A Three-Pronged Approach Addressing Capacity Concerns in Advanced Turbine Airfoil Coatings

By

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

Master of Business Administration
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ABSTRACT

Following the tragedies of 9/11 in the United States and the ensuing down years for the aerospace industry, there are now signs of a comeback. This increase in demand is causing stress on the operations of many aerospace companies, who reduced operations and cut costs during the slowdown.

This thesis proposes a three-pronged approach to undertake when looking to increase the capacity of an operation. The first step is to start changing the mindset on the shop floor to value all production pieces. The second step is to utilize all the analytical tools (such as Statistical Process Control) available to reduce set-up time and improve the targeted improvement activities of the operation. The third step is to properly evaluate the costs of purchasing new equipment and comparing that with potential alternative technologies. The proper utilization of these steps requires a thorough understanding of the organization's culture and how these change initiatives impact the relevant stakeholders. Without this organizational understanding, the chance of successfully meeting the increased customer demand is reduced.

A case study was performed using this methodology at the Turbine Module Center at Pratt and Whitney. A potential way to change the mindset of the operators on the floor was identified surrounding the qualifying of machines to run a given part. Then, by using a more rigorous SPC program, a significant amount of wasted capacity was identified and the potential gains were mapped out. Then assuming that the implementation of the previous two-steps did not yield enough of an improvement to cover the missed demand, two alternative technologies were evaluated to determine what kind of equipment to purchase. This three-pronged approach will ensure that the organization can meet their expected demand long into the future.

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1 Introduction

After many slow years following the 9/11 tragedies, the aerospace manufacturing industry is starting to see a comeback. This increase in demand has forced many manufacturers to reevaluate their production plans going forward and figure out how their operation can expand in capacity to meet this demand while still remaining true to their recently implemented "lean" processes. Pratt and Whitney, a division of United Technologies Corporation, is in a position where it is dealing with this challenge. Demand for many parts is exceeding the current capacity of operations to deliver them. Therefore Pratt and Whitney has started a number of initiatives to increase their capacity to manufacture advanced turbine airfoils.

This thesis work looks at finding ways to relieve a capacity constrained operation. While the case study provided in this thesis is in the aerospace industry, the methodology and approach should be transferable to other large, capital-intensive production operations. The approach taken here was three-pronged: first the impact of small dollar-value changes were examined that were designed to start changing the way the employees think about capacity; the second prong involved developing the data collection capabilities of the operation and utilizing this data to drive operational improvements in shift set-up time; the third leg in dealing with capacity shortages is the purchase of new equipment. An example of a thorough cost comparison between competing production technologies is the primary tool supporting this step. A key part of this thesis is that the three prongs are laid out in cost order, as in the least expensive step is done first with the most expensive step being the final one. This thesis will also look at some of the reasons why American companies often approach capacity shortages by looking only at purchasing new technology instead of the host of options available to increase real capacity. This thesis also examines the potential positive and negative consequences of a strong culture on the implementation of the changes prescribed here and elsewhere in the lean ideology.

The thesis proceeds as follows:

Chapter 2, Background on Aerospace Industry and Pratt and Whitney provides a brief overview of current trends in the aerospace industry and takes a closer look at Pratt and Whitney, a division of United Technologies Corporation. Within Pratt and Whitney, the research for this work was conducted in the advanced coatings area of the Turbine Module center (TMC). The final sections in this chapter introduce the reader to the TMC and some of the basic technologies found in advanced coatings.

Chapter 3, Problem Statement and Methodology is where the basic problem this thesis addresses is defined and described in detail. The capacity problem facing Pratt is first examined and then the author's own experiences dealing with the variability of production at the TMC are described. This chapter also makes the connection between what is happening at Pratt and Whitney with the current literature on lean transformations. The final section of this chapter discusses the basis of the three-pronged approach to solving this problem.

Chapter 4, A Cultural Snapshot of the Turbine Module Center first introduces a framework with which to analyze the culture and then examinea the Turbine Module Center. This includes breaking down the Artifacts, Espoused Beliefs and Values as well as the Underlying Cultural Assumptions found in the TMC.

Chapter 5, Changing Mindsets: Building the Base For Radical Capacity Improvements details the first aspect of the three-pronged attack on capacity constraints. This chapter first details the financial merits of finding an alternative to cutting up production parts for quality testing. The second half of this chapter proposes a solution to this problem using the cultural elements of the TMC to be successful.

Chapter 6, Data Collection and Statistical Process Control shows the potential impact on operations from better process control. This chapter looks at not only basic quality improvements, but also on the time and subsequently the capacity savings that can be achieved through proper SPC use. One work cell from Advanced Coat is offered as an example of potential gains on time wasted in set-up functions.

Chapter 7, A Cost Comparison of New and Old Coating Technologies describes the analysis used to evaluate the potential of a new coating technology as a replacement to the current technology.

Chapter 8, Conclusions summarizes the results of the thesis and offers recommendations for future studies at Pratt and Whitney to better understand their capacity issues. It also expresses how the approach described here can be used to address capacity shortfalls found in other companies.

2 Background on Aerospace Industry and Pratt and Whitney

This chapter starts off with a brief background on the current state of the aerospace industry. It then narrows down to describe United Technology Corporation, a large conglomerate that is active in the aerospace sector. The next section describes the business of Pratt and Whitney, a large division of UTC that is responsible for the design, manufacture and support of aircraft engines. Continuing down into more specific areas within Pratt and Whitney, the next two sections detail the business of the Turbine Module Center, the division at Pratt and Whitney that produces turbine airfoils for use in large airplane engines and the advanced coatings areas of the TMC. The final section in this chapter introduces an important cultural framework that will be used to determine how best to approach future capacity problems at Pratt and Whitney.

2.1 The Aerospace Industry

The aerospace industry is well known as a highly cyclical business. Airplanes are large expenses for companies to purchase and as a durable good, tend to be vulnerable to the ups and downs of the general economy. The aerospace industry is typically divided into three large segments; military, commercial and space. The Standard and Poor's estimate for total earnings of the three segments was roughly $465 Billion in 2004[1].

Boeing and Airbus dominate the commercial portion of the aerospace market. They are the only two players in the large commercial aircraft segment. Boeing had revenues of $21.3 Billion in 2004 and Airbus had revenues of $27.1 Billion in 2004. The business and regional jet market is made up of smaller players such as Embraer, Bombardier, and General Dynamic's Gulfstream business. Standard

[1] Friedman, Robert. "Industry Surveys: Aerospace and Defense." November 3, 2005, pg 8.

and Poor's estimate this market to have revenues of around $16.1 Billion in 2004. These two segments sell new aircraft to the roughly 500 different operating airlines in the world today. There is also a significant market for the maintenance, repair and overhaul (MRO) of aircraft for the airlines and defense industry. This portion of the market took in roughly $37 Billion in 2004 and is of increasing importance for OEM suppliers who are trying to grow profits.

Another segment of the commercial market that creates a lot of value is the engine market. The three major players in the jet engine market are GE, Rolls-Royce, and UTC's Pratt and Whitney. Total revenue for this segment was over $38 Billion and operating margins average around 13% between 2000 and 2004. However new engine development has gotten more expensive as the large engines get more complex and the ability of the primary customers to pay has forced serious cost concessions. This has led the "big three" to experiment with joint development of new engines to offset the costs of engine development and has put more of a focus on the service contracts that can accompany a new engine sale.

Recently the commercial airline sector has started to rebound from the post 9/11 slump. The sales of commercial aircraft for 2005 were expected to be close to 20% higher than in 2004[2]. However increasing competition and the weakness of the major commercial customers (US airlines) has contributed to the deterioration of profit margins which has increased the overall volatility of the market.

With the recent military operations in Iraq and Afghanistan, military spending has helped pick up some of the slack created by the September 11th downturn in the commercial aviation industry. The military spending growth has been primarily due to the repair and maintenance of the current fleet. As far as future growth, the most important program is the F-35 Joint Strike Fighter (JSF) for which

[2] Biesecker, Calvin. "Aerospace Sales to Hit Record This Year and Again Next, AIA Says." Defense Daily: NA, December 15, 2005.

Pratt and Whitney has the primary engine contract and GE and Rolls-Royce have a joint venture producing the secondary engine. However there have been some reports of the military dropping the second source and going with Pratt as the sole provider of the JSF engine. There are some estimates that the US will purchase close to 4,000 airplanes over the next 30 years and with lucrative MRO contracts, this program is valued at well over a billion dollars. The table below shows the increasing value of maintenance contracts and the range of military spending on procurement:[3]

	2000	2001	2002	2003	2004	2005
Procurement	$61.5billion	68.9	68.4	84.5	86.6	81.3
Maintenance	$127.6billion	131.7	160.3	188.2	187.7	161.3

The third market segment included in the aerospace industry is the space industry. The space industry is focused on commercial satellites and military/government space programs. There is some overcapacity in the commercial launch sector and that is keeping future growth from getting too high. The revenue from 2004 was roughly $18.8 Billion and expected growth is expected to be around 5% for the foreseeable future.

2.2 United Technologies Corporation (UTC) Background

United Technologies Corporation is a global manufacturing company with operations in diverse industries such as elevators, air conditioners, fuel cells, alarm systems, jet engines, aerospace systems and helicopters. The companies that fall under the UTC umbrella are Pratt and Whitney, Hamilton Sundstrand, Sikorsky, Otis, Carrier, UTC Power and their newest acquisition UTC Fire and Security (which is made up of primarily Chubb and Kidde). For fiscal year 2005, UTC had revenues of $42.7 billion of which 64% was from the industrial businesses and 36% from the Aerospace companies

[3] Friedman, Robert. "Industry Surveys: Aerospace and Defense." November 3, 2005, pg 14.

(Pratt and Whitney, Sikorsky and Hamilton Sundstrand).[4] This was a 14% increase over revenues in 2004. In 2005, UTC employed 220,000 people with 67% of them based outside the United States. UTC was also awarded Fortune Magazine's Industry Champion Award as America's "Most Admired" aerospace and defense company for the 6th straight year in 2006.[5]

2.3 Pratt and Whitney Background

Pratt and Whitney (Pratt) had revenues of almost $9.3 billion in 2005, a 9% increase over their 2004 sales of $8.3 billion.[6] Pratt is a division of United Technologies Corporation that is a worldwide leader in the design, manufacture and service of advanced turbine engines and space propulsion systems. There are now Pratt representatives in over 76 cities and 47 countries around the globe manufacturing and servicing Pratt's engines. Pratt and Whitney has 16,000 commercial engines and over 11,000 military engines in operation today[7]. With this established base, it is no wonder that the aftermarket business (MRO) accounts for over half of Pratt's revenues[8]. Figure 1 shows a distribution of market segments the revenues from 2004 came from.

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[4] http://www.utc.com/profile/facts/index.htm
[5] ibid.
[6] 2005 Annual Report
[7] http://www.pratt-whitney.com/about_facts.asp
[8] 2004 Annual report.

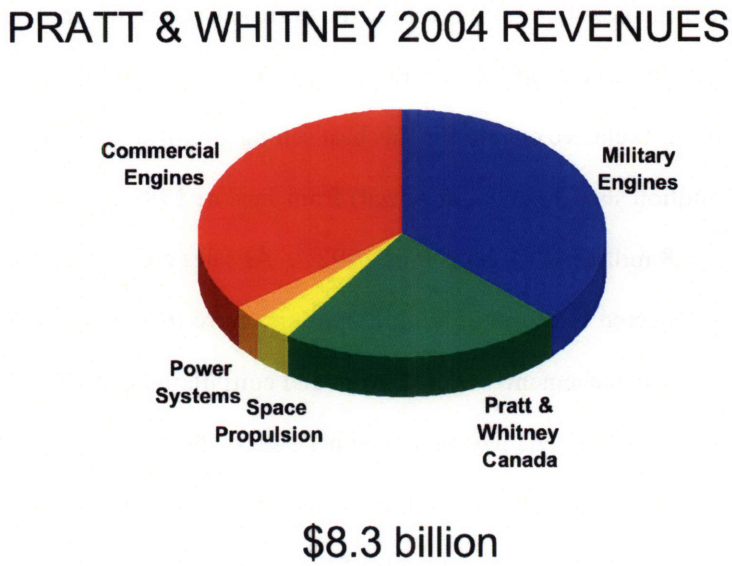

Figure 1: Approximate division of Pratt and Whitney's 2004 revenues[9]

Pratt's early success shaped a lot of what they are working with today. Pratt was founded in 1925 when Frederick Rentschler used the excess capacity at a Connecticut tool manufacturer to make the world's first air-cooled engine. Pratt's "Double Wasp" was the engine of choice in World War II and Pratt and Whitney provided over half the total horsepower used by the entire US military[10]. After the war, Pratt moved on to jet engines with great success. By the end of the 1960's they had a 95% market share of the world's commercial jet engine sales (not including the Russian bloc countries) and over 50% of the US military market[11]. In achieving such market dominance, Pratt and Whitney excelled at mass-producing extremely complex engines. To help achieve this, functional silos were built to warehouse all the technical knowledge needed to make advanced engines.

Pratt's market dominance started to come to an end in the late 1980's and early 1990's. In 1984, after a slow response in fixing operational problems in the engine used in the Air Force's F-16, the Air Force decided to dual source the engine with GE. Pratt also misjudged the market for large single-

[9] Estimates from an internal presentation 8/31/05.
[10] http://www.pratt-whitney.com/timeline_1920.htm
[11] Womack, James and Jones, Daniel. *Lean Thinking*. New York, New York, Free Press, 2003, pg 160.

aisle aircraft. When Boeing created the new 737's, sales took off. Pratt had no engine for the 737, choosing instead to develop engines for large double-aisle aircraft. This let a joint venture between GE and Snecma in France develop the exclusive engine for this best selling aircraft. The amount of work that Pratt had fell from 11 million shop hours (annualized) from June of 1991 through July of 1992 down to a annualized rate of 8.8 million in December of 1992[12]. As sales continued to falter, the amount of work for 1994 was expected to be only 5.4 million hours, more than a 50% reduction from 1991. Change was needed. New management was brought in and consultants with experience at Toyota were hired away from GE to make the changes that were necessary. Pratt could not guarantee anyone, hourly or management, a position once the changes were implemented. The number of senior operations managers was cut in half, and half of the remaining managers were replaced. New UTC President, George David, worked out an agreement with the union to reduce headcount from 51,000 to only 29,000 workers. As is well documented in the book by Womack and Jones, *Lean Thinking*, the new management at Pratt and Whitney were able to make the necessary changes and reduce the costs for Pratt to deliver new engines to customers. Work was organized into Product Centers for the part of the engine being worked on, "monuments" were removed from the grinding lines for making turbine airfoils and a continuous flow line was established in final assembly. Operating profits were -$283 million in 1992 and rebounded to $530 million in 1995, even as sales remained flat.[13] Revenues for Pratt and Whitney have slowly improved and operating profit has increased dramatically, maxing out at 17% in 2001.

[12] ibid, pg 169
[13] ibid, pg 187

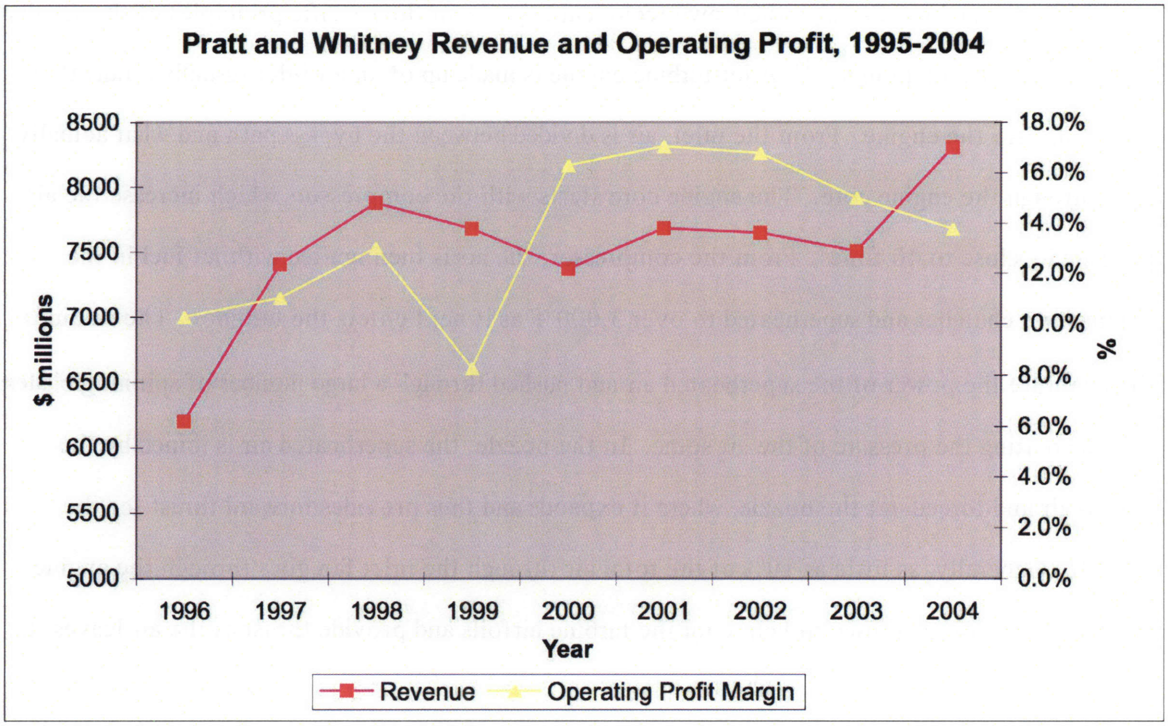

Figure 2: A comparison of Pratt and Whitney's Revenue and Operating Margin[14]

As can be seen in the above graph, starting in 2004, revenues have increased by almost 11% from 2003, thus showing the start of the aerospace recovery being felt at Pratt. However, in dealing with this new growth, Pratt has been unable to maintain their large operating margins that they maintained during the downturn. This is in part due to competition, but it could also be due to a steady increase in costs trying to keep up increasing demand without appropriate system support.

2.3.1 Introduction to the Jet Engine

Pratt and Whitney started their business making piston engines. After World War II, they made the technological leap into making jet turbine engines, the technology currently in use. Pratt was able to

[14] Compiled From UTC Annual Reports

make this change by refocusing their own technical experts on the specific principles of the science required to make a jet engine.[15] A jet turbine engine is made up of an air inlet (usually a fan) that forces air into the engine. From the inlet, air is divided between the bypass path and what actually goes through the engine core. The engine core starts with the compressors which increase the air pressure by close to 40 times. From the compressor, the air is then ignited with jet fuel in the combustion chamber and superheated to over 3,000°F as it next enters the turbines. The turbines then capture the power of the superheated air and pushed through a large number of spinning blades, thus decreasing the pressure of the air some. In the nozzle, the superheated air is joined by the bypass air and forced out the nozzle, where it expands and thus provides forward thrust for the aircraft. Generally, as little as 10% of the total air through the inlet fan goes through the engine core. The bypass air is used to help cool the turbine airfoils and provide thrust as the air leaves the nozzle.[16]

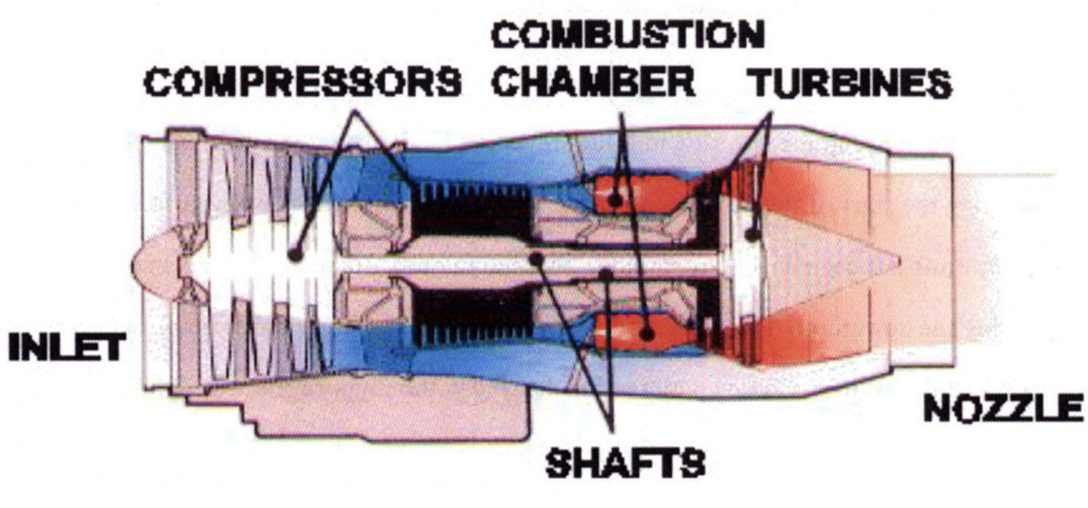

Figure 3: A generic jet engine cutaway[17]

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[15] Womack, James and Jones, Daniel. *Lean Thinking*. New York, New York, Free Press, 2003, pg 159.

[16] Information compiled from GE Aviation Engines 101 and from Wikipedia jet engines. http://www.geae.com/education/engines101/index.html, http://en.wikipedia.org/wiki/Jet_engine

[17] http://www-psao.grc.nasa.gov/Reengine/tfbasics.html

Most of the power from an engine comes from the turbine section. The hotter the air is able to get in the combustion chamber, the more energy the turbine airfoils are able to extract to power the craft. The turbine section is made up of blades, which rotate around the shaft, and vanes, which are stationary around the shaft. That makes keeping the turbine airfoils below their melting point a key factor in both the power and efficiency of an engine. This is done primarily in two ways. First, the airfoils are hollow and bypass air is pushed through the airfoils in intricate patterns to draw away heat. Turbine airfoils are also coated with thermal barriers which further protect the underlying metal of the airfoil. After long use, the thermal coating will wear down and need to be replaced. The longer an engine can go before needing to an overhaul, the more valuable it is for the customer. An engine will need to be overhauled many times over the course of its life, which is why the overhaul market for jet engines is so lucrative. Many engine manufacturers will sell the engine at a loss so they can make money back replacing worn parts and refurbishing the turbine airfoils. A picture of some turbine blades and vanes is in Figure 4.

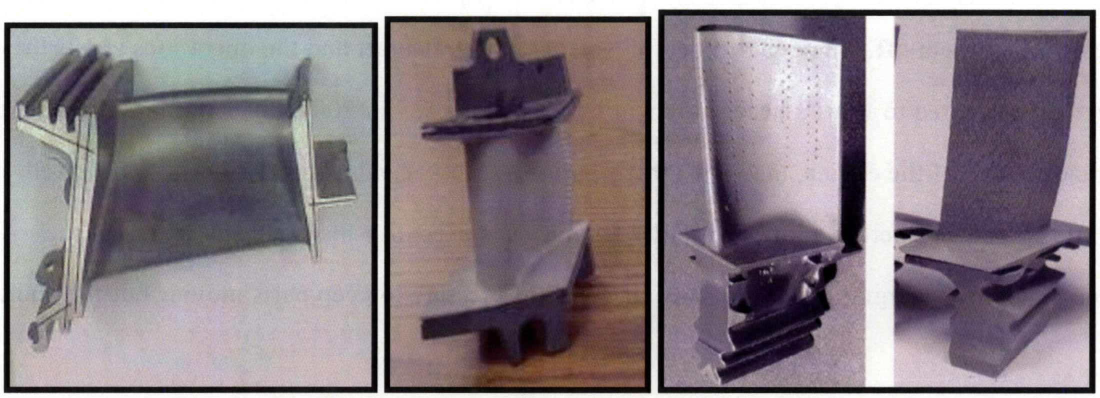

Figure 4: Sample Turbine Airfoils. The left two are vanes and the right two are blades. The left two from Pratt and Whitney, and the right two from NASA files[18]

[18] http://www.grc.nasa.gov/WWW/5000/featuredinnovators/mackay.htm

2.3.2 Introduction to the Turbine Module Center (TMC)

The Turbine Module Center is the Product Center that designs and manufactures turbine airfoils. It is also the focus of one of the chapters in Womack and Jones' *Lean Thinking*. In *Lean Thinking*, the TMC is located in North Haven, Connecticut in a large room. Ed Northern was brought in to manage the TMC in 1993 to get costs back under control and spread the use of "Lean." To get an idea of Ed Northern's leadership principles, when asked if he was the manager brought in to shut the plant down (a likely scenario considering how unprofitable they were in 1993), he replied, "They could bring in anyone to close the plant down. I'm here to keep it open."[19] By 1996, North Haven was producing low cost/high quality airfoils in an immaculate, but old, building. In speaking of Ed's leadership capabilities, a supervisor under him stated that Ed was "one of the most inspirational and passionate leaders I've ever worked for." Under this leadership, the improvements that they made allowed Pratt to start competing for more overhaul and repair business. He did this since as lean was introduced and fewer people were needed in the operation, he needed something new for them to do so as not to lay them off. Since that time, Ed Northern has left Pratt and the operations at North Haven were relocated to Pratt's headquarters in East Hartford, CT in 2001. Since turbine airfoils are the "razor blade" of the engine, much of Pratt's business success can be directly linked to how well the TMC operates. There is a lot of visibility from UTC's executive management into what the revenues and profit margins are at the TMC and a lot of pressure to keep parts moving out the door.

Today, the TMC is made up of four primary business units. There is the Blades BU (divided into military and commercial), the Vanes BU (again divided into military and commercial), Turbo-tip/Vapor Coat BU and the Advanced Coatings BU. The blades and vanes business units are contained on opposite sides of an aisle in one large building, with the vapor coat business unit located with the blades. An adjacent building contains the advanced coatings business unit. The typical path for a blade would be for the blade to come in from a supplier and go through some initial grinding steps.

[19] As recounted in a personal interview with a TMC supervisor working at the TMC in 1996.

After grinding, the blade is sent to have a vapor-coat put on it, then to advanced coatings for a ceramic or metallic coating, then to hole drill (to manage the cooling airflow) and final test before being shipped to assembly. For a vane, the flight path is from the supplier to the grind line, to advanced coatings and then back for hole-drilling before final test and shipment to assembly. As can be seen from this description of the flow path, each major operation for a blade or vane is contained in its own business unit. This is done to help build expertise in each process and to better manage the flow through each stage of production. Figure 5 shows the general layout of the Turbine Module Center.

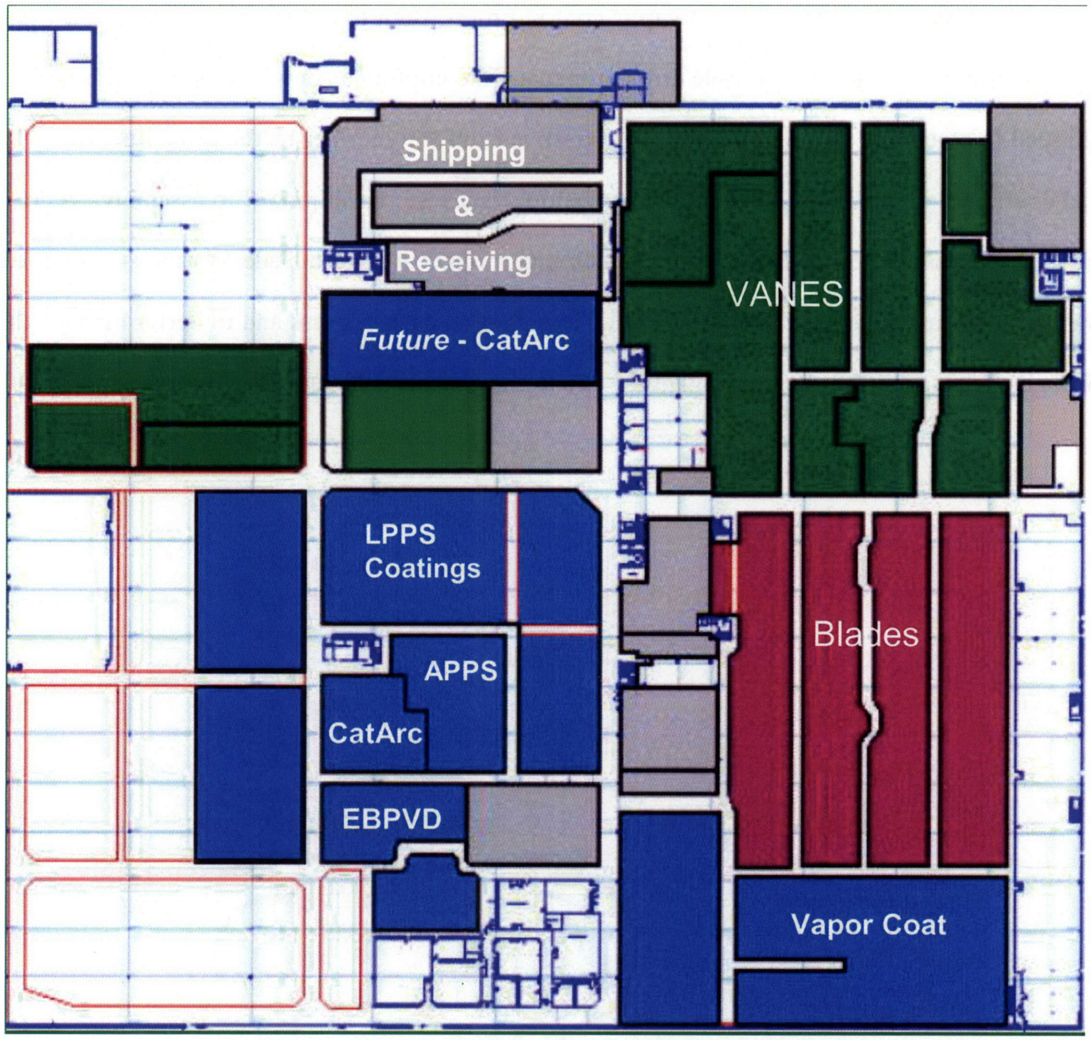

Figure 5: Physical Layout of the Turbine Module Center in East Hartford. LPPS, APPS, CatArc and EBPVD are all advanced coatings.[20]

2.3.3 Advanced Coatings For Turbine Airfoils – BU241

The advanced coatings business unit at Pratt and Whitney's Turbine Module Center was where most of the research for this thesis was conducted. It is composed of 4 different coating technologies.

[20] From an internal TMC presentation, 2005.

Low Pressure Plasma Spray (LPPS) – This is a coating technology that has been used on turbine airfoils since the early 1980's. It operates inside a vacuum and applies a metallic coating to the part. LPPS can be used as a bond coat to help prevent additional coatings from slipping off the airfoil, or it can be used as a lesser quality thermal/corrosion barrier. The substrate used for the coating is a MCrAlY based material. Both turbine blades and vanes receive LPPS coatings. This is usually the first step in the advanced coatings process before a part goes and receives additional coatings. The average age of an LPPS coater was roughly 19 years.

Air Plasma Spray (APS) – APS coatings are performed at normal pressure levels and apply a ceramic coating to the part. This coating is only applied to turbine vanes. The average age of an APS coater at press time is 23 years.

Cathodic Arc (Cat Arc) – These are small, modular coaters that can be configured to deliver either metallic or ceramic coatings. These coaters are recent additions to Pratt's arsenal of coaters and are used exclusively with turbine blades. The average age of the Cat Arc coaters is 5 years.

Electron Beam Physical Vapor Deposition (EBPVD) – EBPVD is a vacuum based process for applying a ceramic based coating. The average age of an EBPVD coater is 15 years.

There are approximately 60 individual parts that pass through the advanced coatings area. The point of entry for parts entering the business unit is through LPPS coatings, which forms the base coat upon which other coatings are applied. A base coat is needed to ensure that a ceramic coat can bond correctly with the part. All of these machines, with the exception of the Cat Arc coaters, are extremely large monuments. Each part coming in requires different tooling and different coating programs to successfully coat an airfoil. This, combined with the average age of many of the machines, makes the changeover of parts a time consuming task. It also limits the effective capacity available for each process. As monuments, these machines are also extremely expensive to replace and maintain.

In advanced coatings, a production run is usually between 30 and 80 airfoils, depending on the size of the engine for which the airfoils are destined. It can also take anywhere between 4 minutes to an hour to coat a blade or vane, depending on the size of the airfoil and the type of coating being applied. Most operators prefer to run a batch for an entire shift so they can avoid changing over the coater during the shift. However this isn't always possible and a lot of time is taken preparing a coater to coat a new part. Chapter 6 suggests a plan to improve the changeover time between shifts, and also between in-shift changeovers.

2.4 Chapter Summary

This chapter discussed the basic background information needed to better understand the following chapters. Looking at the aerospace industry, it is clear that the market is on the upswing of the business cycle. This has created difficulties for companies that cut capacity during the downturn in meeting customer demand in a timely manner. The following chapter will show that one place this could be seen up close is at Pratt and Whitney's Turbine Module Center. Then it will discuss what can be done to solve this problem for the advanced coatings area that was introduced in this chapter.

3 Problem Statement and Methodology

The major problem this thesis is designed to address is the current capacity shortfall facing the TMC. Information was collected from a series of informal and formal interviews at Pratt, as well as the author's own observations taken from spending over six months at the TMC including one month in a supervisory position. The first two sections of the chapter describe problem and how it is impacting the operation of the advanced coatings area. The final section puts it all together and proposes a three-pronged approach to address those challenges.

3.1 Capacity at Pratt

For the reasons detailed in the previous chapter, demand for engines has been increasing. Pratt and Whitney has seen their share of business increase in 2004 (visible in Figure 2), with the turbine module center receiving more than its share. This is due to the nature of turbine airfoils, the razor blade of the engine. The TMC sees a lot of business when engines are repaired or portions need replacing, not just when a new engine is sold. The ways in which Pratt has attempted to meet this demand has been through working an alternate workweek (increase hours of operation to almost 24x7), temporary vendor assist (outsource excess production to contractors), and putting orders on backorder. The addition of the alternate workweek means that employees work 12 hours on Fri-Sun on two shifts. The major costs associated with this move are that Pratt needs to add the additional labor to staff the other shifts appropriately. This has already been done, although most of the off shifts are staffed at lower levels than the normal weekday shifts. For the vendor assist option, it takes close to 6 months to qualify a vendor for a coating process. These partners also need to be strategically selected so that proprietary Pratt information is not lost to competition. It is also much more expensive on a per part basis to have vendors coating parts that could be done in-house. At this point, Pratt has exhausted all of their potential vendors' capacity. This leaves Pratt with only one option, placing customer orders on backorder. This is not a sustainable option. Not being able to meet their customer needs is what caused the government to source more engines from GE in the 1980's. As can be seen in Figure 6, drastic improvements are needed if Pratt and Whitney expects to close the gap between what demand they can satisfy and what customers are requiring. Closing this gap is the highest priority of the Turbine Module Center at this time.

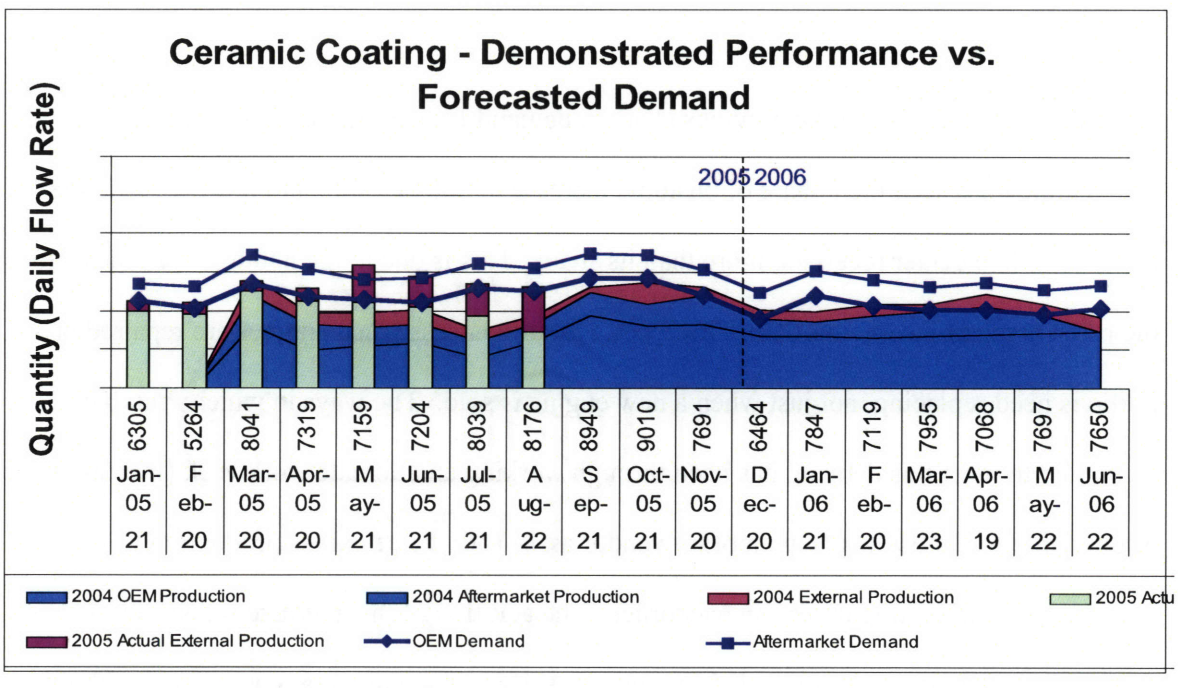

Figure 6: Diagram showing gap in production capacity availability and planned demand[21]

[21] Internal TMC "Gap Analysis" chart, 9/2005.

3.2 Reasons For The Capacity Shortage

Aside from the recent increase in demand following the cutbacks performed during the industry downturn, a major reason for the capacity shortage in the TMC is due to process variability. Looking at the problem from the perspective of an operator on the floor at Pratt and Whitney's Turbine Module Center, you are faced with many different sources of variability. Some common sources of variability found at Pratt are: machine uptime, product quality, demand, and staffing. Coater uptime impacts when you can run a given coater. Variability in product quality impacts how much time is spent reworking parts. Demand variability can be seen in what parts are qualified to run on the coaters and what parts are available to be coated. Chapter 5 will discuss in greater detail the qualification of parts on a coater. Staffing is a final source of availability since the number of people available to run the coaters is tight across the three shifts and any absences can reduce the output of the cell.

In the TMC, Pratt works to an MRP schedule which means a certain number of engine sets' worth of airfoils are due to final assembly on a given date. Raw material is sourced and the grinding cells work on the part and get it ready for being coated. This is a "push" process. In advanced coatings, they look at what parts are available in starting inventory and what parts have been committed to the next stage, and then coat those parts. The ability to meet these commitments is a key factor in evaluating the area, and the area shows room for improvement. Based on having a known MRP system in place, there should be some consistency in how many parts can be coated on a daily or weekly basis. However this is not the case. There is a great amount of variability here that is wreaking havoc on the local supervisors' ability to commit parts on time. The high level of production achieved on certain days (primarily at the end of the month) illustrates what might be possible if Pratt could maintain its focus. One way to help keep that focus at a high level and limit the daily variability in output could be found through better process control. Better process control could not only assist with the variability caused by machine downtime, but also increase the overall capacity by allowing better management of shift and part changeovers. The impact of variability can be seen in the daily output of the APS cell, which has a standard deviation that is 30% of the mean and can be seen in Figure 7. Looking at it on a weekly basis, where daily differences in product mix and maintenance performed should be relatively equal, also shows a high degree of variability. Variation of the weekly output from the APS cell is still 20% of the mean (Figure 8).

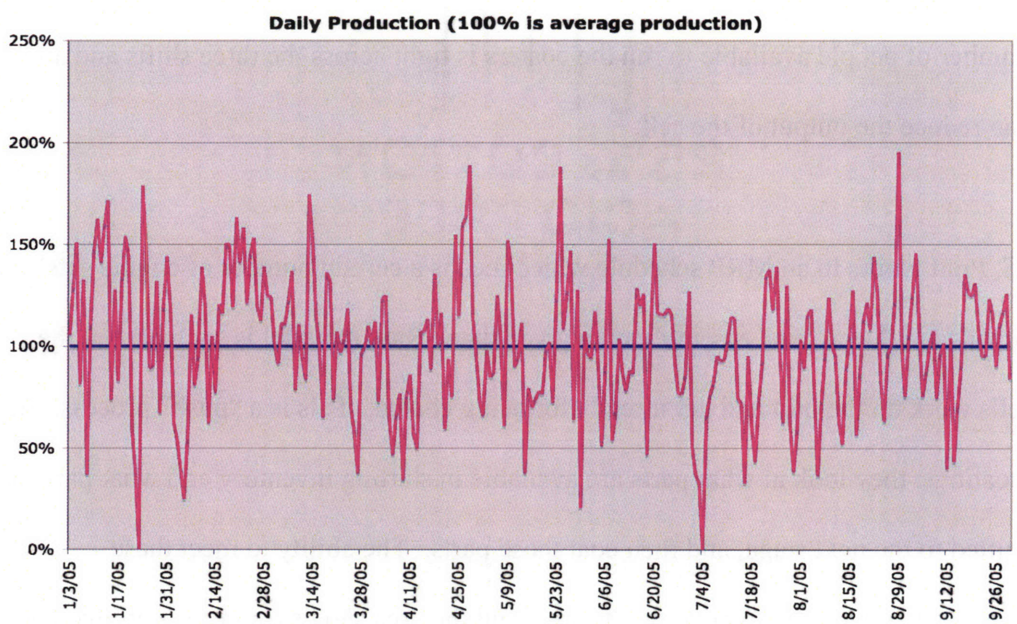

Figure 7: Daily production from the APS cell

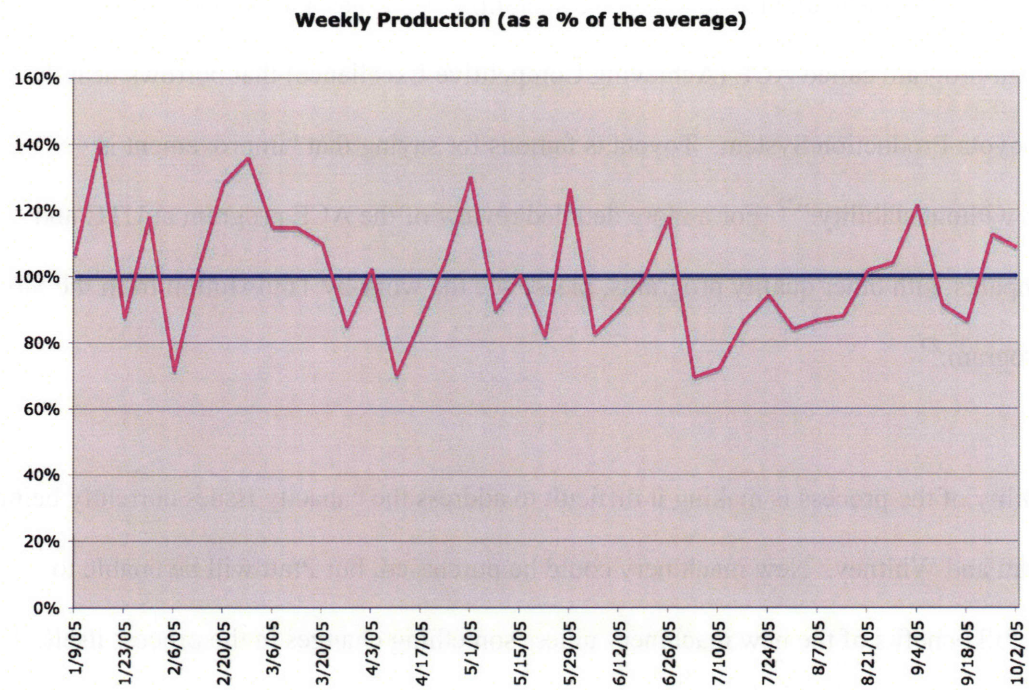

Figure 8: Weekly production from the APS cell

This variability of output from the APS cell is not the result of having not enough parts to work on (although that sometimes does happen). The variability is primarily the result of machine uptime issues. This can be traced to the age of the machines and lack of a consistent preventative maintenance program due to the pressure to get parts out the door. They do try and conduct preventative maintenance and run the developmental parts during the beginning of the month because they know that operations will not give up a working machine at the end of the month due to monthly production targets. But even this usually gets pushed back as long as possible since there are so many backorders still to be processed. There is also some impact on production from the human element; if the machine was down for a day and inventory was building up, the operators tended to work a little faster since there would be more pressure on them to reduce the work-in-process and push parts out. This lack of process stability makes it very difficult to plan ahead and run an effective operation. UTC has a large operational improvement program called ACE (Achieving Competitive Excellence) that borrows heavily from the Toyota Production System. Toyota is famous for saying that "improvement is impossible without stability."[22] For a more detailed review of the ACE program at UTC and how it compares with other quality programs, please see the work by Tom Hutton from the Sloan Fellows program.[23]

The variability of the process is making it difficult to address the capacity issues currently being seen by Pratt and Whitney. New machinery could be purchased, but Pratt will be unable to realize the full benefits of the new machinery unless something changes in the process itself. It was also found that the newer machinery currently in use was not significantly more stable then the older coaters. This suggests that the problem is systematic in nature and can't be solved by the introduction of new equipment alone.

3.3 A Three-Pronged Approach to Address Capacity Shortfalls

The approach developed to address the capacity shortfall at Pratt and Whitney consisted of three major activities. The first activity dealt with standardizing the process of having parts available for laboratory testing and not just using production parts. The second activity was providing a framework for evaluating the overall production quality of a given machine over all the different parts coated. The third activity was the actual financial evaluation of purchasing new coaters.

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[22] Dennis, Pascal. *Lean Production Simplified: A Plain Language Guide to the World's Most Powerful Production System*. Productivity Press, 2002.
[23] Hutton, Thomas. "ACE vs. Six Sigma." Published MBA Thesis. MIT Sloan Fellows Program, Massachusetts Institute of Technology, Cambridge, MA. 2004.

This consisted of comparing a new coating technology to the current technology and each one's ability to economically meet future demand. Each of these activities was designed to work on a different aspect of the capacity problem faced by advanced coatings at the TMC. The purpose of these activities were to 1) change the mentality on the shop floor regarding the value of each part in meeting production targets, 2) improve the information available for evaluating how well equipment meets the production needs of advanced coatings, and 3) finally address the most obvious way to increase capacity, adding new equipment.

One inspiration for the three–pronged approach was taken from the reduction of crime in NYC during the 1990's. During this time, Rudy Giuliani and his chief of police, William J. Bratton, implemented a policy of "zero tolerance" for all petty crime and worked to improve general "quality of life." This meant arresting people for small infractions (subway fare dodging, pan-handling, etc) under the premise that the atmosphere of disorder makes it more likely for larger crimes to be committed. This philosophy was inspired by the work of James Wilson and George Kelling in their article "Broken Windows." This theory states that vandalism "can occur anywhere once communal barriers – the sense of mutual regard and the obligations of civility – are lowered by actions that seem to signal that no one cares."[24] So that if "a window in a building is broken and is left unrepaired, all the rest of the windows will soon be broken.[25]" This has relevance on the shop floor and is clearly visible in the Toyota Production System in the focus on 5S and a clean and orderly work area. It is also important to take this beyond just the appearance of the shop floor, but also to the attitude towards their work itself. If "no one cares" that parts are being cut-up for testing, which slows down the work flow and reduces the yield of

[24] Kelling, George L. and James Q. Wilson. "Broken Windows." The Atlantic Monthly, March 1982, volume 249, no 3, pgs 29-38.
[25] ibid

good parts, then that mentality is likely to expand to other areas of production. That is why it is important to fix that "broken window" as quickly as possible and help the shop floor community police itself in eliminating waste. The "Broken Windows" theory has been widely debated in economics, urban studies and criminology circles including most recently in the book *Freakonomics* by Steven Levitt and Stephen Dubner. They offer a different explanation for the drop in crime throughout the US during the 1990's, which had to do with the legalization of abortion many years before. Which was why the drop in crime was not isolated to New York City or other cities putting the "Broken Windows" theory into practice. This debate shows that the matter is a complex one with no simple answers. However, in translating the ideas onto the shop floor, there is less controversy.

The reason for addressing new equipment last was because there were many things that won't get fixed just through the addition of new equipment. Research that supports this assumption can easily be found in management journals such as the Harvard Business Review. One article by Robert Hayes and Kim Clark found that "many companies today are trying to meet their competitive problems by throwing money at them – new equipment and new plants. Our findings suggest that there are other things they ought to do first, things that take less time to show results and are much less expensive."[26] This is why the purchase of new equipment is proposed as the final stage in solving capacity problems and other, less costly initiatives should be taken care of first. This also ensures that a plant doesn't purchase more equipment than they really need before they really need it. Other lean literature comments focuses on this aspect of things, that using lean techniques allows you to do more with less. In *Lean Thinking* the rule of

[26] Hayes, Robert and Kim Clark. "Why Some Factories Are More Productive Than Others." Harvard Business Review, September-October 1986, pg 69.

thumb given was that converting from "a pure batch-and-queue activity to lean techniques you can eventually reduce human effort by three quarters with little or no capital investment."[27] This leads to greater capacity at a lower cost. However, *Lean Thinking* and other the literature on lean does not address overall capacity planning in any greater detail than that.

3.4 Chapter Summary

Undercapacity for meeting their current demand is a major problem facing the TMC today. The primary factor preventing the TMC from scaling up their current operations to meet this demand is due to process variability. Looking at the capacity problem and the variability in production output indicates the need for a systematic approach to solve these issues. This can be found in the three-pronged approach which is made up of addressing the little issues on the floor before they become large problems, introducing robust process controls and finally looking at the addition of new equipment. The three-pronged approach will be fleshed out in greater detail in chapters five through seven. Before attempting to implement this methodology, it is important to first understand the culture in of the group where these changes will be introduced. The subsequent chapter will introduce a framework for doing this and then analyze the TMC using these tools.

[27] Womack, James and Daniel Jones. *Lean Thinking.* pg 257-258/

4 A Cultural Snapshot of the TMC

Pratt and Whitney has had a long history in which to firmly establish many elements of their culture. There have been many challenges over the years that have reinforced the assumptions that form the basis of Pratt's culture. The Turbine Module Center, as a key division of Pratt and Whitney, has played an important role in establishing those assumptions. This chapter first introduces a framework to examine the culture at the TMC and then uses that to describe the culture in the TMC. We will then use this knowledge in future chapters to see how to implement the three-pronged approach at Pratt.

4.1 Cultural Framework For Implementing Successful Change

A lot has also been written about how culture impacts the success of different change initiatives within an organization. The framework detailed by Ed Schein in the book *Organizational Culture and Leadership* is one that is most appropriate for analyzing the Turbine Module Center at Pratt and Whitney. He breaks culture down into three different levels: Artifacts, Espoused Beliefs and Values, and Underlying Assumptions.

First, to understand how culture will impact a change initiative, it is important to understand what culture is. Ed Schein defines culture as "a pattern of shared basic assumptions that was learned by a group as it solved its problems of external adaptation and internal integration, that has worked well enough to be considered valid and, therefore, to be taught to new members as the correct way to perceive, think, and feel in relation to those problems."[28] Pratt and Whitney, with its long history and successful resolution of many challenges, is likely to have a very strong culture deeply embedded in the corporate DNA. The corporate DNA is made up of the shared assumptions of a group, "with more or less central or governing assumptions driving the system, much as certain genes drive the genetic structure of human DNA."[29]

Artifacts are the visible aspects of the organization. They include both the physical structures and processes within a group. While these are the first aspects of an organization's culture that someone from the outside sees, it is also among the most difficult to truly understand. The example Ed Schein uses is one of the pyramids in ancient Egypt; they are easy to see and experience, but their true purpose is very much a mystery.

The espoused beliefs and values of a group go beyond what is stated in the mission statement or code of beliefs of a company. They are the shared learnings of a group over time that have come to define how a group acts in a given situation. If the shared value or belief continues to be successful in addressing problems, it will cease to be just an espoused belief, but a shared assumption that is taken as the right way to act.

The underlying assumptions of a group are the beliefs that have worked in the past and are now taken for granted and are overwhelmingly the dominant way of acting within a social unit. The basic assumptions of an organization are often the basis for a firm's success over a long period of time and are very hard to change. It is here that culture is at its most powerful. It shows "us

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[28] Schein, Edgar. *Organizational Culture and Leadership.* 3rd Edition, Jossey-Bass, San Francisco, 2004, pg 17.
[29] Ibid, pg 22.

what to pay attention to, what things mean, how to react emotionally to what is going on, and what actions to take in various kinds of situations.[30]"

It is through these three levels of culture that the author will examine Pratt and Whitney and see how the suggested changes can be implemented using selected pieces of the culture to advance the cause. The key objective is to take the cultural aspects that are first seen as barriers to effective change, and model the policy to use the strongest parts of the culture as an enabler of change. The examples illustrated in this chapter were taken from the author's personal experience from working on the shop floor for six months and are typical of the attitude within the TMC.

4.2 Artifacts of the TMC

The artifacts of an organization are all the visible organizational structure and processes. Driving onto the East Hartford campus, which is the home of the TMC, it isn't always clear where everything is. There are some guard shacks scattered around and some gates that require an ID to get through. As an outsider, you need to have someone on the inside give you detailed instructions on where to go. Once you figure out where to go, you won't be able to get into the building without a badge. Now a badge signifies many different things. There are badges that indicate you are full-time employee, a visitor, a long-term contractor, or a daily contractor. And each badge means you can go to different areas within Pratt and you will get treated differently based on the type of badge that you have. The author saw this firsthand by working on the shop

[30] Ibid, pg 32.

floor with both contractor and employee badges. The author started off on a contractor badge and employees were never sure how much they could actually say to the author during interviews. They were also very hesitant and often refused to go into any detail about the processes that they were working on. After spending a month working as a supervisor, where one employee said outright that they didn't have to listen to the author because they had the wrong badge, the author was able to become more of an insider. By the time the author received the badge that indicated they were an employee, it didn't matter because the author was already an insider with that workgroup. If the author had not spent that extra time on the floor trying to help the employees, than the author would not have had any credibility with them and would not have been able to get the feedback that he did. The implication is that the employees do not really trust outsiders and that any change efforts need to come from within.

Office space is another interesting artifact at Pratt. For the most part a supervisor will attempt to secure a desk for their employee close to the rest of that department. However, this usually doesn't work out and open desks are often claimed on a first-come first-serve basis. This results in an unusual layout with a group having a base area near the supervisor but with people usually scattered about the building. In some organizations this may lead to better communication between departments, however in Pratt this seldom happens and people are generally left not knowing the people working around them. The office space itself is generally open with the larger, semi-private cubes for supervisors and managers and a few closed off offices reserved for the higher-level managers. Desk location is indicated with a row and a column number so as to make someone's desk easier to find. However if you were given just a string of numbers indicating the row-column combination and a building and floor code, you would be completely lost as an outsider.

The buildings themselves are fairly industrial and unmemorable from the outside. However, during the fall of 2005 there were a number of buildings on the campus that were designated for demolition and they looked ready to be demolished (ie. broken windows and such). On the inside, there was also an enormous contrast between different areas in terms of quality of the floor operations. Within two business units of the TMC that were housed in adjacent buildings, there was a stark contrast between the operating conditions of the two. The first area that is closest to the offices of the TMC management is the blades and vanes business units. This area is clean, well lit, relatively quiet and air-conditioned. After walking through this area into the next building where advanced coatings is located, it is like walking into another world. If it was a warm day in the summertime, as you walk towards the entrance to the building, you can feel the heat radiating through the door. Your senses are also assaulted by the noise of coaters operating and once your eyes adjust to the darkness, you can see that it is not nearly as clean as the building you just left.

Also, obvious to visitors are the information boards posted on the aisle closest to each work cell. These boards show those passing by what the cell does and shows the results of various metrics pertinent to the area. For the most part these were all up-to-date and current, except in parts of advanced coatings where the lack of an ACE pilot (an hourly worker pushing ACE initiatives on the floor) to fill out these boards caused them to fall behind. Information contained here included status of scheduled preventative maintenance appointments, quality metrics, and other production metrics.

4.3 Espoused Values and Beliefs in the TMC

The espoused values and beliefs of Pratt and Whitney and hence the TMC start with what is listed as commitments in the 2005 Annual Report. "Our commitments define who we are and how we work. They focus our business and move us forward."[31] The commitments listed are Performance, Pioneering Innovation, Personal Development, Social Responsibility, and Shareowner Value. These are common across all of UTC.

The primary tool and methodology for UTC to meet their commitments is through the widespread deployment and utilization of ACE (Achieving Competitive Excellence). ACE is:

- *a philosophy about competitive excellence*
- *an operating system (with tools) for controlling and improving our processes and eliminating waste*
- *the competence, commitment, and involvement of the entire organization to live the philosophy and to apply the operating system to everything that we do*[32]

[31] 2005 Annual Report.
[32] UTC ACE Criteria, version 11.4, February 4, 2005.

ACE assigns different levels that every group at UTC is judged upon. The levels start with Qualifying, Bronze, Silver and finish with Gold. The scores needed to attain a given level get more rigorous every year which make it an important driver of continuous improvement. ACE was first introduced in 1995 and it is still not recognized by the union at the TMC (per the union contract no one has to take part in any ACE events) as something that they are required to take part in.

ACE is heavily influenced by the Toyota Production System and has a deep focus on the customer. It was borne out of the realization that UTC was losing over $1billion from poor quality products and trying to get them to meet the customer's expectations.[33] ACE is focused on process improvement with an equal emphasis on quality and flow. And that "Customers Define Quality" and it is the job of everyone to "Delight the Customer." ACE levels take into account improvement from one period to the next, as well as the overall score in the metric being measured. ACE also requires that everyone at UTC be involved in the continuous improvement efforts required. So even staff and office functions are graded on the ACE scorecard.

Some of the philosophy behind ACE was partially illuminated in an article that quotes a Senior Vice President at Pratt and Whitney:

> *Behind the ACE operation system is a philosophy that focuses not only on process improvement but places equal emphasis on the human element – on tapping the human potential throughout Pratt & Whitney and involving every employee in the company.*

[33] ibid.

Involvement requires sharing data and information across the organization.[34]

An example of sharing data (or lack thereof) can be found in chapter 5. Another example is illustrated through the QCPC process. QCPC (Quality Clinic Process Charts) is supposed to be a meeting that takes place on the shop floor every week to discuss quality issues and what is happening to fix them. It is designed to involve everyone in driving continuous improvement and address any concerns of the line employee. However, for a large part of the year in advanced coatings, they stopped having these meetings. This was due to the backlog of parts that were committed to the customer. Then when they started having the meetings again, they could not manage the duration of the meetings and they went over the allotted time allowance, thus putting the group further behind in meeting their daily commitments. This shows the prevailing attitude in the TMC that the most important thing is to get parts out the door. It is important to identify these espoused beliefs before getting to what the underlying assumptions of the group actually are. It is also an important benchmark that can be used to put the planned change initiatives in language that the entire organization can understand.

4.4 Underlying Cultural Assumptions at the TMC

To understand some of the basic underlying cultural assumptions of the TMC required in-depth interviews with employees of all levels and a full immersion into the daily processes of the TMC. This led to the development of 3 of the basic assumptions that are relevant to this thesis.

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[34] Birch, Doug. "ACE in the Pack: The Winning Edge to Impact Results." MRO Management, June 2003, reprinted on Pratt and Whitney's website.

It was found that the commitments listed in the annual report are well aligned with the culture of Pratt and Whitney.

1. Technological Innovation – Pratt was founded on innovation and has a strong reputation for over-engineering their products. This incremental drive for unique solutions (common in engineering based firms) is seen in examples from *Lean Thinking* where the proliferation of turbine airfoil models that had only incremental performance gains at a significant cost to manufacturability of the part.[35] During one interview, the individual said that Pratt had "the best technology out there, but not always the most cost effective." The TMC is looking for large technological leaps ahead at what may be the expense of continuous improvement. This can be seen through the misapplied use of the term "Kaizen" to describe discrete improvement events. Instead of looking for some of the incremental gains that can be made through small improvements in the process, they seem to be waiting or looking for a large leap ahead. They are also in danger of creating isolated "islands of success"[36] which miss the full benefits of the improvements already made and secondly it often does not reflect the focus of the greater organization.
2. Insider Complex – As illustrated in many of the artifacts listed above, Pratt is a place that values those that work at Pratt and ideas that are developed at Pratt. This can be seen from their development of ACE instead of trying to implement a straight six-sigma program similar to the one developed at Motorola and implemented with great success at GE. This is fairly strong and could even be seen to create problems implementing best practices from other UTC divisions. There is a strong belief that what worked at one

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[35] Womack, James and Daniel Jones. *Lean Thinking*. New York, New York, Free Press, 2003, pg 165.
[36] Murman, Earll, et al. *Lean Enterprise Value: Insights from MIT's Lean Aerospace Initiative*. Palgrave, NY, 2002 pg 6.

division will not be applicable to another since they are different businesses (engines vs. air conditioners for example). This could explain some of the problems the TMC has had in successfully implementing many of the aspects of ACE why it is not fully accepted yet. In a presentation by one manager, they were describing ACE as the "Japanese" way of doing things. This was because the consultants who helped develop ACE were from Toyota in Japan (Shingijutsu). This manager, and many others like him, had still, after almost nine years of ACE, not fully taken ownership of the program because it was partially developed somewhere else.

3. Maintaining part flow is the highest priority – This is one of the strongest aspects of the TMC's culture. The TMC was described in one interview as "aggressive, there is constant motion all the time" and that you "work on whatever is hottest that day according to the manager." For example, at a cross-functional meeting a consultant had organized to help one of the business units within the TMC, he ran into the negative side of this cultural assumption. The meeting was scheduled for 8am but experience had taught them that the operations people would probably be late. When 9:30 came around and still no one had showed up they cancelled the meeting. There was no notice given and the penalty for this was virtually non-existent. The excuse that was presented was that the people from the work cell could not spare the time to sit in a meeting when parts needed to get out the door. It didn't matter that this wasn't the first time it had happened, but since the parts needed to be made, that took priority over any other scheduled meeting with a third party.

This list is not exhaustive, but it does provide a reasonable basis that can be used to make recommendations later.

4.5 Chapter Summary

This chapter first describes Ed Schein's framework for understanding an organization's culture and then uses it to describe the TMC. The underlying assumptions of the TMC are that they value technological innovation, they require things to be developed within their own organization and that above all else, the parts need to get out the door. Understanding these assumptions is critical to the success of any change initiatives and will be the most challenging aspects to successfully implementing the three-pronged approach to increasing capacity.. The next three chapters will describe how to use the TMC's culture to successfully implement the three-pronged approach and increase the capacity in the advanced coatings area.

5 Changing Mindsets: Building the Base for Radical Capacity Improvements

This chapter looks at the first action in the three-pronged approach to address the capacity issues in the TMC. The root of this chapter is based on how relatively small actions play a large role in changing the attitude of a group. We first look at the financial value the use of production parts for destructive testing has on the TMC. Then we look at how to implement a change to using scrap pieces and what the next steps are.

5.1 Financial Costs of Production Parts For Destructive Testing

Currently, a major part of being a cell leader in advanced coatings involves making sure that each part number is qualified to run on a given coater. To qualify a part number to run on a coater, a part from that part family needs to pass a test measuring the microstructure and thickness of the coating. This is done either once a month, if it has passed each of its past five tests, or roughly once a week, if it has failed any of the previous five tests. These tests are a key piece of Pratt and Whitney's quality control program to ensure that the coaters are coating in a manner that satisfies the requirements of the customer. This is how the TMC attempts to control overall quality and qualify certain coaters to run a given part. What currently happens is that the cell leaders need to use production quality parts for these tests because any alternative parts are too difficult to find. This is a problem because the TMC is capacity constrained and when good parts are cut up they cannot be sold to customers. This is also a problem because if the coater is not coating correctly and multiple production parts were coated to pick out a test piece, all of these pieces are lost too. Using an MRP system to schedule test pieces through the process so that they are ready to be coated and used for qualification would also be difficult to implement. The pressure to get all good parts out the door as well as the cost of holding those test pieces in inventory would make it difficult to keep this testing inventory ready when needed.

Another problem with waiting for production parts to qualify a given coater aside from the cost is one of timeliness. The work cell basically coats parts based on the priority sheet given to it at the beginning of the shift and is usually based on what is available. Coaters are qualified to coat specific parts and this qualification needs to be updated on a monthly basis or earlier depending on the quality of the last cut-up part. To qualify a coater on a single part, it needs to submit a coated part to the lab for testing. This can only happen when parts are available to coat. So when a large batch of parts needs to be coated and it is just past the qualification period, the area cannot run that part. They need to coat a couple pieces and send them to the lab for destructive testing and wait for the results. This delays when the full batch of parts gets coated and disrupts the flow of parts on the coater. However there were some occasions where the engineering group was able to find appropriate scrap pieces that could be used instead of actual pieces. Those instances were rare and there was seldom the time to find pieces that would be suitable to use. To remedy this, a standardized process of identifying and obtaining scrap pieces from other areas of the shop is necessary. This will allow the cell leaders to better plan ahead for when testing is due, creating a more streamlined operation and reducing the delay in delivering parts to the next stage in the process.

To see how large a problem the cut up of actual parts was, a three-month sample was taken to see how often actual production quality parts were used for destructive testing and what the dollar value of the castings were. The chart below shows the results with the dollar value averaged out on a monthly basis. In total, each month saw over $20,000 worth of parts cut up in the lab for destructive testing.

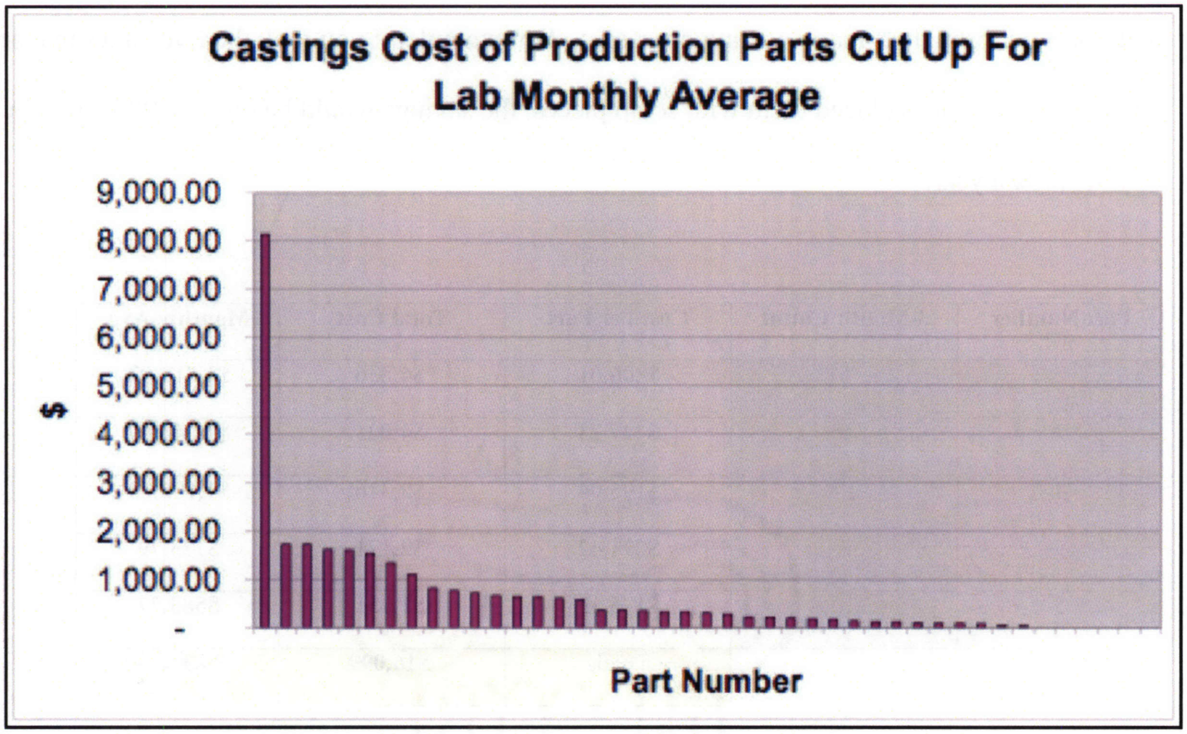

Figure 9 Monthly average value of airfoils destroyed in verifying a coaters quality

What jumps out first is how high the value is for the first airfoil. With over $8,000 a month, on average, being cut up, this can quickly equal a full engine set of parts. This part is being cut up so frequently primarily because it goes through the most coating processes (LPPS, Cat-Arc, and EBPVD) and for Cat-Arc especially, it is qualified on a large number of coaters, which gets expensive to maintain. This would also make it difficult to secure any scrap material to use for testing, the fact that it goes through so many different coating processes would make any such system too prohibitively complicated and impossible to keep up.

5.2 Using Scrap and a Standardized Process to Build Change

To simplify the process of using scrap pieces for lab testing, it would be better to look at pieces that don't go through as many coating processes. For example, if you took the five vanes that are cut up the most and replaced them with scrap pieces, the savings would be over $5,000 a month and $60,000 a year.

Part Number	3-Month Count	Cost Per Part	Total Cost	Monthly Avg
2	6	$806.01	$4,836	$1,612.02
3	9	$447.23	$4,025	$1,341.69
4	17	$195.04	$3,316	$1,105.23
5	8	$271.42	$2,171	$723.79
6	10	$175.13	$1,751	$583.77
		Totals	**$16,099**	**$5,366.49**

The difficult part now is to implement this plan. The reason scrap parts were so difficult to find in the past is because people in the different departments didn't talk to one another. The vanes engineers did not really talk to the coatings engineers to see if there are things that happen across the wall that could impact them due to the insider cultural assumption. When there are quality problems that they think are the other area's fault, they find the rework table and leave the piece there. So when the veteran engineer who crossed that wall and knew that the quality people in vanes kept a supply of scrap parts for other processes to use for testing retired, he took that knowledge with him. Since the dollar value is not a large one, no one has looked into why they destroy production parts more often then they used to.

To solve this, a standard work plan was developed and distributed to the engineering and operations people so that either one could go and secure scrap material. However this is not enough. It is the insider cultural assumption that is the major barrier to change here. However it will be possible to leverage the stronger assumption regarding pushing out parts, that can be used to make this happen. Based on what we know about the cultural significance of keeping the machines pushing out parts, this process needs to stress the importance of maximizing the output of good parts and reduction of delays to the next step. The customer focus now being pushed may help by stressing that the customer is paying for the number of good parts that get to them and not the ones that are cut up. The initiative will also have to be dictated down from a higher level because it requires people to look outside their own business unit to solve the problem. With each major production area organized into its own business unit, there is a strong cultural push to look only within their own area to fix a problem. A strong voice from a higher level of the organization will help force each business unit to look beyond their own four walls because Pratt is also a company that values the hierarchy of its leadership (common in many union environments). A "Kaizen" event is another possible way to get everyone talking together, but with the small expected payout, it would be difficult to get the organizational momentum going forward to make it happen. All of these efforts will eliminate an obvious source of waste that is currently ignored because it does not seem like a very innovative solution. But it does have the potential to start forcing people to look closer at what they are doing and find new ways of speeding up the process.

The solution presented above is a short term one. It will reduce some of the costs associated with the destructive lab testing which is an integral part of ensuring quality and has the potential to improve the flow of parts through the work cell. Over the long term though, to reduce the monetary and temporal costs associated with lab testing, it is necessary to improve the process. As the process quality improves, there will be less reason to do monthly checks in the lab and less reason to cut up good parts. The following chapter will show how to monitor the process and determine when testing would be needed based on actual machine performance relative to the specifications for a part. Another solution plays to the strength of Pratt's cultural assumption regarding innovation. The UTC Research Center could be commissioned to develop a new way of in-line testing that does not require cutting up parts. However, the time frame and potential costs of this solution would make this option a challenging one to pursue.

5.3 Chapter Summary

This chapter examined the first part of the three-prong approach to increasing capacity with an application in the TMC's advanced coatings business unit. The example from the TMC shows that with small changes that have long been overlooked, it is especially important to have the cultural understanding to know why it was overlooked for so long and what can be done to fix it. Recognizing that some aspects of the cultural assumptions themselves are causing problems and breaking through those routines are "the key to getting others to want to change the way they do things."[37] Taking this step before purchasing new equipment is critical since it may show that the new equipment is not really needed if other parts of the process are improved first. This is extremely difficult because "even if the assumptions are brought to consciousness, the members of the organization are likely to want to hold on to them because they justify the past and are the source of their pride and self esteem. Such assumptions now operate as filters that make it difficult for key managers to understand alternative strategies for survival and renewal."[38] It is through small changes, like the one proposed here, that "create small wins that build credibility for new ideas and, when corrected, can create a chain reaction."[39]

The example from the TMC also leads directly to the second part of the three-pronged approach to capacity. The next chapter looks at using a statistical process control (SPC) methodology to evaluate when part testing may be necessary and also to increase capacity in advanced coatings.

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[37] Klein, Janice. *True Change.* Jossey-Bass, San Francisco, 2004 pg 32.
[38] Schein, Edgar. *Organizational Culture and Leadership.* 3rd Edition, Jossey-Bass, San Francisco, 2004, pg 312-313.
[39] Klein, Janice. *True Change.* Jossey-Bass, San Francisco, 2004 pg 40.

6 Data Collection and Statistical Process Control

This chapter details the application of statistical process control techniques to judge the overall quality of a coater. It starts by looking at time wasted during shift changes because of a lack of confidence in the process to stay in control between shifts. This chapter then looks at what the current process yields in terms of its process reliability ratios and finally looks at what the future steps would be to improve this score.

6.1 SPC to Help Reduce Shift-Change Costs

In looking at the capacity problems that the TMC currently faces, the most obvious place to find some quick improvements is in reducing the time taken between shifts. This is a combination of the employees' lack of urgency as well as a lack of confidence in the process. Using the weightgain database that tracks the number and timing of parts coated, for a standard week of operation, the APS cell averaged almost 2 hours offline between shifts. [40] This is almost 6 hours per day, or 25% of the time available for coating. Addressing this issue could solve a large part of Pratt's capacity problems.

During a shift change, an employee does the following activities:

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[40] The weightgain database is a collection of pre-coating and post-coating weights that is used as a proxy for measuring actual coating thickness on a part.

- End of Shift
    - Finish OpCert of Parts[41]
    - Sweep Area
- Beginning of Shift
    - APS Daily Walkaround (check filters, powder levels, etc)
    - Collect Necessary Tooling
    - Test Gram Rates
    - Run Button Program
    - Run Weightgain Piece
    - Adjust As Necessary

Some of these activities are necessary and should not be eliminated, although they could be done concurrently with the operation of the coater. However, with a proper SPC plan in place and the associated confidence in the process, the following steps are ripe for reduction:

- Test Gram Rates
- Run Button Program
- Run Weightgain Piece
- Adjust As Necessary

By eliminating or reducing these tasks, it may be possible to convert at least 12.5% of the day (three hours) into useful production time, thus increasing the capacity of the operation and

[41] OpCert is a method for each operator to certify that they completed all the required steps for a part before passing it along to the next stage.

delaying more costly capital equipment purchases. Additional management attention would be required to see any larger gains.

6.2 Current SPC State of Advanced Coatings

In the Advanced Coatings area of the TMC, they are currently set up with a tracking system that measures the weight of an airfoil both before and after it is coated. Every piece coated is (or should be) weighed and the results input into a database. With this information it is a small step forward to start measuring the coating process capability. In fact, the manufacturing engineering group is already starting to measure the process variability for individual part families on each coater. However it is also important to understand the effectiveness of each coater overall, so it can be determined how much of the time between shifts needs to be spent correcting a process that may or may not need correcting. If the process is in control at the end of one shift and nothing changes going to the next shift, then why would almost two hours need to be spent between shifts adjusting the coater? That's why it's important to find out if the coater needs fixing as quickly as possible.

Standard measures of process capability are the Cp and Cpk process capability ratios. The Cp ratio is a measure of the process' potential, or how much of the specification band is used by the process. The Cpk ratio measures actual capability within the specification limits, meaning how close to center is the process operating at. So the difference between the two ratios is how far from center the process is operating at. The formulas are as follows:

$$Cp = \frac{(USL - LSL)}{(6 \times \sigma)} \qquad Cpk = \min\left(\frac{(USL - \mu)}{(3 \times \sigma)}, \frac{(\mu - LSL)}{(3 \times \sigma)}\right)$$

USL = Upper Specification Limit

LSL = Lower Specification Limit

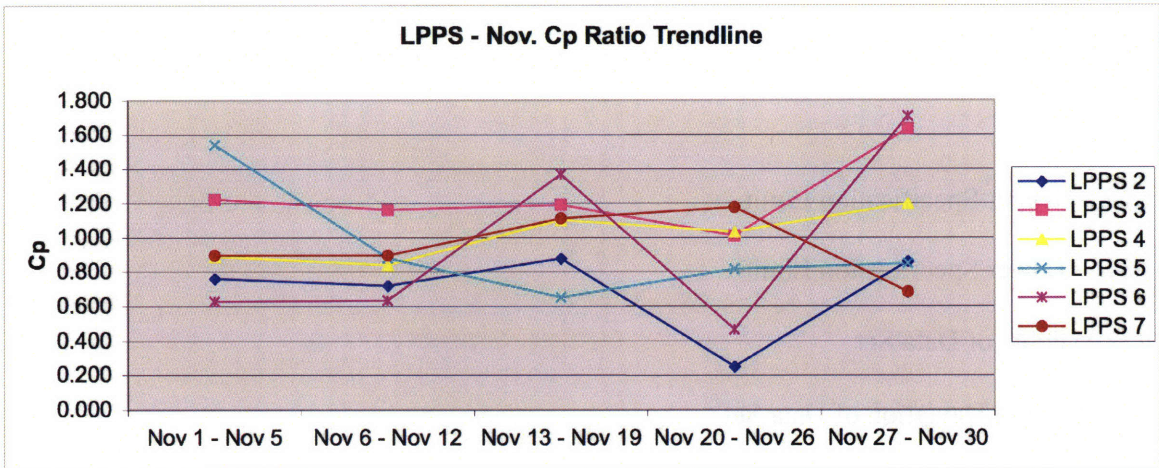
μ = Average of Data Set

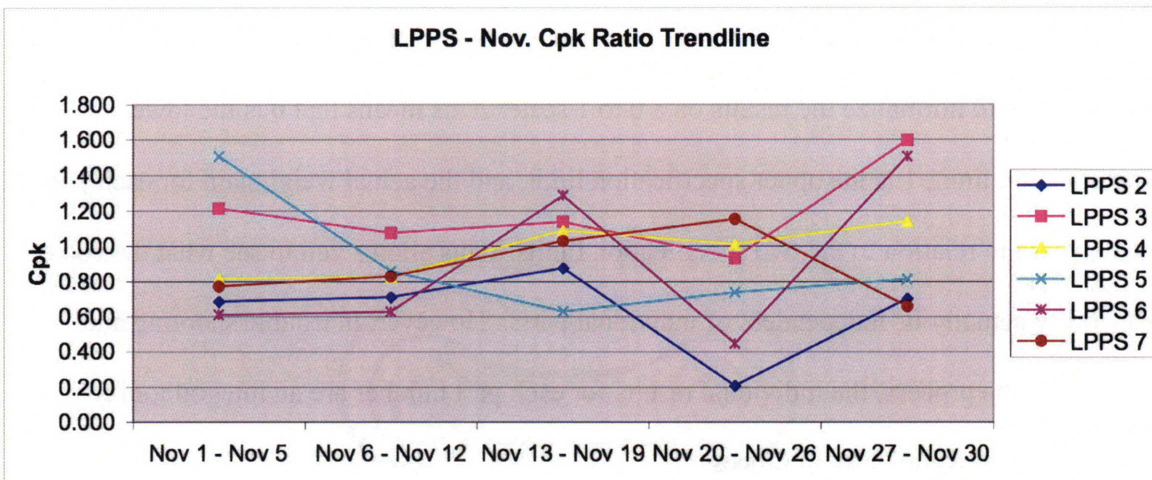
σ = Standard Deviation of Data Set[42]

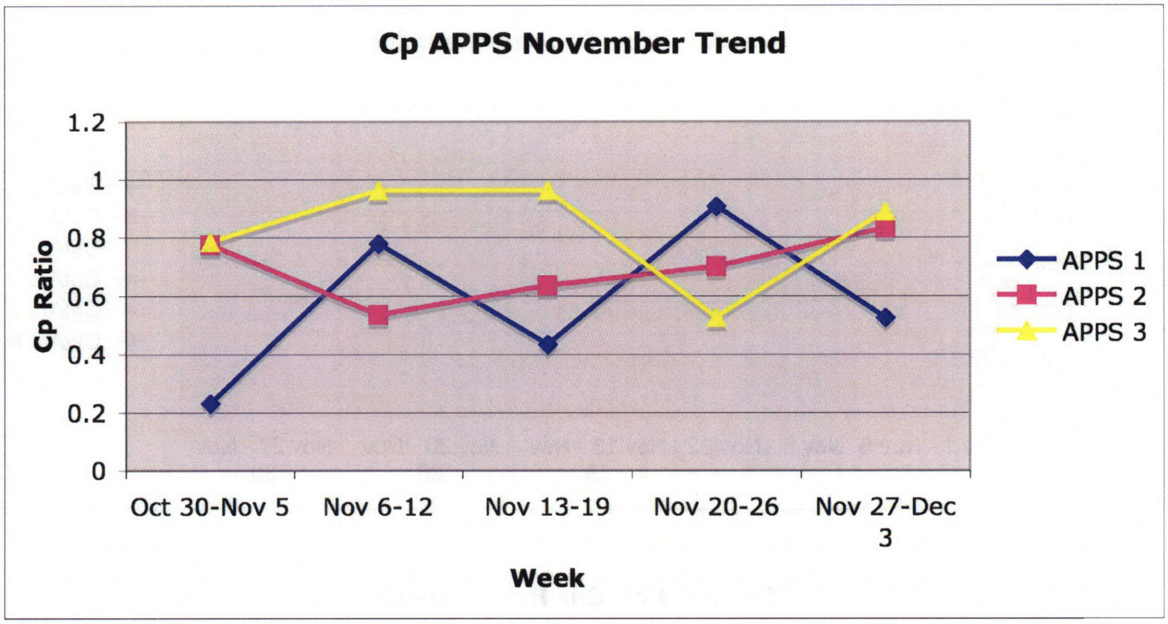
To account for all the different parts being coated and their different specification limits, it makes sense to normalize the results on a 0 to 1 scale. This means that 0 is the lower specification limit, 1 is the upper specification limit, and the actual weightgain for each part lies somewhere in relation to the two specification limits. This allows you to see what the coater capability actually is, independent of individual parts. However, in trouble shooting and improving the process, the individual results for each part number are an integral tool for improving the overall system process.

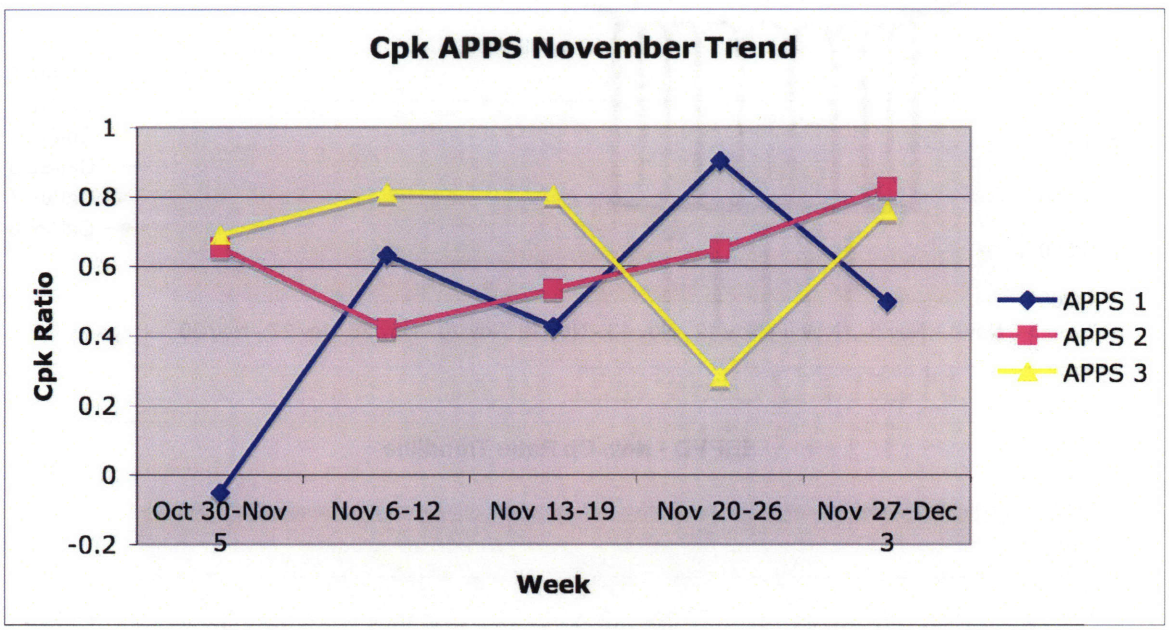
The results from a month-long sample taken of the four coating processes in advanced coatings are shown below. This analysis also includes the removal of all developmental work, where the specifications have not been fully developed yet.

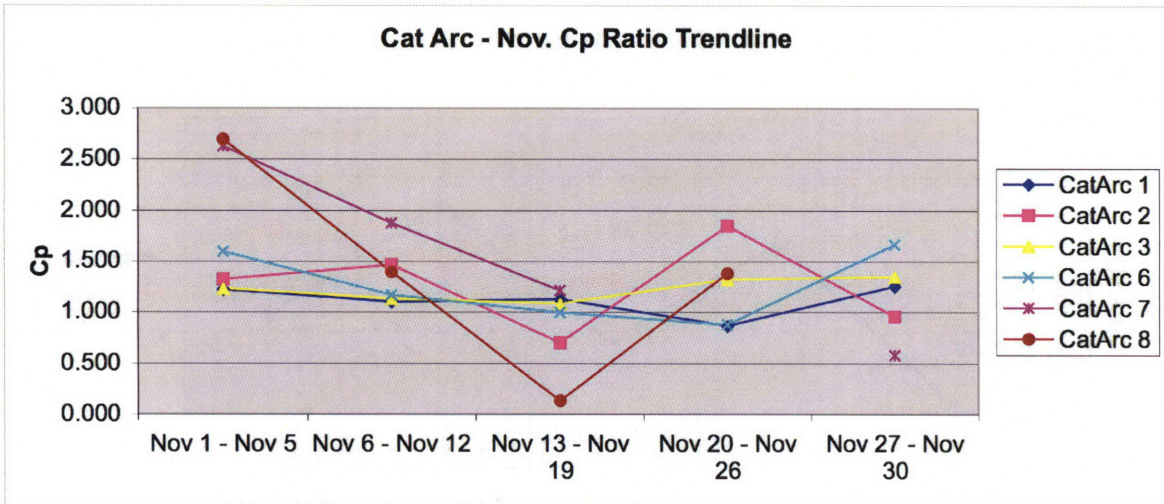
[42] Montgomery, Douglas. *Introduction to Statistical Process Control.* Third Edition, John Wiley and Sons, USA pg 439.

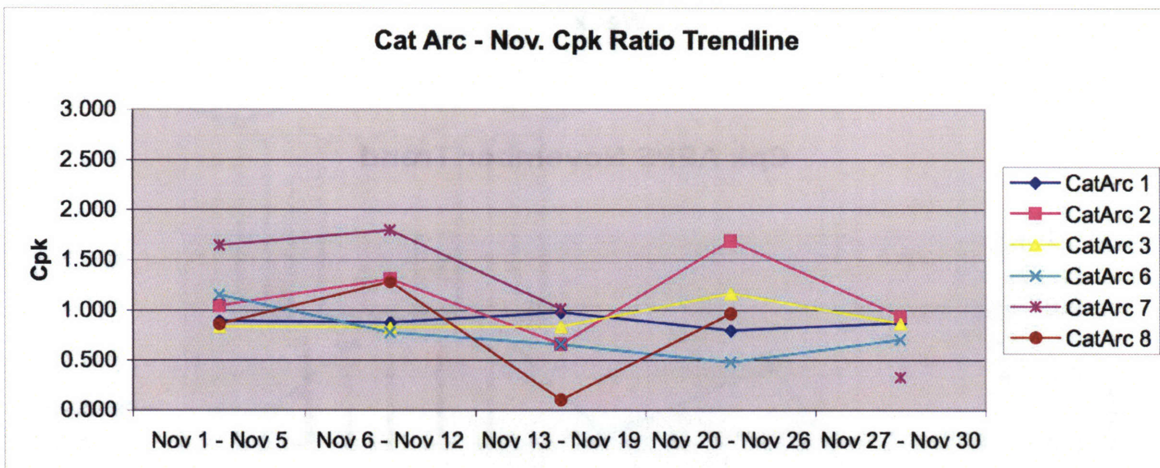

LPPS - Nov. Cp Ratio Trendline
1.800
1.600
1.400
1.200
1.000
0.800
0.600
0.400
0.200
0.000
Cp
Nov 1 - Nov 5
Nov 6 - Nov 12
Nov 13 - Nov 19
Nov 20 - Nov 26
Nov 27 - Nov 30
LPPS 2
LPPS 3
LPPS 4
LPPS 5
LPPS 6
LPPS 7

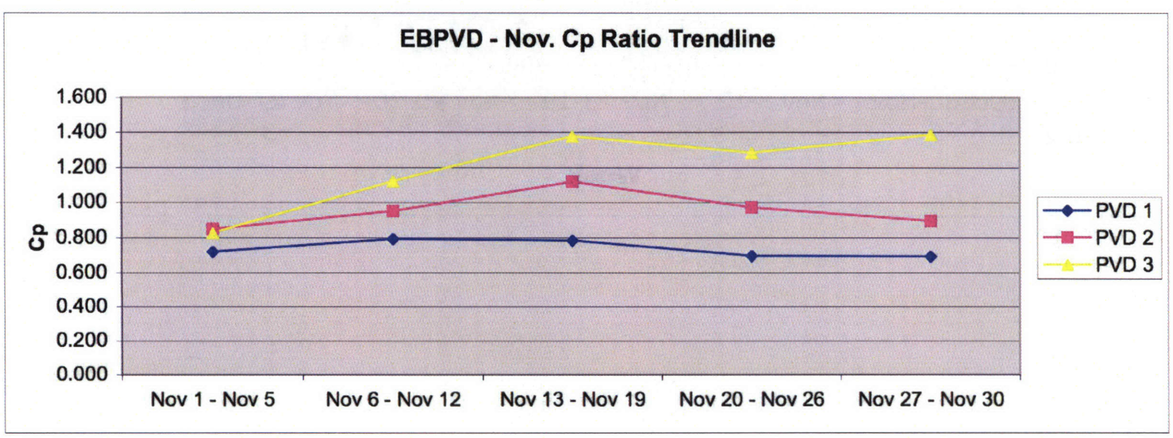

LPPS - Nov. Cpk Ratio Trendline
1.800
1.600
1.400
1.200
1.000
0.800
0.600
0.400
0.200
0.000
Cpk
Nov 1 - Nov 5
Nov 6 - Nov 12
Nov 13 - Nov 19
Nov 20 - Nov 26
Nov 27 - Nov 30
LPPS 2
LPPS 3
LPPS 4
LPPS 5
LPPS 6
LPPS 7

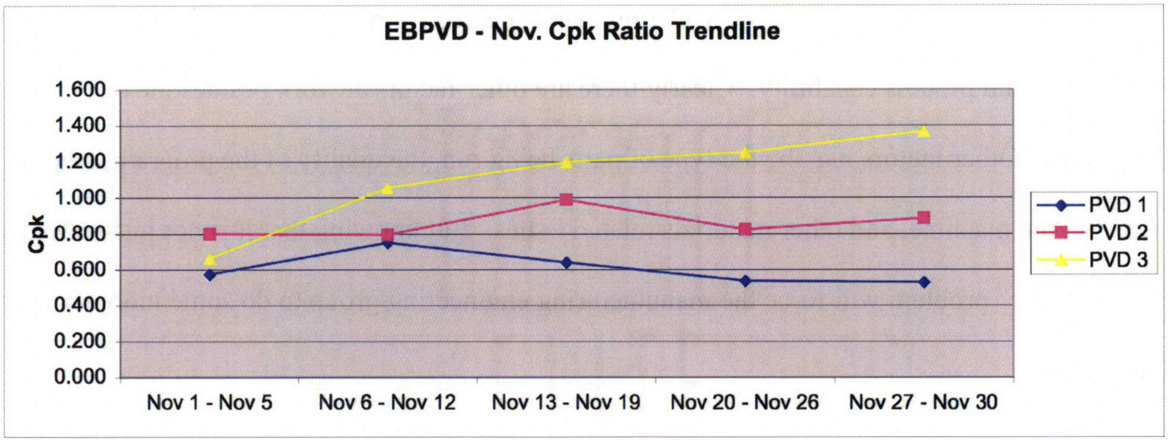

Cp APPS November Trend
1.2
1
0.8
0.6
0.4
0.2
0
Cp Ratio
Oct 30-Nov 5
Nov 6-12
Nov 13-19
Nov 20-26
Nov 27-Dec 3
Week
APPS 1
APPS 2
APPS 3


Cpk APPS November Trend
1
0.8
0.6
0.4
0.2
0
-0.2
Cpk Ratio
Oct 30-Nov 5
Nov 6-12
Nov 13-19
Nov 20-26
Nov 27-Dec 3
Week
APPS 1
APPS 2
APPS 3


Cat Arc - Nov. Cp Ratio Trendline
3.000
2.500
2.000
1.500
1.000
0.500
0.000
Cp
Nov 1 - Nov 5
Nov 6 - Nov 12
Nov 13 - Nov 19
Nov 20 - Nov 26
Nov 27 - Nov 30
CatArc 1
CatArc 2
CatArc 3
CatArc 6
CatArc 7
CatArc 8


Cat Arc - Nov. Cpk Ratio Trendline
3.000
2.500
2.000
1.500
1.000
0.500
0.000
Cpk
Nov 1 - Nov 5
Nov 6 - Nov 12
Nov 13 - Nov 19
Nov 20 - Nov 26
Nov 27 - Nov 30
CatArc 1
CatArc 2
CatArc 3
CatArc 6
CatArc 7
CatArc 8


EBPVD - Nov. Cp Ratio Trendline
1.600
1.400
1.200
1.000
0.800
0.600
0.400
0.200
0.000
Cp
Nov 1 - Nov 5
Nov 6 - Nov 12
Nov 13 - Nov 19
Nov 20 - Nov 26
Nov 27 - Nov 30
PVD 1
PVD 2
PVD 3



The average results for each coater during November was:

Coater	Average	
	Cp	Cpk
LPPS 2	0.693	0.636
LPPS 3	1.242	1.189
LPPS 4	1.012	0.976
LPPS 5	0.947	0.910
LPPS 6	0.959	0.894
LPPS 7	0.951	0.887
APPS 1	0.575	0.482
APPS 2	0.695	0.617
APPS 3	0.825	0.670
CatArc 1	1.115	0.883
CatArc 2	1.257	1.125
CatArc 3	1.224	0.905
CatArc 4	1.131	1.016
CatArc 5	0.984	0.802
CatArc 6	1.260	0.754
CatArc 7	1.573	1.192
CatArc 8	1.402	0.800
PVD 1	0.737	0.606
PVD 2	0.956	0.857
PVD 3	1.199	1.106

As you can see, Cpk is always less than Cp since Cp is a measure of how much of the specification band is used, not where it is centered. It is also interesting to note that the coaters with the highest Cp scores are some of the newest machines, the CatArc coaters. This shows that with newer technology it is easier to achieve higher process capability than with older equipment. However there is less correlation than expected for other coating processes regarding coater age and process capability. Clearly there are other factors at work besides the age of the machines. Other factors may be the type of parts being run, the quality of the program, who is running the machine, and other materials related issues. But knowing that it is not just an "age of the machine" problem will force the manufacturing engineering group to do some more targeted studies.

It is also important to realize what these scores mean. To put it most simply, how many parts will be out of spec on average with these Cp scores? For APS, which has an average Cp score of 0.70 for November, assuming the weightgains are normally distributed, means that there will be roughly 1 defect for every 30 parts coated. This is generally the number of parts coated in one shift, when the coater is reconfigured for the next shift. APS does not normally see that many defects, so an argument could be made that the extended set-up times are required. However, it seems more likely that it is the extra set-ups that are causing at least some of the excessive variability. Tracking the Cp and Cpk scores over time will allow the manufacturing engineering team to better diagnose the root causes of these scores and drive improvements that will justify a tighter shift start-up routine. A common Cp value for an existing process that has some level of control is usually around 1.33 and Motorola usually sets a Cp target of at least 2.0 for its "Six-Sigma" program.[43]

The results of this analysis show some interesting trends. First off, over Thanksgiving week for APS and LPPS, there was a drop in process capability. This was primarily due to the high number of vacations and having less experienced operators coating parts. For Cat Arc, the week

[43] ibid pg 441-442.

before Thanksgiving saw Coater 8 have one blade at four times the normal weightgain level and one that was at a negative weightgain. This could be just be an operator error inputting the data or perhaps there was some other error with the coater. Regardless it shows that something happened and it needs to be investigated and resolved so that other pieces are not lost to this.

The results of these capability trend charts should be posted in the operating area and be a source for discussion at the QCPC meetings held each week. This way there are measurable results for what is done at the QCPC meetings and the employees can see where their input is making an immediate difference.

In looking at the weightgain levels for parts with respect to their specification limits, it is also interesting to look at how many of those parts were actually sent to quality control as "out of spec" and how many made it through to the next step. Data was available from April 2005 and by a careful analysis you could tell how well the quality control measures were operating.

In the month of April the APS cell had a 92% yield. During this same time period, less than 1% of parts coated were either below or above the specification limits. However, only 30% of those were actually sent to quality control as non-conforming airfoils. This means that over 70% of the parts that were out of Spec on their weightgain, were not sent to quality control. They were sent on through to the next stage of processing. This is a little concerning since this measurement is the primary measure of coating thickness available and a primary factor in part quality. It leads us to believe that the pressure to get parts out the door has been the justification for employees passing parts out the door that do not meet the specification limits.

6.3 Future SPC State of Advanced Coatings

The weightgain system used in the TMC is an indirect measure of the thickness required on a given part. It is the thickness that matters and not the change in weight from before and after coating. The ideal scenario would be to accurately measure the thickness at various key points on the airfoil, record that, and then accept or reject it. With this information, you can specifically target the area that is out of spec and have a more precise idea on how to fix it and provide a higher quality part to the customer. This can be done with ceramic coatings by using an eddy-current permascope attached to one of the current measurement devices currently used in other areas of the TMC to target and record the thickness at different points. Fischer Technology is a company that offers permascopes that would work for this process, but they do not provide a robotic method for ensuring the same point is hit with each part. For this reason it may be best to purchase the permasope and then "moonshine" it onto the existing measurement platform and place these in-line with the coater. This would appeal to Pratt's assumption regarding innovation and allow them to implement something would enable higher quality parts to the customer and improve the internal flow of parts. To avoid running against the insider assumption, the implementation of this needs to be led by the local manufacturing engineers who have the most credibility with the employees on the floor so that it is seen as a "TMC" process. Taking the SPC process to the next level, linking airfoils to their respective engines and the future warranty issues that may arise, could lead to the re-evaluation of what the specification limits should be for each distinct face of the blade or vane.

While the SPC information should be posted weekly for every area and coater, an excellent pilot area for starting to reduce the shift set-up activities in the cell is with the APS coaters. The APS cell is currently in line to replace their three coaters with new ones. With the new coaters comes the opportunity to change the behavior and tolerated operating procedures of running them. New "investment unfreezes old assumptions, generates more efficient concepts and designs for a production system."[44] Through the set up of the coaters and the work of the engineering team in qualifying them, there should be enough data on the capabilities of the coaters to establish new guidelines for when certain tasks need to be performed (the tasks highlighted in the beginning of this section). There will also need to be some additional training to educate the machine operators what all of these new measurements rally tell them and also what impact they have on things. Linking their individual performance to what work needs to be done with the coater can build a new level of ownership of the process and lead to greater acceptance of these results. This will also provide a template for what is needed to reduce the set-up activities in the other cells, thus increasing their utilization too. This will go a long way in helping relieve the capacity problems that are currently plaguing the TMC's advanced coatings business unit.

As stated in the previous chapter about quality testing, as confidence in the process grows (higher Cpk scores), there exists the opportunity to reduce the amount of cut-ups required to certify the process. Depending on what the process capability actually achieved is, you can structure your destructive testing regime to match the capability of the process. If only 1 out of 35,000 parts should fall outside the spec limits (a Cpk ratio of 1.4), then maybe a cut-up is required once every quarter instead of monthly (assuming the microstructure has historically

[44] Hayes, Robert and Kim Clark. "Why Some Factories Are More Productive Than Others." Harvard Business Review, September – October 1986, pg 68.

been in good condition). At the very least, knowing this information starts to allow you to challenge some of the long held operating principles that have defined how turbine airfoils have been processed in the past.

6.4 Chapter Summary

Currently there is an excessive amount of time spent in between shifts not processing any parts on the coaters. This has accentuated the capacity shortfall being felt in the operation by reducing the effective hours available for coating parts in the TMC. A large reason for this wasted time (*muda)* is due to the lack of confidence that the operators have in the process. The process capability analysis performed here shows that this lack of confidence may be somewhat justified due to their low Cp and Cpk scores. However, by using a proper SPC plan, the manufacturing engineers can target a process capability score for when they can start reducing unnecessary activities from the daily routines of each operator. A proper SPC plan can also help reduce the likelihood of operators feeling pressure to move parts that barely miss their specification limits on to the next step. These gains in capacity are estimated to be roughly 13%, with additional improvements possible through tighter division of labor during a shift change. The next chapter will cover the final part of the three-pronged approach to increasing capacity, adding additional equipment.

7 A Cost Comparison of New and Old Coating Technologies

The final phase of the three-pronged capacity attack plan deals with investing in new technologies to add to the available capacity. The previous two chapters have dealt with improving the little things to be able to produce the right part at the right time (no more delays waiting for qualifications) and improving the real capacity of an area by utilizing better data collection and analysis tools to reduce the time wasted between shifts. This chapter builds on that and looks at a cost comparison between two competing technologies for coating turbine airfoils. The first part of the chapter reviews the considerations taken into account during the cost analysis, while the second half of the chapter looks at the results and what they mean to the TMC.

7.1 Cost Analysis Methodology

There are two competing technologies that the TMC is looking at to help alleviate their capacity shortfall. These shall be called "Existing Technology" and "New Technology." The existing technology is just what it sounds like. It is the current coating technology for this particular coating type. The new technology is a newer application of coating technology that offers higher quality, lower upfront cost and greater uptime than the current technology. However it also comes at a cost of slower coating time and higher per unit coating costs. It would also cost roughly $450,000 to validate this particular coating process for use on Pratt's turbine airfoils. In summary, it comes down to whether or not the lower upfront investment and higher uptime achievable with the new technology offsets the higher per-unit costs and slower processing time.

The basic structure of the cost model was to take the base costs for a given component and then identify what a best case and a worst-case cost would be. Then summing up the various costs for both the old and new technology you get a best, worst and most likely cost scenario for each technology. Once the costs have been identified, the probability of each scenario happening was developed with the help of operations and engineering. The final step to the model was to take the expected demand for the next twenty years and map out the purchases over this time frame. Then to account for the fact that the forecast is not accurate, a high and low demand case was developed (plus and minus 20% of the base-case) with the purchase of new equipment mapped out onto the new demand curves. The probability of each demand scenario occuring was then developed and a final cost comparison was available taking into account variability in expected costs and demand.

There were a few assumptions that needed to be made to determine the economic feasibility of competing technologies. A standard vane was used as a base for all calculations for coating times. A 20-year time horizon was used because that seems to be how long Pratt plans to operate their coaters. A discount rate of 10% was used at the suggestion of the Finance group to develop the present value of the operating life of the coaters. Variable costs were developed from the time needed to coat each part and the current prices of consumable materials (gasses and the coating material for example). Uptime for the new technology was developed based on other operating group's experiences and given a range for the best and worst case scenarios. For the current technology, the worst-case uptime used was an estimate of the current uptime for the coater. The base-case and best-case scenarios used the future utilization goals of the TMC. Another assumption was that it would take only six months from the purchase of a new technology coater to when it was up and running and it would take almost one and a half years to purchase and install any new coaters utilizing the existing technology. A new technology coater costs roughly 1/6th the price of purchasing an existing technology coater. However that does not include the one-time research fee of $450,000 to validate the new technology. If demand can't be satisfied with current coaters, it will be outsourced at the current price.

Below is a summary of the basic cost data for both the new and existing technologies. The medium cost option for the new technology is 100% and the other costs are listed in relation to that. "Uptime" is listed on a 0-100% scale for all technologies and the "probability of occurring" is the likelihood that a given scenario occurs for each technology.

New vs. Existing Technology
Cost Assumptions

	New Technology			Existing Technology (as compared to corresponding new technology cost)		
	Low Cost	Med Cost	High Cost	Low Cost	Med Cost	High Cost
Total Fixed Costs, Equipment	73%	100%	127%	826%	605%	477%
Yearly Cost (12 year amortization)	73%	100%	127%	826%	605%	477%
HVOF Research Expense	90%	100%	110%			
Time to Coat a Part (hours)	100%	100%	100%	62%	62%	62%
Uptime (in absolute terms)	95%	90%	85%	80%	70%	60%
Capacity (assuming 5625 hours per year)	106%	100%	94%	148%	136%	124%
Probability of Occurring	40%	50%	10%	10%	50%	40%
Labor Cost per Piece	95%	100%	106%	68%	73%	81%
Total Material Costs per Piece	70%	100%	142%	30%	38%	42%
Maint. Cost per Piece	65%	100%	140%	217%	193%	189%
One Year Variable Cost per Piece	**75%**	**100%**	**135%**	50%	55%	58%
One Year Fixed Cost per Piece	69%	100%	134%	559%	443%	385%
Total Cost per Piece (at capacity)	**74%**	**100%**	**135%**	75%	76%	75%

This chart illustrates that the existing technology is roughly 600% more expensive per coater to purchase upfront, but the variable costs are about half that of the new technology coaters.

7.2 Cost Analysis Results

The initial results for the base-case cost analysis show that depending on the different cost assumptions made, either technology makes financial sense. However, based on the likelihood of each scenario happening, the new technology is the better financial option. The factors that have the largest impact on the results include the expected uptime of the coaters and the overall cost and utilization of materials.

To account for the three different demand scenarios, a matrix showing the present value of savings of the using the existing technology versus the new technology is shown below for each demand scenario. The way to read this is that negative numbers mean the new technology is less expensive.

Present Value of Savings (Base Case)	Existing Technology		
New Technology	Low	Med	High
Low	$(78,809)	$(4,003,100)	$(9,209,470)
Med	$6,403,024	$2,478,733	$(2,727,637)
High	$15,286,121	$11,361,830	$6,155,459

Present Value of Existing versus the New Technology (Base Case)	**$(915,809)**

Present Value of Savings (High Demand Case)	Existing Technology		
New Technology	Low	Med	High
Low	$(11,985,144)	$(20,428,141)	$(31,629,495)
Med	$1,398,519	$(7,044,477)	$(18,245,831)
High	$19,758,177	$11,315,181	$113,827

Present Value of Existing versus the New Technology (High Case)	**$(14,198,219)**

Present Value of Savings (Low Demand Case)	Existing Technology		
New Technology	Low	Med	High
Low	$1,514,211	$1,292,950	$999,402
Med	$2,859,818	$2,638,556	$2,345,008
High	$4,695,937	$4,474,676	$4,181,127

Present Value of Existing versus the New Technology (Low Case)	**$2,188,632**

The net present savings for pursuing the new technology versus the old technology is roughly $1.6 million. This was calculated using 70% as the likelihood the base case occurs and a 20% and 10% probability of the low demand and high demand cases respectively.

Looking at just the base case, the most likely scenario, if the new technology is used, Pratt will need to purchase four coaters in the next four years to satisfy demand. By comparison, if the existing technology option is pursued, an additional two coaters will need to be purchased next year. If the new technology is able to hit the low cost targets, it doesn't matter what the existing coaters' costs are since the new technology will always be the lower option. However, if the costs for new technology are going to be high, than the existing technology has the advantage no matter what its costs are. If the costs for the new technology are in the medium range, which is most likely, than it depends on what costs are achieved for the old technology. For the most likely individual scenario, where both new and existing technologies have their medium costs, the existing technology has a present value $2.5 million cheaper than the new technology. However this point estimate does not include all the variability that the model was designed to capture. That is why it is necessary to look at all the different scenarios and the probability of them occurring before making a final decision.

In the high demand case where demand is forecasted to be 20% higher than currently expected, for the next five years before holding steady for 15 years, the new technology coater is the clear cost winner. This is primarily due to the fact that the new technology is significantly easier to add capacity with. During the 20-year time horizon, the TMC would end up purchasing 8 new technology coaters over the next five years to satisfy this higher demand. The existing technology would require that 5 coaters be purchased in the next two years to keep up with demand. The new technology is much less expensive and has a smaller lead-time which makes adding incremental capacity fairly easy. This more than offsets the advantage the existing technology has in per-unit costs.

In the low demand scenario, continuing to use the existing technology is the most cost effective option. This is due to the fact that only one of each type of coater is needed in four years. Otherwise current internal capacity and those of temporary vendors can easily satisfy demand.

Putting it all together, the new technology is the most cost effective option and has the potential to save Pratt and Whitney a large amount of money in coating parts. Some of the basic differences between the two technologies are listed below.

New Technology	Existing Technology
Lower Capital Hurdle (much cheaper up front)	Lower Variable Cost
High Flexibility (shorter lead time so you can purchase closer to when actually needed)	Known Technology
More Potential Vendors for Demand Variability	New Technology has More Potential Competitors (removes capital barrier for competition)

The new technology, with its lower capital hurdle, will make it easier to have the purchase approved. This will be even more important in the future as the current coaters will eventually need to be replaced and the new technology will allow the TMC to replace them much quicker. With a shorter lead-time to receive the coaters, the new technology can be deployed and put onto the production floor much earlier than new existing technology coaters can. Even though the new technology has higher variable costs, the uptime that other Pratt users have been able to demonstrate with them is enviable. This will ensure that there is a high degree of predictability in how many parts can be coated each day. Another two factors that are important but not included in this analysis, are that the new technology coaters generally have 1/3 the footprint of existing coaters and use much less electricity. The electricity costs for the existing technology were not available at press time, so they were not included in the analysis, although it is understood to be significantly higher than for the new coaters, which would only make the new technology an even more attractive option.

Another reason the new technology is attractive for Pratt and Whitney is because its deployment is in line with the culture of the TMC. Purchasing the new technology allows the engineering group at Pratt to develop further expertise in coatings and presents a good chance to file for new patents. This is extremely appealing for the engineering group and a motivating factor to proceed with this project. Even if the new technology led to no cost savings over the existing technology, it is likely that the TMC would still pursue it. That is due to the strength of the culture to develop new patents and innovative processes. Fortunately in this case the lower-cost solution is in line with the existing cultural norms and was received favorably by management and the engineering group. Knowing Pratt's culture, this also means that the TMC management needs to be extra careful to fully establish the previous two measures and improve the existing process before too much of the new technology is purchased. With the cultural forces at work within Pratt, it may be easier to proceed with the purchase of new equipment and expect it to lead to a long-term solution. In this specific scenario the new technology is the right path to pursue, but without proper procedures in place, will eventually lead to a degradation of capability with the new equipment. Since it is primarily engineers who are making this decision, the TMC is able to bypass the cultural impulse for a "faster" coating machine that dominates the thinking on the shop floor. It is also a technology that is being proven for the first time at Pratt on turbine airfoils, so this solution fits in with the insider aspects of the culture.

Other things to consider in pursuing the new technology have to with more strategic issues. There are many other companies out there that use this new technology for other coating applications such as automotive parts and other parts of an aircraft. A large number of these companies would be more than happy to be vendors to handle Pratt's overflow capacity or as a more permanent vendor. This is good and bad since it will give Pratt more flexibility to handle surges in demand, but it will increase competition from some potentially lower cost industrial coatings companies. This may mean more competition from Pratt for the initial business, but it should also mean lower costs for outsourcing those surges in demand. Right now several of the TMC's current overflow vendors already have this new technology for other customers (not for turbine airfoils) and are awaiting approval to coat turbine airfoils. These companies appear to be Pratt's biggest competition in promoting coatings with the new technology. But with Pratt's capacity constraints, the TMC is currently outsourcing as much coatings work as possible just keep up with demand. These companies are already getting a large chunk of business and are careful not to jeopardize that revenue. When Pratt builds their internal capacity up further, these same companies will fight to keep their revenues up. But it does not seem likely that they will be able to capture any more of the business than they currently have. As long as Pratt limits how many vendors they initially contract overflow capacity with, they should not see too many additional companies enter in this arena. It is also important to factor in the value of flexibility if volume initially spikes and then drops. Pratt would have purchased new coaters to satisfy demand that is no longer there. So if they needed to dispose of some coaters, it is likely that the new technology will have more applications for other businesses than the existing technology.

7.3 Chapter Summary

The final leg of the three-pronged approach to increasing capacity is the addition of new equipment. The reason this is the final leg is because if the initial two steps are not taken first, then you will end up purchasing more equipment than is necessary. It was approximated in chapter two that the SPC program could add an additional 13% to the current capacity. If that step is not accomplished, then you end up paying for that extra capacity by purchasing additional new equipment, regardless of the technology selected. It is also important to recognize that unless attitudes and procedures are first optimized, any new equipment purchased is likely to be run in a suboptimal manner and fail to live up to initial expectations. This could limit the viability of the entire operation to effectively deliver on promises and make either relocating this process or outsourcing it completely a more attractive option in the future. This chapter specifically looked at evaluating the cost effectiveness of two different technologies in meeting the TMC's customer demand. The new technology that was evaluated here is the more cost effective option when compared with using existing technology. This is especially true when considering any of the higher demand scenarios that were evaluated where the flexibility afforded by lower upfront costs carries more weight. The final chapter will review the entire three-pronged approach to a capacity shortfall and discuss future projects that the TMC may be interested in pursuing.

8 Conclusions

This thesis has attempted to lay out a framework for companies dealing with capacity shortfalls. The basis of this framework lies in continuing to improve current procedures before committing to purchasing new equipment. New equipment should be looked at once the current system has the infrastructure in place to take advantage of what any new technology may bring with it. For example, with the new technology the TMC is looking at it would be unlikely that they could achieve the 90% uptime that the other division at Pratt that is utilizing the new technology has achieved unless current processes are improved to a level consistent with other areas of Pratt and people have confidence in that process. This is where the SPC comes into play. Once people are already accustomed to evaluating the quality of the coaters based on reasonable SPC guidelines, then getting the most out of new equipment becomes much easier and fewer coaters will need to be purchased to meet a given demand. It would also be useful to use the carrot of a new equipment purchase as a motivating factor to spur changes in sub-optimal processes.

During the author's research conducted at the TMC, it was indicative of their culture the kind of organizational support received during each phase of the project. With the scrap testing project, support came mainly from the machine operators and maybe the cell leader level. With the SPC project, support was found in the engineering group and not really anywhere else. In evaluating the new equipment purchases, there was high-level support from all of the plant management as well as the engineering groups. This is partially due to the dollar value of the decisions being made, but also because of the cultural push to solve problems through the addition of new equipment.

The research methods utilized in creating this thesis also had large impact on the conclusions that are shown here. The author spent a great deal of time on the shop floor conversing with all of the employees about everything from their jobs, what changes have taken place over the years to what they think of Pratt and Whitney. This helped the author appreciate the impact of any changes that might be made from their perspective and view things as an insider would. However, being an outsider allowed the author to look at the capacity problem as more than just an excuse to purchase new equipment. A major limitation to this approach was that the author may have identified too strongly with the organization and lost some objectivity. Another limitation to the full immersion the author undertook is that it is difficult to keep track of the larger picture since you are mired in the details of how the operation actually works.

To apply this three-pronged approach to other organizations it is important to recognize their own independent barriers to change. The cultural framework referenced in this thesis is a good place to start but other frameworks will work equally well. The important thing is to understand what will block any change initiative and what will enable it to happen. Continuing with the three activities, it will be important to first start by addressing the "broken windows" that are in almost every organization. Then move on to make sure the group has the proper tools to evaluate the status of their operation. Then finish off the change initiatives by doing a proper cost analysis to determine what kind of new equipment will improve the situation for the foreseeable future.

For the TMC, the introduction of new equipment in advanced coatings brings a unique opportunity to radically improve certain process control measures. This in turn can lead to an increase in equipment utilization and an increase in effective capacity for the area (leading to fewer capital purchases). Furthermore, as data collection improves, the ability to act proactively and change the current "firefighting" mentality will emerge. Looking at the new coating technology for airfoils is also an important aspect of planning for future capacity. Based on the flexibility and potential savings, this new technology is something that should be looked at in greater depth in the future. The addition of more employees on the floor is another possibility for increasing capacity that the union and lower management would like to see. However this option has been ruled out to a great extent, by upper management. This may be due to the desire to maintain flexibility over the future location of the coating process or that this is a temporary upswing that doesn't warrant the long-term addition overall employment.

8.1 Future Steps and Projects

One project and that can be looked at in greater detail in the advanced coating area is how parts are assigned to machines. The current process for assigning and qualifying parts on a given machine is done through a tedious, manual process. The volume on a machine is estimated and things are placed wherever they may appear to fit. A more sophisticated way to look at the problem involves evaluating the benefits of flexible manufacturing. A methodology for doing this is described in an article written by William Jordan and Stephen Graves called "Principles on the Benefits of Manufacturing Process Flexibility." This paper describes that the benefits of full process flexibility can essentially be matched by linking a chain of parts and machines. As far as the TMC is concerned, one area this can be applied to is in planning what machines to qualify parts on in the advanced coatings area. Knowing the expected demand and variability of each part family and the expected capacity of each machine and using the framework provided by Jordan and Graves will allow Pratt to satisfy as much demand as possible while limiting the costs of qualifying parts on every coater.

Another area that could provide some value for Pratt and Whitney would be to do a project using real options for capital purchasing decisions. Using real options means matching the aspects of a project with the elements of the Black-Scholes option-pricing formula. In this case, since the value of pursuing the new technology coaters was already positive, a real option approach would only further accentuate the value of the new technology and pursuing that here would be purely an academic exercise. But the development of a standard tool for using real options to evaluate the research and capital equipment decisions would be a valuable tool for UTC as a whole.

Building on one of the suggestions contained earlier in this thesis, another project would be to develop the measuring device to directly measure the thickness of the ceramic coatings on turbine airfoils. As mentioned in chapter six, this would consist of taking current automatic CMM machines and equipping them with an eddy current probe to measure the thickness of the coating. This will then require the build-up of new SPC capabilities and the re-evaluation of many of the core assumptions around the coating process. An intern with a significant material science background could help yield additional insights for Pratt about the impact different manufacturing processes have on the coating structure and the bond between the coating and the base metal. It may also be beneficial to Pratt and Whitney to have someone look more closely at the connection between the coating specifications on a part and the actual performance in the field. Having the actual thickness data for this exercise would allow a significant review of what the thickness should be for each face of the part.

Some additional areas that warrant a closer look are the details of long-range forecasting and the use of incentives. Looking at how forecasts are made and updated would be good place to start. If the forecasts had been accurate heading into 2005, then the TMC may not be in the situation they are in today. The use of incentives would be another area to examine. Answering why most people look only at optimizing their own area to the detriment of the greater system is often the result of improperly aligned incentives. An example of this is that the union workers on the floor are paid a great deal for overtime and weekends. This creates some negative incentives for them to volunteer information that will eliminate this part of their paycheck. A project in this area could provide major gains in costs and productivity for Pratt and Whitney.

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