Lean Transformation and Relocation of Jet Engine Assembly Operations

by

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B.S. Mechanical Engineering, Brigham Young University, 2006

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

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Abstract

As part of continuing lean transformation efforts at Pratt & Whitney, the Middletown Engine Center has turned its focus on the GP7000 turbofan engine as a target for lean implementation. Projected increases in GP7000 production volume over the next few years, along with aggressive cost reduction targets, are driving the current push to optimize GP7000 assembly and test operations.

The internship work described in this thesis was sponsored to achieve three primary objectives: (1) Identify and then implement opportunities to reduce waste and increase productivity for GP7000 assembly and test, (2) determine an optimal configuration for restructuring GP7000 assembly and test operations and create a business case demonstrating the value of the proposed configuration, and (3) organize an implementation team and begin execution of a GP7000 strategy.

This thesis details an approach for lean transformation of assembly and test operations in an aerospace company. Additionally, the thesis provides a framework for making difficult relocation decisions and shows how lean transformation can be part of an assembly relocation strategy. As a direct result of this work a lean transformation and relocation strategy is in place for the GP7000 and the implementation of that strategy was underway at the conclusion of the internship. The thesis also describes a comprehensive risk management plan that employs the Operational Risk Management (ORM) process from the U.S. Air Force together with a phased implementation approach.

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1 Introduction

It has been nearly two decades now since United Technologies Company (UTC) first embarked in earnest on a lean transformation journey. Over that time span, remarkable improvements have been realized in UTC manufacturing facilities across the globe. By all accounts, the business units of UTC operate much leaner today than they have at any time in past.

Multiple Leaders for Global Operations (LGO) theses have tackled difficult lean transformation projects within UTC's three aerospace businesses; Hamilton Sundstrand, Sikorsky, and Pratt & Whitney. This thesis builds on that body of work by addressing the lean transformation of assembly operations for the GP7000 turbofan jet engine at Pratt & Whitney.

1.1 Problem Statement and Objective

As part of Pratt & Whitney's continuing lean transformation efforts, the Middletown Engine Center has for several years pursued and achieved aggressive cost reduction goals through the deployment of lean production practices in assembly and test operations. Throughout this process, the GP7000 commercial jet engine has resurfaced multiple times as a potential candidate for a lean implementation project. This is partly because, as a relatively young production engine, the GP7000 still has plenty of low hanging fruit to pluck in terms of making operational improvements. Additionally, the GP7000 has the most modular design of any engine assembled in the Engine Center. A relatively small number of large, complete modules flow into the final GP7000 assembly line for what has the potential to be a comparatively straightforward final assembly process. This modularity in design, together with the fact that there are no major monuments tying GP7000 assembly to any particular area of the factory, gives the Engine Center flexibility in deciding how and where the GP7000 will be assembled.

Management at the Engine Center has twice commissioned internal teams to look at relocating GP7000 assembly operations from the final assembly hall in Building 220 to the production test facility in nearby Building 410. The theory is that collocating final assembly with production test operations will improve product flow and decrease lead time. It is also thought that the move could eliminate the time intensive and wasteful process of transporting assembled GP7000s from Building 220 to Building 410. Additionally, management hopes that relocation to Building 410 can provide the opportunity to combine the final stages of assembly with early stages of test preparation, reducing the total number of process hours necessary to build and test an engine. Unfortunately, both previous efforts to relocate the GP7000 were stopped short of completion for various reasons. Most recently, in early 2009, the project was dropped when the projected GP7000 production volume for 2010 did not materialize and the business case, which was based on incremental cost savings per engine, no longer supported the capital investment.

In 2011, the GP7000 production volume is expected to reach levels originally planned for 2010 and over the next three years the annual demand for engines is expected to more than double as shown in Figure 1 below (demand is normalized to the 2010 level to protect proprietary information). At the same time, other engine models will also be ramping up production. Most notably, the G195 (name masked to protect confidential information) military engine will be ramping up production over the next several years and may need to expand from its current floor space footprint in Building 220. Additionally, the Engine Center has set aggressive process hour reduction targets for the GP7000 for 2011 and beyond. These factors are all driving the current push to work out how to optimally restructure GP7000 assembly operations.

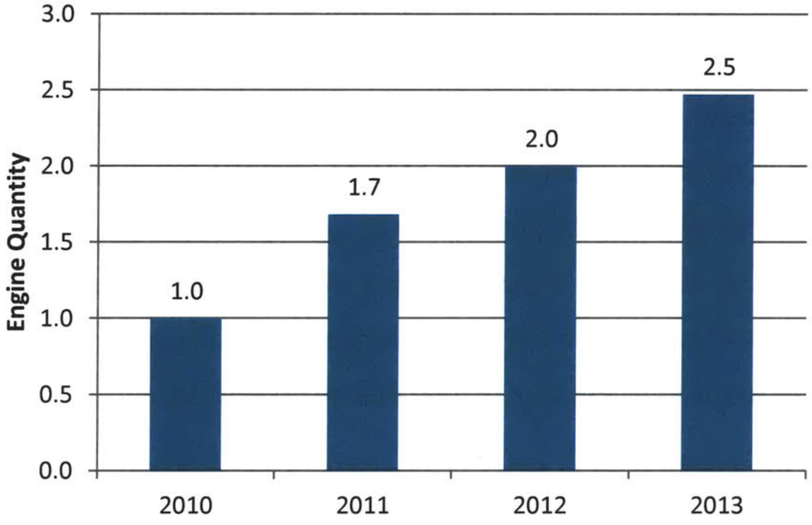


Figure 1. GP7000 Demand Forecast

The objectives of this internship project are threefold:

1. Use principles of lean manufacturing to identify and then implement opportunities to reduce waste and increase productivity for GP7000 assembly and test
2. Determine an optimal configuration for restructuring GP7000 assembly and test operations and create a business case demonstrating the value of the proposed configuration
3. Organize an implementation team and begin execution of the GP7000 assembly and test strategy

1.2 Approach

The project was organized into three phases, with each phase corresponding to one of the three objectives stated above. The three phases are (1) current state analysis (2) business case and recommendation and (3) implementation.

Current State Analysis

Phase one is a current state analysis of GP7000 assembly to identify opportunities for improvement leading up to the possible move to Building 410. This effort is important because as a relatively young engine program, the GP7000 has the potential to realize substantially improved lead times, cycle times, and quality. To diagnose the current state and lay out a future state, tools of lean manufacturing such as value stream mapping and build studies are employed.

Business Case and Recommendation

Phase two is an evaluation of multiple strategies for preparing to handle the increased production volume in the engine center. This includes a scenario analysis of various GP7000 relocation strategies with a careful consideration of the challenges and benefits of each potential strategy. The result of this phase is a business case and recommendation for the emergent strategy.

Implementation

The final phase of the project is the implementation of the strategy from Phase II of the project. This includes the formation of a cross-functional implementation team that includes representatives from all major functional areas with a stake in the project. The bulk of the implementation will be carried out after the completion of this internship, but at the conclusion of the internship implementation was well underway. An integral part of implementation for this project is execution of the Operational Risk Management (ORM) process that will be described in detail later in this thesis.

1.3 Thesis Overview

Below is a summary of each of the chapters in this thesis:

Chapter 2: This chapter synthesizes relevant concepts from some of the seminal literary works on lean production. It begins with a brief account of the birth of lean production at Toyota Motor Company and describes the key tenets of the Toyota Production System. Lean production is then compared and contrasted with the mass production system. This is followed by a discussion of lean manufacturing in the aerospace industry. Finally, the chapter concludes with a presentation of a framework for approaching enterprise lean transformation.

Chapter 3: This chapter provides pertinent background information needed to understand the work presented later in the thesis. This includes an overview of UTC, Pratt & Whitney, and the Middletown Engine Center. An overview of the evolution of the Pratt and Whitney production system is also given here. The chapter then provides a basic lesson on how turbofan jet engines operate. Finally, the reader is introduced to the GP7000 turbofan jet engine, including an overview of the current assembly and test processes for that engine.

Chapter 4: The approach and methodology employed for this internship project are presented in this chapter. The chapter begins with a detailed current state analysis of GP7000 assembly and test operations. The case for GP7000 assembly relocation is presented next followed by a detailed description of the process followed in the design of a lean final assembly flow line. Finally, the chapter concludes with a detailed description of a risk mitigation plan for executing GP7000 assembly relocation.

Chapter 5: This chapter presents a summary of the key findings and results from this internship project. The chapter provides suggestions for successful implementation of the recommendations from the project and ends with concluding remarks.

2 Key Concepts and Literature Review

The origins of modern lean production have their roots in the production system developed in Japan by Taiichi Ohno of Toyota Motor Company soon after World War II. This revolutionary approach to manufacturing has since spread all over the world and has become the new standard for numerous industries and companies. This chapter gives a brief history of the birth of lean production and the Toyota Production System. Later in the chapter, lean manufacturing is compared to the traditional mass production system that it supplants.

The aerospace industry has been one of the last to adopt lean production in favor of mass production. A section of this chapter addresses why this is the case and provides evidence to support the hypothesis that the tools and principles of lean production are transferable to aerospace companies. The final section of the chapter presents a framework for enterprise lean transformation as described in *Lean Thinking* by Womack and Jones (Womack and Jones 350).

2.1 Toyota Production System & Lean Methodology

After the conclusion of World War II, the Toyota Motor Company (at that time named Toyoda) found itself struggling in a difficult domestic market. Toyota faced a labor market that demanded more favorable working conditions, a war-torn economy with little access to capital, and the constant competitive threat from motor vehicle manufacturers that were eager to get a foothold in the Japanese market. They knew that in order to survive they would have to learn to do more with less.

In 1950 Eiji Toyoda, a member of Toyota's founding family, visited Ford's Rouge plant in Detroit and witnessed firsthand what at the time was the most efficient mass production plant in the world. He came away from the experience with the impression that mass production could be greatly improved. Back in Japan, Toyota's Taiichi Ohno was just the sort of visionary that could help Eiji and Toyota to develop a new production system better suited to the unique challenges they faced. This was the beginning of what has come to be known as the Toyota Production System (TPS) and lean manufacturing (Womack, Jones and Roos 48).

Ohno himself visited Detroit multiple times in the ensuing years and was struck by the amount of waste, or "muda", visible in the mass production system. Muda is a Japanese term for waste that refers to "any human activity which absorbs resources but creates no value." Ohno identified seven specifics forms of muda and Womack and Jones add an eighth in their book, *Lean Thinking*. The eight forms of muda are listed below (Womack and Jones 15).

1. Defects in products
2. Overproduction of goods
3. Inventory awaiting further processing or consumption
4. Unnecessary processing
5. Unnecessary movement of people
6. Unnecessary transport of materials
7. Waiting for parts and material from upstream processes
8. Products that do not fulfill customer's needs

The production system designed by Ohno was centered on two main tenets: (1) The elimination of muda and (2) respect for people (Black 5). Some of the methods for realizing these two tenets are described below.

Elimination of Waste

In the Toyota Production System, the foremen from mass production systems are replaced by team leaders who work side by side with their teams performing assembly work in a particular area. The team leader coordinates a team's work and also sets aside time, periodically, for the team to engage in process improvement activities. Continuous, incremental improvement is one of the hallmarks of the Toyota Production System and is a fundamental component of any lean production system (Womack, Jones and Roos 56).

Ohno challenged the prevailing wisdom that an assembly line must keep moving at all times to avoid costly delays. Instead, in the system he pioneered, any line worker has the authority to stop the line by pulling an "andon" cord when a quality defect is discovered. When the cord is pulled the whole team swarms to fix the problem while the line is still moving forward. If the team cannot fix the problem in time for the vehicle to move on to the next station then the line is stopped and the issue is quickly escalated until it is resolved. Then, instead of moving on and hoping that the same defect doesn't happen again, the root cause of the defect is searched out and countermeasures put in place to prevent a recurrence (Womack, Jones and Roos 57).

It is worth noting that Toyota later changed this approach because workers were often hesitant to bring the factory to a standstill by pulling the andon cord. They introduced buffers to decouple line segments thereby allowing for isolated line stoppages while the rest of the factory continues to run. Although this violates the lean principle of eliminating inventory, it has resulted in workers being more willing to pull the andon cord.

In lean production, the batch and queue system from mass production is replaced with rapid changeovers and small batches. Changeover here refers to any time a production device is reconfigured to perform a different operation. Rapid changeovers enable the flexibility to build only what there is demand for and only at the time the demand takes place. If the changeover time for a machine is a full day, then the machine must run large batches between changeovers to achieve an acceptable utilization for an expensive piece of capital equipment. This results in large inventory buffers on both ends of the process. In lean production, changeover times are relentlessly improved until it takes only minutes to perform each changeover. This eliminates the need for large batches and inventory buffers and has the added benefit of making defects easier to spot and quickly correct (Womack, Jones and Roos 53).

Inventory throughout a lean production system is reduced to minimum necessary levels. Ideally parts arrive at a process in the precise quantity needed and only at the precise time needed. In the Toyota Production System the Just in Time (JIT) philosophy is accomplished by the use of "kanban" signals that let upstream processes know that downstream processes are ready for parts. These kanban signals can be electronic or physical in form of a card or container sent up-stream to trigger production for consumption downstream. This forms the basis for a "pull" system where orders from customers trigger production and each step along the way only produces what is required by the next step. When implemented well, a pull system eliminates the need for large buffers between processes and also for large finished-goods inventory levels (Womack, Jones and Roos 62).

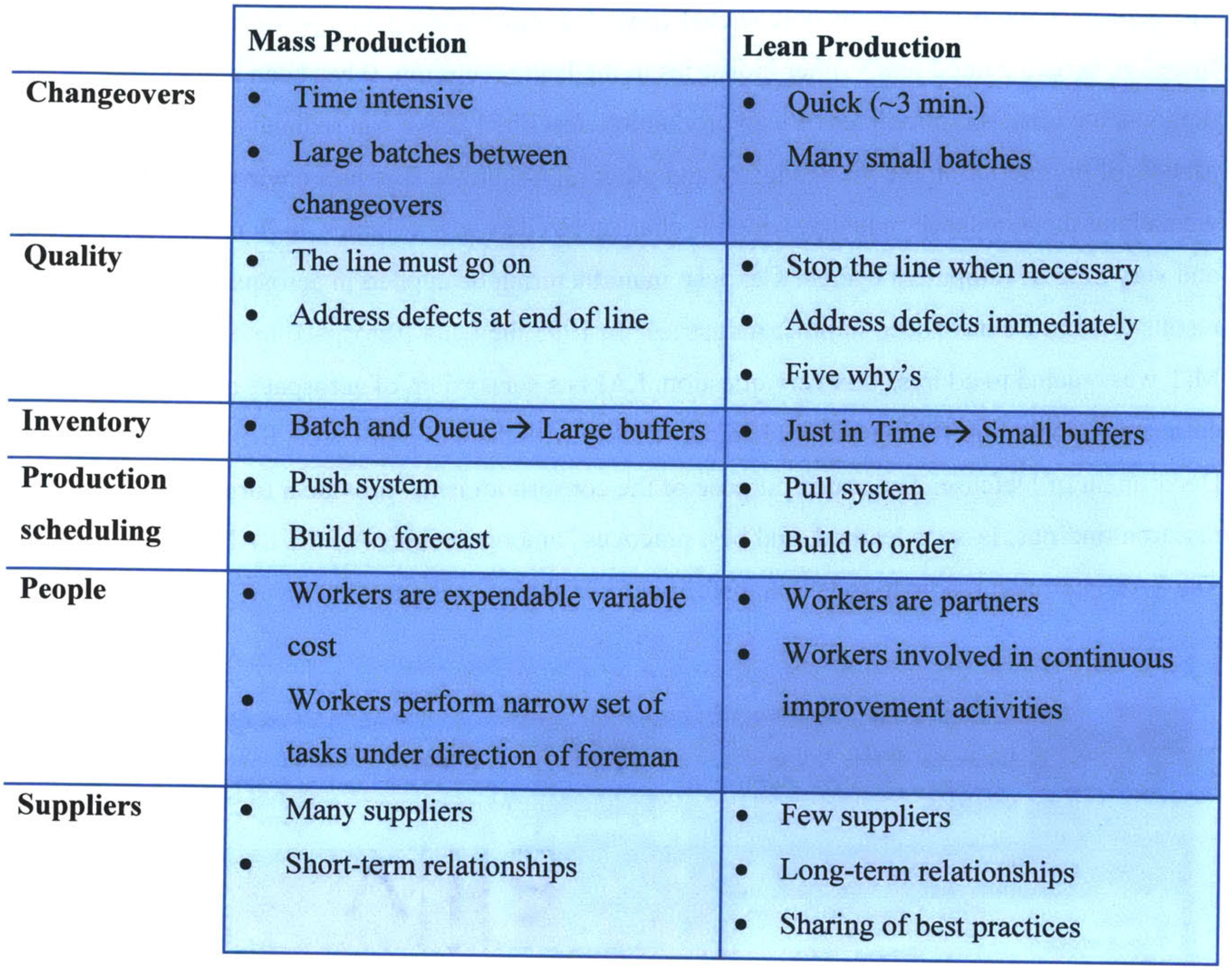
Respect for People

In addition to a focus on eliminating waste, lean production also focuses on relationships with workers, managers, suppliers, and partners that are characterized by mutual trust and respect. In mass production, workers are commonly treated as an expendable variable cost. Lean production calls for treating workers as partners in a company's success by allowing them the right to participate in improving operations and to benefit from the company's success. In the early days of lean production at Toyota, workers were given a guarantee of lifetime employment in exchange for a commitment to a continuous improvement philosophy (Womack, Jones and Roos 54). Although a guarantee of lifetime employment is less common today, companies can show their commitment to employees by providing job security to employees that help to implement lean production. Implementing lean inevitably frees up resources as companies learn to do more with less. The wise lean producer uses the newly available manpower and equipment to bring in more work whenever possible as an alternative to letting go of the very people who helped to achieve greater operational efficiency.

In mass production systems, producers maintain arms-length relationships with suppliers. New parts are put out for bid and given to the supplier who comes in at the lowest cost. As conditions and needs shift, suppliers are readily dropped in favor of other suppliers with lower costs or perhaps more advanced capabilities. In contrast, the lean producer builds long term relationships with a small number of suppliers with which the producer partners to share best practices and continuously improve quality.

Toyota maintains very close relationships with all of its suppliers and typically holds an equity share in its first tier suppliers. This partnership aligns incentives between Toyota and their suppliers and promotes high quality while at the same time facilitating lower costs through implementation of lean practices in supplier facilities (Womack, Jones and Roos 59).

Figure 2 below provides a summary of some of the key elements of lean production discussed above and compares those elements to analogous practices from mass production.



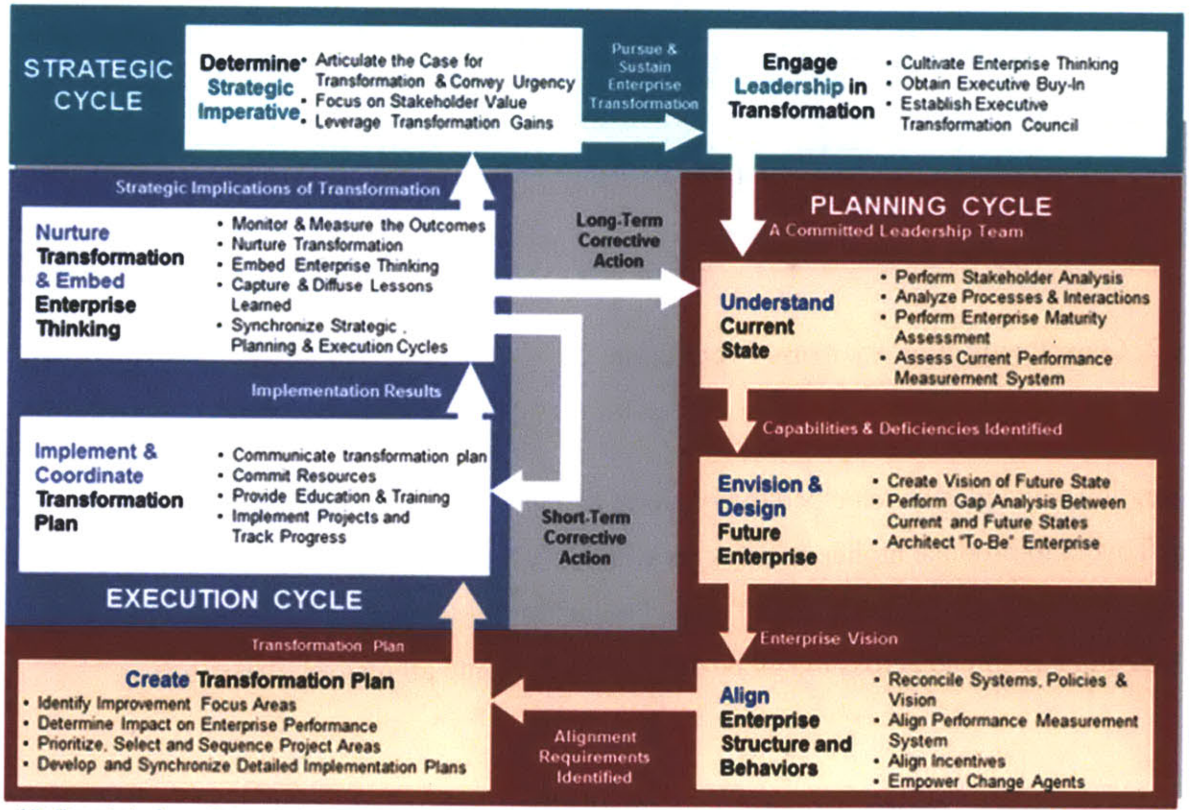
	Mass Production	Lean Production
Changeovers	• Time intensive • Large batches between changeovers	• Quick (~3 min.) • Many small batches
Quality	• The line must go on • Address defects at end of line	• Stop the line when necessary • Address defects immediately • Five why's
Inventory	• Batch and Queue → Large buffers	• Just in Time → Small buffers
Production scheduling	• Push system • Build to forecast	• Pull system • Build to order
People	• Workers are expendable variable cost • Workers perform narrow set of tasks under direction of foreman	• Workers are partners • Workers involved in continuous improvement activities
Suppliers	• Many suppliers • Short-term relationships	• Few suppliers • Long-term relationships • Sharing of best practices

Figure 2. Lean Production vs. Mass Production

These guiding principles have helped to give form to a new way of producing cars that has allowed Toyota to produce higher quality cars with less effort and fewer resources expended than any competing auto manufacturer. The Toyota Production System created a manufacturing revolution that has spread across the globe and has reached into all major industries.

2.2 Lean manufacturing in the Aerospace Industry

The aerospace industry presents unique challenges for implementing lean production and has therefore lagged behind many other industries in the lean revolution. It has been amply demonstrated that the principles of lean production described above can radically improve all aspects of production in the auto industry and other high-volume, low-mix environments. But what about the aerospace industry, which is characterized by low volumes, high mix of products, and very long development cycles? Can lean manufacturing be applied in aerospace with similar results to what we have seen in other industries? In 1993 the Lean Aerospace Initiative (LAI) at MIT was created to address this very question. LAI is a consortium of aerospace and defense companies (including P&W) and MIT in partnership with the U.S. Air Force, the U.S. Navy, and Department of Defense. The stated purpose of the consortium is to "provide a forum for sharing research findings, lessons learned, and best practices" among members of the LAI community. The LAI enterprise roadmap to lean transformation is shown in Figure 3 below (Lewis and Hengen).



http://lean.mit.edu Source: Nightingale, Srinivasan and Mize - Updated 08/10/10 - Version009

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Figure 3. LAI Enterprise Transformation Roadmap

After conducting numerous studies across multiple aerospace companies, LAI researchers have concluded that the tools of lean production are indeed applicable to the aerospace industry. Examples of LAI successes, among many others, include the following (Lewis and Hengen):

- C-17 unit price decrease of $82M for a net savings of $6.5B
- Atlas launch program lead time reduced from 48.5 months to 18 months
- F-16 wing shop flow time at Hill AFB decreased from 62 days to 27 days
- Northrop Grumman Integrated Systems reduced throughput times by 21% for major systems

These findings demonstrate that even the aerospace industry, which arguably provides a more difficult challenge to lean production than any other industry, can benefit from remarkable improvements in cost, quality, lead time, and productivity by implementing lean production principles.

2.3 Enterprise Lean Transformation

In *Lean Thinking*, Womack and Jones identify five key principles that are critical for a organization with lean ambitions to understand. These principles are (1) value, (2) the value stream, (3) flow, (4) pull, and (5) perfection. A brief description of each principle is given below (Womack and Jones 29-90).

1) **Value:** The starting point for lean thinking is defining precisely what "value" means for a company's products or services, as defined from the perspective of the customer.
2) **The Value Stream:** The value stream is the entire set of actions required to carry a product from concept through production. This includes product development, sales and marketing, and manufacturing operations among other activities. When the value stream is examined in its entirety it becomes apparent that many process steps add no value but cannot be eliminated, some steps unquestionably add value, and others add no value and can be eliminated.
3) **Flow:** Once the value stream has been identified, the next step to lean transformation is enabling value to "flow" through the system. This means eliminating unnecessary steps, delays, and backflows, thereby allowing a product to progress efficiently through the process steps that add value.

4) **Pull:** This principle relates to making exactly what a customer wants at the time that the customer wants it. The customer in essence "pulls" the product from the producer instead of the producer "pushing" unwanted product on to the customer. This means reducing dependence on forecasts (to the extent possible) and building only what the customer orders.
5) **Perfection:** Even after a company has successfully internalized the first four principles, there is always room for improvement. This principle is based on the previously discussed lean production concept of continuous incremental improvement. Lean thinking is a journey, not a destination.

Womack and Jones argue that the company that can internalize these five principles and then put them into action can successfully achieve a lean transformation. The initial, radical realignment of an entire value stream, or "kaikaku" in lean terminology, will typically yield drastic improvements in throughput times, cost, quality, and productivity. Then, through continuous incremental improvement, or "kaizen", the gains from the kaikaku can be sustained and further improved upon. Together these concepts can lead to endless improvements (Womack and Jones 27).

3 Background

This chapter presents background information that paints the contextual setting for this internship project in Pratt & Whitney's Middletown Engine Center. An overview of United Technologies, Pratt & Whitney, and the Middletown Engine Center are all presented here, including a history of the evolution of Pratt & Whitney's current production system. This is followed by a discussion of lean production practices within Pratt & Whitney and the Middletown Engine Center.

The reader is then introduced to the basics of the turbofan jet engine. The GP7000 turbofan engine, the focus of this project, is then introduced, including a description of its current state assembly and test processes.

3.1 United Technologies Corporation

Headquartered in Hartford, Connecticut, United Technologies Corporation (UTC) is a technology and manufacturing conglomerate with business units that compete in the aerospace, building systems, and energy markets.

The seven major business units that make up UTC are (Epperson):

- **Carrier:** World's largest HVAC manufacturer
- **Hamilton Sundstrand:** Supplier of high technology aerospace systems and industrial products
- **Otis:** World's largest elevator and escalator manufacturer
- **Pratt & Whitney:** Leader in the design, manufacture, and service of commercial and military aircraft engines
- **Sikorsky:** Leader in the design, manufacture, and service of helicopters
- **UTC Fire & Security:** Fire and security product provider
- **UTC Power:** Developer of fuel cell technologies for buses, automobiles, and buildings

In 2010 UTC reported revenues of $54.32B with a net profit margin of 8.05%. Pratt & Whitney typically brings in the most revenue of all business units, followed closely by Otis and Carrier as shown in Figure 4 below (dollars are in billions). In addition to having the highest revenues, Pratt

& Whitney also consistently reports the highest net profit margin (14.63% in 2009) of the business units (Daniels).

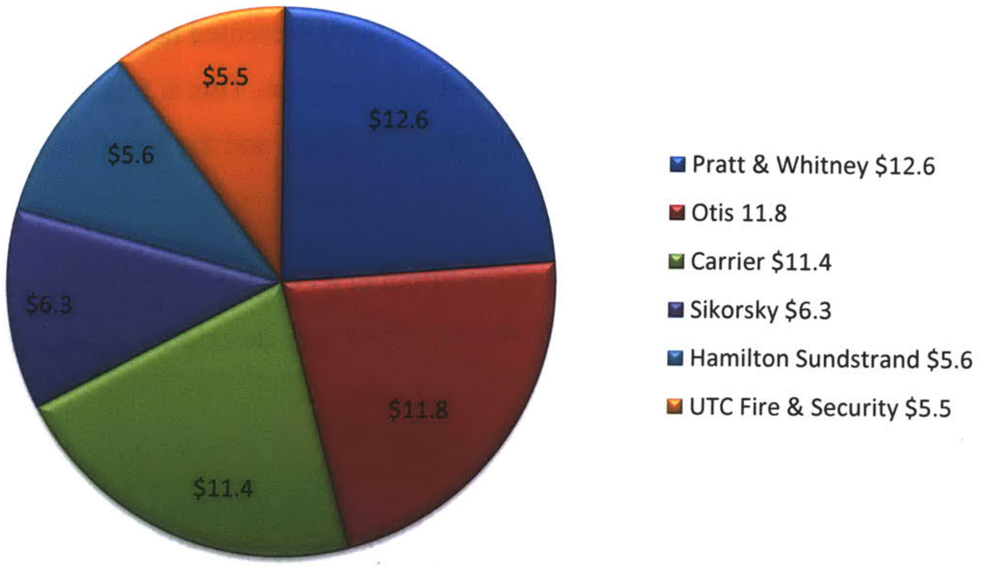


Figure 4. UTC Business Unit Revenues (2009)

UTC's diversified mix of aerospace and commercial/industrial companies has helped the corporation weather the business cycles of these sectors that tend to not be closely synced with each other. Carrier, Otis, UTC Fire & Security, and UTC Power are sensitive to changes in interest rates, construction activity, and access to capital markets and therefore all four felt the full force of the recent global recession. UTC's aerospace and defense businesses, while relatively protected from recession conditions, are more susceptible to fluctuations in the commercial aerospace and military contracting markets caused by changes in the political climate.

Recent downturns in both the aerospace and construction markets forced UTC in 2009 to streamline all business units to cut cost in order to remain competitive. Manufacturing and service facilities were consolidated and some even sent overseas to lower labor-cost locations. In all UTC's workforce was cut by 14,600 employees, bringing its total number of employees down to 206,700 at the end of 2009. Hiring rebounded modestly in 2010 with 208,200 employees at the end of the year(Epperson). UTC has been named the world's most admired aerospace and defense company by Fortune Magazine for 9 out of the last 10 years, only narrowly missing the designation in 2007 when they were rated a close second ("World's Most Admired Companies 2010 - from FORTUNE.").

3.2 Pratt & Whitney

Pratt & Whitney (P&W) is a world leader in the design, manufacture, and service of aircraft engines. In addition to aircraft engines, P&W also makes space propulsion systems and industrial gas turbines for power generation. P&W jet engines provide power for more than 30 percent of the world's passenger aircraft and also power military jets, like the F-15 Eagle, F-16 Fighting Falcon, F-22 raptor, F-35 Joint Strike Fighter, and the C-17 Globemaster III transport. P&W Canada is a major player in engines for corporate jets, regional aircraft, and helicopters. P&W Rocketdyne has been a key engine provider to the U.S. space program for decades and has powered more than 1,600 launches (Daniels).

3.2.1 Pratt & Whitney Production System Evolution

Before we can fully understand the current P&W production system it is necessary to examine the history of P&W and the industry conditions that, over time, have helped to shape the way P&W builds engines today. This section will highlight the key moments in P&W's evolution and is meant to shed some light on how the modern P&W corporate culture and production system have come to be.

P&W's roots can be traced back to the company founded in 1855 by Francis Pratt & Amos Whitney as a supplier to Samuel Colt's gun armory. Pratt and Whitney became experts in building the machine tools and gauges needed to achieve "mechanized" gun production with interchangeable parts. They became pioneers of the American System of manufacturing that, unlike the European System, did not require skilled craftsman to fit each part individually to other components. In 1860, Pratt and Whitney left Colt to form the Pratt & Whitney Company specializing in building special purpose machines and tools to enable high speed, high volume production of interchangeable parts. This became the foundation for a batch-and-queue system of manufacturing that at the time was a revolutionary advancement in manufacturing (Womack and Jones 153).

It was 65 years before P&W joined forces with Frederick Rentcshler and ventured into aircraft engine manufacturing. In 1925, Rentschler, armed with a concept for a large, radial, air-cooled engine, borrowed a million dollars from P&W to form Pratt & Whitney Aircraft Company (Womack and Jones 154). In return, Rentschler gave P&W half of the stock in the newly formed company. P&W Aircraft Company attracted the most experienced engineers in the industry and in remarkably short time (only nine months) they were able to design the new Wasp engine which was more powerful and much lighter than the next closest competing engine. Orders poured in and by 1929 P&W was the world leader in the aircraft engine business (Womack and Jones 155).

As Wasp production volumes increased it became necessary to organize the company by functional disciplines (i.e. – engineering, production, sales, quality, etc.) to ensure each of these activities could keep pace with demand. With only the Wasp in production it was easy to coordinate across these new functional boundaries and the pooling of expertise allowed P&W to more efficiently carry out tasks owned by individual functions. Soon, however, P&W's product offerings began to rapidly expand and coordination between functions was no longer a trivial matter. To face this new challenge the position of "product engineer" was created to serve as a central point of contact to coordinate all activities that comprise the design, test, and production of a particular engine model. The concept of one entity, or person, assuming responsibility for the entire value stream was forward thinking and in line with current principles of lean manufacturing. However, in practice, the product engineer lacked the authority really manage the value stream and the end result was that no one assumed responsibility for the entire value stream (Womack and Jones 156).

As P&W grew, changes in the factory were needed to compliment the organizational changes described above. Initially, machines were small and lined up, more or less, in the proper order to facilitate the flow of parts through the factory in a straight line. In time, however, the machines became larger and more specialized and special shops were created for operations such as heat treating, painting, and polishing. Materials now had to travel all over the factory before they became finished parts. Additionally, all part inspections were performed in a central location necessitating all people and parts to converge to a central location between process steps.

At that time, P&W had an "assemble it, then tinker until we get it right" mentality that resulted in multiple cycles of build, test, tear down and build again before an engine was finally ready to ship to the customer (Womack and Jones 157).

All of these changes were cemented in place with the advent of World War II when skilled labor became scarce and production volumes skyrocketed. P&W had now completed its transformation from a skilled-craftsmen production system to mass production. The new mass production environment created a low skilled workforce under tight management control. The company was now ripe for labor to organize into a union, which it did in 1945 with the International Association of Machinists (IAM). Another important result of World War II was that the constant pressure to design engines that weighed less and produced more power created the need for even deeper technical silos (Womack and Jones 158). As engines became increasingly complex each of the many technical silos developed extensive specialized knowledge for their own small area of expertise.

Soon after WWII, P&W realized that jet engines were the technology of the future and they abandoned development of reciprocating piston engines to focus on catching up with competitors in jet engine design and production. Given the highly scientific nature of knowledge needed to design jet engines the technical silos, already firmly in place, now deepened even further and coordination across functional boundaries became more difficult. However, the expertise P&W had developed in manufacturing reciprocating piston engines transferred well to jet engines and by the end of 1960s P&W dominated the jet engine market (Womack and Jones 160).

Jet engines were manufactured using the same mass production methods as described above with specialized machines, large batches, long lead times, and each worker performing a narrow set of tasks. At the time, P&W's customers consisted of regulated commercial airlines that competed on service rather than price, and the military for which performance was the most important concern. Given this environment, the mass production system in place at P&W was more than adequate to keep customers happy and maintain a competitive edge over rival aircraft engine manufacturers. In the engineering and technology centered culture at P&W, selling price and production costs were calculated as a byproduct only after senior engineers had decided which new technologies would be incorporated into a new model or configuration. Also contributing to the general lack of focus on production costs was the jet engine business model, still very much in effect today, of selling engines at or below cost in anticipation of generating substantial profits selling spare parts over the life of the engine (Womack and Jones 161).

Predictably, the days of easy profits without significant focus on improving manufacturing operations were not destined to last forever. The first real sign of trouble came in 1984 when the military grew tired of quality problems with P&W F100 engines and awarded General Electric (GE) with half of the business as a second source for the engine. P&W was also experiencing quality problems with some commercial engines and began to feel the effects of erosion of market share as competitors took business away. Also, around this same time, P&W famously blundered by betting that large, dual-aisle aircraft were the future of the airline industry and chose not to aggressively position themselves with new product offerings for the single-aisle market. GE and Snecma formed a joint venture called CFM that did produce a new engine for the single-aisle market that was chosen by Boeing for their updated 737 aircraft (Womack and Jones 163). The 737 has gone on to become the best selling aircraft of all time resulting in P&W losing its grip on the dominant market share it once enjoyed.

In response to the fierce competition that P&W now faced on all of its major product lines, the company took its first real steps towards lean production. P&W reorganized into "focused factories" with each factory taking end to end responsibility for one category of parts. Within each factory the machines were arranged in flow lines where possible to minimize the distance each part traveled. Additionally, P&W began to develop material and design standards for design engineers to use as guidelines in designing engine parts (Womack and Jones 164). This eliminated a great deal of wasted engineering time fine tuning material specifications for each individual part. Another important advancement was the creation of Integrated Product Development (IPD) teams that included representatives from various functional groups helping to break down the communication barriers between those functional silos. To address quality concerns P&W adopted a Total Quality Management system that integrated well with IPD teams (Womack and Jones 165). The results of these changes were significant, but ultimately not very sustainable. It was not until later that change agents in senior management were able to successfully realize a true cultural shift that would result in more lasting improvements.

The first of these change agents, Mark Coran, who in 1991 had just been given the role of Senior Vice President of Operations, was initially tasked with cutting the size of the business by about

10% to adjust to worsening market conditions. The end of the 1980s and the early years of the 1990s were a tumultuous time period for P&W and the rest of the aerospace industry. The cold war had just ended and the demand for military engines had plummeted. Additionally, commercial aircraft engine orders, which had peaked in 1989, fell by nearly 80% over that time span. It soon became apparent that more than just cost cutting would be necessary to survive this new crisis. Multiple competing strategies were proposed to address the new challenges. The strategy ultimately selected by Coran was to restructure the entire P&W production system by implementing lean methodologies and principles (Womack and Jones 151-152).

Coran immediately went to work reducing P&W's supply base to a smaller number of companies with whom long-term relationships could be established. He also began to rearrange machines into work cells that would allow one operator to tend multiple machines. Coran next enlisted the help of the lean manufacturing gurus Yoshiki Iwata and Chihiro Nakao from the lean manufacturing consulting firm Shingijutsu (Womack and Jones 168). In short order, Nakao and Iwata succeeded in drastically reducing the amount of shop floor space, tools, and effort required in the Middletown plant, but the gains were lost nearly as quickly as they had come when management and the workforce resorted back to their old ways (Womack and Jones 169).

The next real change agent came in 1992 when Karl Krapek was appointed as president of P&W. Krapek previously had been the president of another UTC division, Otis Elevator, where he had demonstrated the ability to infuse lean thinking into an organization. The steps that Krapek, along with Coran and other key managers, took in the various P&W production facilities were the following (Womack and Jones 180):

1. Cut headcount to long-term sustainable levels
2. Standardize work
3. Replace managers that would not or could not adapt to the new system
4. Aggressively attack quality problems
5. Implement continuous flow

As part of this effort, P&W divested non-core portions of the business, closed some facilities, and let go of a substantial number of workers. These were difficult decisions to make, but ultimately P&W came out the other end a much leaner, healthier business that was now prepared to thrive despite the difficult market conditions. In the next section we will discuss current lean manufacturing practices at P&W and the organizations that have been formed to support lean implementation. The lean principles in place today are the direct legacy of change agents that paved the path to lean thinking at P&W and also reflect the unique history and culture that have shaped the modern day company.

3.2.2 Lean Manufacturing at Pratt & Whitney

Achieving Competitive Excellence (ACE) is a proprietary operating system at United Technologies that is designed to drive continuous improvement and lean methodologies throughout the entire company. Each business unit has its own ACE organization that reports up through to the corporate ACE office. The ACE operating system is comprised of 12 unique tools that are used together to reduce costs, improve quality, and engage the workforce in continuous improvement activities. Organizations within P&W (and other UTC business units) progress through Bronze, Silver, and finally Gold levels of ACE certification as they implement ACE tools and demonstrate sustainable improvements in their operations. In 2010 P&W was working toward a goal of 100% of sites qualifying for either Silver or Gold by the end of the year. P&W's progress through 2009 on the journey towards ACE Gold can be seen in Figure 5 below.

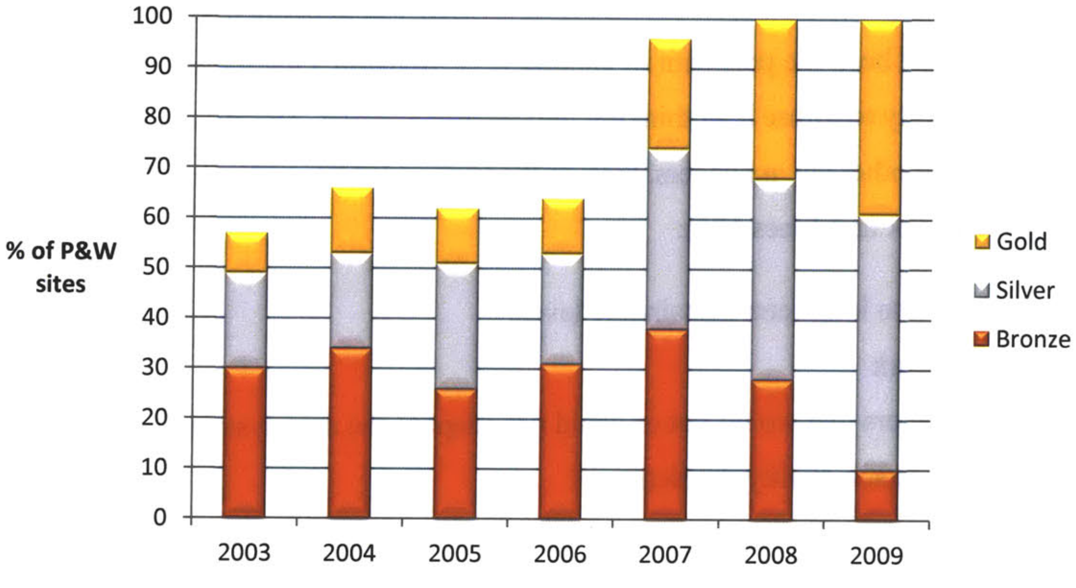


Figure 5. ACE Progress at P&W

The ACE tools borrow elements of the Toyota Production System as well as from the Total Quality Management (TQM) philosophy pioneered by Edward Demming (Frauenberger 32). The 12 tools are each briefly described below.

ACE Tools

1) **6S & Visual Factory:** A set of guidelines for maintaining a clean, safe, and efficient working environment. The six component of 6S are:
2) Sort – determine what is needed and what is not and remove the latter
3) Stabilize – a place for everything and everything in its place
4) Shine – keep all work areas clean
5) Standardize – set in place standard work practices that ensure the other elements of 6S are carried out in a uniform and consistent manner
6) Safety – eliminate hazards
7) Sustain – maintain the gains achieved from executing the first five components of 6S

8) **Total Productive Maintenance (TPM):** A system designed to maximize the amount of "up-time" for each machine. This involves using 6S along with scheduled preventative maintenance and other measures to make sure machines are functioning properly (*Continuous Improvement Methodology at Pratt & Whitney* 51).
9) **Quality Clinic Process Charts (QCPC):** A tool used to continuously monitor a process to identify improvement opportunities and process inefficiencies.
10) **Relentless Root Cause Analysis (RRCA):** A process used to identify the root cause of quality defects or "turnbacks" and to put in place measures to prevent future occurrences of the same problem. At P&W, the term turnback is defined as "anything that impedes the flow of material (or information) along its intended path (*Continuous Improvement Methodology at Pratt & Whitney* 56)."
11) **Mistake Proofing:** A preventative approach to addressing turnbacks by designing tools, processes, and products that have built in checks that do not allow mistakes to be made or, at the very least, make it very difficult to make a mistake.
12) **Market Feedback Analysis (MFA):** The use of customer feedback data to track and analyze product performance, ensuring customer's expectations and needs are met and that quality and reliability are continuously improved.

13) **Process Certification:** A tool that is used to ensure that new processes have been reviewed, approved, and are ready to be put into operation.

14) **Standard Work:** A methodology that is used to document and create a guide for how work is to be performed to reduce variability and improve the quality of work output (*Continuous Improvement Methodology at Pratt & Whitney* 57).

15) **Setup Reduction:** A process that is used to reduce setup time, thereby increasing the effective capacity of a machine or workstation (*Continuous Improvement Methodology at Pratt & Whitney* 44).

16) **Passport System:** A system of review gates that ensure a product or process design is low risk and has achieved a satisfactory level of maturity before proceeding on to a subsequent stage of development/implementation.

17) **Production Preparation Process (3P):** A process that utilizes low cost mock-ups to simulate an actual production process in early stages of design. This allows for more effective collaboration between design and production disciplines and helps to build quality into products.

18) **Value Stream Mapping (VSM):** A visual representation of the end-to-end flow of information and material that goes into producing a product. The VSM helps to identify and eliminate waste and improve lead time.

Cost Reduction

The Middletown Engine Center has its own unique group, called Cost Reduction, which has synthesized the ACE tools into a set of procedures for performing "assembly optimization." Assembly optimization is used to drive down costs and improve quality in engine assembly operations by shortening lead times, reducing total process hours, and improving the flow of engines and materials. The assembly optimization process uses a phase-gate approach with ACE tools and activities divided among five phases and with periodic gate reviews to make sure objectives are being met and that projects are on track.

The exact details of the assembly optimization toolkit are proprietary and therefore not included in this thesis. However, a high level overview of some of the major activities involved is provided to give the reader a better sense of what the Cost Reduction group does. The process is divided into four categories: Define, Investigate, Verify, and Ensure.

In the Define stage, Cost Reduction engineers start with a problem statement. A project plan is created which defines the project timeline, budget, and required resources. The expected outcomes of assembly optimization, including the financial impacts, are also identified at this time.

In the Investigate stage, one of the first activities is to create current and future state value stream maps for the assembly and test operations of the engine under study. This exercise helps Cost Reduction engineers to visualize where there is waste that can be eliminated using ACE tools. Another key activity during the Investigate stage is the execution of "build studies," where Cost Reduction engineers physically observe every sequence of assembly and test from beginning to end. Every minute that each mechanic works on the subject engine is recorded and classified as either assembly (A), rework (R), level 2 or 3 inspection (I2 or I3), or turnback (T). Each turnback that occurs is also classified into one of a group of categories (quality, material, tooling, etc.) and any information pertinent to the turnback is recorded. The build study data is then used by kaizen teams to address each of the turnbacks that have been identified. Other activities performed include balancing work content among assembly stations, reducing where possible the number of required inspections, and organizing incoming material into "pitch" increments that contain one shift's worth of work. All of these activities help to enable the smooth flow of engines and material through the assembly process.

After the improvements described above have been implemented, the Cost Reduction team transitions to the Verify and Ensure stages of assembly optimization where they track key cost and productivity metrics and put in place measures to sustain the gains achieved from the kaizen activities.

The Cost Reduction group has been successful in achieving substantial improvements in lead time, cycle time, and overall cost on multiple engine assembly lines over the past 2-3 years.

3.2.3 Middletown Engine Center

Located in central Connecticut, the Middletown Engine Center, hereafter referred to as the Engine Center, is one of seven P&W module centers that were organized as part of the focused factory movement in the late 1980s. The other six module centers are the following:

- Turbine Module Center (TMC)

- Compression Systems Module Center (CSMC)
- Combustor, Augmentor & Nozzle Module Center
- North Berwick Parts Center (TMC module partner)
- International Parts Center
- Electronic & Mechanical Systems

Each of these "focused factories" supplies completed modules to the Engine Center for use in engine final assembly (*Engine Center Overview*).

The four main activities housed in the Engine Center are validation assembly, production assembly, production test, and engineering. This internship project takes place within production assembly and production test.

The engines assembled and tested in the Engine Center fall into one of four categories; (1) military, (2) industrial, (3) commercial mid-thrust, and (4) commercial high-thrust. Commercial engines comprise the majority of engine production in the Engine Center; followed by military engines, with industrial power generating turbines accounting for only a small percentage of the overall Engine Center production volume as shown in Figure 6 below.

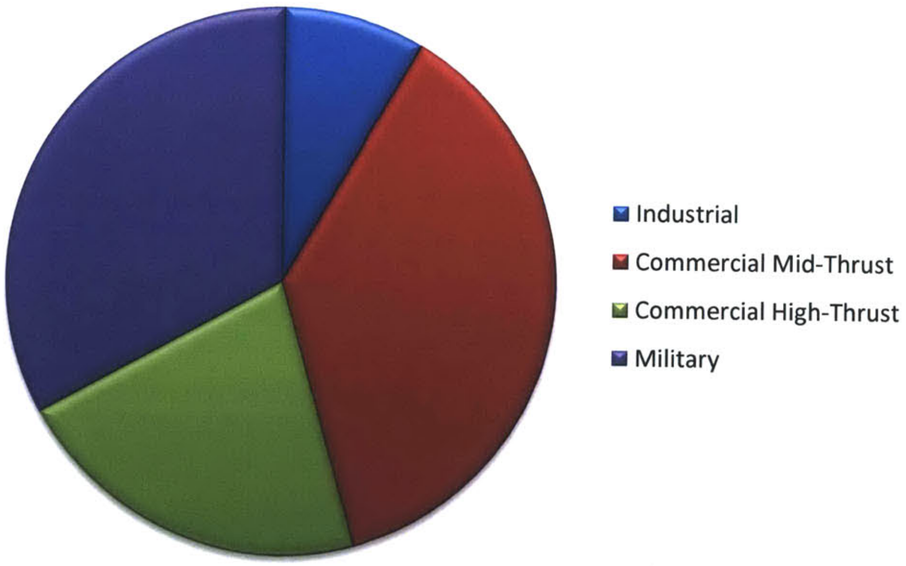


Figure 6. Engine Center Production Engines by Category (2009)

Over 2,000 employees work at the Middletown site, which includes the Compression System Module Center and Core Procurement in addition to the Engine Center. The Engine Center hourly workforce is unionized under the banner of the International Association of Machinists and Aerospace Workers (IAM).

3.3 Turbofan Engine Basics

The turbofan engine, a member of the jet engine family, is the engine of choice for commercial passenger aircraft due to its high fuel efficiency. Other jet engine types include, among others, the turbojet, commonly used in military fighter jets, and the turboprop, typically used for smaller, lower speed jets.

There are five major components that are critical to the operation of a turbofan engine. Those components are the (1) fan, (2) compressors, (3) combustor, (4) turbines, and (5) exhaust nozzle ("Engine Education - Turbofan Engine."). These five components work together in perfect harmony and synchronization to generate the thrust to propel an aircraft through the sky. Figure 7 is a simplified graphical representation of these components and should be used as a reference for the discussion that follows ("Turbofan.").

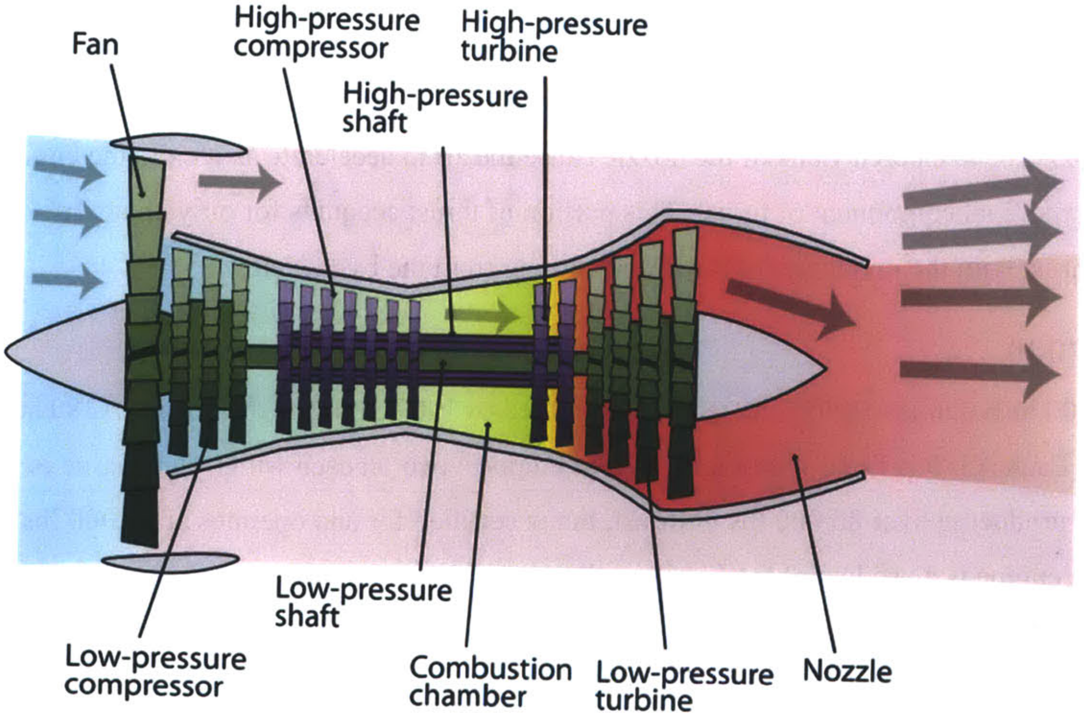


Figure 7. Turbofan Engine Operation

The thrust generation process begins when air is drawn in the front of the engine by the fan. At this stage the air is divided into two streams; the primary air (~15%) which passes through the engine's core and bypass air (~85%) which bypasses the engine core. The large volume of bypass air accelerated by the fan generates the majority of the thrust in a turbofan engine.

The primary air begins its journey through the engine core by passing through the compressors where temperature and pressure are increased dramatically. A typical turbofan jet engine has two compressors, a low-pressure compressor (LPC) and a high-pressure compressor (HPC). Air first passes through the LPC and then is compressed even further by the HPC.

After passing through the compressors, the high pressure, high temperature air enters the combustion chamber where fuel is added and burned. At this point the air has reached extremely high pressure and temperature. Much of the energy in the air that exits the combustion chamber is then re-captured by the turbines which turn the coaxial shafts that drive the fan and compressors. The HPC and high-pressure turbine (HPT) are connected together by the high-pressure shaft, and the fan and LPC are connected to the low-pressure turbine (LPT) by the low-pressure shaft.

The hot air that has passed through the turbines is then forced to exit the engine through a tapered nozzle. The tapered walls of the nozzle cause the air to accelerate as it exits the engine producing the final component of thrust. This portion of thrust accounts for only about 10% of the total thrust with the remainder of the thrust coming from the bypass air.

3.4 GP7000

The GP7000 turbofan jet engine, the largest assembled by P&W, powers the Airbus A380 super jumbo jet. Each A380 is fitted with a total of four engines; two on each wing. The engine is capable of producing over 80,000 lbs of thrust, but is certified for and operates at 70,000 lbs of thrust. The engine is a product of the Engine Alliance, a 50/50 joint venture between P&W and GE. These two fierce competitors have chosen to partner on the GP7000 to share risk on a highly capital intensive project and also to leverage the best technologies from both companies to produce a high-performance, high-reliability, high efficiency engine. This section provides a brief contextual background of the GP7000 and also provides an overview of the GP7000 assembly and test processes.

3.4.1 GP7000 Background

The GP7000, produced by the Engine Alliance, is one of two engines that Airbus A380 customers can choose between when purchasing an aircraft. The other engine is the Trent 900 produced by Rolls-Royce. The Trent 900 initially powered nearly the entire world fleet of A380s, but in recent years the GP7000 has closed the gap to the point that it powers nearly half of all A380s in operation. The largest customer for the GP7000 is Emirates Airlines who with one large order of 55 aircraft (55 X 4 = 220 engines, plus spares) enabled the GP7000 to close the market share gap ("Engine Alliance GP7000.").

Major production delays for the A380 have trickled down to all major suppliers for the aircraft, which has resulted in production delays for GP7000. The 2010 production volume was only about half of what was originally forecast, but now many of those orders are scheduled to come through in 2011 as discussed earlier in the project background section.

In the section on the evolution of the P&W production system we learned that P&W in the 1990s changed their product design philosophy to move toward more modular designs with risk bearing partners supplying some of the major modules. This philosophy is evident in the product and supply chain design for the GP7000. GE, P&W's primary partner in the Engine Alliance, is responsible for the design and assembly of the engine core which includes the HPC through to the HPT, or the "hot section" of the engine. GE delivers the engine core directly to the Middletown final assembly plant. Other major suppliers include:

- MTU Aero Engines – HPT and LPT
- Snecma - HPC
- Techspace Aero (Snecma Group) – LPC

The LPT arrives in Middltown from MTU in three major sub-assemblies that are integrated together in the Engine Center assembly hall to form a completed LPT module. The LPC arrives from Techspace Aero as a completed module. The other modules listed above are shipped to GE in Durham, NC for inclusion in the engine core (Kandebo 43). P&W manufactures the Fan and Fan Case in Connecticut.

In the most simplistic view, there are four major modules that feed the final assembly line in Middletown: (1) The engine core, (2) the LPC, (3) the LPT and (4) the Fan and Fan Case. This highly modular design creates the potential for high efficiency on the final assembly line where the engine can easily "snap" together. Of course, in reality, assembling such an advanced and highly complex piece of machinery is no trivial matter as will be demonstrated throughout this thesis.

3.4.2 GP7000 Assembly and Test Overview

The following section will give a high level overview of the process steps involved in final assembly and test of a GP7000 engine. The description has been simplified to describe how the major modules come together to make a completed engine that is ready for shipment. Greater detail on some of the assembly steps will be given later as necessary to describe work done as part of this internship project.

Assembly

Assembly begins when an engine core arrives in Middletown from GE in Durham. The core is brought into a large receiving bay where an overhead hoist lifts it from the truck and carries it to the assembly floor. The core is then placed on pedestals in a horizontal position where it awaits other engine modules for assembly. Most engine models in the Middletown final assembly plant begin assembly in a vertical position and remain vertical until the engine is ready to receive its Fan and Fan Case, at which time the engine in rotated into a horizontal position for the remainder of assembly. Because the GP7000 is so large, the entire assembly process is done in the horizontal position with the engine resting on pedestals.

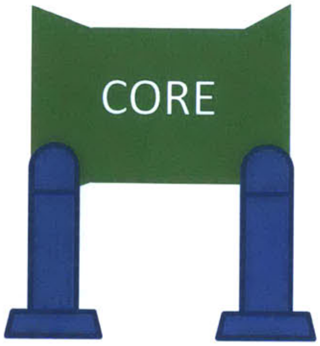


Figure 8. GP7000 Core on Pedestals

The first major module to be assembled to the core is the LPT, which comes from a LPT assembly cell a short distance away from the final assembly line. The LPT module includes the low-pressure shaft and is transported on a special dolly that holds the LPT and shaft in a horizontal position. The transport dolly is positioned underneath an overhead hoist which is then used to lift the LPT out of its stand and position it behind the engine core. Mechanics use the hoist to carefully insert the shaft through the core until the LPT becomes flush with the core is and is secured in place with fasteners.

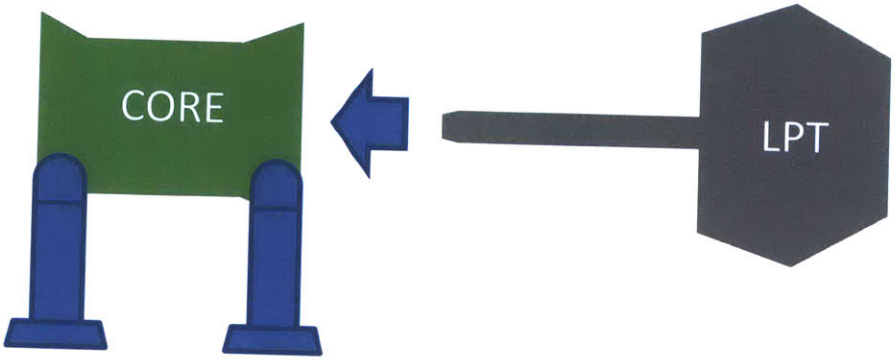


Figure 9. LPT Assembly to Core

Next, the LPC is delivered to the assembly line in time to coincide with the end of LPT assembly to the core. The LPC arrives in a large wooden crate and is unboxed using the overhead hoist and then inspected for damage or defects prior to assembly. After inspection the LPC is positioned in front of the core using the overhead hoist and secured in place in much the same manner as the LPT.

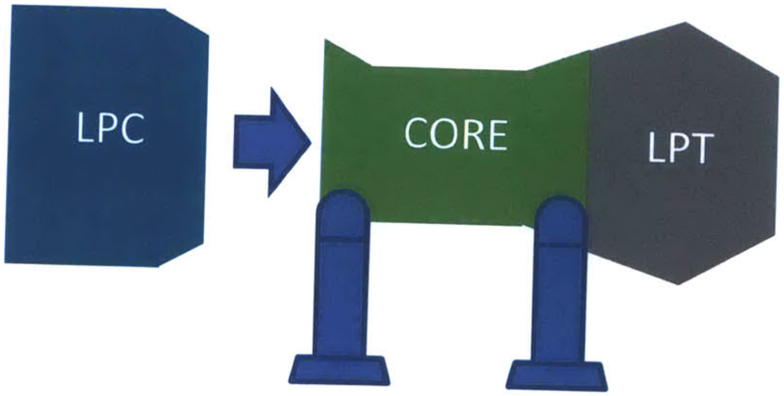


Figure 10. LPC Assembly to Core

At this point the engine has achieved a state of assembly where it is called a propulsor. Because the Fan has a longer service life than the rest of the engine, customers will occasionally order propulsors as spares and reuse the Fans from other engines when they are taken out of service.

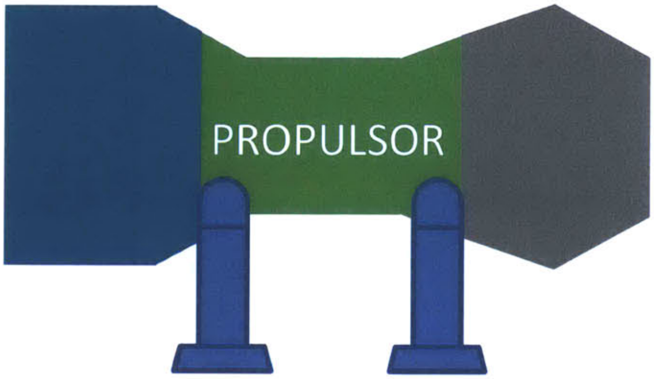


Figure 11. GP7000 Propulsor

The next, and final, major module to be assembled to the engine is the Fan Case and Fan. The Fan Case is has two major components, the containment case and the exit case, that are assembled together in a special build stand located adjacent to the engine final assembly line. A completed Fan Case is taken off the build stand with the hoist and placed in the fan case dolly which is then rolled by hand into position in front of the engine in a horizontal position. The Fan Case is carefully mated to the engine and then secured in place with bolts. The fan blades arrive to the assembly line separately from the Fan Case and are placed in special stands that hold them in an easily accessible position for picking up with the hoist for assembly. The blades are then assembled to the engine one at a time until the Fan is complete.

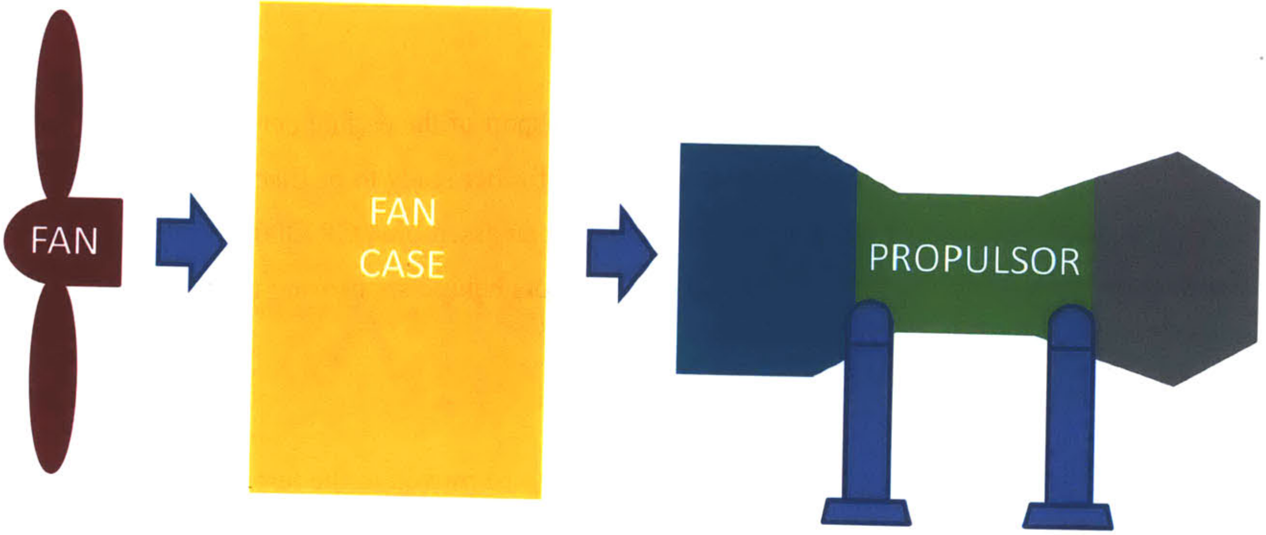


Figure 12. Fan Case Assembly to Propulsor

At this point all of the major modules have been assembled to the engine, but much assembly work still remains. The next step is to assemble all of the engine externals to the engine. This includes the engine plumbing and electrical harnesses that form a tightly packed web encompassing most of the engine when finished. The engine is then ready for an assembly check-out procedure that involves thorough inspections, weight measurement, and a stack of paperwork prior to being transported to the test building.

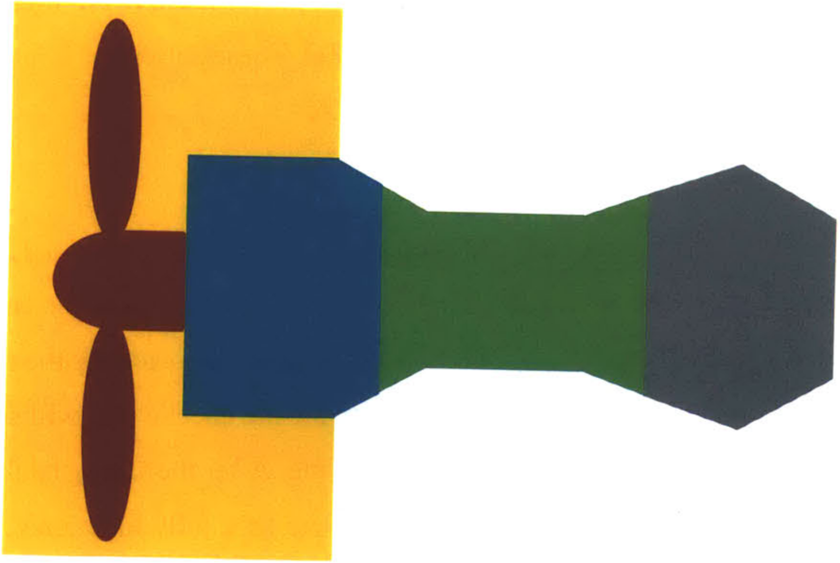


Figure 13. Fully Assembled GP7000

The assembly check-out procedure and subsequent transport of the engine between buildings are steps that add no value to the engine and are subject of further study to be discussed later. In fact, the visible waste in the processes necessary to transport an assembled GP7000 from the assembly floor to the test building was one of the motivating factors behind sponsoring this internship project.

Test

All engine models, except for the GP7000, when ready to be moved to the test building are picked up by a hoist, moved along overhead rails to the receiving/shipping bay, and placed on a flatbed truck for delivery to Building 410. The GP7000 is transported differently because it is too large to make it out of the door well of the shipping bay when on a flatbed truck. Instead, the engine is placed in a special shipping buck which is then towed to the test building using a small industrial tugger. The process of loading the engine into the shipping buck is time intensive and the tugger and shipping buck do not handle well in inclement weather. This means that in the event of ice, rain, or snow the GP7000 must wait in its shipping buck for the weather to improve before being transported to Building 410.

Once the engine has been delivered to Building 410 it is removed from the shipping buck and again placed in pedestals ready to begin the test preparation process. There are four main activities that are involved in testing and shipping a GP7000. These activities, in the order they occur, are (1) dress, (2) test, (3) strip, and (4) pack and ship.

Dress

Engine Dress includes all activities necessary to prepare an engine for a test cell. The main object of this stage of the process is to install a duct set or “strong back” onto the engine. The strong back serves as a structural support to hold the engine firmly in place for the test process. It contains all the interfaces and connections needed to simulate the nacelle that will serve as the mounting structure for the engine when it is installed on-wing. After the strong back is installed, all engine systems (i.e. – electrical, mechanical, hydraulic, etc.) are fully functional. The strong back is suspended from an overhead rail by two high-load capacity hoists. Once all connections to the engine have been made the pedestals are removed and the engine is now fully supported by the strong back. The hoists then carry the strong back/engine assembly along an overhead rail that leads into a test cell.

Test

In the test cell each engine is run through its paces with a series of tests designed to tune the performance of the engine, balance the fan blades, ensure there are no fluid leaks, check for unwanted vibrations, and generally make sure the engine is fit to be shipped to the customer.

Strip

After the testing has been completed the engine is removed from the test cell and the strong back is "stripped" from the engine. All special equipment that was added to the engine in the dress stage is removed and all open tubes and connections are capped. During this stage the engine undergoes a borescope inspection where a camera on a flexible shaft is inserted into the engine through open ducts to inspect rotors and turbine blades. If everything checks out the engine is moved to final stage before being shipped to the customer.

Pack & Ship

The pack and ship process is much more labor intensive for the GP7000 than for any other engine model. The reason for this is that, because of the large size of the engine, the Fan Case and Fan must be removed from the propulsor and shipped in a separate shipping buck in order to fit multiple engines on a cargo plane for delivery. The process of splitting the engine for shipping is tedious and labor intensive. The parts that are removed from the engine are all inspected and then packed into two large shipping containers. When a GP7000 leaves the factory it has been broken down into a propulsor in a shipping buck, the Fan Case in a separate shipping buck, and the two shipping containers mentioned above.

Work Instructions

Each sequence of assembly and test is carried out in accordance to electronic standard work instructions that are displayed on computer monitors at each workstation. Assembly mechanics swipe their badge at the beginning and end of each work sequence creating a wealth of assembly data. This data is used to track, analyze, and improve assembly performance.

The work instructions for a series of assembly sequences (SEQ) make an Assembly Floor Sheet (AFS). Parts and material that feed assembly operations are grouped by Bill of Material (BOM) and each BOM contains material for a group of AFS's. All materials for a given BOM are delivered to the assembly floor together in a series of kit karts. Each major engine module (MOD) that is assembled to the engine has several BOMs. Figure 14 above gives a graphical representation of this hierarchy for the hypothetical example of a fan MOD.

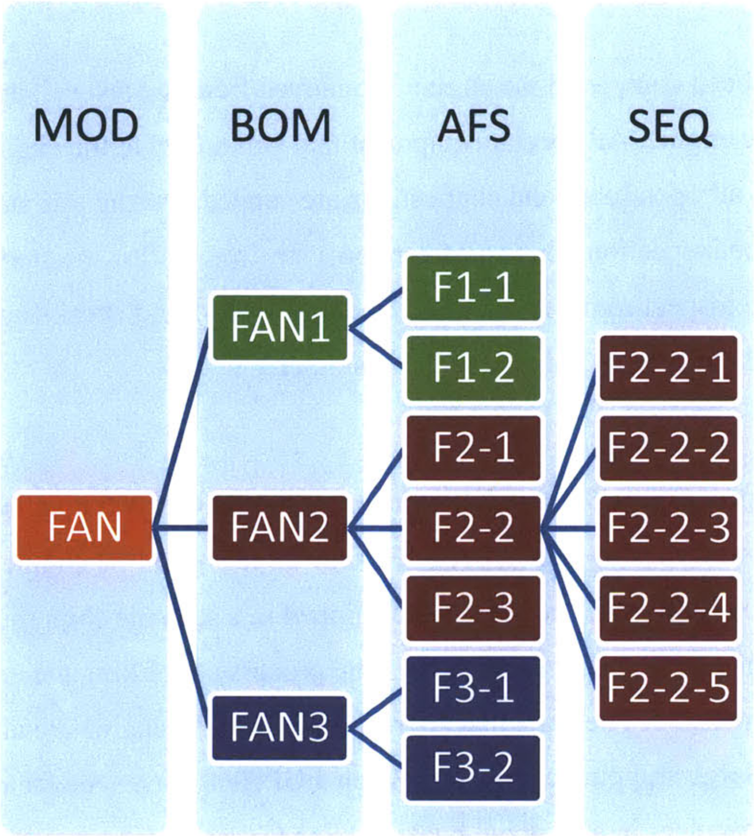


Figure 14. Assembly Work Instruction Hierarchy For Fan Module

4 Approach & Methodology

This chapter details the approach taken in this project to initiate a lean transformation of GP7000 assembly and test operations as well as to put in place a strategy for GP7000 assembly relocation. Although the steps taken here are specific to the GP7000, the general approach can be thought of in a more generic sense as a roadmap for approaching final assembly lean transformation and/or assembly relocation for highly complex, long lead time aerospace products.

As described in the introductory chapter of this thesis, the approach taken can be broken down into three distinct project phases. The three phases are (1) current state analysis (2) business case and recommendation and (3) implementation. This chapter addresses each of these project phases, in order, with GP7000 data, analysis, and examples included where appropriate. Section 4.1 talks about phase one, section 4.2 deals with phase two, and the rest of the chapter contains information relevant to phase three.

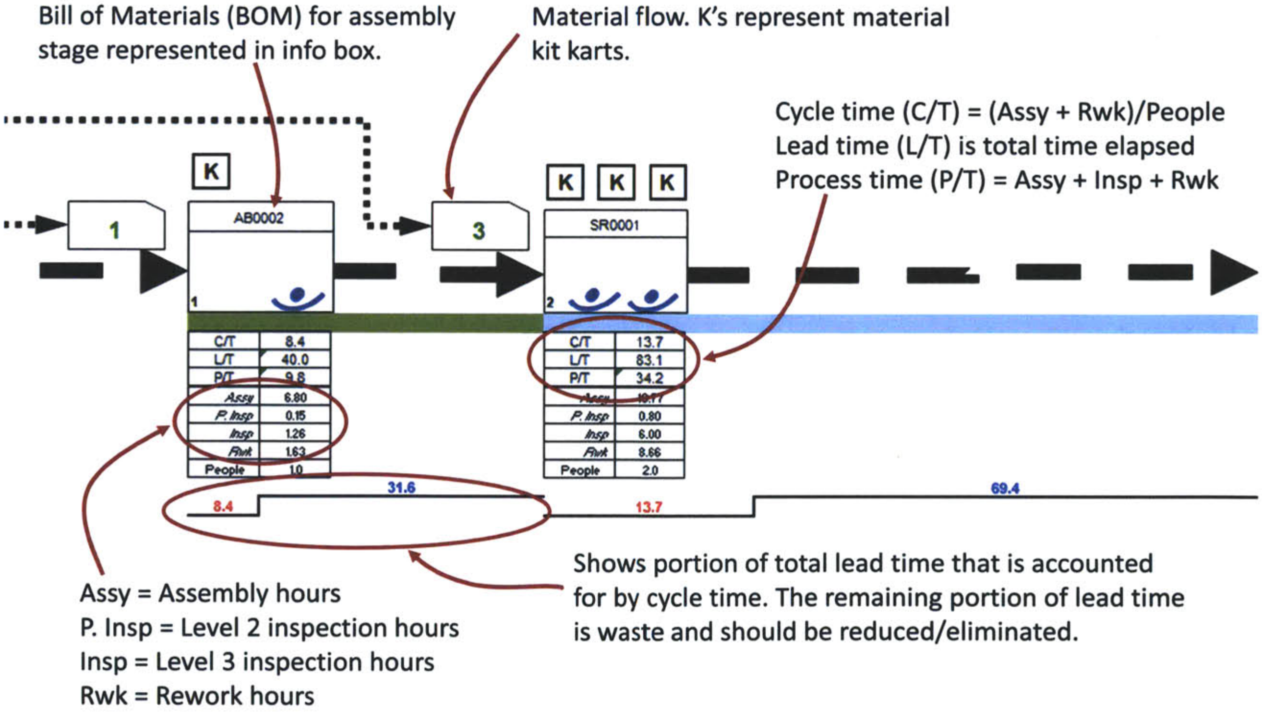
4.1 GP7000 Current State Analysis

The first step in any lean transformation is to diagnose the current state of the operations that will be the target of improvement efforts. For the GP7000, the current state analysis began with an end to end value stream map of assembly and test operations, starting at the first assembly step in the process and ending when an engine is shipped. The next activity in the GP7000 current state analysis was the collection and analysis of manufacturing data to draw additional insights into the health of current operations. Build studies were then used to validate the results from the value stream map and data analysis, and to document firsthand the opportunities for process improvements. Finally, a future state value stream map was constructed to help visualize what the process should look like in its streamlined, waste-free form.

4.1.1 Current State Value Stream Map

A value stream map is a tool that is used to understand the flow of information and materials that make a product. The output of this tool is a visual representation of product flow from one step to the next through to completion. The tool can be applied at various levels of a value chain; at a macro level that includes raw materials all the way through to customers, or a more micro level looking at a particular assembly line. In the case of the GP7000, the value stream map focuses on the all final assembly and test operations that are performed at the Engine Center. This thesis assumes that the reader is familiar with value stream mapping and will therefore not discuss in great detail the process of creating a value stream map. For more information on value stream mapping please refer to the book, *Learning to See,* by Rother and Shook (Rother, Shook and Lean Enterprise Institute 102, [10]).

The Cost Reduction Group at the Engine Center has developed a process for creating what they call a Synchronized Value Stream Map (SVSM). A traditional value stream map includes an information box for each process that displays key process metrics and also includes a visual display of the proportion of process lead time that comes from value-added activities. However, it fails to provide a visual representation of the relative length of each process. The SVSM contains all of the information from a traditional values stream map, but it also gives a to-scale visual representation of the end to end timeline of the product flow through the system. Figure 15 below is a snapshot of a portion of a SVSM with annotations explaining some of the key elements.



Bill of Materials (BOM) for assembly stage represented in info box.

Material flow. K's represent material kit karts.

Cycle time (C/T) = (Assy + Rwk)/People
Lead time (L/T) is total time elapsed
Process time (P/T) = Assy + Insp + Rwk

Assy = Assembly hours
P. Insp = Level 2 inspection hours
Insp = Level 3 inspection hours
Rwk = Rework hours

Shows portion of total lead time that is accounted for by cycle time. The remaining portion of lead time is waste and should be reduced/eliminated.

Figure 15. Synchronized Value Stream Map Example

Unlike traditional value stream maps which typically show a linear product flow along its critical path, the SVSM includes other processes, or feeder lines, that flow into the main assembly line. The end result is complete visual representation of the entire product assembly. A SVSM makes the relative length of processes and how the processes flow into each other easy to see and understand.

The SVSM for GP7000 assembly and test brought a number of issues into much clearer focus. Two of the more important results will be highlighted here. The first, and most obvious, of these issues is the excessively long lead time relative to cycle time for most of the assembly stages. This result indicates the presence of waste and helps in understanding the magnitude of lead time reductions that may be possible through assembly optimization. Some of the causes for this disparity between lead time and cycle time were brought to light through build studies, as will be discussed later.

Another result, apparent form the SVSM exercise, is the high degree of overlap between the process stages. Process sequences that are intended to be carried out in series, in many cases show up as overlapping in the SVSM. To understand this result, recall that the beginning and end time for each assembly sequence are recorded when an assembly mechanic swipes his or her badge. The fact that the data shows overlapping assembly sequences indicates that mechanics are not performing work in the order determined by process engineers.

This could arise from situations when some parts are late to arrive to the assembly workstation and mechanics move forward to assemble the parts that are available. If that is the case, then the overlapping assembly sequences could suggest that mechanics are being flexible and efficient. In build study observations this type of behavior was evident on some occasions. It could also suggest that disruptions in the supply chain and/or material handling need to be addressed. The high degree of overlap may also suggest the possible need to re-sequence work to create a more natural order of operations for mechanics to perform.

4.1.2 Data Collection and Analysis

As part of the SVSM effort, GP7000 process hours and lead time data were collected for all engines built in 2010 up to the point in time when this analysis was performed. The data includes the beginning and end time for every sequence of assembly and test with every unit of time classified as either assembly (A), rework (R), or level 2, or 3 inspection (I2/I3) as discussed previously. The data also identifies which mechanic or inspector performed the tasks of each assembly sequence. This data was used to analyze the year-to-date lead time, cycle time, and total process time performance for each assembly and test MOD.

Process time (the sum of assembly, rework, and inspection) is the metric that is tracked most closely in Engine Center because it has the most direct impact on cost. Histograms of total process time for each MOD in most cases follow an approximately normal distribution with some obvious outliers. This indicates that special causes may be contributing to the high number of process hours in specific cases. Figure 16 below is a histogram for one assembly MOD that clearly demonstrates the behavior stated above. Most of the MODs display a similar pattern.

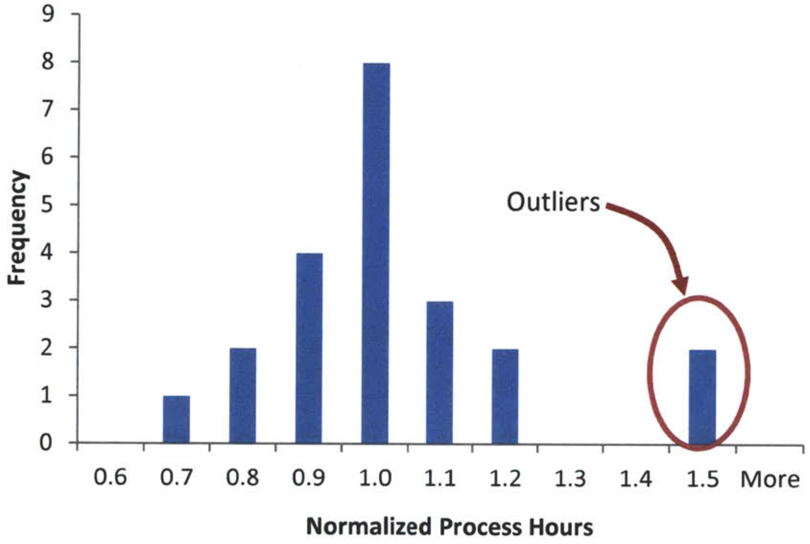


Figure 16. Process Hours Histogram for Representative GP7000 Assembly Module

In a later section, when discussing balancing the GP7000 assembly line, we use the result above to justify excluding outliers from the data when dividing work among workstations. The build studies discussed in the next section uncover some of the special causes for the outliers in the process time data and help to give confidence that those causes can be addressed through assembly optimization efforts.

When looking at total process hours per engine over the life of GP7000 production it is apparent that substantial reductions have been achieved. The process time reduction from engine to engine can best be characterized by a Crawford learning curve with a near constant rate of improvement for every doubling of engine output. The learning curve can be described by the equation below ("The Learning Curve.").

$$P_X = T_1 * X^b$$

Where:
P_X = Process hours needed to assemble the X^{th} engine
T_1 = Theoretical process hours for the first production engine
X = Sequential number of the engine for which the process hours are to be computed
b = A constant reflecting the rate process hours decrease from engine to engine

Figure 17 below is a plot of total process hours for all GP7000 engines starting from the first production unit until the latter part of 2010. The data has been normalized by the process hours for the first unit such that the process hours value for any subsequent engine can be read as a percentage of the first unit process hours. Excel was used to estimate parameters T_1 and b by adding a power trendline to the plot. The learning curve equation with appropriate parameter estimates is shown on the plot. Approximately one third of the data points were not available to the author; however the data points that are included are from the most critical regions of the curve and are enough to adequately define the shape of the learning curve. The parameter b can be used to calculate the learning curve slope using the equation below.

$$slope = e^{b*ln2}$$

Plugging b = 0.305 into the slope equation we find the GP7000 learning curve has a slope of 81%. This means that each time the total number of GP7000s produced doubles we can expect process hours per engine to decrease by 19%.

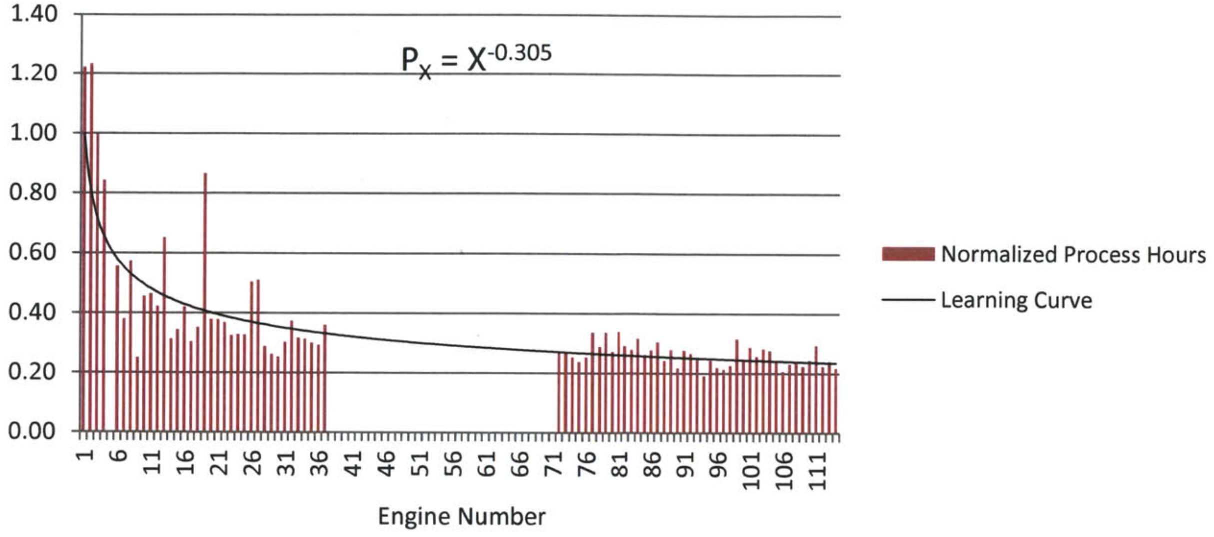


Figure 17. GP7000 Process Hours Learning Curve

An important insight from the GP7000 learning curve is that we have reached a flat area of the curve and reductions in process hours are not going to come as easily as in the past. To illustrate this fact, consider engine 114, which is the last on the chart above and required approximately 0.217 process hours (normalized) to build. Ten engines later we would expect the process hours for engine 224 to have decreased by about 2.4% to 0.212. Contrast that with the 14.3% reduction over the same number of engines from engine 14 at 0.396 to engine 24 at 0.339. This means that, although some additional improvement can be expected from learning curve effects, any substantial improvement will have to come from concerted assembly optimization efforts.

Another insight drawn from the examination of the data is that there is high variability in process lead time for the GP7000 BOMs. Recall from Figure 14 that a BOM is an individual bill of material and the BOM lead time is the time elapsed between the start of the first assembly sequence under that BOM and completion of the last assembly sequence. To measure the variability we use the coefficient of variation (CV) which is the sample standard deviation divided by the mean. Because the CV measures variability relative to a mean value it allows us to compare the degree of variability in the lead time for different BOMs.

The lead time CV for individual BOMs are much higher compared to the CV for the overall engine lead time. The large variations in lead times make it difficult to have a predictable flow of engines through the factory. Figure 18 shows the lead time for one particular BOM which is representative of the degree of variability present for most other BOMs. The data is normalized by the average lead time.

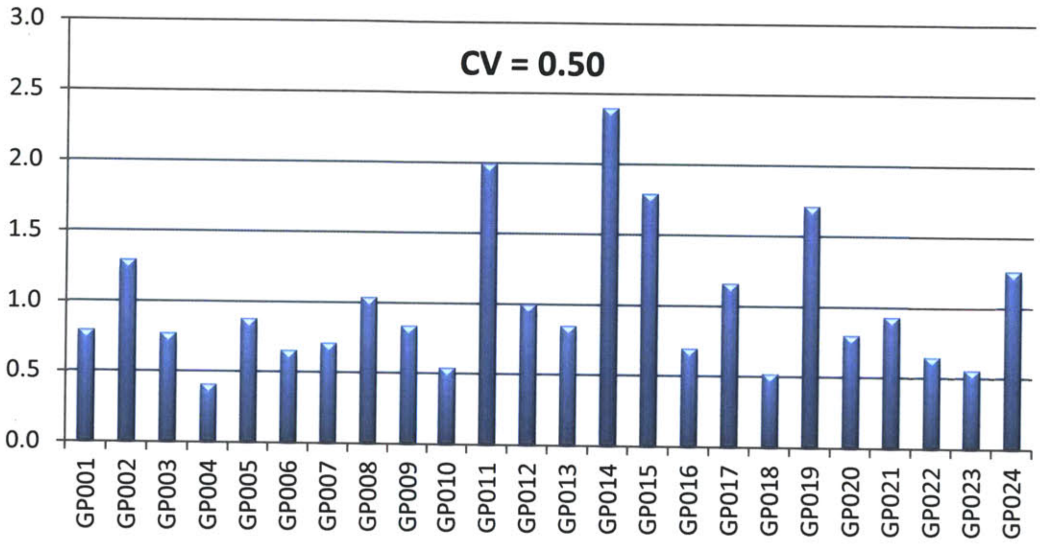


Figure 18. GP7000 Lead Time for Individual BOM

Before a predictable pulse flow can be achieved (as will be discussed later) the variation in BOM lead times will have to be reduced. Cost Reduction's assembly optimization process can help to bring this variability under control. Part of the cost reduction process is to organize incoming materials into "pitch" increments that contain one shift's worth of work. With pitch material management in place, mechanics' progress relative to tact time can be visually monitored by the amount of material remaining on a material kit kart as a shift progresses. On other engine programs that have successfully implemented pitch material karts, the expectation for what work a mechanic is to accomplish in one shift is made clear. As a result, mechanics are more likely to pace themselves accordingly and variability is reduced.

Another way in which assembly optimization can reduce BOM lead time variability is by systematically rooting out and addressing the most prevalent turnbacks that disrupt assembly. Turnbacks account for a significant portion of the overall variability in current state GP7000 assembly, and eliminating some of those recurring turnbacks will help in achieving the more consistent lead times that will be necessary for a pulse flow.

Figure 19 below shows the total engine lead time (from start of assembly to shipment) of 22 consecutive engines. Again, the data is normalized by average lead time to mask proprietary information. The total lead time CV for this set of engines is 0.24 which is less than the CV for individual BOMs, but still large enough to cause concern. Although it is true that the variances of independent random variables are additive, the CV expresses variation as a percentage of the mean and therefore does not add in the same way. The CV of the sum of random variables is lower than the CV for the individual variables because some of the variation cancels out when the variables are added together. In this case, the random variables are the BOM lead times which added together make up the total engine lead time.

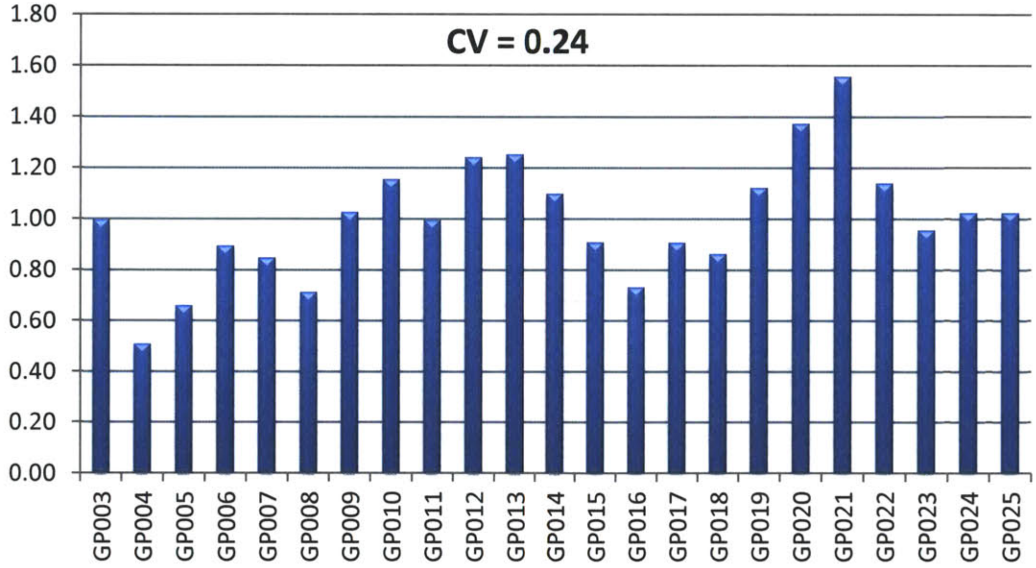


Figure 19. GP7000 Total Engine Lead Time

This analysis of GP7000 data demonstrates the opportunity for substantial improvements in lead time variability and thereby in overall lead time. If the causes of high variability in lead time and process time can be identified and corrected the GP7000 program stands to gain significant cost savings. The build studies in the next stage of the current state analysis help to uncover some of these causes and to validate the magnitude of improvements that should be expected from assembly optimization.

4.1.3 Build Studies

Using the tools created by the Engine Center's Cost Reduction group, build studies were performed on a select number of GP7000 build sequences. Typically, when the Cost Reduction group performs build studies on an engine model, they complete three full observations of each MOD for that engine. Due to limited available resources, the intern narrowed the scope of the build studies to target only select assembly sequences and to complete one full observation for each of those sequences rather than three. The goals of this exercise are to validate assumptions about process hour reductions available through assembly optimization and to identify the most prominent turnbacks that slow down GP7000 assembly.

Prior to this internship, a group within the Engine Center undertook an exercise to estimate the minimum process hours that should be required to complete each GP7000 MOD assembly. The results of that exercise were compared to current GP7000 MOD process hours and the MODs with the greatest disparity between actual process hours and theoretical minimum process hours were selected for observation.

Findings from the build study for one MOD that was studied are shown in Figure 20 and Figure 21 below. Figure 20 gives a lead time breakdown for the MOD and shows what portion of lead is attributable to cycle time, what portion is attributable to waste (turnbacks), and what portion is unused. The unused lead time represents the amount of available manufacturing time that the engine was not worked on for one reason or another. In an ideal scenario, cycle time would account for the entirety of the MOD lead time. Although such a result is not likely to be achieved, unused lead time and waste from turnbacks should be reduced to the extent possible. In this example, 44% of lead time could be eliminated without reducing the time available for value adding activities. Other MODs that were the subject of build studies displayed similar results.

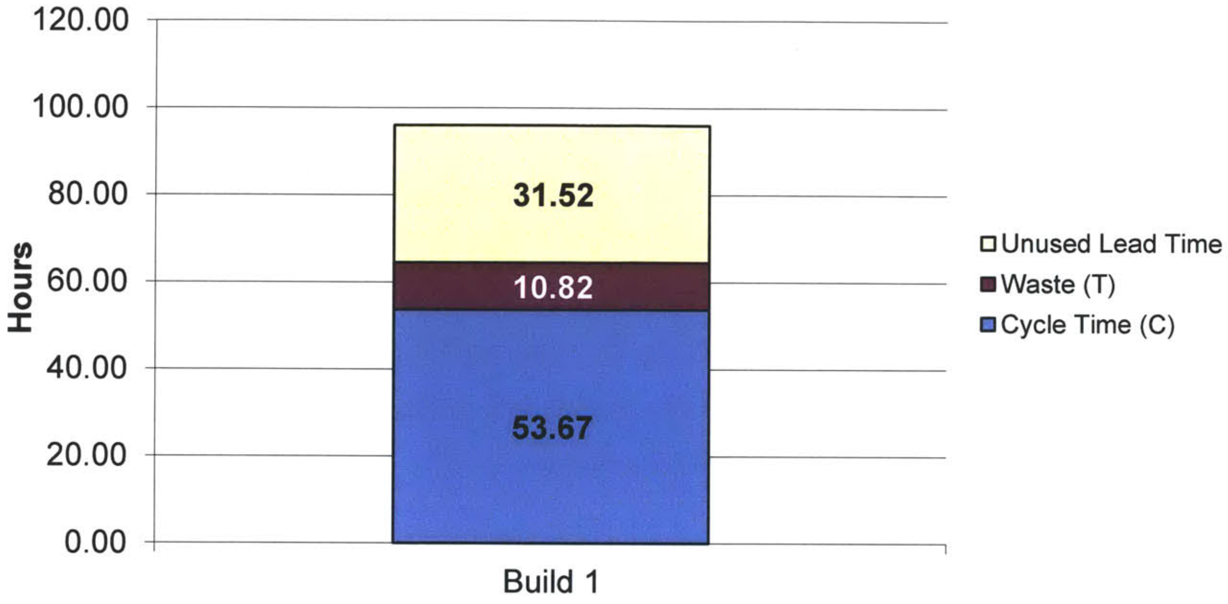


Figure 20. Example Module Lead Time Breakdown from Build Study

Figure 21 gives a breakdown of the turnbacks that were observed during the build study observations for the same MOD. The figure shows a count of turnbacks observed in each of four categories as well as the hours that were lost to each of the five umbrella categories of turnbacks. For this particular MOD, management and quality turnbacks were the most prevalent and also the most costly in terms of hours wasted.

The most common turnback in the quality category is waiting for an inspector to come to the workstation to perform a level 3 inspection. When a level 3 inspection is needed, a flashing light is activated to alert the nearest inspector to report to that workstation. Mechanics will sometimes wait for 30 minutes or more before an inspector arrives. In many cases the inspection is needed before work can continue resulting in assembly mechanics sitting idle while waiting for the inspection to be performed.

Under the management turnback category, shown in Figure 21, the predominant turnback is work interruption when mechanics stop to chat with other mechanics about non work-related topics. Many hours of productivity are lost as mechanics gather during work hours to socialize while engines sit idly awaiting further work.

Although not very prevalent in the observation for this particular MOD, turnbacks in the material category often comprise a significant portion of the total time lost to turnbacks. It is often the case that a delay in receiving material at the workstation results in what is referred to on the shop floor as the "GP7000 pose" where mechanics are sitting with arms folded waiting for a part to arrive. In some cases the missing part is really needed before work can continue, while in other cases there is probably opportunity to move on to a different assembly sequence. Supply chain issues pose a real threat to achieving a smooth product flow through the factory.

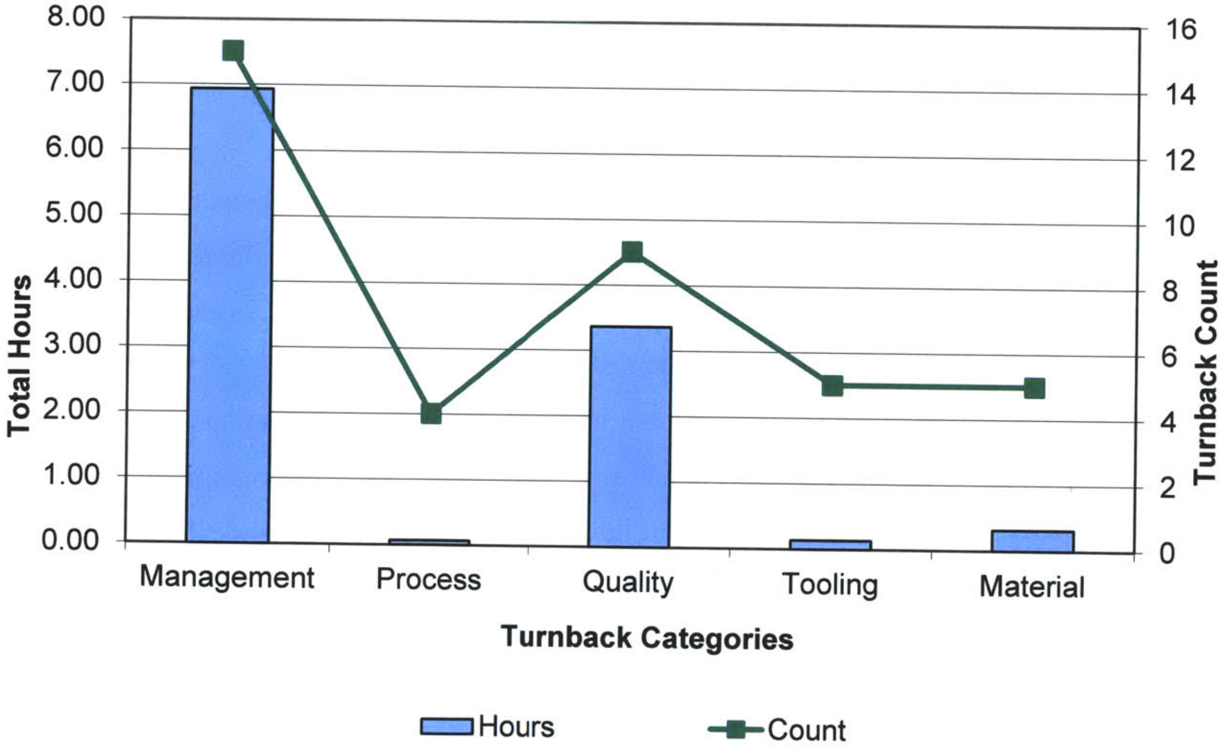


Figure 21. Module Turnback Breakdown from Build Study

These results serve to validate the supposition that lead time, cycle time, and subsequently cost are ripe for reductions through execution of Cost Reduction's assembly optimization process. In fact, later we will see that fully funding and resourcing the Cost Reduction group to perform assembly optimization on the GP7000 is one of the recommendations resulting from this project. Additionally, substantial gains in productivity appear to be possible from improved management practices that motivate mechanics to work efficiently despite disruptions from missing parts or slow-to-arrive inspectors.

4.1.4 Future State Value Stream Map

Based on the results from the current state SVSM, data analysis, and build studies, a future state value stream map was constructed to provide a visual representation of what post-optimization GP7000 assembly and test should look like. The future state value stream map reflects a vision for an improved product flow with shortened lead times. It also shows cycle times accounting for the bulk of process lead time. The values used for lead times and cycle times are taken from the analyses described in the preceding sections and represent what are believed to be realistic targets that can be achieved through assembly optimization.

4.2 The Case for Assembly Relocation

One of the stated objectives of this internship is to build a case either for or against GP7000 assembly relocation to the test building and to prepare a strategy for executing the relocation decision. Originally, it was thought that an economic model could be built that would capture the financial implications of various relocation strategies. However, as the intern began to gather inputs to the model it quickly became apparent that many of the strongest arguments for relocating GP7000 assembly operations could not be readily captured by an economic model. This section discusses the key considerations that inform the GP7000 relocation decision. Some of these considerations are strategic in nature, while others deal with more immediate, concrete benefits. The section concludes with a high level description of the relocation strategy recommended by this internship project.

4.2.1 Assembly Relocation as a Vehicle for Lean Implementation

One argument in favor of relocating GP7000 final assembly operations to the test building is that doing so would provide an opportunity for a fresh start without the burden of the engrained habits and processes that have developed over time. The GP7000 is sometimes referred to among mechanics as the "forgotten" or "neglected" engine, because mechanics are often pulled from the GP7000 to help meet production targets on other engine models. The GP7000 will sit without being worked on for extended periods of time more often than any other engine on the assembly floor. This is in part because, up until this point in time, GP7000 production volumes have been low relative to other engine models. Also contributing to this phenomenon is the perception among management that the GP7000 is easier to assemble than other engines and therefore does not require the same level of focus to keep things running smoothly. This somewhat lackadaisical attitude toward the GP7000 seems to have trickled down to the shop floor assembly mechanics who take a relatively leisurely approach to assembling the engine.

As the demand ramps up sharply starting in 2011, this hands-off approach to managing GP7000 assembly will no longer be sufficient to meet production targets. As is the case in many aerospace companies, the hourly workforce at the Engine Center is well tenured and fairly rigid in the way they do work. Attempts to make changes quickly are often met with resistance. GP7000 production is in need of a culture shift and relocating assembly operations may provide the right opportunity to make difficult changes. That is not to say that by merely moving assembly operations from one building to another a cultural transformation will automatically take place. It will take a deliberate effort from operations management and shop floor supervisors to ensure that new cultural norms are established to complement a new assembly flow line in a new location.

One way this might be accomplished is to put incentives in place that will encourage the most motivated and engaged mechanics to volunteer for assignment on the new GP7000 assembly flow line. This could be done by giving mechanics the opportunity to participate in the design of the new work area. Having helped design the work area, mechanics would likely feel more invested in its successful operation. Another potential incentive to working on the new GP7000 flow line is the opportunity to work in a newer, cleaner, better organized facility. These are two possible tactics for making the new GP7000 flow line something that mechanics will want to be a part of.

Relocating assembly to the test building could open up a critical window of opportunity to establish new work standards and processes before workers become accustomed to the new environment and new process flow. After a period of time, new habits will be cemented in place and if managed correctly this can be a great benefit for GP7000 assembly.

4.2.2 Engine Center Strategic Outlook

The GP7000 is just one cog in the Engine Center production system that assembles and tests a variety of commercial and military engines. Relocating part or all of GP7000 assembly operations will therefore have system wide effects. Concurrent with the uptick in GP7000 demand, the Engine Center is planning for increased production of the G195 military engine, which will likely need to expand from its current floor space footprint in the assembly building. Other engine programs are winding down and will no longer be in production in a couple of years. Although there are many unknowns in the future of the Engine Center, freeing up floor space in the assembly building clearly creates flexibility in preparing for the upcoming changes.

Beyond the advantage of increased flexibility for handling the Engine Center's current mix of engine models, relocating GP7000 final assembly would also create the possibility to bring in new assembly work. For instance, the Next Generation Product Family (NGPF) of geared turbofan engines is currently slated for assembly at P&W Canada. Perhaps the Engine Center can make a competitive bid to bring in that additional work if the GP7000 footprint in the assembly hall becomes free.

4.2.3 Capacity Analysis

Unless the current factory layout for GP7000 assembly is modified there will likely be capacity constraints for some assembly MODs when production volumes increase over the next three years. A capacity analysis was performed to identify which MODs are in danger of running up against capacity constraints. The capacity analysis assumes the as-is assembly layout and staffing levels to highlight shortcomings that need to be addressed. Capacity is calculated by dividing total available hours by current average process hours for each BOM. For the Fan and LPT MODs, both of which utilize special build stands for part of the assembly process, the capacity analysis looks only at time spent on the build stands which are the process bottleneck for both BOMs.

The five MODs in this analysis are:

1) **Fan** – Assembly of fan exit case to the containment case to make a fan case module that feeds the main assembly line
2) **LPT** – Final assembly of the LPT module before it is transported to the main assembly line
3) **HORZ** – Assembly of the Fan Case, Fan, LPT, LPC, and engine externals to the engine Core

4) **GBOX** – Assembly of the engine gearbox which is subsequently shipped to GE for inclusion on the engine Core
5) **Core** – Receiving and performing initial assembly operations on the engine Core

The results of this analysis can be seen in Figure 22 and Figure 23 below. Figure 22 shows a low, or conservative, estimate for MOD capacity while Figure 23 shows a high, or optimistic, estimate. The horizontal lines in the figures mark the expected demand for the next three years and the vertical bars represent MOD capacity. The figures also show what happens to MOD capacity if additional shifts are added to the assembly operations. AWW is an alternative work week schedule that is in operation from Friday through Sunday each week.

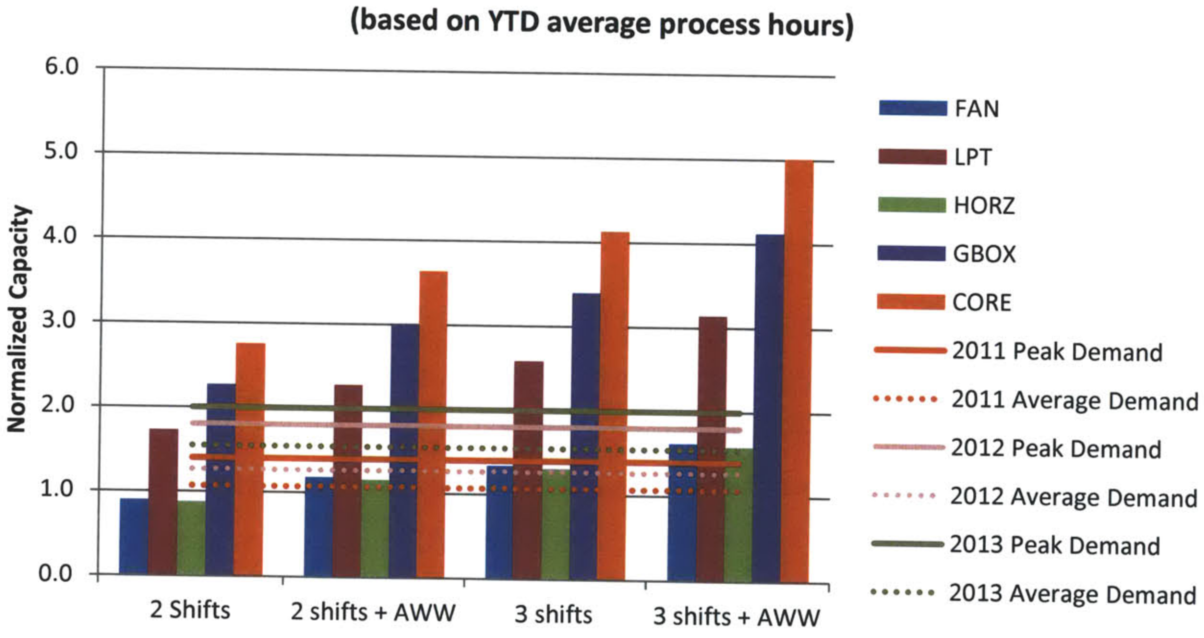


Figure 22. GP7000 Module Capacity - Low Estimate

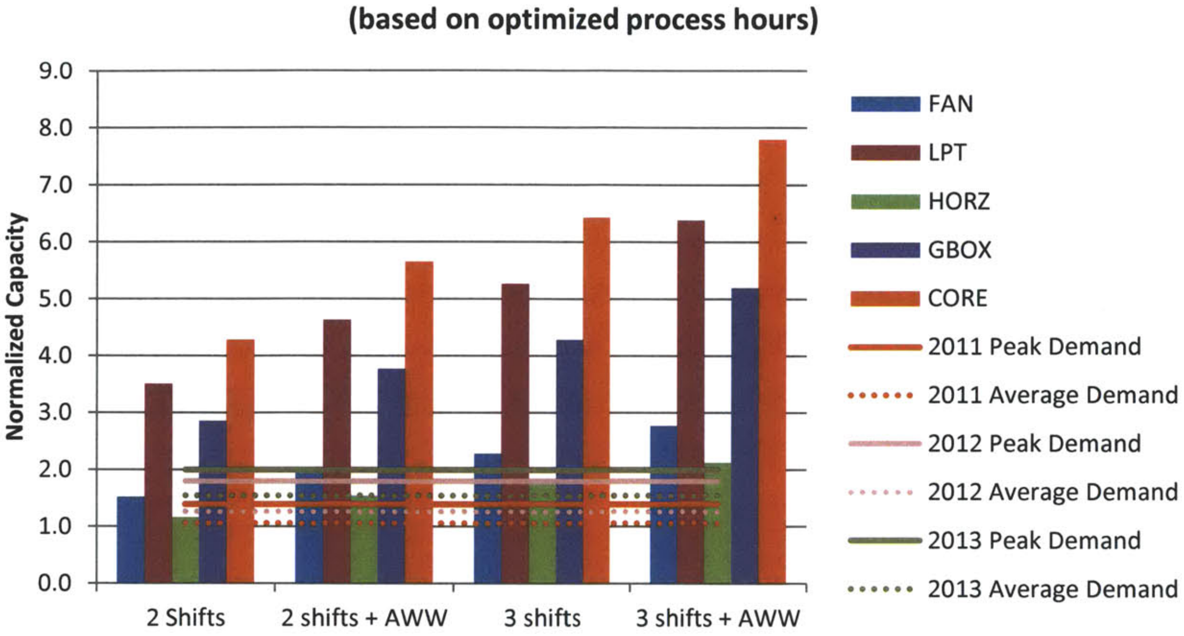


Figure 23. GP7000 Module Capacity - High Estimate

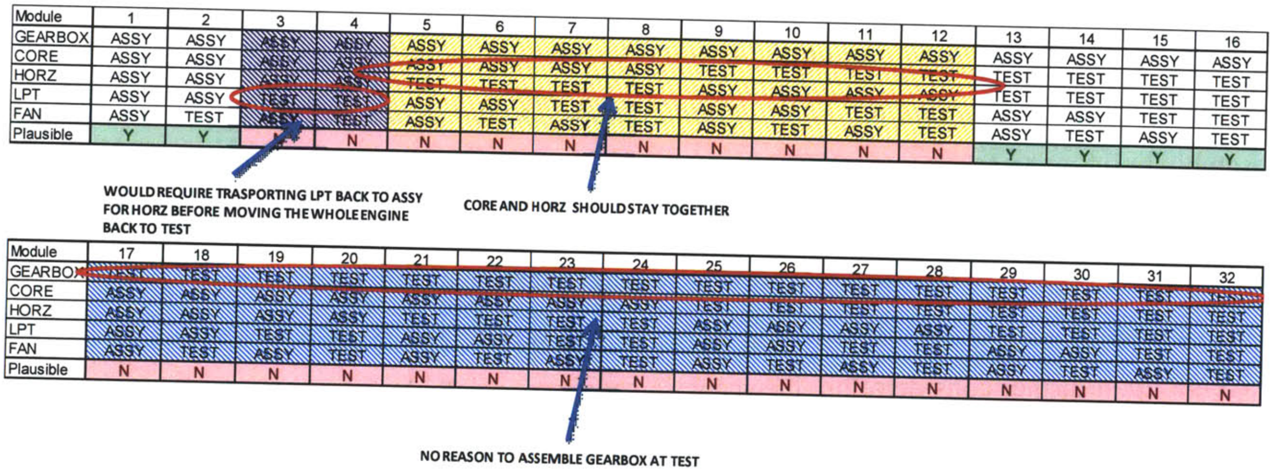
For both the high and low capacity estimates the LPT, GBOX, and Core MODs all appear to easily have enough capacity to handle the increased demand. The Fan and HORZ MODs, however, appear to be at risk. Fan assembly for the GP7000 currently takes place in a special build stand in the assembly building that is also used for one additional engine model that, like the GP7000, is expected to see an increase in demand in 2011. Combine this with the fact that the assembly building currently operates for only two shifts per day and it becomes apparent that the one Fan build stand will not be sufficient to handle the increased demand.

Fan capacity then becomes one compelling reason to support relocating GP7000 assembly to the test building. The test building operates for three shifts per day which would boost Fan capacity enough to meet demand in 2011 even with the low capacity estimate shown in Figure 22. It should be noted, however, that to continue to meet demand in 2012 and 2013, process hours will need to be eliminated from the Fan MOD.

Although the HORZ MOD appears to also be approaching maximum capacity, its capacity can more easily be increased because multiple mechanics can work in parallel on that MOD.

4.2.4 Scenario Analysis

We have to this point identified a number of reasons why relocating GP7000 assembly operations could benefit the Engine Center. The question then becomes, what portions of GP7000 assembly should be moved to the test building if relocation is indeed the right strategy? There are five MODs that comprise GP7000 assembly and assembly of any of those five MODs could conceivably be moved to the test building. To help answer this question a matrix was created showing all possible scenarios of MOD assembly between the assembly and test buildings (see Figure 24). With five MODs and two possible locations for each MOD that makes total of $2^5 = 32$ scenarios.



Module	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
GEARBOX	ASSY	ASSY	ASSY	ASSY	ASSY	ASSY	ASSY	ASSY	ASSY	ASSY	ASSY	ASSY	ASSY	ASSY	ASSY	ASSY
CORE	ASSY	ASSY	ASSY	ASSY	ASSY	ASSY	ASSY	ASSY	TEST	TEST	TEST	TEST	TEST	TEST	TEST	TEST
HORZ	ASSY	ASSY	ASSY	ASSY	TEST	TEST	TEST	TEST	ASSY	ASSY	ASSY	ASSY	TEST	TEST	TEST	TEST
LPT	ASSY	ASSY	TEST	TEST	ASSY	ASSY	TEST	TEST	ASSY	ASSY	TEST	TEST	ASSY	ASSY	TEST	TEST
FAN	ASSY	TEST	ASSY	TEST	ASSY	TEST	ASSY	TEST	ASSY	TEST	ASSY	TEST	ASSY	TEST	ASSY	TEST
Plausible	Y	Y	N	N	N	N	N	N	N	N	N	N	Y	Y	Y	Y

WOULD REQUIRE TRASPORTING LPT BACK TO ASSY FOR HORZ BEFORE MOVING THE WHOLE ENGINE BACK TO TEST

CORE AND HORZ SHOULD STAY TOGETHER

Module	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32
GEARBOX	TEST	TEST	TEST	TEST	TEST	TEST	TEST	TEST	TEST	TEST	TEST	TEST	TEST	TEST	TEST	TEST
CORE	ASSY	ASSY	ASSY	ASSY	ASSY	ASSY	ASSY	ASSY	TEST	TEST	TEST	TEST	TEST	TEST	TEST	TEST
HORZ	ASSY	ASSY	ASSY	ASSY	TEST	TEST	TEST	TEST	ASSY	ASSY	ASSY	ASSY	TEST	TEST	TEST	TEST
LPT	ASSY	ASSY	TEST	TEST	ASSY	ASSY	TEST	TEST	ASSY	ASSY	TEST	TEST	ASSY	ASSY	TEST	TEST
FAN	ASSY	TEST	ASSY	TEST	ASSY	TEST	ASSY	TEST	ASSY	TEST	ASSY	TEST	ASSY	TEST	ASSY	TEST
Plausible	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N

NO REASON TO ASSEMBLE GEARBOX AT TEST

Figure 24. Module Assembly Scenario Matrix

With the use of this matrix it is easy to eliminate scenarios that intuitively do not make sense. For example, the Gearbox MOD would never be moved to the test building because finished gearboxes are shipped to GE to be assembled to the engine core and therefore do not directly feed the GP7000 final assembly line. Additionally, the GP7000 gearbox is assembled alongside gearboxes for other engine models in a special gearbox build area. That eliminates half of the 32 scenarios. Another 10 scenarios can be eliminated for the reasons indicated in Figure 24. This leaves just six scenarios to consider, one of which is to keep all of GP7000 assembly MODs in the assembly building.

Of the remaining five scenarios that involve relocating at least one GP7000 assembly MOD, four pose significant technical challenges. One particularly troublesome challenge arises from the high level of vibration present throughout the test building when a high thrust engine is running live in a test cell. This vibration would likely be the most harmful to the operations in the HORZ assembly MOD that are involved in inserting the LPT with shaft into the engine core. The LPT and shaft are suspended during assembly and the vibrations from the test cell would be likely to propagate through the overhead rails to the shaft which could begin to oscillate. Such a result could potentially cause damage to the engine during LPT assembly. There may be ways to address this issue, but they would likely add additional cost and complexity to assembly.

That leaves only the second scenario from the scenario matrix remaining as the most likely for an assembly split between the two buildings. The second scenario calls for Fan MOD assembly to be moved to the test building while the rest of the MODs continue to be assembled in the assembly building. In essence this would mean building propulsors (i.e. no fan case or fan) in the assembly building and then transporting the completed propulsors to the test building where they would receive the Fan MOD and engine externals. Technically, this also means completing a porting of the HORZ MOD assembly work (i.e. – engine externals, fan case assembly to the propulsor, fan blades) in the test building. Although this was not the expected result of this exercise, upon further consideration, the scenario shows considerable promise and offers some distinct advantages.

Recall that one of the major difficulties in transporting the GP7000 to the test building is that the engine is too large to fit through the cargo bay door when loaded on a flatbed truck. This forces the use of the cumbersome shipping buck and tugger. A propulsor, however, is small enough to transport on a flatbed truck just like any other engine model. This would significantly cut down on the wasted effort and time needed to transport the GP7000 to test. It would also solve the problem of having to wait out inclement weather to transport GP7000s between buildings because the truck handles much better than the tugger in wet or icy conditions. Additionally, this scenario would allow for a simplified final assembly flow line in the test building that involves only marrying the fan case to the propulsor and finishing assembly of the engine externals. This scenario is much lower risk than relocating all of GP7000 to the assembly building. It also aligns nicely with results from the capacity analysis and would mitigate the Fan MOD capacity constraint risk discussed previously.

4.2.5 Relocation Strategy

The analysis described to this point in the thesis leads us to a three part GP7000 assembly relocation strategy. The components of this strategy are:

1. Build propulsors on the assembly floor and perform the remainder of assembly in the test building
2. Fund the Cost Reduction group to perform assembly optimization
3. Put a risk mitigation plan in place

Component one of this strategy involves the design of a lean assembly flow line for the portion of assembly operations that is to take place in the test building. This will be discussed in greater detail in the next section of the thesis. Figure 25 is a graphical summary of the recommended split of assembly work between the assembly and test buildings.

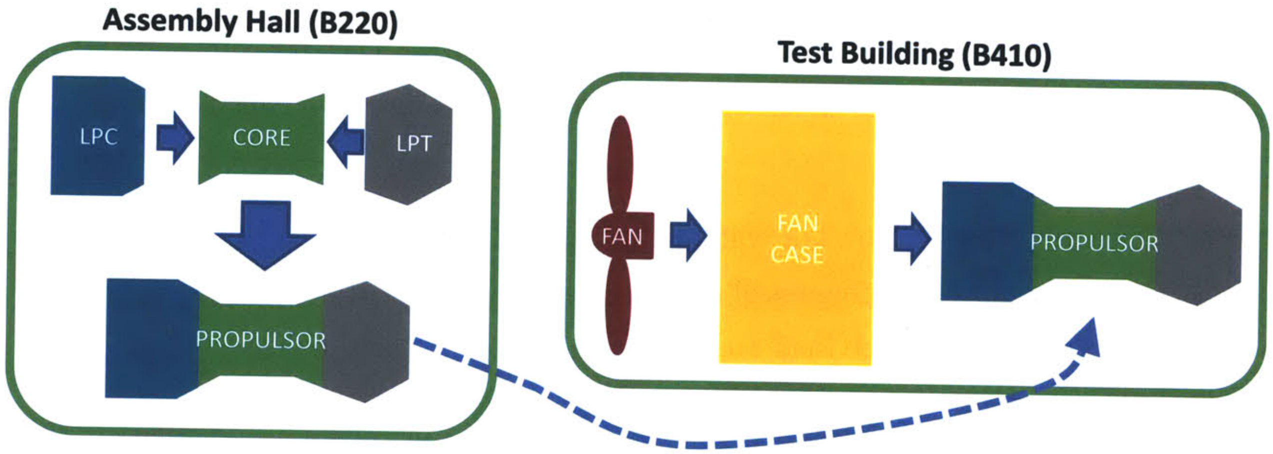


Figure 25. GP7000 Assembly Relocation Recommendation

Component two of the strategy, assembly optimization, should be performed whether or not GP7000 assembly operations are relocated to the test building. The current state analysis demonstrates that there is ample room for lead time, cycle time, and cost improvement. The assembly optimization process has a proven track record of success on other engine models and it is reasonable to expect similar results for the GP7000.

The final component of the strategy, a risk mitigation plan, will be discussed in greater detail later in the thesis.

4.3 Design of a Lean Assembly Flow Line

One of the key principles in a lean production system is flow, as discussed previously in this thesis. Once value is defined and the value stream mapped and understood, the next step in a lean transformation is to enable the flow of value through the factory. The absence of flow in current state GP7000 assembly and test operations results in increased costs, long lead times, and high inventory levels.

The main GP7000 assembly area was originally designed to be a flow line with multiple workstations that each engine would pass through on its way to completion. Unfortunately, in practice, the GP7000 does not flow down the line, but rather it is typically built from start to finish in one spot on the line. There can be as many as three GP7000s on the line at any given time in various states of completion. One byproduct of this system is that, when an engine encounters a turnback, mechanics can simply be reassigned to another engine without immediately addressing the turnback. It is not at all uncommon to see a GP7000 sitting idle on the assembly floor with a red QN tag indicating that a quality issue must be addressed before assembly can continue.

Implementing a true assembly flow line will force turnbacks to be addressed immediately so an idle engine does not impede the progress of other engines. While there will likely be growing pains initially as mechanics, supervisors, and management adjust to the new system, the benefits in lead time and inventory can be substantial. To implement flow for the GP7000 will require a new culture of addressing the root cause of turnbacks quickly and aggressively. Due to the coming increase in demand, achieving flow will be a crucial factor in keeping pace with that demand.

This rest of this section discusses some of the important considerations that go into the design of a lean flow line. We will begin by talking about the balancing of work among assembly workstations followed by a discussion on establishing pulse flow. We will then talk about how simple flow simulations were used to create a factory layout for GP7000 final assembly.

4.3.1 Balancing the Line

One prerequisite for establishing flow is to divide work evenly among assembly workstations so that each workstation requires approximately the same amount of time to complete its tasks. The workstation with the longest lead time will be the process bottleneck. High variability in process time and lead time complicates this task for the GP7000. Recall, however, from the data analysis discussed previously that much of the variation is a result of outliers in the data, which are the result of turnbacks that can likely be eliminated through assembly optimization. We therefore remove these outliers from the data when designing the future state assembly flow line.

Using historical process lead times and making assumptions about the process hour reductions likely to be achieved through assembly optimization, process sequences were divided evenly between workstations. Figure 26 shows the workload balance resulting from this exercise. Note that the workstation load hours have been normalized by Takt Time to mask confidential data. The fact that some processes can be worked by multiple mechanics simultaneously creates an additional lever for balancing the assembly line since cycle time is proportional to the number of mechanics working the process.

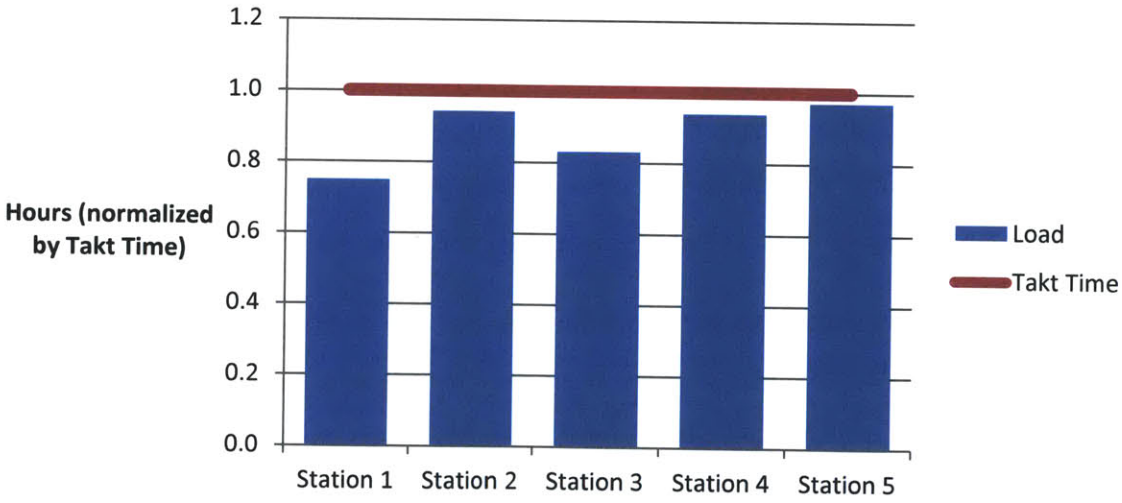


Figure 26. GP7000 Final Assembly Workstation Load Balance

In parallel with balancing work between workstations on paper it is necessary to look at assigning those workstations to physical areas of the factory in a layout that supports flow. The next section talks about creating the flow line layout.

4.3.2 Flow Line Layout

When creating a flow line layout in the test building for GP7000 assembly and test, special consideration must be given to the overhead rail system. Each workstation must be located directly underneath a rail so that the overhead hoist can be used to manipulate the engine and assembly tooling. Additionally, once an engine is lifted by an overhead hoist its orientation relative to the rail system is locked in. The initial orientation determines the orientation of the engine when it arrives at the various workstations. When an engine reaches the test cell it must be in the correct orientation to be backed in to the test cell such that, once in the test cell, the engine is facing the front of the cell.

To help to better visualize the flow of engines, and to brainstorm various flow line layouts, to-scale "paper doll" cut outs of engines, tooling, and materials were arranged on a large printout of the factory floor. This allowed the team to rapidly test a variety of different layouts and to quickly eliminate those that are infeasible.

In addition to the paper models, visual simulations were used to further test the most promising layouts. This was done in Microsoft PowerPoint using a drawing of the factory floor as a background and animations to show the movement of engines, tooling, and materials. Because the GP7000 is so large and the assembly area in the test building so small, the movement of engines must be carefully choreographed to ensure no engine becomes trapped and unable to advance to the next assembly workstation. The PowerPoint Simulations created the opportunity to visualize the flow of engines and to identify potential problems.

Using the information generated from the line balancing exercise and the flow simulations described above multiple layouts were created, some utilizing the as-is rail system and others requiring modifications. The different layouts were evaluated based on the amount of floor space required, total engine travel distance, fan case travel distance, and whether rail modifications are required. The results are summarized in Figure 27 below. Other factors that are less easy to quantify were also considered in the evaluation.

	SQ FT REDUCTION	ENGINE TRAVEL DISTANCE (FT)	FAN CASE TRAVEL DISTANCE (FT)	RAIL MODIFICATION REQUIRED
LAYOUT 1	7%	776	50	NO
LAYOUT 2	10%	821	25	YES
LAYOUT 3	3%	821	35	YES
LAYOUT 4	10%	985	25	NO
LAYOUT 5	3%	985	40	NO

Figure 27. Flow Line Layout Evaluation

Based on these considerations Layout 1 was selected for implementation because it requires the least amount of engine travel and does not require overhead rail modification. Additionally, the selected layout will result in overall floor space reductions of 7 % from the current GP7000 layout. Although that may not seem like much, if viewed in terms of floor space required per engine output it is actually much more efficient than the current layout. The selected flow line layout is designed to accommodate nearly double the current production volume. The increased capacity comes from operating the line with a pulse flow that will be synced with the tact time. This will compress engine lead time and allow more engines to flow through the factory in any given period of time compared with current operations. Establishing the pulse flow that will make this possible is discussed in the next section. The actual flow line layout is considered confidential and is therefore not presented here.

4.3.3 Establishing a Pulse Flow

Establishing flow for jet engine assembly is quite different from the continuous flow seen in other industries with moving assembly lines. This is in large part due to the difference in the time scale by which jet engines are assembled. In the auto industry, for example, flow is measured in minutes, while for jet engine assembly flow is measured in hours or even days. In auto manufacturing each part can be assembled to the engine in typically less than one minute, while some jet engine parts take hours to assemble to the engine. Some envision a future state where imperceptibly slow moving assembly lines will set the pace for jet engine assembly. However, such a system would be costly to implement and is not likely to be put in place in the Engine Center in the near future.

This does not mean, however, that flow cannot be achieved. For the GP7000, flow can be achieved in pulses that are synced with the tact time. This means that every time an engine ships, all in-process engines are moved forward to the next workstation. To achieve a pulse flow it is critical that the load is balanced evenly among workstations as discussed above. The ability to quickly address turnbacks and put in place corrective measures is also critical to maintaining a pulse flow.

4.4 Risk Management

Relocating assembly operations to a different building with a new flow line layout inherently carries certain risks. Even with well laid plans, unanticipated obstacles to implementation will undoubtedly arise. The engine center will not have the luxury of postponing GP7000 production when it comes time to execute the relocation strategy described above. Engine deliveries must continue according to the production schedule.

It is critical, then, that a risk mitigation plan is in place to ensure that engines are delivered on time and that quality standards are upheld throughout the relocation process. A phased implementation approach was designed to achieve these aims. Additionally, an Operational Risk Management (ORM) process, adopted from the U.S. Air Force, was initiated to systematically identify and address potential risks. The remainder of this section describes the phased implementation plan and ORM and discusses how they work together to create a comprehensive risk management approach for GP7000 relocation.

4.4.1 Phased Implementation

Carrying out the GP7000 relocation strategy in phases provides the opportunity to prove out sections of the final assembly flow line one at a time without creating undue risk exposure. Each phase of the plan calls for putting one assembly or test MOD into operation in the newly designed flow line. The initial phase carries with it only limited commitment to full implementation of the relocation strategy with each subsequent phase escalating in commitment and required capital investment. Advancement from one phase to the next is only to occur after the required production rate has been demonstrated with acceptable quality and consistency.

The six implementation phases are:

1) **Temporary New Pack Line** – Move engine split, pack, and ship operations to the new GP7000 area in the test building while facility improvements (unrelated to this project) are carried out in current pack line location.
2) **Facility Improvements –** Temporarily move engine split, pack, and ship operations back to original location while facility improvements (i.e. – new flooring, divider walls, paint, etc.) take place in new GP7000 assembly area.
3) **Final Pack Line –** Finalize pack line setup in new GP7000 area and demonstrate necessary rate can be achieved. Also begin performing dress and strip operations in the new area.
4) **50% Propulsors From Assembly Building –** Transport every other engine from assembly to test as a propulsor and perform final engine assembly operations on the new flow line. The other half will continue to come to the test building as fully assembled engines ready for test. During this phase, half of the fan case assemblies will be transported to the test building for assembly to the propulsors that arrive at the test building without a fan case.
5) **50% Fan Build in Test Building –** Begin operation of the Fan MOD build area in the test building and build fan cases for the half of engines that arrive to the test building as propulsors. The Fan MOD build area will feed the final assembly flow line.
6) **Full Implementation -** Once adequate production rate has been demonstrated at all stations, begin sending only propulsors from the assembly building to the test building and complete all Fan MOD assembly in the test building. The final flow line will now be fully operational beginning with receiving a propulsor from the assembly building and ending with engine shipment to the customer.

4.4.2 Operational Risk Management

ORM is a risk management philosophy developed by the U.S. Air Force. The philosophy and tools of ORM were originally given to P&W by the Air Force to ensure that robust risk management processes are in place for military jet engine programs. These tools have since been utilized in a variety of projects and engine programs within P&W with great success. According to an official Air Force publication, "ORM is a decision-making process to systematically evaluate possible courses of action, identify risks and benefits, and determine the best course of action for any given situation (Phillips 7)."

Four main principles serve as a guide to all actions undertaken as part of an ORM effort.

1. Accept no unnecessary risk
2. Make risk decisions at the appropriate level
3. Accept risk when benefits outweigh the costs
4. Integrate ORM into operations and planning at all levels

P&W has developed its own ORM process and toolset based on these principles. When executed effectively, the P&W ORM process provides a structured and thorough method for managing risk out of jet engine assembly operations. The steps of this process are described below.

1) **Assemble cross-functional team.** The team should include representatives from all functions that have a stake in the operations addressed by the ORM. This includes representation from shop floor mechanics. A wide variety of perspectives help to ensure that all major risks are identified.
2) **Hold kick-off meeting.** An initial meeting is held with all ORM participants to explain the ORM process and make sure everyone understands the operational challenges that are being assessed.
3) **Brainstorm potential risks.** After the kick-off meeting each participant has an assignment to identify potential risks (especially risks that pertain to the functional expertise of the participant) and to capture those risks in a specially prepared spreadsheet. The risks are then aggregated into one complete list by the ORM facilitator.
4) **Conduct ORM workshop.** The workshop is typically a multiday event during which participants discuss the list of potential risks and assign a likelihood and severity to each one. Additional risks can be added to the list at this time. A spreadsheet tool is then used to assign a composite risk score to each risk based on its likelihood and severity. The risks are rank-ordered and categorized as either high, medium, or low. High and medium risk items must be satisfactorily mitigated before the project can move forward, while low risk item can be accepted if no simple solution is available.

5) **Define and implement risk mitigation plans.** Before the conclusion of the ORM workshop an owner is assigned to every identified risk. Risk owners then create mitigation plans for their assigned risks and record those plans using a special form. Risk mitigation plans are reviewed and agreed upon by the appropriate level of management for each risk. The plans are then executed to reduce risk to an acceptable level.
6) **Supervise and Review.** Progress is continuously monitored by the appropriate levels of management and controls are put in place to ensure the improvements are sustained over time.

At the conclusion of this internship the first three steps of this process had been completed for the GP7000 relocation project. The remaining steps are scheduled to take place over the first half of 2011. For the GP7000, the risk mitigation plans from the ORM will be tied to the phased implementation plan through management reviews that will take place at the conclusion of each of the implementation phases. The reviews will serve to ensure that the risks associated with each phase of implementation have been adequately addressed before the project moves forward. Together, the phased implementation plan and ORM will enable the Engine Center to effectively manage the risks associated with relocating portions of GP7000 assembly to the test building. This will greatly increase the likelihood of a smooth and successful implementation.

5 Conclusion

This thesis has demonstrated an approach for lean transformation of assembly and test operations in an aerospace company. Additionally, the thesis has provided a framework for making difficult relocation decisions and shown how lean transformation can be part of an assembly relocation strategy.

Using ACE tools, a current state analysis of GP7000 assembly and test operations revealed ample opportunity for lead time, cycle time, and cost reduction. Specifically, it was noted that currently cycle accounts for only a small fraction of the overall lead time for most GP7000 BOMs. Build studies were used to identify the most common turnbacks that slow GP7000 assembly and cause the unwanted disparity between lead time and cycle time. Additionally, the current state analysis validated the assumption that total process hours can be reduced to the target levels set by the Cost Reduction Group. These results have been used to solicit funding to initiate assembly optimization of the GP7000 by Cost Reduction engineers.

The thesis has also presented the analysis and considerations that led to making the strategic decision to relocate portions of GP7000 final assembly to the test building. Long term strategic objectives, together with shorter term tactical and financial motivations, informed the decision to go forward with assembly relocation.

With the relocation decision made, the thesis then addressed the design of a lean assembly flow line for the GP7000 in the test building. Important considerations include balancing the line and establishing a pulse flow. Successful execution of assembly optimization will be critical to enabling the smooth operation of the GP7000 flow line in the test building.

A key component of executing the GP7000 relocation strategy is managing the risks associated with making substantial changes to the production processes for such a large and complex piece of machinery. The ORM process, adopted form the U.S. Air Force is the risk management solution that will be used for GP7000 relocation. The ORM process was initiated at the end of 2010 and will continue to guide implementation efforts through the first half of 2011.

This lean transformation and relocation strategy project for the GP7000 engine has provided an outstanding educational experience for the author. It is the author's hope that Pratt & Whitney has found value in the knowledge gained from the experience and will continue to reap the benefits they desire from sponsorship of the project.

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6 References

Black, J. Temple. *The Design of the Factory with a Future*. New York: McGraw-Hill, 1991. Print.

Continuous Improvement Methodology at Pratt & Whitney. Internal Presentation ed., 2009. Web. 12/15/2010.

Daniels, Nancy. "Pratt & Whitney - Company Overview - Hoover's." 2011.Web. <http://subscriber.hoovers.com/H/company360/overview.html?companyId=99062000000000>.

"Engine Alliance GP7000." March 12 2011.Web. Wikipedia. <http://en.wikipedia.org/wiki/GP7000>.

Engine Center Overview. Internal Presentation ed., 2009. Web. December 15, 2010.

"Engine Education - Turbofan Engine." 2010.Web. <http://www.pw.utc.com/About+Us/Engine+Education/Turbofan+Engine%3Fguid=74bf627e6dd7a110VgnVCM100000c45a529f____>.

Epperson, Lesley. "United Technologies - Company Overview - Hoover's." 2011.Web. <http://subscriber.hoovers.com/H/company360/overview.html?companyId=11559000000000>.

Frauenberger, Douglas H. "Lean Transformation in Aerospace Assembly Operations." Master's Thesis, Massachusetts Institute of Technology, 2007. Print.

Kandebo, Stanley W. "Engine Makers Solidify GP7200 Design." *Aviation Week & Space Technology* 156.22 (2002): 43. Print.

"The Learning Curve." 2010.Web. <http://fast.faa.gov/pricing/98-30c18.htm>.

Lewis, Dick, and Nicolene Hengen. *LAI Overview*. Massachusetts Institute of Technology, 2011. Web.

Phillips, John D. "Operational Risk Management." April 1 2000.Web. <http://www.af.mil/shared/media/epubs/AFI90-901.pdf>.

Rother, Mike, John Shook, and Lean Enterprise Institute. *Learning to See : Value Stream Mapping to Create Value and Eliminate Muda*. Version 12 ed. Brookline, Mass.: Lean Enterprise Institute, 1999; 1998. Print.

"Turbofan." 2011.Web. <http://en.wikipedia.org/wiki/Turbofan>.

Womack, James P., Daniel T. Jones, and Daniel Roos. *The Machine that Changed the World : How Japan's Secret Weapon in the Global Auto Wars Will Revolutionize Western Industry*. 1 HarperPerennial ed. New York, NY: HarperPerennial, 1990. Print.

Womack, James P., and Daniel T. Jones. *Lean Thinking : Banish Waste and Create Wealth in Your Corporation*. New York: Simon & Schuster, 1996. Print.

"World's Most Admired Companies 2010 - from FORTUNE." 2011.Web. <http://money.cnn.com/magazines/fortune/mostadmired/2010/index.html>.