |
| **344H (sur. tech.)** | 4 | 2 | 4 | 1 | 11 | 10.143 |
| **380H (welders)** | 3 | 2 | 6 | 1 | 12 | 15.2145 |
| **400H (insp.)** | 2 | 6 | 12 | 8 | 28 | 30.429 |
| **464H (NDT tech.)** | 1 | 1 | 3 | 2 | 7 | 5.0715 |

Figure 36: Example summation table for the capacity planning model. Each cell sums the amount of time that the specific product family requires from each occupation code. The "Daily Total" is compared to the "Current Capacity" to determine if the occupation code is over or under capacity.

Since the cells outlined in blue update automatically every time the sheet is recalculated because of the random number generators, the daily total changes with every simulated day. A macro was written to update and store the Daily Total column for 100 simulated days and then compare that to the "Current Capacity" column, noting the percentage of days that each occupation code is over capacity, as shown in Table 2. Current capacity is defined as:

$$Current\ Capacity = (Employees\ in\ this\ occupation\ code)(1 - H)(1 + J)(C - G)(\rho)$$

where $H$ is the absenteeism (%), $J$ is the overtime rate (%), $C$ is the number of hours per shift, $G$ is the length of the breaks, and ρ is the employee efficiency. Note that the model assumes employees can multi-task (load and start an oven, then continue working on another machine) while equipment cannot.

Practically, this model indicates when to increase or decrease overtime levels, borrow employees, examine the efficiency rates of different occupation codes, or get a quick understanding of how a volume and product mix combination affects the cell. As an example, Table 2 shows the screenshot results of 100 simulated days in which welders (380H) experienced capacity problems 22% of the time, while machinists (176H) encountered labor shortages 76% of the time and surface mechanics (344H) were over capacity in every one of the simulated days. These results show management which specific occupation codes would be stressed when facing a particular combination of volume and product mix.

| Occupation Code | Days Over Capacity |
|---|---|
| 176H (Machinists) | 76 |
| 344H (Surface Mech.) | 100 |
| 380H (Welders) | 22 |
| 400H (Inspectors) | 64 |
| 464H (NDT Tech.) | 97 |

Table 2: Sample results from one 100-day simulation of the manpower capacity within the Small Components Cell. Please note that these results are for illustrative purposes only.

*Chapter 4.2.3 – Model Variants*

The model also allows estimates for the capacity of the equipment of the Small Components Cell. A few changes were made to the original model to incorporate this aspect of the business. When conducting a capacity analysis for equipment, the equipment processing times were added to any employee-driven times, as described in the model assumptions above. Table 3 shows sample results from a 100-day simulation of equipment capacity for an arbitrary volume level and product mix.

| Equipment Type | % Over Capacity |
|---|---|
| Welder | 23% |
| CNC Mill #1 | 0% |
| FPI Booth | 74% |
| Furnace | 1% |
| Super-Abrasive Machine #1 | 0% |
| Drill Press #1 | 17% |
| Part Washer | 30% |
| Super-Abrasive Machine #2 | 0% |
| Weld Booth A | 3% |
| Part Marking Machine | 0% |
| CNC Mill #3 | 58% |
| CNC Mill #4 | 27% |
| CNC Mill #6 | 23% |
| Media Blast Booth #1 | 0% |
| Oven | 100% |
| Blend Booths | 1% |

Table 3: Sample results from one 100-day simulation of the equipment capacity within the Small Components Cell. Please note that these results are for illustrative purposes only and do not reflect the performance of the Small Components Cell.

The validity of the model is driven by the underlying data. In many cases, these data are inaccurate because of discrepancies between idealized theories and the actual practices employed. The "Clocked Times vs. Engineering Standard Times" assumption above is an excellent example of this. Likely the most important of the model assumptions, the difference between clocked times and engineering standard times spurs the need for two additional model variants. At times, these differences can be quite significant. Clocked times are the processing times recorded automatically by a computerized system when employees scan a barcode to record their labor hours. These times are very valuable, as they take into account the day-to-day variations that time estimates would not. However, they are subject to human errors and habits. For example, if an employee takes a break but forgets to 'punch off' a job, that break time is applied to the processing time, artificially inflating it. Similarly, if an employee batches their paperwork and clocks all the jobs at the end of a shift, labor hours are distributed evenly across all jobs, regardless of the actual processing time. As a result, some clocked values show significant differences from the engineering standard times that sprang from the time studies conducted by Pratt & Whitney. On average, clocked times are higher than engineering standard times within a range of 5% - 200% in some extreme cases.

Engineering standard times are generated by the engineering staff as an estimate of the ideal processing time needed to complete one particular operation. They are the result of time studies performed with cell employees. Just like the famous Heisenberg Principle, the very act of observing changes the observed properties. The situation is no different in aerospace overhaul, as employees may remain focused during a time study but may not maintain that pace under normal working conditions. As a result, the observation process can skew the data. It is important to capture both clocked times and engineering standard times in the models, as the differences between the two can highlight operational problems that need to be addressed by the cell leader or engineering team. A second set of models was created to take advantage of the availability of engineering standard times: one to examine manpower capacity and the other for equipment capacity. All other information in these two models is identical to the clocked time model variants. Conclusions are drawn from the engineering standard time models, as these variants remove many aspects of human error that otherwise obscure the data.

*Chapter 4.2.4 – Efficiency Rates and Implications*

While portions of the capacity inputs are obvious or contractual, such as 8 working hours per shift or 0.5 hours of permitted breaks per shift, other capacity inputs are more difficult to pin down. One example is the efficiency rate. To determine the efficiency rate for each occupation code, the model is set up to represent several months in the recent past. With known overtime rates, demand fulfillment histories, and other information, a baseline efficiency rate emerges. These efficiency rates are used in subsequent iterations to determine overall capacity under several different scenarios. It is important to note that these rates are not a comment on how 'hard' an occupation code is working but rather form a catch-all for a variety of events. For example, inspectors spend more time in meetings to review emerging regulatory quality requirements. This time is not specifically accounted for elsewhere in the model, and thus the efficiency rate appears lower for inspectors than for other occupation codes. Similarly, the NDT process lends itself to parallel work much more readily than a machinist's blending operation, which requires complete focus on that task. As a result, the types of processes affect the efficiency rate as well. Baseline efficiency rates are shown in Table 4.

| .Occupation Code | Efficiency Rate |
| --- | --- |
| 176H (Machinists) | 80% |
| 344H (Surface Mech.) | 95% |
| 380H (Welders) | 85% |
| 400H (Inspectors) | 70% |
| 464H (NDT Tech.) | 95% |

Table 4: Baseline efficiency rates specific to each occupation code. Baseline efficiency rates are developed from known performance over a period of several months, including overtime rates, demand information, and other data.

These efficiency rates have several practical applications. First, an examination of the efficiency rates gives employees a better understanding of where it is best to pursue training or part familiarization classes. For example, if the cell was experiencing bottlenecks in processes associated with surface mechanics (344H) and inspectors (400H), these efficiency rates suggest that the best solution is to engage in additional training classes for the inspectors to improve the overall efficiency. Since the efficiency rate is quite high for the surface mechanics already, additional training would provide more limited returns. Increasing overtime rates for the surface mechanics is of greater benefit in this situation. Alternatively, one could borrow a surface mechanic from another cell to relieve the bottleneck but must account for any part familiarization or additional training needed.

A second practical application of efficiency rates is the balancing of general cell responsibilities. Traditionally, fixtures and gages that require periodic recertification are tracked by several machinists (176H). In the event that a bottleneck emerges at machinist's process, these efficiency rates suggest that reallocating an inspector or a welder would effectively minimize the impact to overall productivity. Other aspects of cross-training will be discussed more thoroughly in Chapter 4.8.

*Chapter 4.2.5 – Employee Capacity Planning for Demand Changes*

With the baseline efficiency rates in hand, this chapter examines one of the most pressing concerns of resource planning: volume changes. Using the baseline efficiency rates, the following tables show the headcounts needed to meet different fractions of an average demand. The simulations are conducted at 25% intervals ranging from 50% of normal demand (an under-capacity scenario) to 200% of normal demand (over-capacity). Interestingly, both ends of the spectrum occurred during the course of the project. Please note that this chapter assumes a constant product mix, shown in Figure 37, which reflects the average product mix from 2010 – 2012. Chapter 4.2.7 discusses several scenarios with different product mixes. Chapters 4.2.5, 4.2.6, and 4.2.7 also assume that additional employees can be temporarily borrowed from neighboring cells or that idle capacity can be loaned to other cells. This assumption is in line with actual practices. The following figures and table reflect how the capacity planning model can be used to predict the resources needed under certain volumes. These data show that the team is appropriately sized for the average volume of work and provide insight on how the team size can be temporarily adjusted to optimize the cell's capacity.

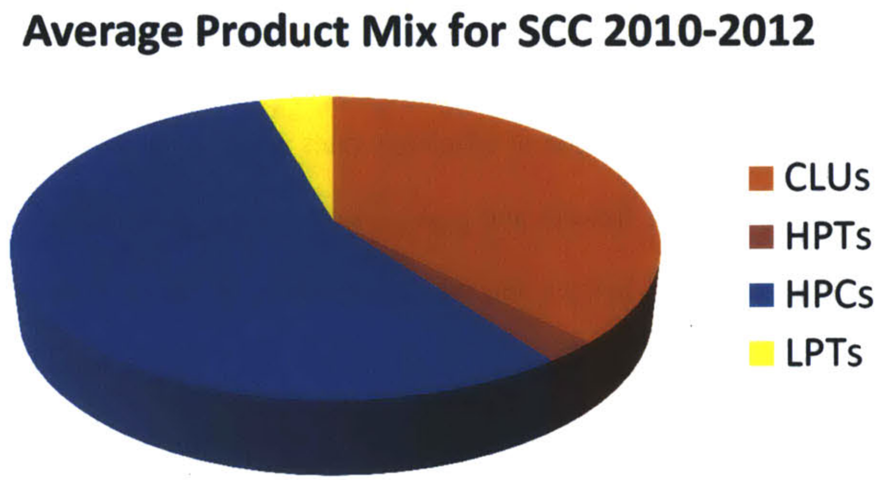



Figure 37: Ratios of the work volume of the Small Components Cell by part family.

| | Fraction of Average Demand (D) | | | | | | |
|---|---|---|---|---|---|---|---|
| **Occupation Codes** | **0.5D** | **0.75D** | **1D** | **1.25D** | **1.50D** | **1.75D** | **2.00D** |
| 176H (Machinists) | 63% | 88% | 100% | 100% | 125% | 138% | 150% |
| 344H (Surface Mech.) | 100% | 100% | 100% | 200% | 250% | 250% | 300% |
| 380H (Welders) | 66% | 100% | 100% | 133% | 133% | 133% | 133% |
| 400H (Inspectors) | 66% | 83% | 100% | 125% | 150% | 166% | 183% |
| 464H (NDT Tech.) | 100% | 100% | 100% | 200% | 200% | 300% | 300% |
| **Total** | **70%** | **90%** | **100%** | **130%** | **150%** | **165%** | **180%** |

Table 5: Required headcount vs. demand. Each row reflects the percentage of the current team size needed to complete the corresponding amount of work. For example, if demand is only 75% of the average demand, the cell needs 90% of the current team, including 88% of the current number of machinists, 100% of the surface mechanics, welders, and NDT technicians, and 83% of the inspectors. There are 8 machinists, 2 surface mechanics, 3 welders, 6 inspectors, and 1 NDT technician in the Small Components Cell at 1D.

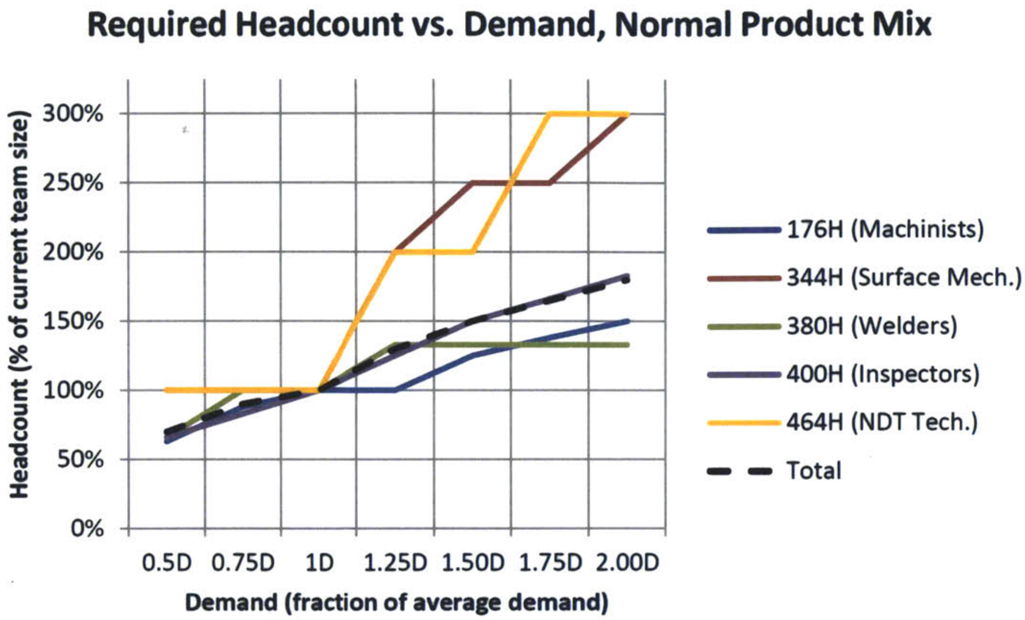



Figure 38: A graphical representation of Table 5. Required headcount vs. demand. Each line reflects the percentage of the current team size needed to complete the corresponding amount of work for that occupation code. For example, if demand is 125% of the average demand, the cell needs 130% of the current team, including 100% of the current number of machinists, 200% of the surface mechanics and NDT technicians, 133% of the welders, and 125% of the inspectors.

*Chapter 4.2.6 – Equipment Capacity Planning for Demand Changes*

A similar analysis exists with the equipment of the Small Components Cell. To obscure the capabilities of the machines, the capacity analysis for equipment over changing volumes will be limited to an oven and a welding machine. The oven represents equipment that can be run without an employee present, while the welder requires continuous employee interaction. As a result, the oven is capacity limited by the length of the oven runs rather than the available man-hours of the employees. In contrast, the welder is constrained by the presence of an employee.

This equipment capacity information is crucial for floor planning, as it points out any additional pieces of equipment needed in situations with varying demand. While employee capacity data is similarly useful when planning floor layouts, the constraints associated with borrowed employees who need access to the same machines can be partially (if not fully) alleviated through adjustments to starting and ending shift times and overtime. Throughout Chapters 4.2.5 and 4.2.6, responses to increasing or decreasing demand appear to be in line with expectations. As overall demand increases, the amount of labor increases in a very similar manner. The equipment responses are extensions of the same pattern, though the differences in the overall demand on the equipment result from certain part families using certain pieces of equipment more frequently.

| | Fraction of Average Demand (D) | | | | | | |
|---|---|---|---|---|---|---|---|
| **Equipment** | **0.5D** | **0.75D** | **1D** | **1.25D** | **1.50D** | **1.75D** | **2.00D** |
| Oven | 77% | 83% | 91% | 100% | 100% | 98% | 100% |
| Welder | 0% | 12% | 29% | 33% | 38% | 42% | 43% |
| **Additional Pieces of Equipment Needed to Meet Demand** | | | | | | | |
| **Equipment** | **0.5D** | **0.75D** | **1D** | **1.25D** | **1.50D** | **1.75D** | **2.00D** |
| Oven | - | - | 1 | 1 | 1 | 2 | 2 |
| Welder | - | - | - | - | - | - | - |

Table 6: Machine over-capacity percentage vs. changing demand. Each row reflects the percentage of time that the equipment is over capacity in the face of the corresponding amount of work. For example, if demand is 125% of the average demand, the welding machine has capacity issues 1 of every 3 working days, while the oven is already over capacity.

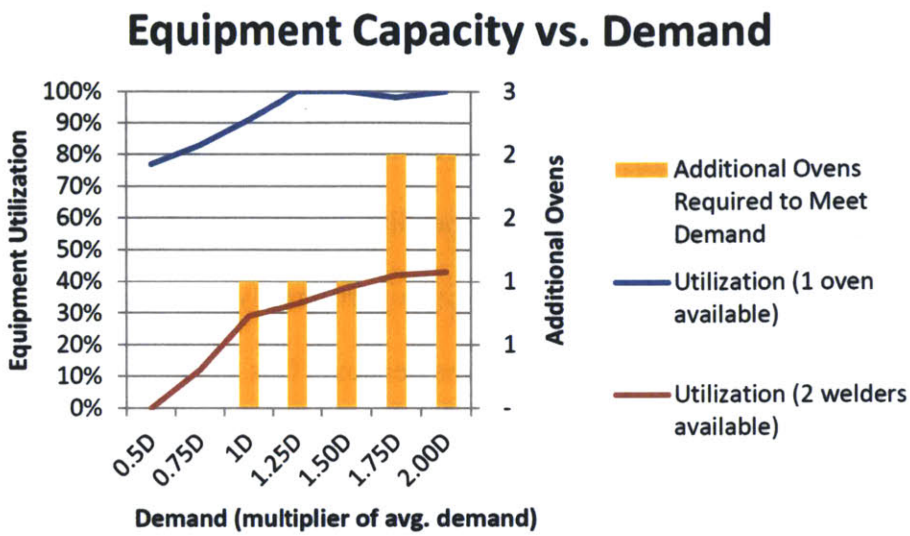



Figure 39: A graphical representation of Table 6Table 6. Equipment capacity vs. demand. Each line reflects the percentage of the time that the equipment experiences capacity issues for the corresponding level of demand. For example, in a situation with only 50% of average demand, the welder never is never over capacity, but the oven utilization approaches 80% . The chart also notes the number of additional ovens that will be required to reliably meet demand (by bringing utilization to the 70%-80% range to significantly reduce queuing).

The capacity planning model is also helpful in determining effective routes to train employees, distribution of general work through the cell, and selecting appropriate times to request support from neighboring cells. In the case of equipment capacity planning, the model is useful for identifying bottlenecks that are driven by equipment processing times, such as the oven mentioned above. This information was used during the course of the project as a part of a business case leading to the purchase of additional oven capacity. While these past chapters focus on the challenging effects of additional demand, the following chapters describe the disruptive effects that variations in product mix have on the cell's capacity.

*Chapter 4.2.7 – Capacity Planning for Variations in Product Mix*

Variability in demand is far from the only driver of capacity issues. One of the more subtle concerns is caused by changes in product mix, the ratio of parts arriving for repair from the customer. Of the four part families described in Chapter 2.4.1, low pressure turbine (LPT) components require particularly manually-intensive repairs. Furthermore, LPT orders tend to arrive in larger quantities than the other three part families. As shown in Figure 14 in Chapter 2.4.1, LPT components have a rather thin metallic structure, making them more susceptible to cracking and fatigue issues. As a result, a disproportionately high fraction of LPT repair work requires significantly more time for the same demand. This situation occurred during the later months of the project, and is represented by the differences between Figure 40 and Figure 41.

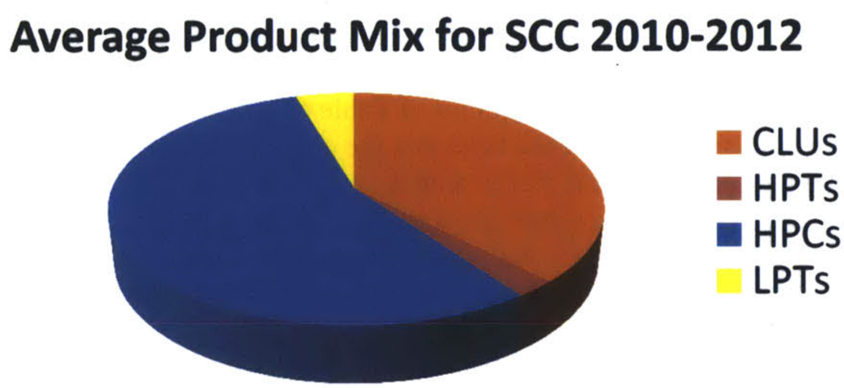



Figure 40: Ratios of the average product mix of the Small Components Cell by part family from 2010 - 2012.

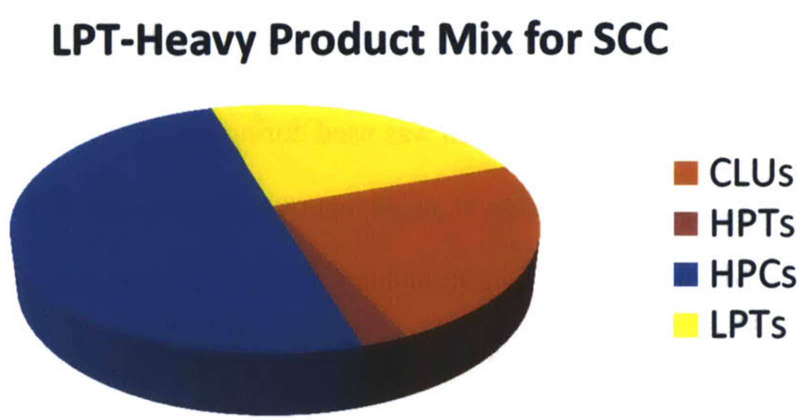



Figure 41: LPT-heavy product mix of the Small Components Cell by part family during the final three months of the project. During that time, the cell received an abnormally high number of LPT orders.

I failed to respond appropriately to this change in product mix and did not accommodate the higher labor content of the LPTs. Instead, capacity planning and overtime decisions were made based on the number of orders in the cell. Additional impacts because of queuing are discussed in Chapter 4.6.1. As noted in Chapter 5.3, this delay is reflected in a significant impact to on-time delivery. The months following this shift in demand see large spikes in overtime rates as the cell struggles to recover.

| | **Fraction of Average Demand (D), LPT-Heavy Case** | | | | | | |
|---|---|---|---|---|---|---|---|
| **Occupation Codes** | **0.5D** | **0.75D** | **1D** | **1.25D** | **1.50D** | **1.75D** | **2.00D** |
| 176H (Machinists) | 88% | 125% | 150% | 163% | 188% | 200% | 213% |
| 344H (Surface Mech.) | 150% | 200% | 250% | 300% | 300% | 350% | 350% |
| 380H (Welders) | 66% | 66% | 100% | 100% | 133% | 133% | 133% |
| 400H (Inspectors) | 83% | 117% | 133% | 166% | 183% | 183% | 200% |
| 464H (NDT Tech.) | 100% | 200% | 200% | 200% | 300% | 300% | 300% |
| **Total** | **90%** | **125%** | **150%** | **170%** | **195%** | **205%** | **215%** |

Table 7: Required headcount vs. demand for an LPT-heavy product mix. Each row reflects the percentage of the current team size needed to complete the corresponding amount of work. For example, if demand is only 75% of the average demand, the cell needs 125% of the current team, including 125% of the current number of machinists, 200% of the surface mechanics and NDT technicians, 66% of the welders, and 117% of the inspectors.

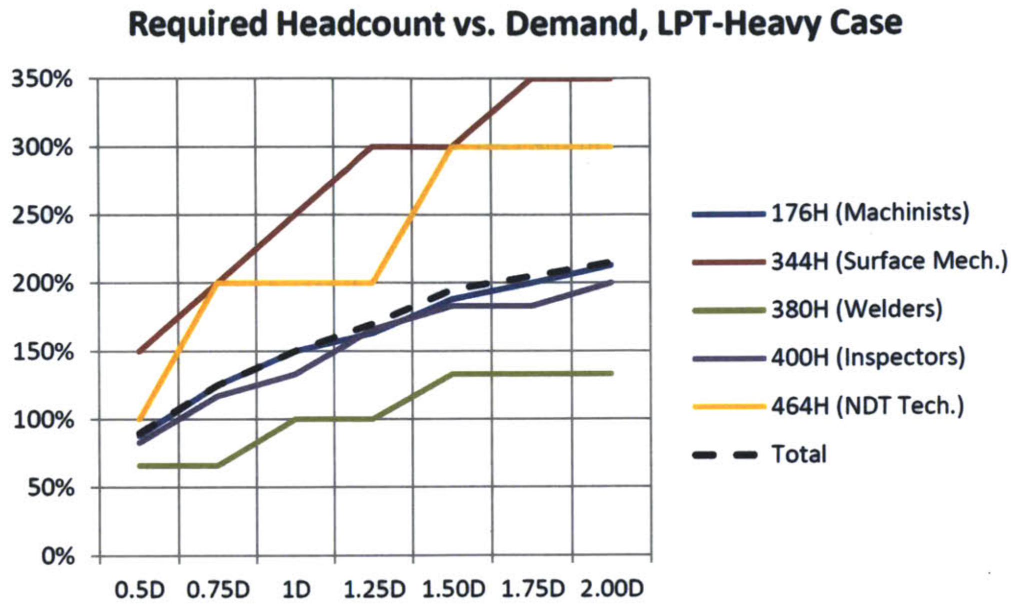



Figure 42: A graphical representation of Table 7. Required headcount vs. demand. Each line reflects the percentage of the current team size needed to complete the corresponding amount of work for that occupation code. For example, if demand is 150% of the average demand, the cell needs nearly 200% of the current team, including 188% of the current number of machinists, 300% of the surface mechanics and NDT technicians, 133% of the welders, and 183% of the inspectors. Note that demand on the machinists is much heavier than corresponding demand levels in Figure 38.

This chapter describes the importance of capacity planning for a mixed-model cell along with several practical applications of the simulation. Specific analytical examples focus on capacity planning in terms of employee headcount and machine availability over a variety of demand cases. Demand may appear to be at or even below the nominal capacity of the cell, but the influence of the product mix requires additional resources. This is borne out by the data in Table 7 and Figure 42, showing that even at 75% or 100% of LPT-heavy demand, the actual resources required to effectively complete the work ranges from 125% of the normal headcount to 150% of the normal headcount. This scenario can devastate the business metrics of the cell.

Chapter 4.3 conducts a case study to determine the most effective means of increasing capacity in the cell. Chapters 4.4 through 4.7 describe the floor plan options for the Small

Components Cell, the project timeframe and logistical considerations, and the reasoning behind the final selections. Chapter 4.8 discusses the cross-training plan which was partially implemented during the course of the project.

### Chapter 4.3 – Capacity Planning Design of Experiment

Adjusting the cell's headcount and available equipment according to the demand and product mix is a crucial component of effectively managing the business. We can gain more information from the model, though. This chapter analyzes the cell's manpower capacity by designing an experiment with four variables based on the capacity planning model's data. The four variables are the length of breaks taken during the day, the employee efficiency (termed 'utilization' in the charts below), the absenteeism rate, and the overtime rate. Management affects employee efficiency and overtime directly by assigning employee training opportunities and adjusting the overtime rate. Breaks and absenteeism are directly influenced through adherence to the policies of the contract between the company and the union. With this information, management can directly answer questions including, 'Which method is a more effective means of increasing capacity: overtime or training?' and 'What are the capacity effects of absenteeism and breaks?'

The model uses data from the inspectors (400H), as the inspectors normally do not rely on significant pieces of equipment in the cell, thus removing the chance of incorporating a complicating factor. Please note that this discussion is focused *solely* on the most effective means of increasing capacity within the Small Components Cell and does not conduct a cost-benefit analysis of these options. The experimental results of a $3^4$ experimental design show that training employees is the most effective course of improving the cell's capacity, followed by reducing absenteeism, increasing overtime, and enforcing contractual restrictions on additional, unscheduled breaks. The following chapters describe the experimental procedure before discussing the results and accompanying conclusions in additional detail.

*Chapter 4.3.1 – Procedure Summary*

The design of experiment follows the summary steps below.

1. Conduct a full-factorial $2^4$ experiment with five replicates. However, only first- and second-order terms are included in the resulting model to save time. Patterns in the residuals suggest higher-order terms are important.
2. Noting a significant lack-of-fit term, conduct a full-factorial $2^4$ experiment, showing several active effects.
3. As $2^4$ experiments do not account for higher-order terms, centerpoints are tested to determine if curvature in the response surface is significant. Curvature is found to be highly significant, indicating the need for a $3^k$-style model.
4. A $3^4$ experiment with five replicates is run. Model fit is good, and the residuals do not show unexpected behaviors.
5. A predictive model is created based on the full-factorial $3^4$ experimental data:

$$\begin{aligned} Capacity = {} & -0.510 + 0.324\rho + 0.131J - 0.155H - 0.108G - 0.024\rho H + 0.019\rho J \\ & - 0.012\rho G - 0.053\rho GH + 0.052\rho HJ + 0.037\rho GJ - 0.014GHJ \end{aligned}$$

where a change in capacity is a percentage increase or decrease of the current capacity, ρ is the utilization (efficiency) of the employees or equipment, *G* is the length of breaks in hours, *H* is the absenteeism rate (%), and *J* is the overtime rate (%).

*Chapter 4.3.2 – Experimental Data and Results*

As noted in Chapter 4.2.1, the data underlying any model are extremely important. In this case, the data are created using the same Excel-based model as described in Chapter 4.2. Inputs are defined by setting the low level and the high level around the normal operating range of the cell. For example, if absenteeism is normally at 9%, the low level is set at 0% and the high level is set at 18%. The data shown here have been disguised to obscure any company-sensitive information yet still reflect accurate trends. Each individual point is the average fraction of 100 days that the inspectors are *over-capacity*. Thus, lower fractions indicate that the inspectors are able to meet demand more effectively while higher fractions suggest that the inspectors require assistance. Each experimental setting consists of five replicates of this measurement. In other words, each trial represents 500 simulated days. The $2^4$ experiment contains 8,000 simulated days. JMP10 generates the reports.

Initial experimentation examines a $2^4$ scenario with the three- and four-term interactions removed, based on the sparsity of effects principle: "the system is usually dominated by the main effects and low-level interactions. Three-factor and higher interactions are usually negligible" (Montgomery, 2005), pp. 585. Although the R-squared and adjusted R-squared values are quite good, the residuals show a distinctly increasing trend (Figure 44). This suggests that the third- and fourth-order terms in the model cannot be eliminated. Several first- and second-order terms are found to be statistically significant, as shown in the normal plot in Figure 43. The greater the input's distance from the red line, the greater the effect on the behavior of the system. Other results of this run are shown below in Table 8 and Figure 44.

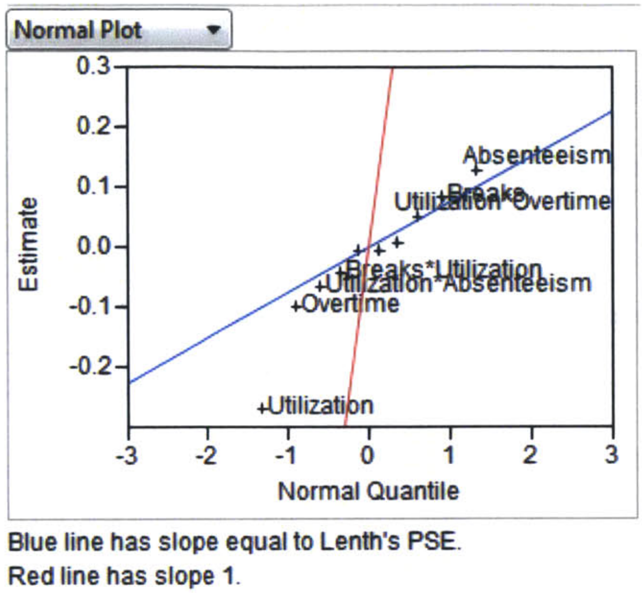



Figure 43: Normal plot of the results of the sparsity of effects experiment. Note that several of the first-order (Utilization, Absenteeism) and second-order terms (Utilization*Absenteeism) appear significant.

| | **$2^4$ Sparsity of Effects Experiment** |
|---|---|
| **R-Squared** | 0.956778 |
| **Adjusted R-Squared** | 0.950513 |
| **Mean Response** | 0.328125 |
| **Number of Observations** | 80 (8,000 simulated days) |

Table 8: Indications of fit for the $2^4$ sparsity of effects experiment. Note that the R-squared and adjusted R-squared values indicate the fit is quite good.

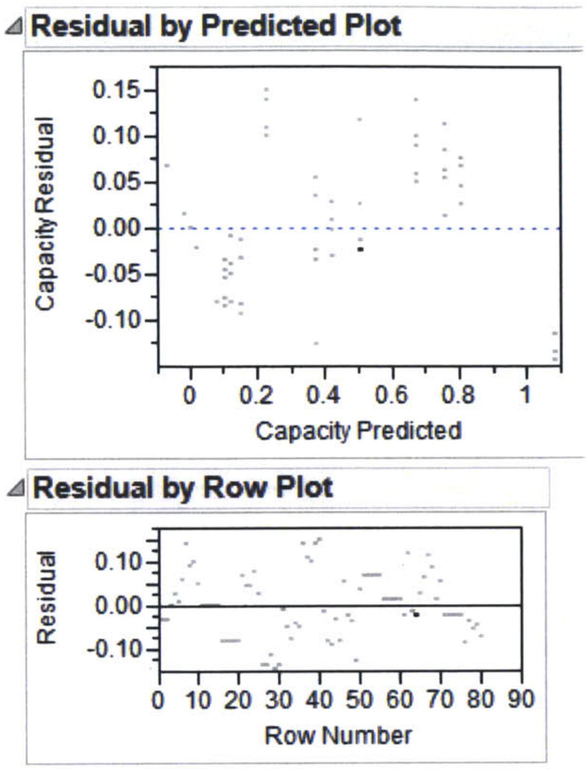
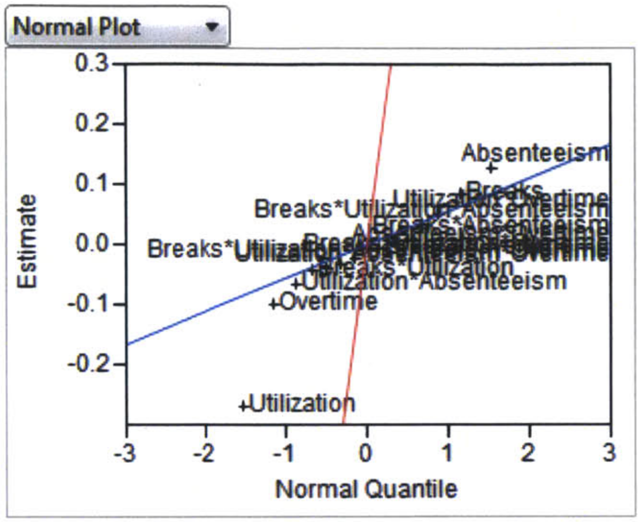



Figure 44: Residual plots of the $2^4$ sparsity of effects experiment. The residuals by row do not show any specific pattern, but the increasing trends shown in the upper "Residual by Predicted" graph show that the terms in the model are not accurately reflecting the system's actual performance. These graphs are automatically generated by JMP10.

Based on the results of the sparsity of effects experiment above, third- and fourth-order terms are included in a second experiment. The fit of the model improves, as shown by the R-squared and adjusted R-squared values, and the troubling patterns in the residuals are resolved, as reflected in Table 9 and Figure 46. Note that the normal plot in Figure 45 shows similar information as the sparsity of effects experiment. The first-order effects continue to be the most significant, but some third-order effects are statistically important as well.




Blue line has slope equal to Lenth's PSE.
Red line has slope 1.

Figure 45: Normal plot of the $2^4$ experiment with all higher order terms. The overall trends hold from the sparsity of effects experiment, but several third-order terms are found to be statistically significant.

| | $2^4$ Experiment with Higher Order |
|---|---|
| **R-Squared** | 0.993598 |
| **Adjusted R-Squared** | 0.992098 |
| **Mean Response** | 0.328125 |
| **Number of Observations** | 80 (8,000 simulated days) |

Table 9: Indications of fit for the $2^4$ experiment with higher order terms included. Note that the R-squared and adjusted R-squared values are improved over the sparsity of effects experiment.

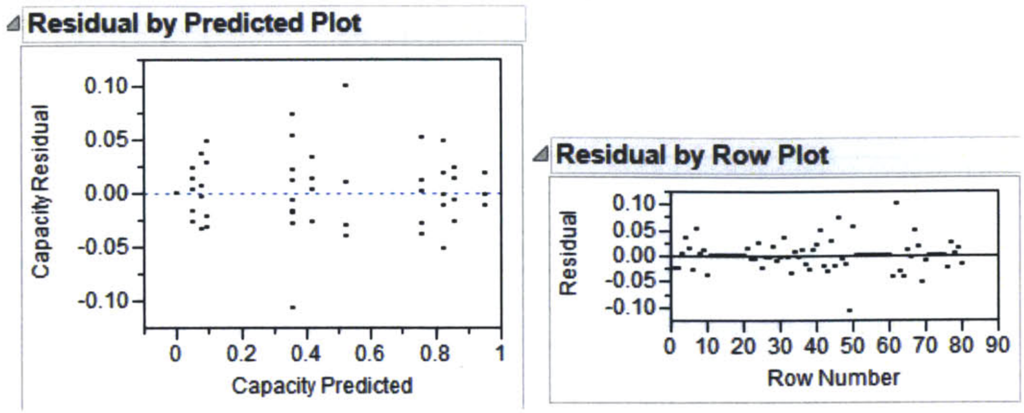



Figure 46: Residual plots of the $2^4$ experiment, including higher order terms. The patterns in the residuals are gone, indicating that the model more accurately represents the system's behavior.

Rapid testing and low experimental costs are major advantages of the $2^k$ experimental structure because of the lower number of trials involved. However, this structure assumes linearity throughout the response region. Montgomery notes that this linearity assumption is somewhat mitigated through the inclusion of interaction terms, but this may not account for all the curvature in the response (pp. 589). Unfortunately, the only way that curvature can be fully examined is through the use of a $3^k$ experimental design. With four variables, this increases the number of experiments from 16 to 81. Including the replicates, the $3^4$ experimental design demands 405 trials (40,500 simulated days) rather than 80 trials (8,000 simulated days).

In this situation, research is conducted without a unit-time cost to Pratt & Whitney and is based on data generated by a simulator, reducing the cost impact. Thus, the $3^4$ experimental structure is palatable in this case, but may not be as feasible in other circumstances. Therefore, the next experimental step uses centerpoints to determine if the curvature is significant before proceeding to a full $3^4$ structure. 10 replicates of a centerpoint allow the curvature to be calculated. As shown in the tables and figures below, the model fit is in-line with previous experiments, but a significant curvature term and the increase in the response mean vs. previous iterations suggest that the curvature is an important aspect of the system.

| | $2^4$ Experiment with Centerpoints |
|---|---|
| **R-Squared** | 0.960901 |
| **Adjusted R-Squared** | 0.952976 |
| **Mean Response** | 0.348222 |
| **Number of Observations** | 90 (9,000 simulated days) |

Table 10: Indications of fit for the $2^4$ experiment with centerpoints included. Note the shift in the mean response, suggesting that the centerpoints do not fall linearly within the response.

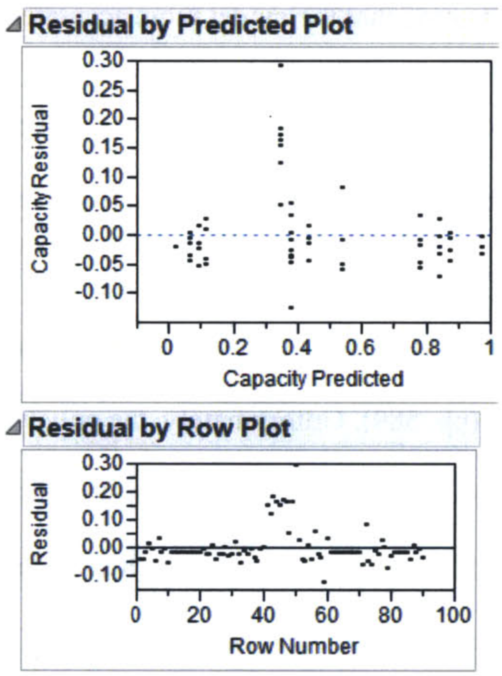



Figure 47: Residual plots of the $2^4$ centerpoint experiment. The patterns in the residuals suggest that there are curvature effects that are being neglected by the $2^4$ experimental design.

Because of the indications of curvature shown in the $2^4$ experimental model with centerpoints, a $3^4$ setup was created. Please note that in many instances, this approach could be prohibitively costly, requiring a significant amount of time to generate the necessary data. In this case, the data could be created from the simulator over a period of several hours rather than days or weeks. In the event that the experiment requires extensive setup costs or labor costs, it would be more effective to examine the uses of fractional factorial experiments such as a $3^{4-1}$ or another structure, keeping in mind that blocking and confounding could obscure some of the higher order terms, depending on how the experiment is structured (Montgomery, 2005).

The results of the $3^4$ experiment are shown below. Note that model fit is quite good and that there has been a shift in the mean response value, indicating that the higher order experiment is warranted to thoroughly understand the behavior of the system.

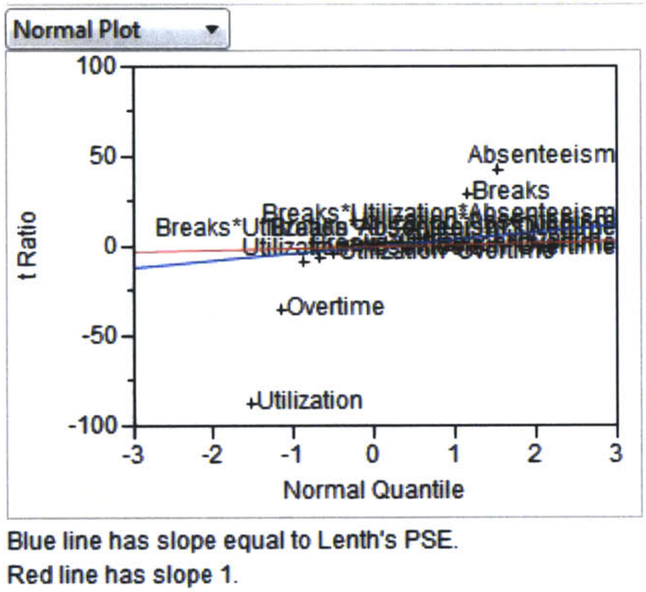



Figure 48: Normal plot of the results of the $3^4$ experiment. Note that the first-order terms (Utilization, Absenteeism, Overtime, and Breaks) dominate the system response compared to the higher order terms, though several second- and third-order effects are significant.

| | $3^4$ Full-Factorial Experiment |
|---|---|
| **R-Squared** | 0.968023 |
| **Adjusted R-Squared** | 0.966875 |
| **Mean Response** | 0.510148 |
| **Number of Observations** | 405 (40,500 simulated days) |

Table 11: Indications of fit for the $3^4$ full-factorial experiment.

The governing equation is

$$Capacity = -0.510 + 0.324\rho + 0.131J - 0.155H - 0.108G - 0.024\rho H + 0.019\rho J - 0.012\rho G - 0.053\rho GH + 0.052\rho HJ + 0.037\rho GJ - 0.014GHJ$$

where a change in capacity is a percentage increase or decrease of the current capacity, ρ is the utilization (efficiency) of the employees or equipment, $G$ is the length of breaks in hours, $H$ is the absenteeism rate (%), and $J$ is the overtime rate (%).

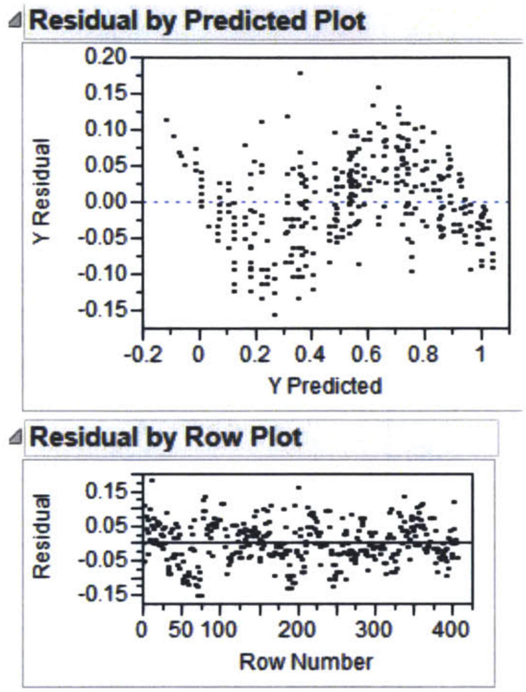



Figure 49: Residual plots of the $3^4$ full-factorial experiment. The residuals do not show any specific pattern, indicating good model prediction of the data.

**Sorted Parameter Estimates**

| Term | Estimate | Std Error | t Ratio | Prob>\|t\| |
|---|---|---|---|---|
| Utilization | -0.324333 | 0.003703 | -87.58 | <.0001* |
| Absenteeism | 0.1547407 | 0.003703 | 41.79 | <.0001* |
| Overtime | -0.13137 | 0.003703 | -35.48 | <.0001* |
| Breaks | 0.108 | 0.003703 | 29.16 | <.0001* |
| Breaks*Utilization*Absenteeism | 0.0525833 | 0.005555 | 9.47 | <.0001* |
| Utilization*Absenteeism*Overtime | -0.0515 | 0.005555 | -9.27 | <.0001* |
| Breaks*Utilization*Overtime | -0.03725 | 0.005555 | -6.71 | <.0001* |
| Utilization*Absenteeism | 0.0243333 | 0.004535 | 5.37 | <.0001* |
| Utilization*Overtime | -0.018722 | 0.004535 | -4.13 | <.0001* |
| Breaks*Utilization | 0.0116111 | 0.004535 | 2.56 | 0.0108* |
| Breaks*Absenteeism*Overtime | 0.0139167 | 0.005555 | 2.51 | 0.0126* |
| Breaks*Overtime | 0.0043889 | 0.004535 | 0.97 | 0.3338 |
| Breaks*Absenteeism | -0.002278 | 0.004535 | -0.50 | 0.6158 |
| Absenteeism*Overtime | -0.001222 | 0.004535 | -0.27 | 0.7877 |

Figure 50: Parameter estimates of the $3^4$ full-factorial experiment, sorted by statistical significance. This figure shows that Utilization, Absenteeism, Overtime, and Breaks are the most important factors, in descending order. Terms without an asterisk next to their probability on the far right are not statistically significant factors.

*Chapter 4.3.3 – Conclusions of the Design of Experiment*

This chapter examines the procedural steps taken to develop a model representation of the inspectors' capacity in the Small Components Cell. Based on this information, the management team is now able to prioritize future options to increase capacity levels. The most critical factors, in descending order of importance, are employee efficiency (utilization), absenteeism, overtime, and break duration. The next step is to combine this information with relevant estimates of the cost of training, the challenges of enforcing attendance and break rules, and a comparison of the sales generated with overtime vs. the costs of overtime. Synthesizing these different facets of the business will transform the model from useful a theoretical compass into a more practical tool to guide managerial decisions for both the short- and long-terms.

Regarding long-term initiatives sparked by this DOE, management can target training initiatives to increase inspection capacity within the Small Components Cell. Targeting positive and negative incentives to reduce absenteeism and limit the number and duration of unapproved breaks will also serve to improve capacity at a minimum of cost. However, this approach must be carefully implemented, as inconsistent enforcement of existing policies across organizations is one of the concerns that employees most frequently mention (Anonymous, Personal Interview with SCC Employee, 2012). Similarly, adjusting overtime policies must also be done delicately. As shown in Figures 24 and 25 of Chapter 3.1.2, employees are accustomed to a certain level of overtime and have begun budgeting for that level. Communicating the expected level of overtime based on the demand and product mix is a vital facet of appropriately setting overtime levels without generating backlash. Chapter 6 discusses these recommendations in greater detail.

### Chapter 4.4 – Process Analysis and the Shared Services Area

With a better understanding of the manpower and equipment requirements resulting from the capacity planning analysis in Chapter 4.2, the project now focuses on developing and implementing the layout of the cell itself in Chapters 4.4 through 4.6. Figure 51 shows the floor layout of the Small Components Cell before the project began.

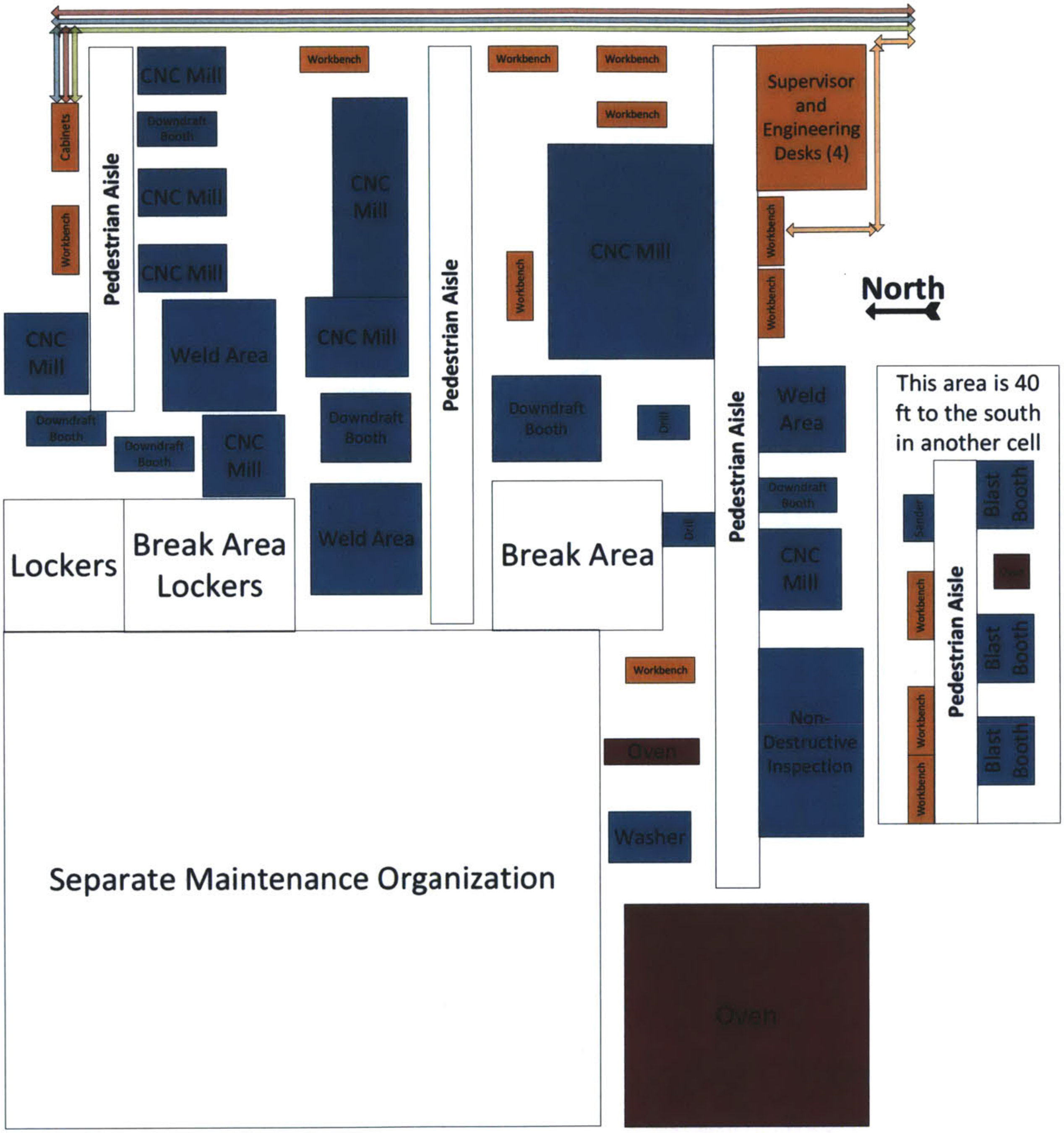



Figure 51: Floor plan of the Small Components Cell prior to the start of the project. Arrows indicate the arrival paths of the four different part families. Blue equipment involves the use of powered machinery; gold stations involve hand tools only, while ovens are shown in red. All equipment requiring CNC capabilities are labeled as such. The cell is roughly 100 ft. (north-south) by 130 ft. (east-west). Please note these dimensions do not include the boxed area on the right side of the figure, which is another 40 ft. to the south.

Two years prior to this project, a mixed group of engineers and shop floor employees examined possible floor plans. Seven different floor plans were created, which were updated and considered for the cell layout during the early stages of this project. As Asef-Vaziri points out, job shops are better suited to "low volume, high variety customized products," with "jumbled workflows, high material handling, long flow time[s], [and a] high cost per unit of production" (Asef-Vaziri, 2011). Although a job shop's structural flexibility likely serves a custom products manufacturer or a research and development group, it is ill-suited to the type of high-volume overhaul work that the Small Components Cell conducts. The transition to a flow line has several advantages, including "high [process] standardization, low [levels of] material handling, and low flow unit processing cost[s]" (Asef-Vaziri, 2011). Ultimately, the decision to move toward a cellular design is driven by the same motives that Karmarkar, et al expressed in their capacity analysis of a manufacturing cell. As the authors noted, "[there are] gains from selecting items that have similar routes, similar processing operations, and similar equipment or resource needs. This is the basic idea behind group technology that results in the reduction of travel times and the reduction of setups due to the similarity in the processing characteristics of the items" (Karmarkar, Kekre, & Kekre), pp166.

As the layout selection process began, the team started with an analysis of the process similarities between the various part families. Two important conclusions developed from this analysis. The first conclusion reveals time savings resulting from grouping different part families based on commonalities. Part travel is minimized distances and equipment is organized more effectively because of this arrangement. Table 12 quantifies those commonalities and establishes the rationale for the different groupings. HPCs share the most similar process paths with LPTs and CLUs have a similar flow path to HPTs.

**Comparison of Part Family Processes**

| | | LPT | CLU | HPT |
|---|---|---|---|---|
| Part Families | HPC | 70.3% | 27.1% | 27.9% |
| | LPT | N/A | 27.9% | 40.0% |
| | CLU | | N/A | 48.6% |
| | HPT | | | N/A |

Table 12: Comparison of the similarities between part families' repair processes. For example, the HPCs share 27.1% of the same processes as the CLUs.

With these data, the team developed two U-shaped flow lines in the Small Components Cell, with the HPC/LPT product families in one line and the CLU/HPT families in the other. Analyses of the time savings which result from these pairings are found in Chapter 4.7.

The second conclusion resulting from the process analysis is that many part families share a similar path through several shared resources, including the ovens, non-destructive inspection, blast booths, and the washer. It is cost-prohibitive to order enough equipment to have an uninterrupted line with no flow reversals. To reduce the amount of part travel, the team examined a shared services area through which all parts would travel. An example layout of one version of the shared services area is shown in Figure 52.

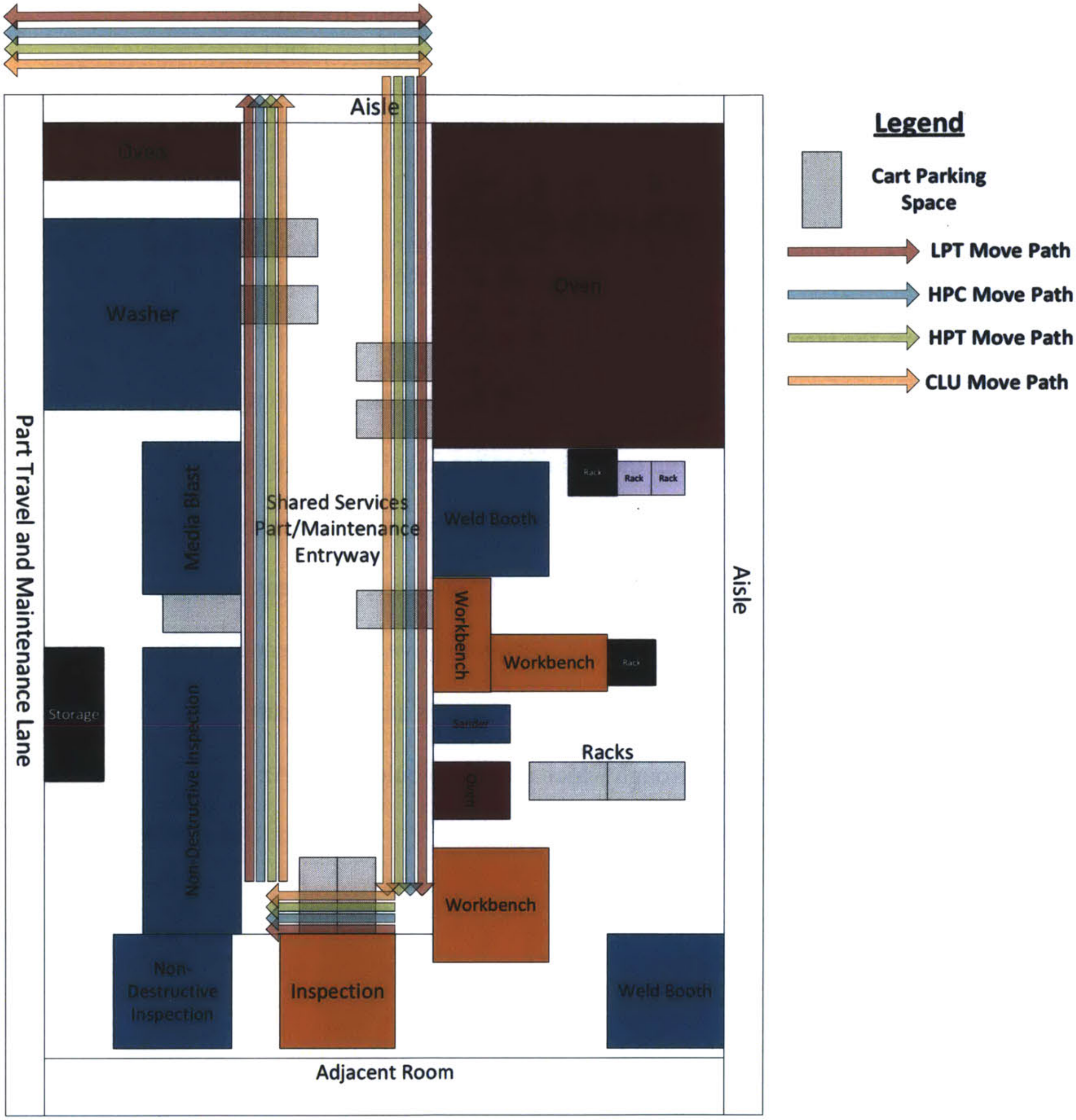



Figure 52: Proposed layout for the shared services area.

This shared services area would form the south-west corner of the cell and operate as a semi-independent area, balancing its own inventory. However, the team raised several concerns with this concept, including the difficulty of effectively maintaining proper inventory levels within the shared services area. Additional issues focus on the lack of effective lines of sight, a common industry concern. Motwani notes "One of the key elements of [lean manufacturing] is the utilization of visual controls for better monitoring process control. The company's management viewed visual controls as communication devices that allowed them to view processes, identify problems, and make improvements" (Motwani, 2003). Because of the visual obstructions created by the equipment, it is difficult to determine if a bottleneck exists and which additional resources are needed to re-establish flow. This situation developed in a neighboring cell and the team believes it can be avoided in the Small Components Cell by eliminating the shared services concept. Removing the shared services area also prevents unnecessary queue time resulting from misplaced parts. Finally, the separate shared services area presents an ideal opportunity to covertly rework parts. Completing the work in a linear or U-shaped line immediately highlights problem parts that require a flow reversal. This approach allows problems to be identified and resolved more promptly than the first.

Following the process analysis and subsequent discussions regarding the shared services area, the floor plan in Figure 53 is the new layout of the Small Components Cell. The next chapters review preparations to physically move almost every piece of equipment in the cell and the development of a project timeframe.

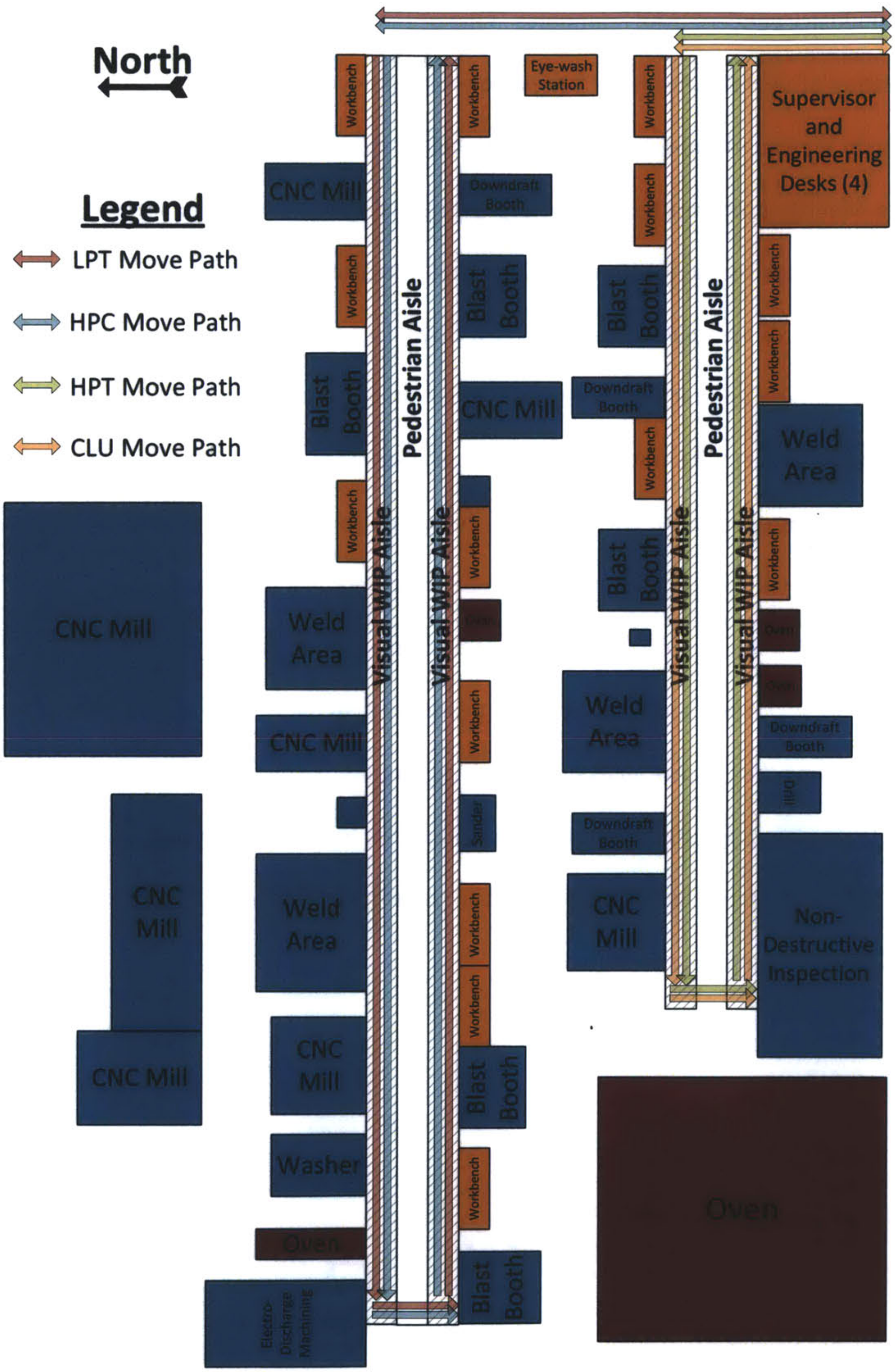



Figure 53: New floor plan of the Small Components Cell. Arrows indicate the arrival paths of the four different part families. Blue equipment involves the use of powered machinery;

gold stations involve hand tools only, while ovens are shown in red. CNC equipment is labeled accordingly.

### Chapter 4.5 – Planning Considerations and Constraints

This chapter briefly describes preparations for the equipment relocation. There are several important restrictions and considerations described below:

- **Shift Planning**: The Small Components Cell is a first-shift only operation. The original plan for the equipment move involved second and third shift work only to reduce production impacts. Machines would be in operation during first shift but utility disconnections, the physical move, and reconnections would occur on second and third shifts. However, it creates additional costs because of second and third shift payroll premiums. As a result, all restructuring was completed on first shift.
- **Inter-organizational Communication**: Three different organizations are responsible for moving equipment. The process is outlined in Figure 54 below, with a different color representing the each organization. As a result, there are several chances that work will come to a standstill as the result of missed communication. First shift work minimizes the likelihood of these problems.
- **Equipment Certification**: After moving equipment, a certification group ensures that machines are capable of holding their designed tolerances and that the CNC programs are still accurate. In some cases, only an outside vendor can perform the tasks. With lead times of several weeks, these machines were flagged for specific move times to accommodate the vendors' schedules.
- **Utilities**: Within the Small Components Cell, all utilities are routed along the ceiling of the building, permitting easy equipment relocation. Because of this

structure, certain equipment could actually have components removed to save floor space and machine complexity. This flexibility enables more effective placement of several pieces of equipment.

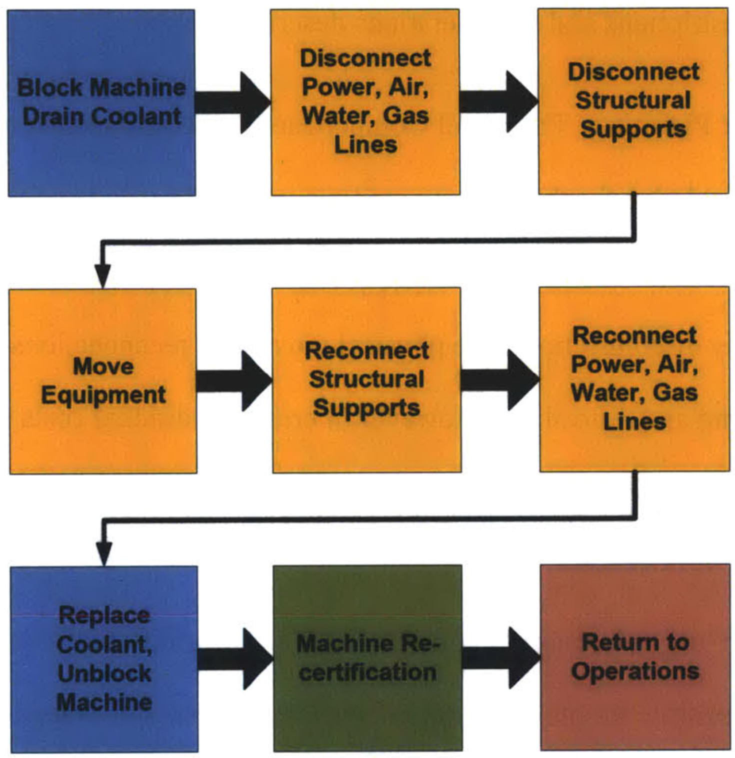



Figure 54: Process flow for a machine move. Each color indicates a different group is responsible for performing the work. Transitions between groups frequently need additional attention to prevent the equipment from sitting idle.

**Chapter 4.6 – Master Schedule**

Figure 55 shows the overall schedule, though it is important to note that there were several other key schedule milestones during the course of the project. The first milestone was the project kickoff meeting in early June, when the Operations Manager and General Manager spoke about the project's scope and intent. The second major milestone was the approval of the floor plan by the General Manager in late July. Only with this approval could the project move forward with equipment relocations and an official budget. The final milestone was a project report out in mid-December.

The schedule flows through various levels of learning. June through August focus on developing an understanding of the repair processes, creating the floor plans, and conducting the capacity planning analysis from Chapter 4.2. September through December center on the implementation of the project, data collection, and the management of cell operations. While there were several schedules with significantly more detail, much of the information is considered company proprietary.

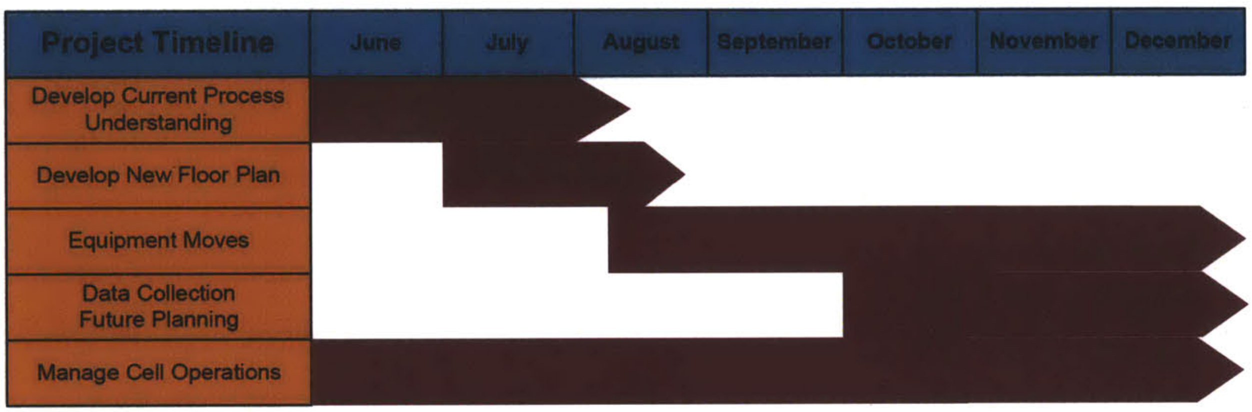



Figure 55: Overview of the project schedule.

**Chapter 4.7 – Manufacturing Lines #1 and #2**

As discussed in Chapter 4.4, the creation of two U-shaped lines stems from several factors, including an analysis of the processing similarities between the part families and a desire to easily identify capacity concerns through visual tracking of parts. However, there are several other qualitative and quantifiable benefits to the final floor plan as well. Chapters 4.7.1 and 4.7.2 describe queuing challenges and ways in which the two U-shaped manufacturing lines will improve on-time delivery performance. Chapter 4.7.1 focuses on the importance of improved lines-of-sight and WIP management while Chapter 4.7.2 discusses reductions in queuing through behavioral and physical changes resulting from the restructuring of the Small Components Cell.

*Chapter 4.7.1 – Small Components Cell Queuing: Capacity and Product Mix*

Many customers of the Small Components Cell are internationally based and thus ship large quantities of parts in a single container because of high shipping costs. A recommendation in Chapter 6 discusses a possible change to this situation. As a result, queues frequently develop in the cell. This chapter examines the development of queues through classical queuing theory, as well as queues which develop from increasing demand or changes in product mix. The queues that develop significantly reduce the Small Component Cell's ability to deliver parts on time. A rapid response is crucial to reducing the impact of queuing and irregular receipts of parts. The two U-shaped manufacturing lines allow for a much more rapid understanding of the current levels of WIP and thus an increased ability to answer effectively.

The Small Components Cell is a chained series of single-server queues, as described in the capacity planning model of Chapter 4.2. Thanks to Pratt & Whitney's excellent data-collection capabilities, the queuing model incorporates the required average processing times and standard deviations for each server. Queue lengths, average queue times, and the overall waiting time can be calculated according to the formulas below. The assumptions listed in Chapter 4.2.3 hold for the queuing analysis as well. An article in the *European Journal of Operational Research* developed the equations used to calculate the mean system queue time for single-servers in series (Wu & McGinnis, 2012). The mean queue time for the overall system is calculated as

$$\sum_{i=1}^{n} QT_i = \alpha_1\left(\frac{\rho_1}{1-\rho_1}\right)\frac{1}{\mu_1} + \alpha_2\left(\frac{\rho_2}{1-\rho_2}\right)\frac{1}{\mu_2} + \cdots \alpha_n\left(\frac{\rho_n}{1-\rho_n}\right)\frac{1}{\mu_n}$$

Where QT represents the mean system queue time and

$$\alpha_1 = \left(\frac{C_{arrival} + C_{service}}{2}\right)$$

$$C_{arrival} = \left(\frac{\sigma_{arrival}}{\mu_{arrival}}\right)^2$$

$$C_{service} = \left(\frac{\sigma_i}{\mu_i}\right)^2$$

μ is the mean processing time of a given station, σ is the standard deviation of the processing time of a given station, and ρ is the utilization of that step. $C_{service}$ and $C_{arrival}$ are frequently called the squared coefficients of variation. $C_{arrival}$ uses the average inter-arrival time and standard deviation of that time for the first station. After the first process, the squared coefficient of variation for the arrival flow is equal to the squared coefficient of variation for the departure flow of the previous process. The squared coefficient of variation for the departure process is calculated as shown below (Johnson, 2012):

$$C_{departure} = (1 - \rho^2)(C_{arrival}) + (\rho^2)(C_{service})$$

The following equation gives additional information on the expected queue length of the system (Johnson, 2012).

$$QL = \left[\frac{(\rho^2)}{(1 - \rho)}\right]\left[\frac{(C_{arrival} + C_{service})}{2}\right]$$

where QL is the length of the queue.

As shown in the previous equations, queue time is a part of any manufacturing process with appreciable resource utilization rates and variability in the processing or arrival times. Figure 56 compares the processing and queue times for each product family in the Small Components Cell. This information reflects average demand and an average product mix. The average product mix is shown in Figure 40.

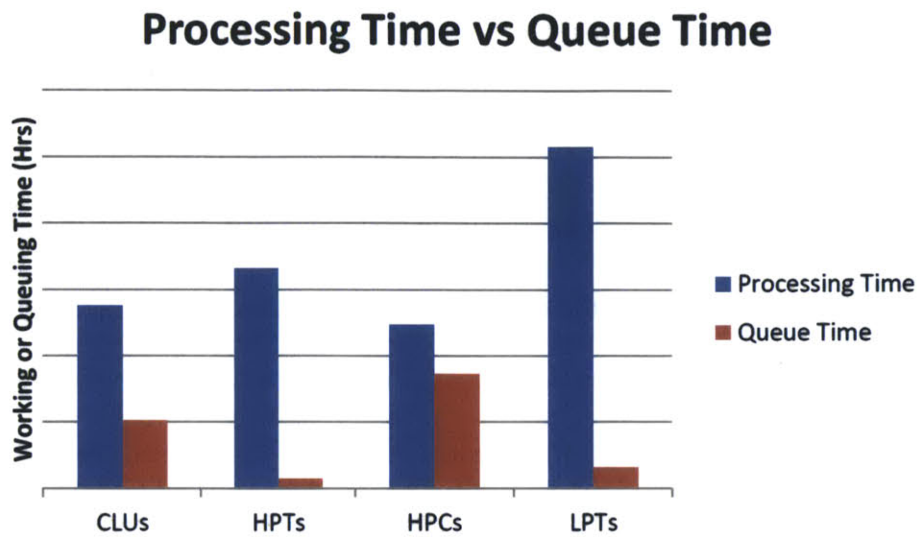



Figure 56: Comparison of queue times and processing times for the four different part families in the Small Components Cell during a period of average demand with an average product mix.

Note that the data in Figure 56 show what is expected based on the product mix and capacity analyses of the previous Chapters. Although the LPTs and HPTs require the most time to process, they have the lowest mean queue times, owing to their low proportion of the overall volume in the cell (and thus, low utilization rates and high mean interarrival times). CLUs and HPCs, on the other hand, require less time to repair, yet will likely see higher queue times resulting from higher resource utilizations and lower average interarrival times.

As utilization rates approach 100% and interarrival times decrease, queue times explosively increase when resources become completely burdened. This scenario occurs as demand increases and is one of the most persuasive arguments for keeping utilization rates at moderate levels through the use of additional shifts, excess machining capacity, or overtime. For example, with no increases in capacity, the Small Components Cell would experience explosive growth in queue times as shown in Figure 57.

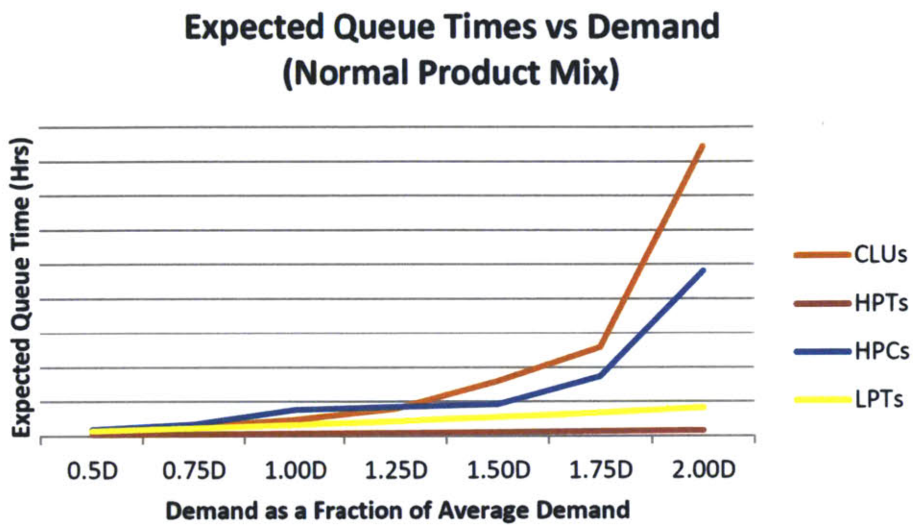



Figure 57: Trends in the mean queue time as demand increases in the Small Components Cell. This figure assumes a normal product mix (Figure 40).

Note that the figure above shows the sudden growth in queue times that are associated with utilization rates of close to 100%. The demand levels at which these resources become over-burdened is clear, a useful managerial tool for determining when to request additional manpower or equipment. Also note that the different processing paths of CLUs and HPCs are an advantage in this situation, as highly burdened resources do not see demand from both the CLU and HPC lines simultaneously. These queue times can have a devastating effect on the ability of the cell to deliver on-time. Even the queues between the 1.25D and 1.50D cases would seriously threaten delivery, and the queue times in the 1.75D and 2.00D scenarios will affect subsequent months as late parts roll over to the following month, exacerbating the situation. The reaction time to demand changes is a key component of being able to successfully navigate high-demand scenarios and is discussed in Chapter 6. This time is reduced through the implementation of the two U-shaped manufacturing cells.

Volume variability is far from the only potential wrench in the works. Changes in product mix can have an even more pronounced effect. Assuming the same LPT-heavy product mix as shown in Figure 41, extreme queue lengths can develop at even lower volume levels. Since the LPTs rely on many of the same resources as the HPCs, one notes the sympathetic queue increases in the HPC line, which is caused by the higher utilization rates of the LPT-burdened equipment. This challenging situation is mitigated through the restructuring of the Small Components Cell to include two U-shaped manufacturing lines. Figure 58 shows the effects of an LPT-heavy product mix on the queue lengths of the Small Components Cell. For reference, Figure 59 has been copied with an adjusted Y-axis to directly compare the two situations.

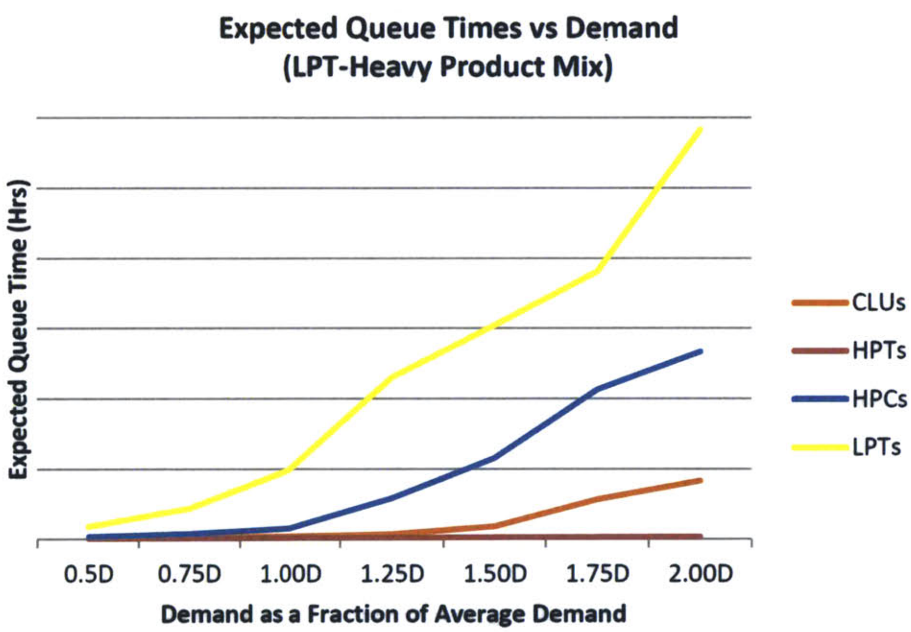



Figure 58: Mean queue time trends with LPT-heavy mix and increasing demand in the Small Components Cell. This figure assumes an LPT-heavy product mix as described in Chapter 4.2.7.

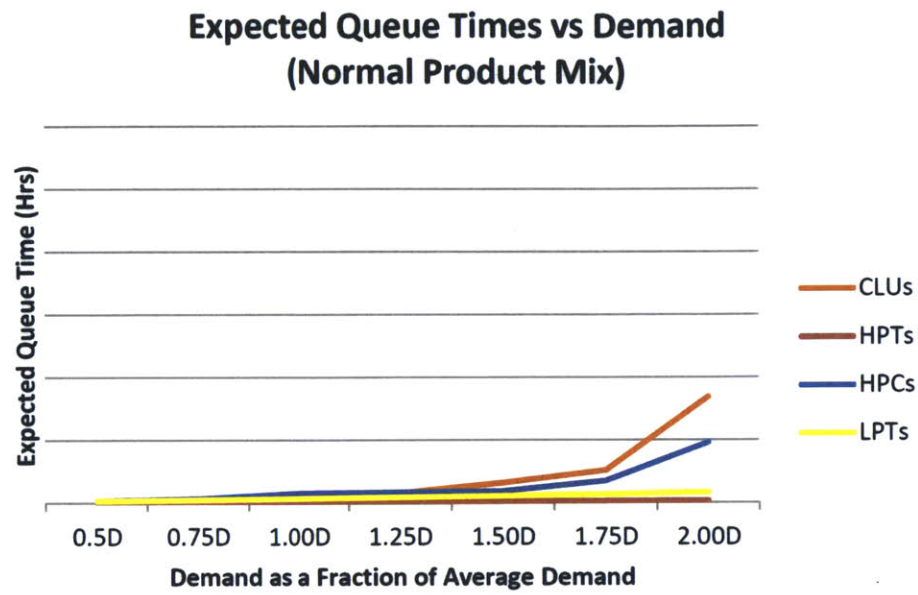



Figure 59: Trends in the mean queue time as demand increases in the Small Components Cell. This figure assumes normal product mix and is identical to Figure 53 except the Y-axis has been adjusted to mirror Figure 58.

This chapter describes the natural queues that result from variation in part arrival times and processing times, as well as the potentially large queues that are caused by demand increases or changes in product mix. These queues can prevent the cell from meeting on-time delivery expectations and are best avoided by rapidly implementing aggressive measures to expand capacity. The two U-shaped manufacturing cells found in the final floor plan are more amenable to quickly revealing a developing imbalance of WIP or a skewed product mix than the original floor plan. Improved lines-of-sight and the segregation of the HPC-LPT and CLU-HPT lines reduce the number of potential holding places for WIP, resulting in a better grasp of the volume levels within the cell. Also, splitting the product families also allows the team to note imbalances or developing bottlenecks much more rapidly. Catching these concerns early allows effective application of overtime, a reallocation of employees to multiple shifts, or the temporary use of additional equipment.

However, additional queues exist that are not captured by the analysis above. Chapter 4.7.2 will discuss how the U-shaped manufacturing lines reduce queue times through the elimination of non-value added transit time.

*Chapter 4.7.2 – Small Components Cell Queuing: Travel, Reversals, and Exits*

The U-shaped flow line offers distinct improvements over the job-shop structure previously in place by improving the management and employee teams' abilities to recognize volume and product mix concerns. The transition offers an additional benefit as well: the reduction of non-value added part travel times. Compare Figure 60 and Figure 61. Figure 60 shows the original floor plan with red lines indicating the routes that a single set of HPC components travels during its overhaul. Needless to say, it is incredibly difficult to get a sense of flow within the cell, and to understand if the part is moving at the necessary pace for an on-time delivery.

Further complicating the arrangement is the aisle that lays between the Small Components Cell's main area and the satellite work centers surrounded by the dashed line. Job code definitions restrict employees from moving parts across an aisle without calling an expeditor, as described in Chapter 2.4.2. This additional queue time was not incorporated into the time recorded on the jobs because the expeditors are incorporated into overhead costs rather than being tracked as direct labor. It is difficult to estimate the queue time saved by moving all equipment within the Small Components Cell, though the reduction in part travel distances, flow reversals, and cell escapes is captured below in Table 13.

When reviewing Table 13, please note that the estimated time savings are drawn from first-person observations over the 6.5 month project. The elimination of 72% of flow reversals saves an estimated 40 man-hours because of behavioral changes as well as reduced part motion.

Frequently, parts would reverse course only to be relegated to the bottom of the priority list depending on an employee's desire to batch parts or work on tasks that were deemed simpler. Reducing the chance that this would occur began to yield significant savings during the final weeks of the project. Similarly, cell exits are predominately for processes in an adjacent cell. However, one cell exit involved moving parts to another building, a task that required an expeditor who was certified to drive a company van. The elimination of this cell exit alone results in a significant time savings. Transitioning to U-shaped manufacturing cells with resources aligned to the processes reduces queue times in several respects.

| | Pre-Transformation | Post-Transformation | Percentage Change | Estimated Time Savings (Hrs.) |
|---|---|---|---|---|
| **Flow Reversals** | 61 | 17 | -72% | 40 |
| **Cell Exits** | 7 | 4 | -43% | 28 |
| **Part Travel (1 set of HPCs)** | 0.99 miles | 0.059 miles | -94% | 16 |

Table 13: Comparison of pre- and post-transformation queuing metrics. Flow reversals occur when the layout of resources dictates that a part move against the overall direction of motion. Cell exits are necessary processes that happen outside the cell. The part travel information is explained visually in Figure 60 and Figure 61.

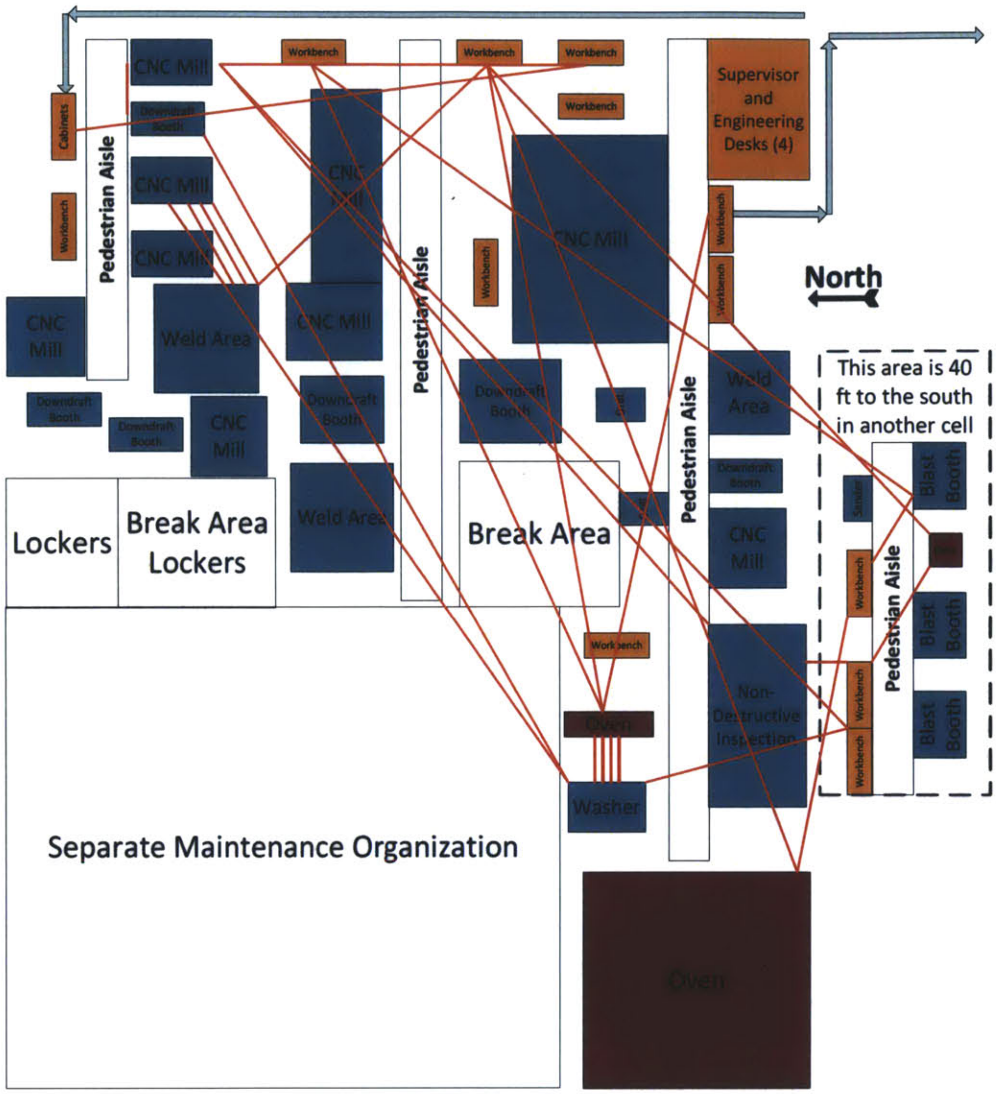



Figure 60: Straight-line distances between sequential processes for the high pressure compressor (HPC) components. Bear in mind that the HPC and CLU components make up the majority of the work volume for the Small Components Cell. This information is the basis for Table 13. The values shown in Table 13 reflect actual walking distances rather than straight-line distances and incorporate the additional 40 ft. to the equipment shown on the right side of the figure. Total walking distance is approximately 0.986 miles per set of parts.

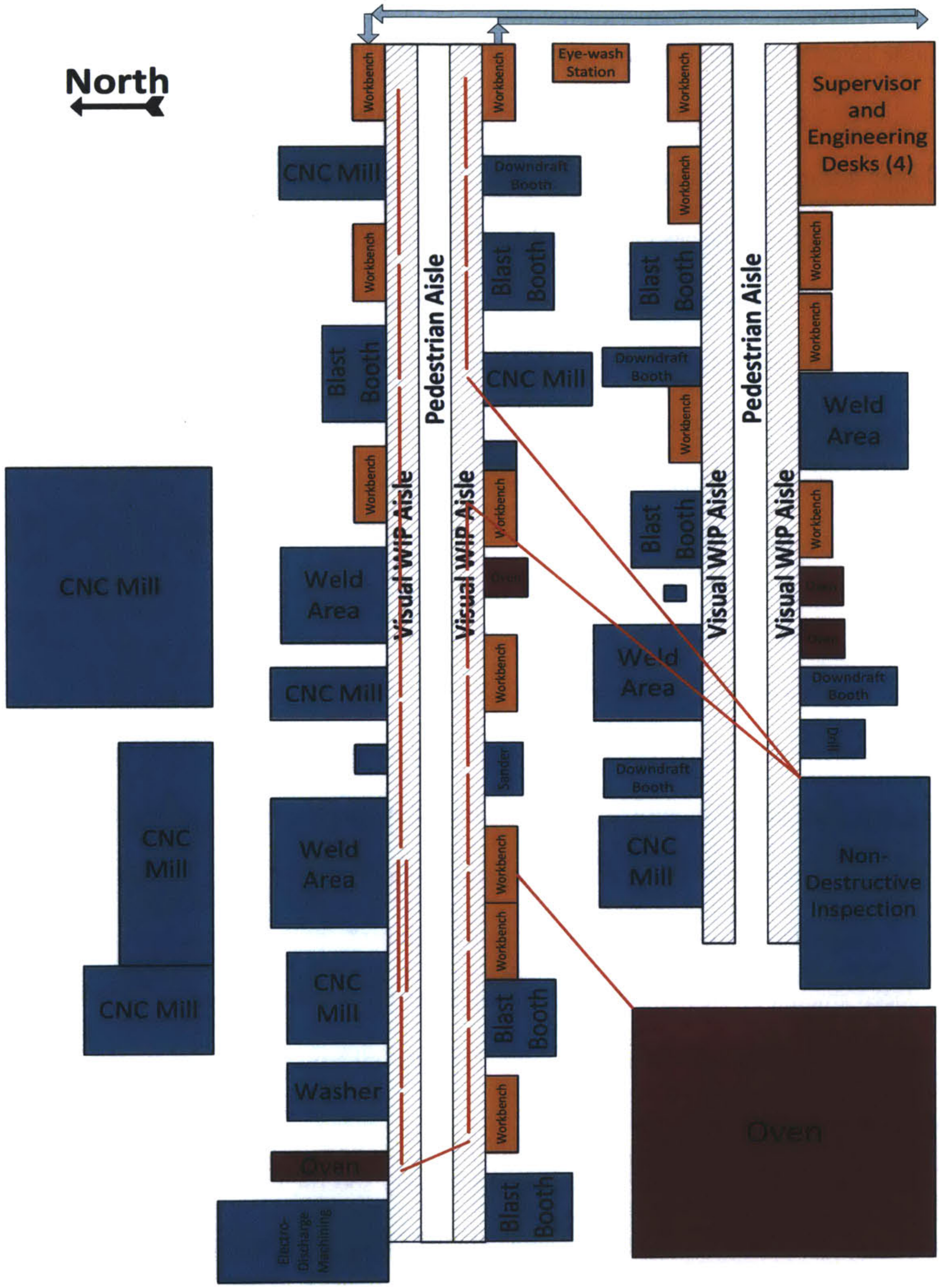



Figure 61: Floor plan of the Small Components Cell at project completion, showing the straight-line distances between sequential processes for the high pressure compressor (HPC) components. Total walking distance per set of parts in this case is approximately 0.059 miles. Bear in mind that the HPC and CLU components make up the majority of the work volume for

the Small Components Cell. This information is the basis for Table 13. The values shown in Table 13 reflect actual walking distances rather than straight-line distances.

Chapter 4.7 describes the reasoning behind the transition from a job-shop to two U-shaped manufacturing lines. The U-shaped lines allow queue lengths to be reduced through faster recognition of imbalances in WIP and product mix as described in Chapter 4.7.1. Furthermore, the transformation of the cell has several additional advantages in the reduction of flow reversals, cell exits, and part travel distances. However, moving the equipment itself is only a portion of completing the transformation. Chapter 4.8 focuses on the development of workforce flexibility through linked redundancies to eliminate capacity concerns caused by limited training, employee illness, and other causes.

### Chapter 4.8 – Cross-Training Plan

Even with a highly experienced workforce, training is a crucial component of developing organizational flexibility. The original intent of the training plan was to completely cross-train all employees so that all employees can complete all operations within their occupation code. This can be an expensive and time-consuming proposition. The following chapter discusses how linked redundancies within the training plan reach near-optimum levels of experience with a reduced amount of time and labor spending. Once these linked redundancies are in place, the organization can pursue future instruction towards full cross-training or focus employees on the new repair development.

Historically, employees are tasked with very specific roles within the cell, as discussed in Chapter 2.4.1. Some machinists specialize in hand blending rather than operating the CNC milling machines. This style of working is not limited to the machinists alone. While this structure can be advantageous for developing an extremely deep knowledge base, it leaves the cell vulnerable to single points of failure when employees are out of the factory. Hopp and Van

Oyen discuss several advantages to cross-training, noting "Part of the motivation for workforce agility via cross-training is that cross-trained workers represent *flexible capacity*. That is, workers can be shifted dynamically to where they are needed when they are needed" (Hopp & Van Oyen, 2004). The authors go on to mention several additional benefits, including "quality improvement, learning curve acceleration, improved organizational culture, economy of scope and economy of depth" (Hopp and Van Oyen, 921). As a result, a cross-training plan has been created to develop redundant capabilities for multiple processes.

Owing to contractual obligations with the union, training must be offered within each occupation code. In other words, a surface mechanic cannot be trained as a welder or a welder as an inspector. This requirement and others result in a clearly defined structure for any training plan, but sometimes lengthen the training process, leaving the cell vulnerable for a longer period of time. The remainder of the chapter focuses on an example of a training plan that reduces the cell's vulnerability to single points of failure.

*Chapter 4.8.1 – Example: Effectively Cross-Training Three Machinists*

In this illustrative example, three machinists are responsible for five different machining and blending processes, as shown in Figure 62. Machinist A is a specialized blender and is very well-versed in Blending Operation 1 and Blending Operation 2. Machinists B and C run different CNC milling processes, represented by CNC Mill 1, CNC Mill 2, and CNC Mill 3. Training costs are assumed as 40 man-hours of time (1 work-week) at an hourly rate of $10/hour and we assume another trainer is available. As Figure 62 represents the status quo, there are no costs incurred, but the business is very interested in protecting the repair process from single points of failure. Numbers under the machinists represent units of output that the machinists are capable of per unit time. Numbers under the processes indicate the demand in the same units. Therefore, there are 300 potential units of output that the machinists can perform and 300 units of demand. There is a readily apparent need for training, as the team can only meet 225 units (75%) of demand. What is the best way to increase the amount of demand that can be met at a minimum of cost and training time?

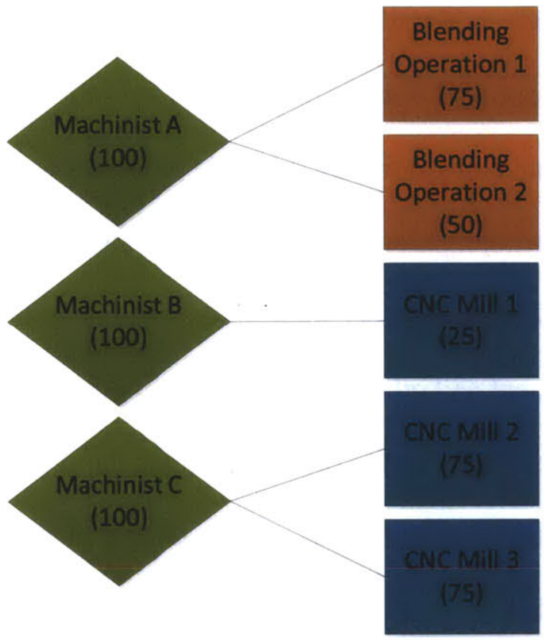



Figure 62: Baseline training example situation in which three generic machinists specialize to accomplish five generic machining processes. Note that the cell is vulnerable to a work-flow interruption if any one of the three employees is absent.

This system must be enhanced to meet demand and tolerate regular vacations, illnesses, and unexpected absences. The business elects to completely cross-train the workforce as shown in Figure 63. This requires ten additional training sessions: three for Machinist A, four for Machinist B, and three for Machinist C. The cost to cross-train is \$4000 = (10 training sessions)(40 hours/session)(\$10/hour). This training plan will take four weeks to complete, assuming that each skill can be taught by another machinist not listed here and there are no seniority conflicts. This solution is distinctly superior to the status quo because the cell can meet all 300 units of demand and single points of failure no longer exist.

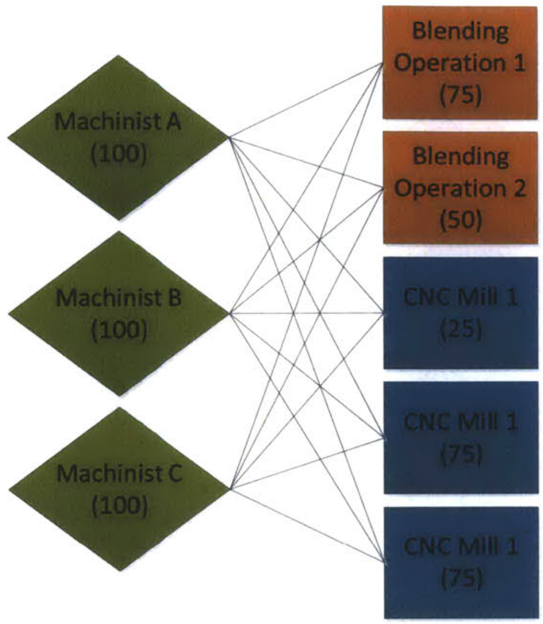



Figure 63: A representation of a fully cross-trained scenario in which three generic machinists are each capable of completing all five generic machining processes.

Reviewing the complete cross-training plan, the hypothetical management questions it. The four week timeframe required to complete the training is significant, as there are rarely three independent trainers who are readily available to train fellow employees. Fortunately, there is an opportunity to meet all demand with a smaller cost time requirement. A linked redundancy option requires only five training sessions and a two-week training period. This option is 'redundant' rather than 'fully cross-trained' because there are at least two machinists capable of performing any of the five jobs, but each machinist cannot perform all five operations.

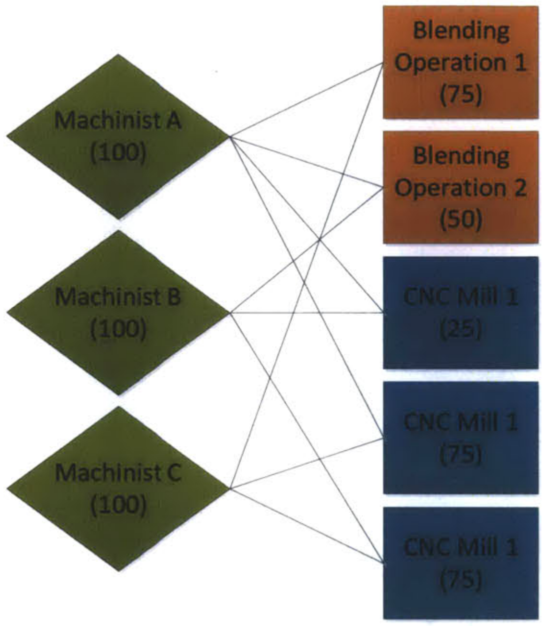



Figure 64: A representation of a partially cross-trained plan in which three generic machinists are each capable of completing certain operations in a total of five generic machining processes. Note that this situation permits machinists to have a multiple skills while preventing the cell from being subjected to a single point of failure in the event of an absence.

| | Additional Training Costs | Training Time (Hours) | Time to Complete | Expected Sales (Units) |
|---|---|---|---|---|
| Baseline | $ - | 0 | 0 weeks | 225 |
| Linked Redundancies | $ 2,000 | 200 | 2 weeks | 300 |
| Fully Cross-Trained | $ 4,000 | 400 | 4 weeks | 300 |

Table 14: Comparison of training plans between baseline training plan, linked redundancy plan, and fully cross-trained plans.

Establishing a closed loop between the machinists and processes creates a path to meet all demand. In that way, excess capacity with one machinist can be re-routed down the loop until that excess capacity can be matched with excess demand. Closing the loop can be accomplished with a full cross-training plan, but is more quickly and economically met by a linked redundancy plan. Practically, this reduces the time needed for the cell to meet all demand minimizes the impact to production as the linked redundancy plan uses fewer outside resources.

## *Chapter 5 – Data Analysis: Small Components Cell Performance*

Chapter 4 describes the changes to the Small Components Cell, the reasons the two U-shaped lines were chosen, the effects of volume, product mix, travel time, cell exits, and flow reversals on queues, and the training plan put into place. These changes make the Small Components Cell a more business unit as measured by the key metrics from Chapter 3. Chapter 5 discusses the trends shown in these business metrics and shows the performance of the cell throughout the course of the project. Chapter 5 also compares the year-over-year performance of the Small Components Cell and highlights parallels and contrasts between the Small Components Cell and larger Connecticut Stators and Components business unit. Chapter 5 measures the effectiveness of the changes made to the cell in the near term and predicts trends in the future based on the experiences from the project. Table 15 qualitatively summarizes the changes in the business metrics throughout the course of the project; more information on each metric exists within the following sub-Chapters. Please note that data from 2013 will not be available prior to the release of this document.

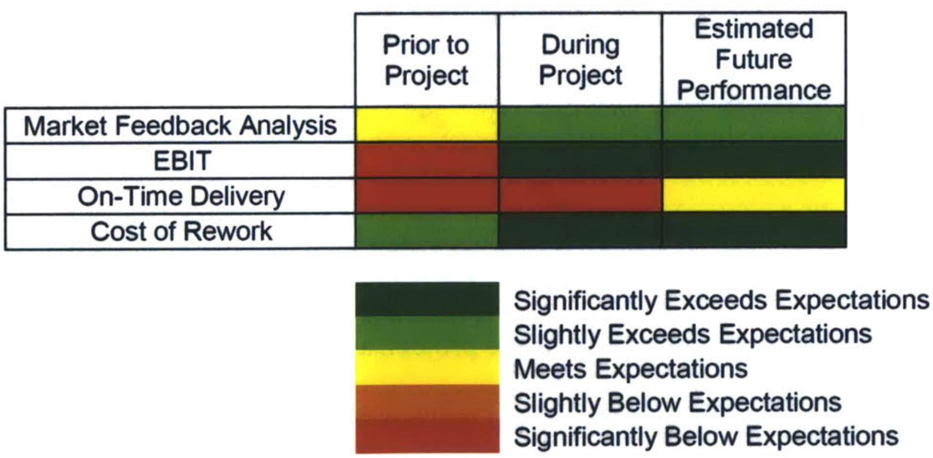



Table 15: Qualitative performance summary of the Small Components Cell across the major business metrics, comparing pre- and post-project states.

**Chapter 5.1 – Market Feedback Analysis**

As discussed in Chapter 3.1.1, the Small Components Cell was meeting the organizational expectations for its market feedback analysis (MFA) prior to the project start. Feedback is based on service times, the technical quality of the repairs, perceived value, customer interactions with Pratt & Whitney, and overall satisfaction. Figure 65 shows a comparison of the pre-project MFA scores with the information received in the third and fourth quarter of 2012, when the project was on-going.

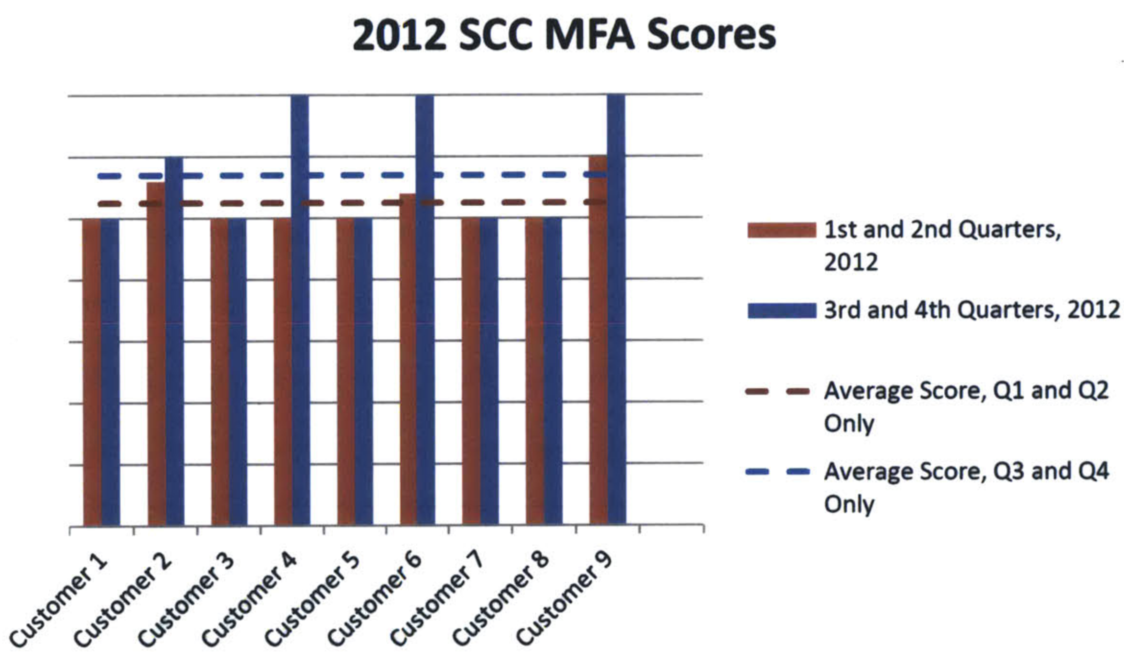



Figure 65: MFA scores prior to and during the project. The bottom of the chart is the lowest possible score, while the top of the chart is the highest possible score.

MFA improved during the course of the project, as shown above, and the cell now leads the Connecticut Stators and Components group, as shown in Figure 66. Of the Small Component Cell's 9 customers, 3 show a significantly improvement in their experiences with the Small Components Cell during the course of the project. Customer 2 notes a marginal improvement, and the other 5 customers remain at a steady level of satisfaction. There are two primary reasons for the improvement. The first is a focused campaign led by the Customer Service organization, which interfaces with the Small Components Cell and other operations on a daily basis. This campaign's message was directed specifically at the Small Components Cell's customers, acknowledging previous customer concerns with on-time delivery. Describing the transformation plan and how it is expected to improve the performance of the Small Components Cell, the campaign gave the customers additional insight into the daily operations of the business.

The second main reason for the improvement in MFA scores is a series of discussions with the customers on part prioritization. Several customers are expanding their capabilities in parallel with the Small Components Cell. As a result, they successfully increased volumes over several quarters. However, in several instances, parts were incorrectly shipped or improperly prioritized prior to arriving at Pratt & Whitney. When these customers requested expedited service on engine-critical parts from the Small Components Cell, the cell met the customers' expediting needs in several situations. Ideally, this situation will continue to improve, with each side learning the other's operational processes more thoroughly. Moving forward, I strongly recommend that the Small Components Cell request a high-level engine assembly process map from their customers. With this information, the Small Components Cell can more effectively prioritize WIP and meet the customers' on-time delivery needs.

Looking to the future, the MFA scores of the Small Components Cell should continue to improve as the physical transformations to the cell take root. Passing on the time savings from reduced part movements and improved queues to the customers in the form of more reliable on-time delivery service will further boost the customers' interactions with the Small Components Cell.

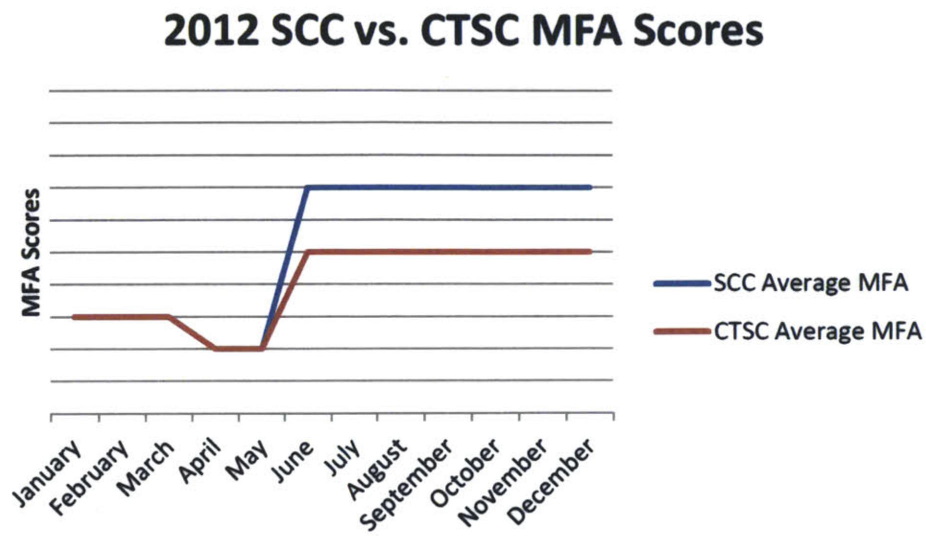



Figure 66: Comparison of 2012 MFA scores of the Small Components Cell and the Connecticut Stators and Components business unit.

**Chapter 5.2 – Sales, Costs, and EBIT Performance**

One of the gravest concerns within the organization prior to the project start was the performance of the Small Components Cell to EBIT targets. During the course of the seven-month project, the Small Components Cell exceeded the target EBIT levels for six consecutive months, only missing the target in June. As shown in Figure 67, the annualized EBIT performance shifted from below target to significantly above the target, an improvement of more than 40% for the year.

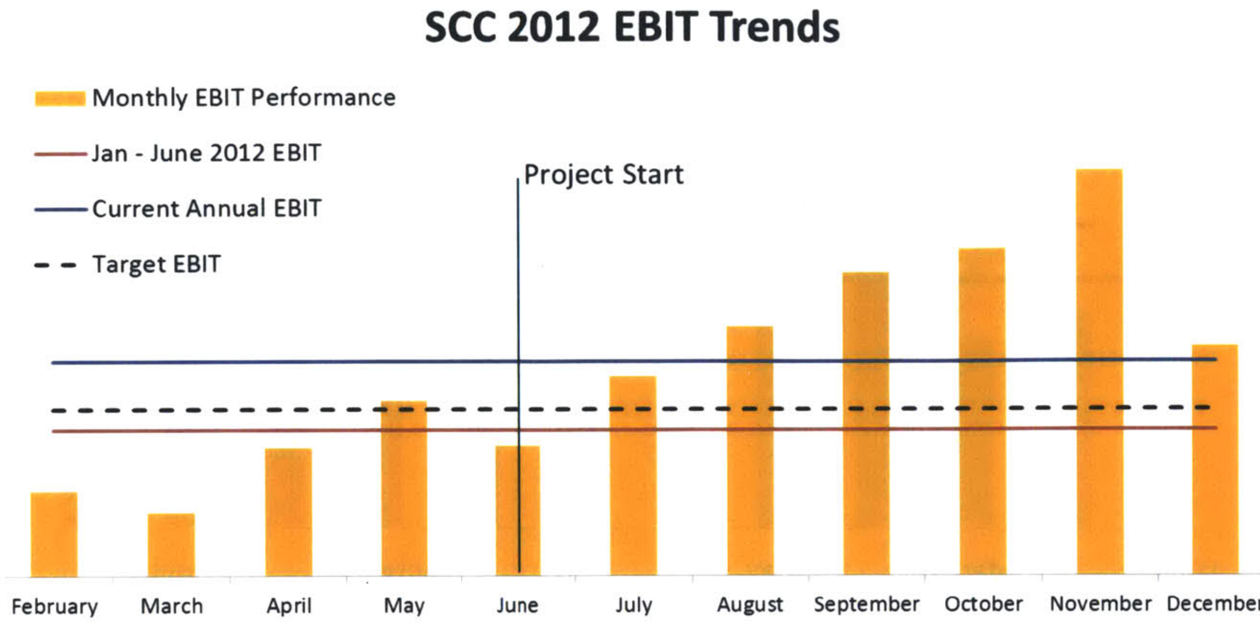



Figure 67: 2012 EBIT performance for the Small Components Cell. The average February – June performance is shown with a red line, while the average annual performance is shown with a blue line, highlighting the difference between the pre- and post-June performances. The EBIT target is shown with a black dashed line.

The next figure highlights sales trends from 2011 and 2012. Again, the sales figure has monthly sales information from 2012 as well as the average annual sales for different periods of 2012 for the Small Components Cell only. There are two key takeaways from Figure 68. The first is to note the increasing sales trend driven by increasing volumes in the fourth quarter of the year. The second item is EBIT increases more rapidly than the sales, indicating good cost control. This is supported by the overtime charts later in this chapter, which show that overtime usage increases more slowly than sales, generating better EBIT returns.

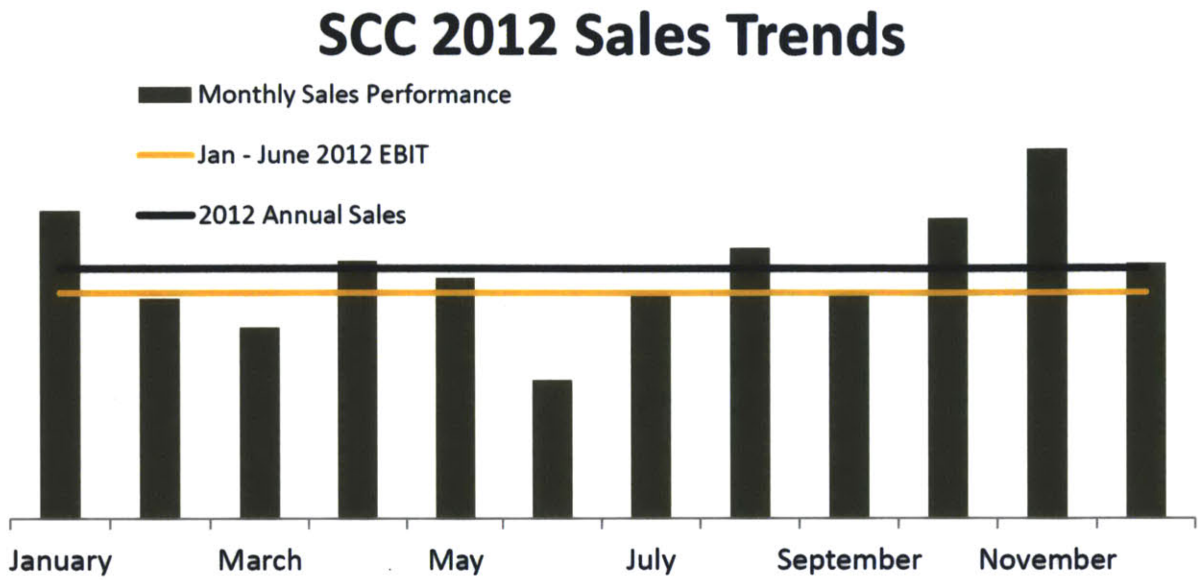



Figure 68: Small Components Cell sales trends in 2012. Note that sales decline more rapidly than overtime usage in the first half of the year, resulting in poor EBIT performance. This pattern reverses in the second half of the year.

The following two figures are focused on overtime as a method of cost control. Both show that overtime is down slightly vs. the previous year, but that the final quarter of the year experiences significant spikes in overtime usage. This is the result of the higher volume, LPT-heavy product mix scenarios that are discussed in Chapter 4. This situation will be discussed more thoroughly in Chapter 5.3, on-time delivery.

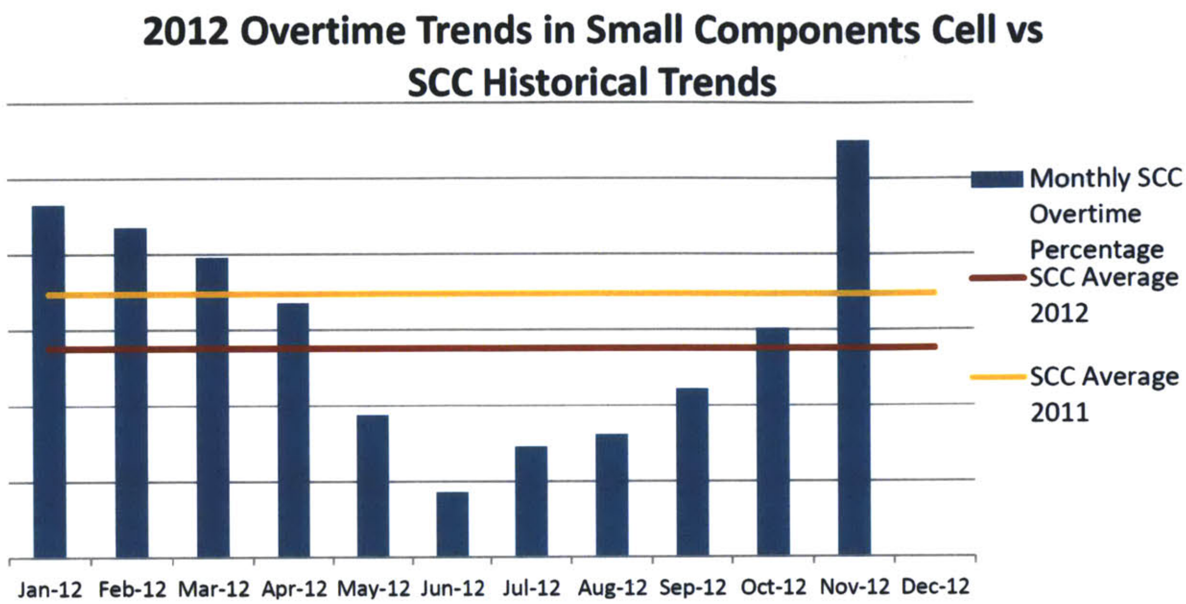



Figure 69: Monthly overtime percentages for the Small Components Cell in 2012. The chart is intended to provide a look at the overall trends within 2012, as well as a reference to the 2011 performance of the Small Components Cell.

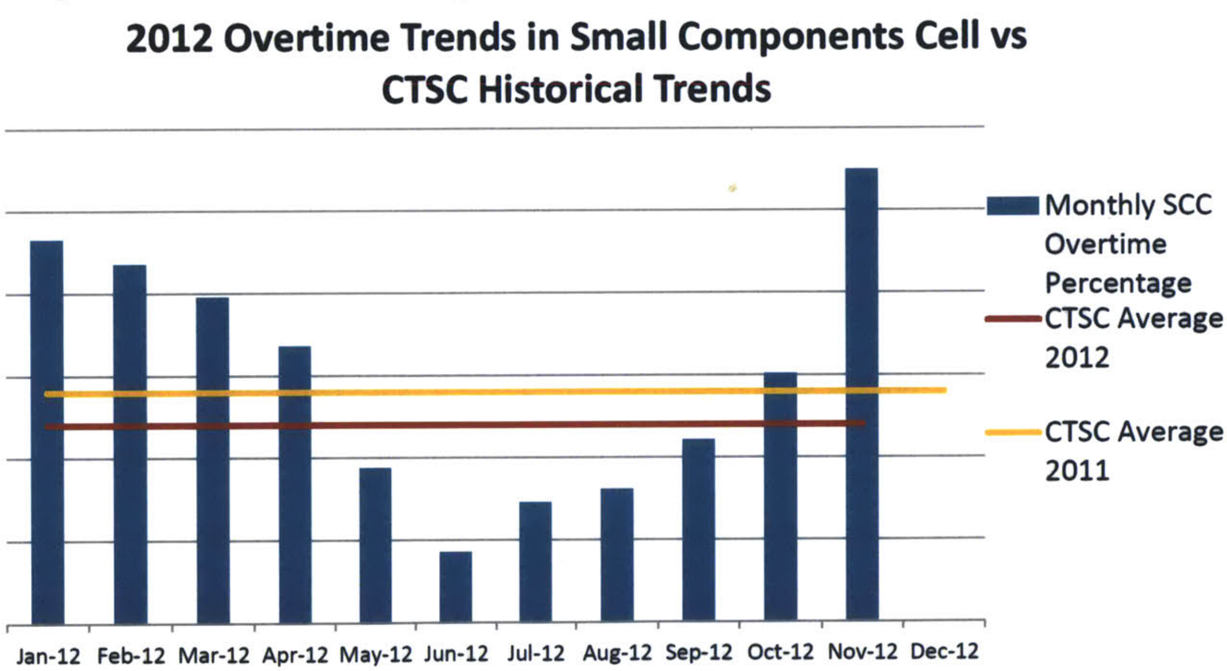



Figure 70: Monthly overtime percentages for the Small Components Cell in 2012 vs. Connecticut Stators and Components averages for the present and prior years.

Overall, the Small Components Cell significantly outperforms profitability expectations through 2012 as a result of high performance levels from July through December. The shift in performance during that time is large enough to boost annualized EBIT performance by more than 40%.

### Chapter 5.3 – On-Time Delivery

On-time delivery suffered during the course of the project for several reasons. The first reason is the most obvious: physically moving nearly every piece of equipment causes inherent disruptions associated with displaced employees, utility interruptions, and much higher levels of equipment down-time than normal. Psychological impacts relating to the general sense of the unknown should not be underestimated. I observed several instances of the team struggling with routine work even when they were not being directly affected by some of the transformation work. This characterization certainly includes my own performance.

The second reason that on-time delivery suffered during the course of the project is the longer-than-expected response time to request additional resources following the spike in demand and the changes in product mix. These shifts, described in Chapter 4, have a tremendous impact on the cell's performance. Tracking the WIP in the cell by the number of jobs alone is insufficient information to make informed decisions about the overtime level, shift structure, and number of employees. Interestingly, one of the employees noted the potential for delivery challenges in a meeting in the weeks before the majority of the work arrived (Anonymous, Personal Interview with SCC Employee, 2012).

Figure 71 shows the Small Component Cell's on-time delivery throughout 2012. Note that the project began in June and the transformation of the cell began in mid-August. The effect of a managerial transition is easily seen in the May-June-July comparisons. The effects of the physical transformation are apparent in the August-September transition, as well as the trend between September and December.

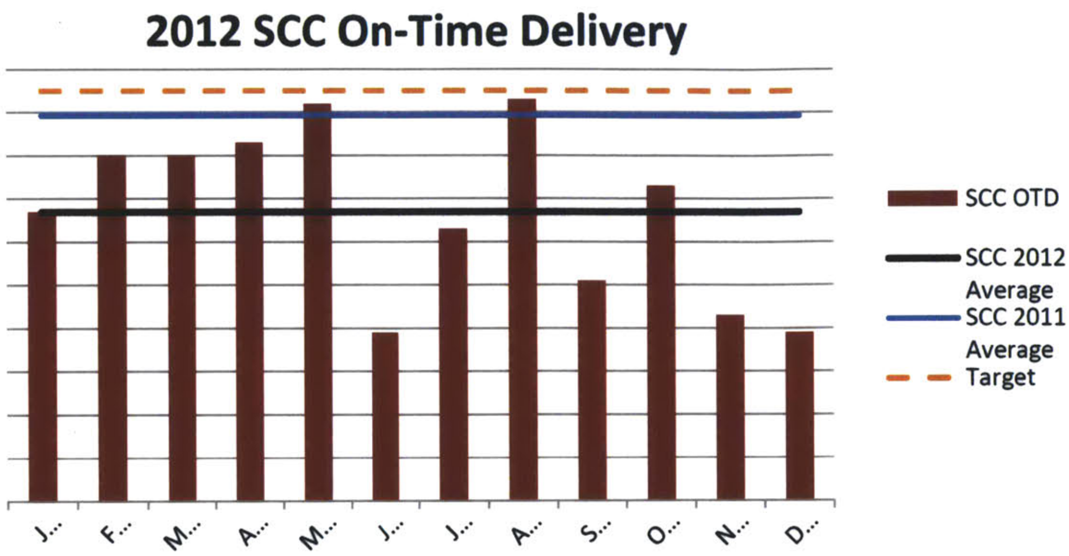



Figure 71: 2012 SCC on-time delivery information. Note the effects of the managerial transition in the May-June comparison, as well as the start of the physical transformation of the cell shown in the differences between August and September.

Although the Small Components Cell struggled with on-time delivery throughout the project, the future is brighter. Owing to the time needed to cycle parts through the repair process, the effects of the cell transformation on on-time delivery are not immediately clear with the data at hand. However, the reduction in queue time, the training plan, and the capacity planning tool all provide reinforcing structures that will make the cell a more effective portion of the business. The establishment of a new normal also aids in returning the cell to a steady state.

**Chapter 5.4 – Cost of Rework**

The Small Components Cell continued a trend of excellent quality work, returning extremely low cost of rework metrics throughout the second half of 2012. Calculated as a percentage of sales, cost of rework has decreased by over 80% since 2011, including an additional drop of over 20% between the first and second halves of 2012. Four of the last seven months of 2012 saw 0.0% cost of rework, as shown in Figure 72.

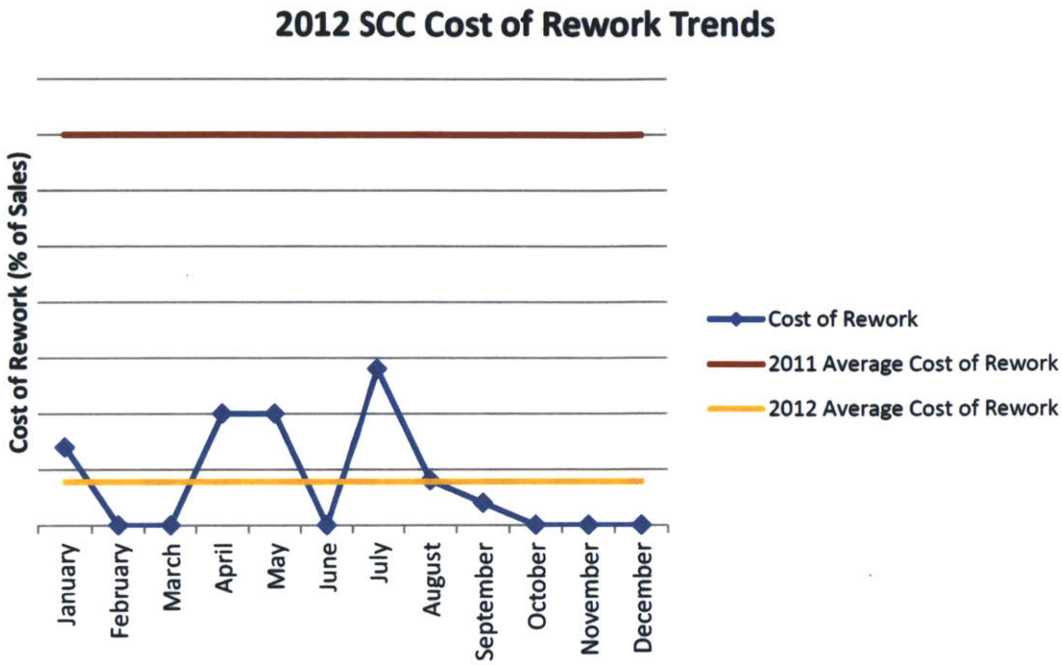



Figure 72: Cost of rework for the Small Components Cell between 2011 and 2012, including monthly results from 2012.

Although this trend was already well-established in the early months of 2012, the restructuring of the Small Components Cell provides several reinforcing channels to maintain this type of performance in the future. The improved visibility of the WIP and the flow line layouts of the equipment permit simpler identification of parts that have been recycled. In some cases, these recycled parts are because of extreme wear that the process cannot correct in a single attempt. In others, employee errors cause parts to move back to upstream processes. In both situations, the linear structure of the Small Components Cell highlights part movements, giving the team the opportunity to examine the underlying reasons for rework. With this data, problems are more likely to be methodically solved.

The second channel which reinforces high quality is tied to the development of the capacity planning model along with the visual-factory layout of the U-shaped lines. Understanding the manpower and equipment needs for a given volume and product mix, the

Small Components Cell can more effectively allocate overtime and resources, lessening the burden on previously over-stretched employees and equipment. As many errors are made under the perceived pressure of an impending delivery date, this avenue allows the cell to maintain the proper manpower loading.

The fact that this extremely low rate of rework occurred during the physical transformation of the cell is a credit to the Small Component Cell team, as equipment relocations, construction activity, and an upswing in demand would easily explain increases in preventable mistakes.

**Chapter 5.5 – Key Findings**

This chapter summarizes key findings and points the reader to additional information on these findings throughout the thesis. Chapter 4.2 examines the uses of a capacity planning model to better allocate headcount and equipment resources under certain demand and product mix scenarios. The model's utility is extended in Chapter 4.3 by a design-of-experiment that indicates the most effective ways to increase capacity in the cell in order of significance are to improve employee efficiency, reduce absenteeism, increase overtime, and adhere to standard break durations. Chapter 4.7 analyzes improvements in queue time which result from the transformation of the cell from a job shop into a lean manufacturing flow line. Savings include more than 80 man-hours of labor, a 94% reduction in non-value added part travel, a 72% reduction in the number of flow reversals, and a 43% reduction in the number of cell exits. These savings have been realized within the cell following the completion of the cell transformation. Chapter 4.8 examines a training plan that will improve employee flexibility as recommended by the capacity planning design of experiment at a minimum of cost and time to the organization as a whole.

Chapter 5 reveals the impact of the transformation on the small components cell in several ways. From a business perspective, on-time delivery suffered as discussed in Chapter 5.3, but cost of rework declined more than 85% and EBIT performance improved by over 40%. Customer feedback also improved over the course of the project. One particularly important finding is outlined below in Chapter 5.5.1: the effects of variability in demand and product mix on the capacity of the Small Components Cell.

*Chapter 5.5.1 – Demand Variability and Product Mix*

This chapter focuses on a quantitative key finding: the impact of variability in demand and product mix. As Chapter 4 shows, variation can be extremely detrimental to the cell if not properly balanced through adjustments in manpower or equipment capacities. Although these chapters concentrated on the overcapacity situations that the Small Components Cell faced in October through December, under capacity scenarios are equally important to consider. Preserving EBIT progress through an appropriate alignment of overtime usage to work volume is often unpopular within the cell. However, this is precisely the approach needed to maintain cost controls. Utilizing lower demand times to conduct cross-training, Kaizen and value-stream mapping events, and time studies permits the cell to be fully prepared when demand spikes in the future.

The concern of overproduction is an important message to convey during under capacity situations. This waste of production is especially easy to fall into during under capacity scenarios, as employees feel social pressures to appear busy at all times. Recognizing this, discussions on adhering to standard working times are crucial. Filling non-production time with training and transformation opportunities will build the abilities of the cell without adversely impacting production. During the course of this project, there would have been significant advantages to beginning the cell transformation in the slower months of June – September, thus enabling the cell to respond more effectively to the demand spikes at the end of the year. This was a painful lesson to learn, but one that will likely have a very positive dividend for the Small Components Cell in the future. See Figure 73 for a representation of the work volume in the cell throughout the project.

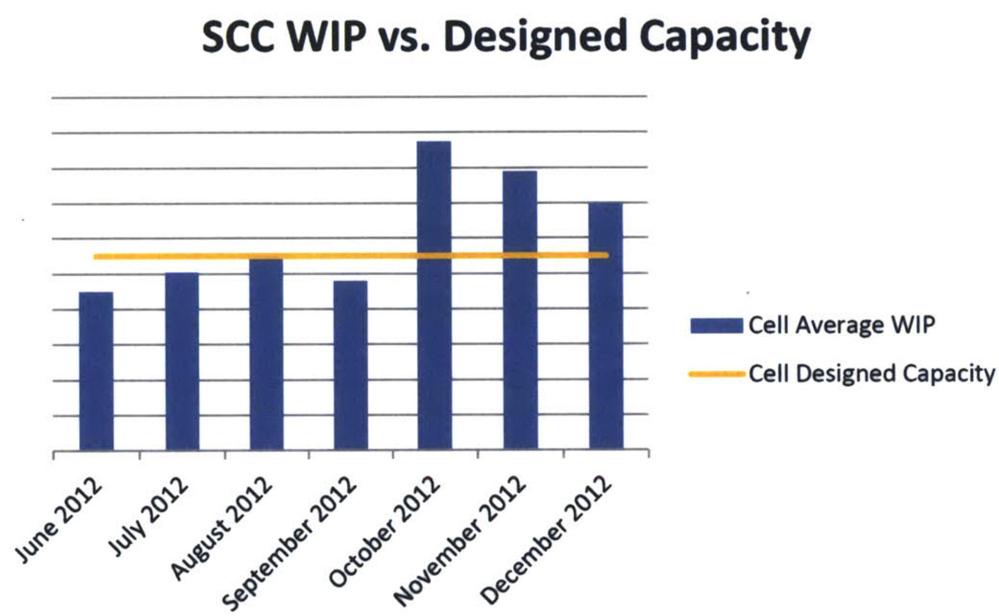



Figure 73: Average WIP levels during the project in the Small Components Cell.

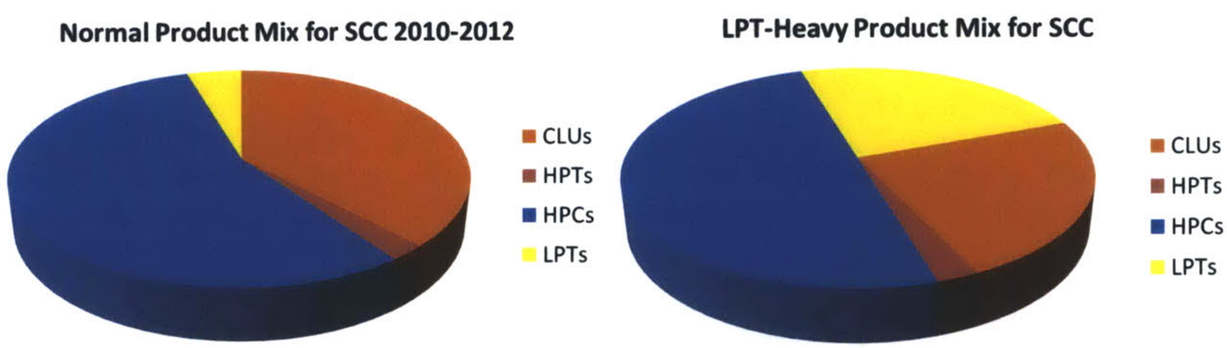



Figure 74: Comparison of product mixes during the project.

### Chapter 5.6 – Future Trends for the Small Components Cell

As briefly described in the preceding chapters, the Small Components Cell enters 2013 with a significant amount of positive momentum. EBIT performance is drastically improved. MFA data suggest that the extensive communication between the operations group, the customer service group, and the customers themselves is improving the business relationship between all three. Quality metrics continue to improve year-over-year, reaching the lowest point in over two years at the end of 2012. That the cell achieved these results during the transformation of the area is a credit to the team and the managerial support from Craig Thompson and Lori Gillette.

On-time delivery continued to struggle throughout the course of the project. However, much of this can be attributed to circumstances that either will not recur or can be appropriately addressed. Following the transformation, the effects of on-going construction within the cell will fade. Also, the capacity planning model and training plan provide management with several tools to more easily react to future high-demand situations. With this information in hand, the Small Components Cell is well-positioned to exceed expectations in the future. This has been borne out with significantly higher on-time delivery rates in the Small Components Cell in early 2013.

## *Chapter 6 – Recommendations and Lessons Learned*

### Chapter 6.1 – Recommendations

This chapter describes recommendations that are focused on the Small Components Cell at Pratt & Whitney but can be extended to other businesses in unrelated industries. Recommendations are organized by the perceived difficulty of implementation, starting with the simplest. Nearly all recommendations are focused on one of four broad topics: the incentive structure, operational improvements, cross-training and skill development, and networking.

#### *Chapter 6.1.1 – Low-Hanging Fruit*

- **Cross-Training/Skill Development – Communicating Business Metrics:** Provide regular updates on the micro-level business to all employees. Pratt & Whitney does an admirable job of tracking organizational performance through a broad array of business metrics. During monthly all-hands meetings, information from the entire business unit is reviewed. I believe it would also be effective to review EBIT, safety, cost-of-rework, on-time delivery, and training metrics on a weekly basis during team meetings. Doing so gives employees a better idea of their performance as a team during the last month, as well as a thorough understanding of the drivers behind many of the decisions they see on a daily basis. In my experience, many of the members of the Small Components Cell hold a keen understanding of business concepts but would not regularly see the relevant information if it were not for our weekly team meetings.
- **Cross-Training/Skill Development – Professional Development:** Host focus groups on particular business topics to facilitate cross-team development. Many employees expressed interest in learning more about other areas of the business

during the course of the project. Having a team member from Finance discuss the effects of overtime on the cost of the part or a machinist describing the challenges of CNC machining could prove very useful. In many cases, highly skilled employees do not often stretch beyond their normal assignments, resulting in a 'siloed' organization. Small lunchtime discussions on specific topics will convey important messages without becoming cumbersome.

- **Networking – Peer Group Formation:** Encourage teams to eat together in the common cafeteria. I was surprised to find that most teams and peer groups would not regularly spend time together during breaks, even though they have worked together for decades. In order to foster a more cohesive environment, I encourage the formation of regular team lunches on the cell and business unit levels. Lori Gillette's establishment of a common cafeteria in the building is certainly a step in the right direction. Unfortunately, the cafeteria is seen as a place where only hourly employees eat in small groups. Encouraging the office staff to eat there as well would generate a more unified environment between hourly and salaried populations, helping to dispel the belief that the office staff is not connected to the realities of the shop floor. This approach would yield dividends. A common gathering area helps to reduce the abuse of break policies by a small subset of employees, boosting morale throughout the majority who adhere to the rules. A second benefit is the development of bridges between cells. Many employees see other cells as potential rivals for overtime and seniority-based perks. Building the community through shared social experiences will foster a better working environment.

- **Operational Improvement – Improved Demand Forecasting**: Send information on product mix, part count, and the projected arrival date to the cells as soon as it is available. Current capacity planning suffers because most incoming demand data provided to supervisors consist only of high-level aggregate forecasts. Requiring data on incoming parts when those parts are shipped from the customer is crucial to making effective decisions. As this information will benefit the Small Components Cell and customers through improved on-time delivery, there are no apparent disincentives to acting on this opportunity.
- **Operational Improvement – Visual On-Time Indicators:** Hang identifying signs to assist with work prioritization. Employees (including supervisors) often find it difficult to know which parts to prioritize. Knowing the required turn-around time and tendencies for queuing within the cell, placing identifying marks on a signpost will help to keep the first-in, first-out policy running smoothly. Figure 75 shows an example placard that could be hung from one of the many signposts in the Small Components Cell. Placing the LPT cart above the HPC would indicate that LPTs should be completed first, giving the cell the ability to prioritize both within and between product families to prevent product mix issues from affecting performance.

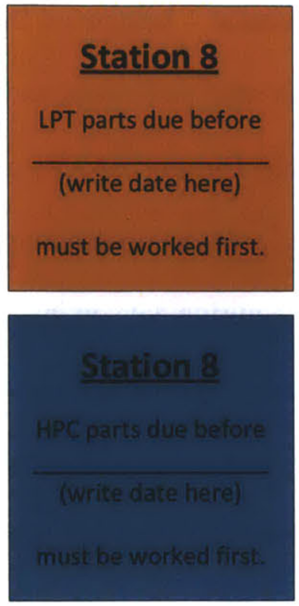



Figure 75: Examples of visual aids for tracking on-time performance.

*Chapter 6.1.2 – Difficult but Attainable*

- **Operational Improvement – Small Batch Flow with Customers:** As many customers are based overseas, entire engines are often disassembled before being shipped in a single container to the Small Components Cell. Unfortunately, this often prevents the Small Components Cell from effectively distributing WIP throughout the cell. Shipping several engine stages rather than the entire engine will drive up shipping costs, but will reduce inventory carrying costs on both ends. This will also permit the Small Components Cell to begin repairing parts while the rest of the engine is being disassembled, reducing the down time for the engine. Customers may resist because of the additional complexity and change from status-quo. A cost-benefit analysis comparing the additional shipping costs to the improved cycle time and reduction in holding costs should eliminate many concerns. Communicating directly with the customer's operations group will likely be more effective than going through standard sales channels. As a back-of-the-envelope estimate, consider a situation with an engine's worth of HPC parts from a Boeing 777. The parts will be shipped from an engine center in Singapore to the Small Components Cell for repair. Shipping costs using four small batches rather than one large shipment of all the HPC parts will increase from $908 from $574, a 58% jump. This assumes international air freight priority shipping using FedEx[1]. However, a single day's delay for the 777 could cost the engine center over $4,270, making the additional shipping a very attractive means of avoiding late delivery penalties from the airline[2]. As orders are already shipped back to the engine center on an individual basis, there would not be an additional cost incurred on the return journey.

- **Operational Improvement – Standardized Working Times:** One of the biggest challenges with overhaul work is the variability caused by differences in incoming part conditions. Developing part flow within a cell is extremely difficult in high-variability conditions. Tracking potential problem parts through the use of standardized times on work instructions would be extremely beneficial. Standard times could be set at a generous level (at the 25th percentile or lower) to ensure that quality is not sacrificed. In the event that certain parts frequently exceed this standard, the engineering and management teams would have a clear indication of

[1] All pricing estimates gathered from quotes on Fedex.com using four 4-kg shipments rather than one 16-kg shipment.

[2] This calculation is based on a Boeing 777 list price of $266 million, assumes a 25-year working life with 250 flying days per year, which yields an amortized cost of $42,696 per flying day. I also assumed that the engine center has sufficient inventory flexibility to insulate the airline from delay in 90% of the cases, yielding an expected penalty to the engine center of (1-0.9)($42,696) = $4,270. If this last assumption is not accurate, the expected penalty could increase sharply as the (1-x) term would grow. Boeing 777 list price from Wikipedia.com and engine center inventory flexibility estimated from internal discussions.

which processes to tackle first for the greatest improvement. Similarly, training plans can be more effectively developed to target difficult or high-variation processes. For example, the phrase "75% of all LPT inspections require less than ______ hours to complete" on an inspector's work routing would give them an indication of how to best plan their work for the day, or when to request assistance on a challenging job. This could be difficult to implement if employees perceive it as an attempt to micromanage their daily work. However, I believe that any short-term challenges would be well-worth the long-term advantages of more effective planning, resource allocations, and training.

- **Incentives – Public Recognition of Awards**: Present team and individual awards publicly. Records show that 92 employees within the Connecticut Stators and Components business unit received some type of award between January and October 1st, 2012 (Pratt & Whitney Human Resources Department, November 13th, 2012). Several were awarded to Small Components Cell employees during the course of the project. Interestingly, many employees asked to be recognized in private, away from the cell, to prevent other employees from becoming jealous. I recommend that this situation be changed through the direct presentation of awards and recognitions to the individual or team during daily team meetings. I believe this approach will initially continue to spark jealousy but will eventually boost team morale by providing positive feedback to those who have gone above and beyond their job descriptions. A blended approach has already been implemented, with employee awards issued in a private meeting with the whole leadership team but no other hourly employees.

*Chapter 6.1.3 – Challenging Opportunities*

Many of these recommendations will be difficult to implement, especially in the near future. However, these are also changes which I believe will spark the greatest improvement in the organization.

- **Networking – Steward/Company Relationships:** Work with the union stewards to foster a more effective and equitable environment. As mentioned in Chapter 3.2.3, the union-company relationship has been tumultuous in the recent past. This is far from the ideal situation, in which the company can work with the stewards (and vice versa) to proactively prevent situations that are unfair to both the company and the employees. In my past experiences as a unionized engineer, stewards were often the first people to reach out to an underperforming employee. Similarly, stewards worked with management and employees alike to resolve any concerns before productivity or employee happiness was impacted. This type of change can be incredibly difficult to implement without peer group formation and the social and professional relationships that would blossom from cross-training sessions between hourly and salaried employees. However, the benefits are immense. A self-policing workforce yields tremendous opportunities for dramatically improving productivity and cost metrics while simultaneously boosting morale.
- **Cross-Training/Skill Development – Cell Engineers and Supervisors:** Cross-train cell engineers and supervisors. Currently, cell engineers are the only employees certified to make changes to work instructions and take the lead to solve technical problems. Unlike cell engineers, supervisors can make work

assignments and allocate overtime. Supervisors are also responsible for ensuring that the cell is delivering parts on-time. Each role is absolutely essential to the cell, yet the areas of responsibility do not overlap. In many cases, this results in the possibility of a single-point of failure, as Chapter 4.8.1 discusses. Cross-training cell engineers and supervisors requires an immense investment of time. However, creating a team of engineers with supervisory capabilities will result in a team that is much more than the simple sum of the two individuals. Drawings could be updated more rapidly, capacity concerns would be more quickly noted, and the cell would not be hamstrung by a vacation or illness from one of the two.

- **Cross-Training/Skill Development – Relaxing the Occupation Codes:** As noted in Chapter 2.4.3, employees often feel more engaged and interested in their work if they can bring a large number of personal and professional skills to bear on the task. In an effort to codify the work performed, the contract between the company and union strictly restricts tasks to different occupation codes. Although this can be helpful for the clarity of the organizational structure as noted in Chapter 3.2.1, employees can often be shoehorned into repetitive, monotonous tasks based on their occupation code. This inhibits the employees' professional development, a goal that both the company and the union would like to enhance. Relaxing these occupation codes would improve employee morale by giving employees more clear-cut opportunities to grow. The additional workforce flexibility would benefit the business, as discussed in Chapter 4.8 and simultaneously result in greater job security.

- **Operational Improvements – Longer Contract Cycles**: Increase union-company contract durations. Throughout the aerospace industry, companies and unions have achieved historic success in reaching long-term contracts that ensure the stability of employees' roles and the company's costs. Pratt & Whitney, as both an OEM and a top-tier supplier, has shorter contract cycles than several of its corporate cousins, resulting in more frequent cycles of contentious contract negotiations. Following in the footsteps of Boeing's 4-year agreement with its own International Association of Machinist employees, Pratt & Whitney's employees and management could focus more exclusively on improving an already impressive corporate resume (Gates, 2011). Other companies have taken this concept even further. Spirit AeroSystems, the world's largest aerospace Tier-1 supplier, secured a 10-year contract with its Kansas- and Oklahoma-based IAM-represented employees and an unheard-of 12-year contract with its IAM employees in North Carolina (McCoy, 2012). This type of labor stability would be a significant competitive advantage for any company.

## Chapter 6.2 – Lessons Learned

This chapter highlights the most crucial lessons and experiences. Please note that this chapter is not an exhaustive review of the conclusions drawn throughout this thesis. While all the lessons described below are a crucial component of the project, I have arranged them in descending order of importance using my experiences during the project.

### *Chapter 6.2.1 – Importance of Communication*

When I began the project, I believed that if I properly analyzed the capacity situation, worked with the engineering team to develop a new floor plan, and successfully facilitated the transformation of the Small Components Cell, 80% of the project would be complete. The remaining 20%, I thought, should be dedicated towards methodically developing a vision and sharing that vision with the team. I was sorely mistaken. In reality, the ratios should be reversed. The most important aspect of the entire project is building a vision of what the Small Components Cell will be, why the transformation is necessary, and how the changes will improve the employees' daily working environment.

This was a distinct challenge that I frequently mishandled. Encouraging the team to recognize the direct benefits of the project and to take ownership of the transformation is the ultimate goal. There are several approaches that yielded significant improvements throughout the course of the project. The first is to get the team more directly involved in the floor plan itself. In weekly meetings, different groups of employees had the opportunity to discuss the proposed layout. Soliciting opinions on machine placements, the location of commonly used tools, and improvements to the status quo helped to get the team more involved in the project. One of the most rewarding moments developed when team members examined the floor plan, asked if they could improve access to point-of-use tooling by moving some cabinets, and immediately implemented their change. This is the type of environment most conducive to effectively transforming the area.

The figure below provides evidence of how this lesson was learned. The importance of communication is clearly shown in Figure 76. Several factors contributed to the spike of union grievances in July. Some were caused by legitimate contractual violations resulting from my own ignorance of the proper procedures. Others, however, were driven by poor communication regarding the planned changes in the Small Components Cell. Initial floor plans were developed with the help of the engineering team, and the plans were presented to the cell as fait accompli.

As many team members have directly participated in multiple cell reconfigurations during their time, they felt excluded from the decisions that would have a substantial impact on their working conditions. Opposition to the plan was swift and understandable.

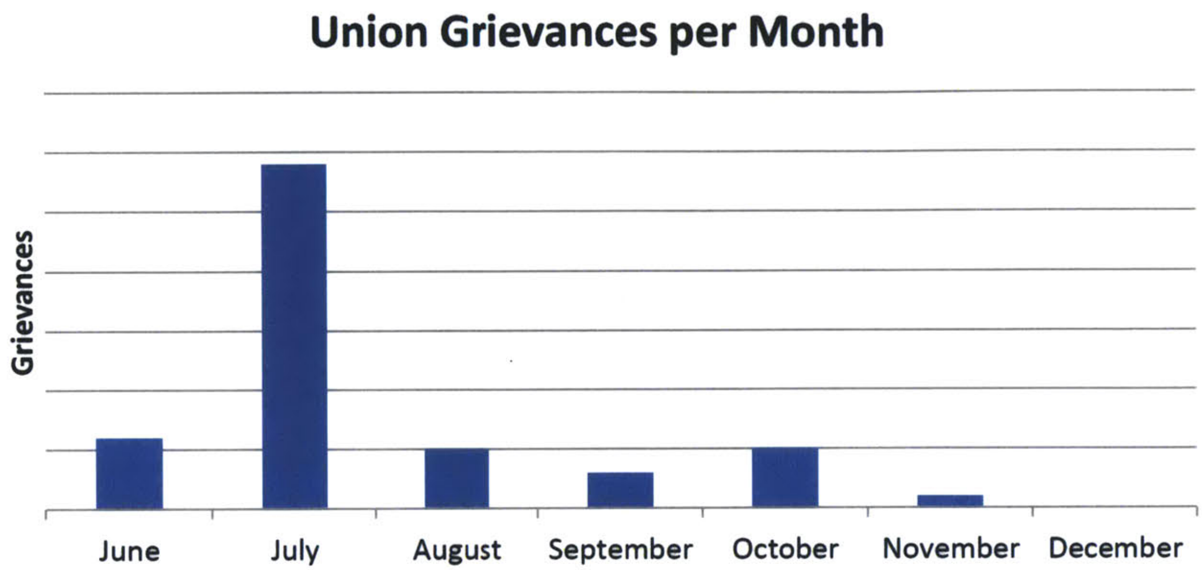



Figure 76: Union grievances by month during the course of the project. A union grievance is a formal complaint by an hourly employee that a portion of the collective bargaining agreement has been breached. Union stewards, the employee, and members of management then meet to discuss and solve the problem.

The second approach which improves the chances of project acceptance is to frequently discuss the cell's performance with the team. Noting the improvement in cost of rework metrics month-over-month, especially when the Small Components Cell resembled a construction zone shows the team that their efforts are highly visible. Regularly discussing key metrics aids in understanding the context for the transformation and how the team is making progress toward the goals. Focusing on how these goals will directly benefit the team is crucial. It helps to point out that reducing queue time, improving on-time delivery, and improving EBIT metrics will permit Pratt & Whitney to bring additional work to Connecticut with local new program development as well as additional repair opportunities. Although I entered the project thinking the goal was to transform the physical cell, the true challenge is to align the workforce with the project.

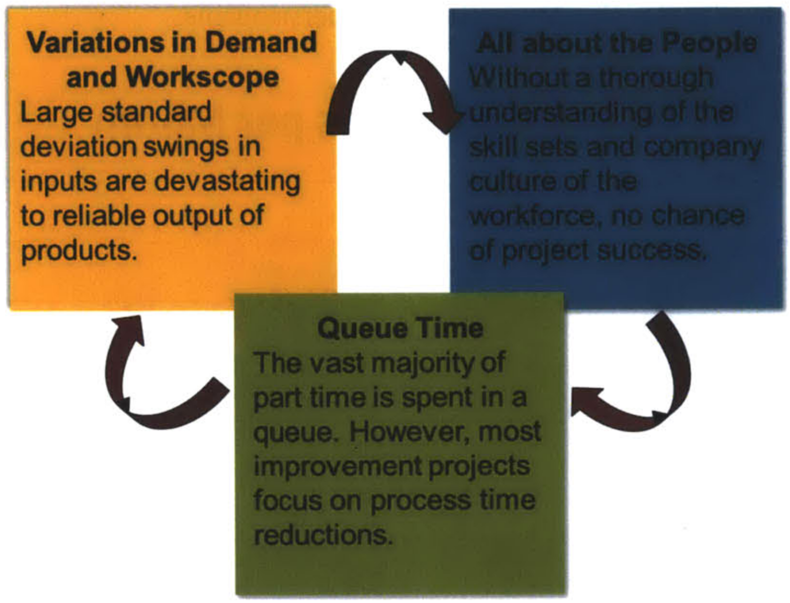



Figure 77: A summary of major lessons learned throughout the project.

*Chapter 6.2.2 – Organizational Boundaries*

While the two previous chapters discuss personal leadership lessons and quantitative takeaways from within the Small Components Cell, this chapter focuses on interactions between the Small Components Cell and support organizations, as well as general thoughts on the working environment.

An important lesson learned relates to the need for continuous communication and frequent follow-up to keep projects moving. For example, the process of moving a piece of equipment requires several organizations (represented in different colors in Figure 78) to seamlessly hand off tasks. Though seemingly trivial, this coordination or lack thereof has a powerful effect on the project's progress. Good communication results in pieces of equipment going through this process in less than 18 hours, a situation that became much more frequent as the project matured. Earlier equipment moves were fraught with missed transitions, complicating the return to production readiness and sowing hard feelings between the different organizations. This was remedied through frequent status updates and discussions on the floor with the relevant parties. It is an easy solution, but one that can prove quite time-consuming. It is time well spent.

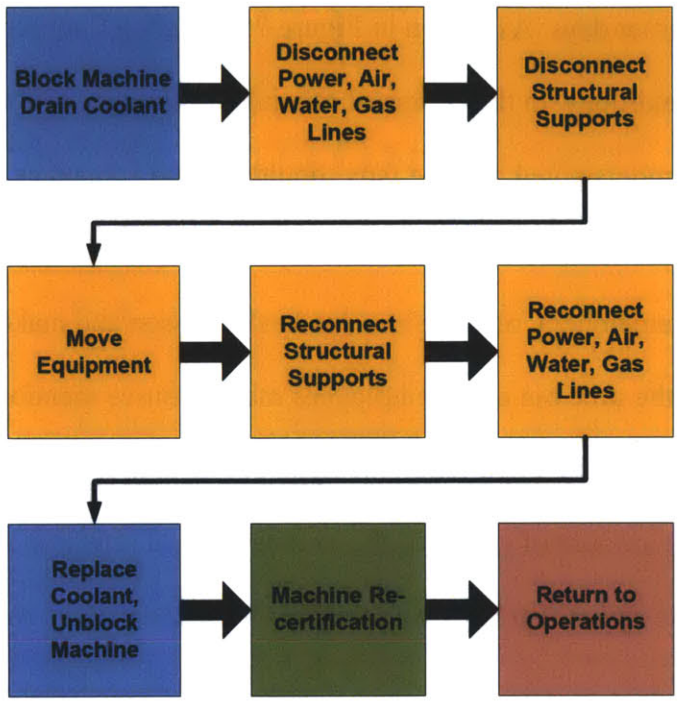



Figure 78: Process steps to move a piece of equipment.

*Chapter 6.2.3 – Attention to Details and Promise Integrity*

This chapter discusses two of the most fundamental leadership lessons: an attention to detail and promise integrity. Colonel D.A. Sims, U.S. Army, once related a story that strongly resonates with me. One of then-lieutenant Sims' soldiers approached him with a paycheck problem. Engrossed in writing a report, then-lieutenant Sims dismissed the soldier and returned to his report. A veteran staff sergeant questioned lieutenant Sims, noting that the paycheck issue was likely the most pressing concern in that soldier's life since he was willing to approach his lieutenant directly about the matter. Colonel Sims reflected on this, saying "Know your troops.

Addressing their concerns promptly shows that they matter to you and that you stand with them" (COL Sims, 2012).

The East Hartford facility does not have air conditioning, and large fans help to circulate the air during hot summer days. As shown in Figure 79, the shop floor temperature has a direct impact on working conditions. In the course of moving the equipment in the Small Components Cell, several team members noted that the fans should be repositioned as well. With other things in mind, I made a note of their concerns and focused on other aspects of the restructuring for that day. Only later did I remember Colonel Sims' leadership lesson and make plans to re-allocate the fans. It was winter at the time but many employees made positive mention of the fans during the following weeks. A seemingly small thing, this type of attention to detail and follow-up generates a significant amount of goodwill. Remembering and acting upon many of the team's suggestions is a simple action that helps align the team and the project very effectively.

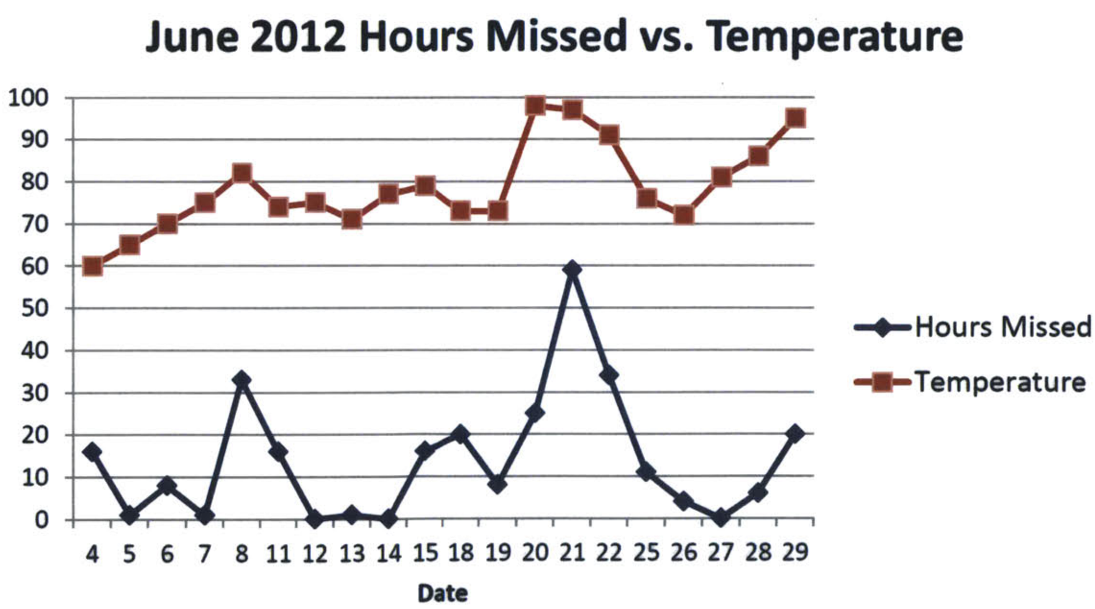



Figure 79: Shop floor temperature vs. hours missed in June 2012. Chart courtesy of Trae Jennette, Pratt & Whitney intern, summer of 2012.

These chapters outline my recommendations and several of the lessons that I learned during the course of the project in the Small Components Cell. The following chapter summarizes the project and concludes the thesis.

**Chapter 6.3 – Conclusion**

This thesis discusses the challenges involved in developing capacity plans and the transformation of the Small Components Cell in Pratt & Whitney's Connecticut Stators and Components business unit. It analyzes the differences between a job-shop and a lean manufacturing flow line from several different perspectives, including queuing theory, and concludes that a lean manufacturing flow line offers several advantages to the cell's operations. Several chapters show the improvement in EBIT performance and large reduction in the cost of rework. On-time delivery failed to improve during the course of the project owing to the machine down time caused by the transformation and the unexpected demand and product mix variations in the final three months.

There are several additional opportunities for improving cost and on-time delivery metrics. A capacity planning model highlights several different scenarios based on the demand and product mix variations experienced during the course of the project. It can be used to accommodate future changes in demand and product mix to result in improved on-time and cost. The model shows that certain product mixes can dramatically affect the required headcount, and also enables management to appropriately loan employees to training programs or other cell improvement activities during slow production scenarios. The model is extended to include a case-study design of experiment that examines the most effective methods of increasing inspection capacity, concluding that increasing employee efficiency through training has the largest effect on capacity. Absenteeism, overtime rates, and the duration of breaks are also statistically significant.

Finally, the thesis outlines a training plan that will reduce the dependency of the cell on any individual while minimizing the costs and time needed to complete the training. It concludes with several key managerial and operational lessons learned and recommendations for the future of the Small Components Cell. The project effectively moves the Small Components Cell closer to several principles of lean manufacturing by reducing non-value added part motion, flow reversals, and cell exits, as well as creating several tools that will serve to highlight value added processing steps and managerial decisions in the future.

Throughout the experience, I have learned an incredible amount about leading a team, effectively managing a significant transformation, and conducting a capacity planning analysis in a high-volume, high-variation scenario. I sincerely hope that Pratt & Whitney finds this information useful and continue to be a world leader in the development and manufacture of jet engines.

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