Strategic Raw Material Inventory Optimization

by

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B.S. Mechanical Engineering, GMI Engineering & Management Institute, 1998

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

Master of Business Administration
and
Master of Science in Mechanical Engineering

In Conjunction with the Leaders for Manufacturing Program at the
Massachusetts Institute of Technology
June 2007

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Abstract

The production of aerospace grade titanium alloys is concentrated in a relatively small number of producers. The market for these materials has always been cyclical in nature. During periods of high demand, metal producers claim to operate near full capacity utilization. During periods of reduced demand, metal producers struggle to remain profitable. Additionally, the manufacturing processes for aerospace grade titanium alloys are capital intensive and require long lead-times in order to bring new capacity online. The combination of these factors often results in an inflexible titanium alloy raw material supply chain for Pratt & Whitney.

At the same time, Pratt & Whitney experiences a variety of rare but disruptive events within the supply chain that affect their raw material requirements. Examples of these disruptive events include customer drop-in orders, manufacturing complications resulting in scrapped material, and planning deficiencies. In order to protect engine and spare part customers from delayed deliveries due to long lead-time raw materials, Pratt & Whitney holds a strategic inventory of various titanium alloy raw material.

This thesis presents a mathematical model utilizing a Compound Poisson Process that can be used to optimize the amount of strategic titanium alloy raw material held by Pratt & Whitney. The associated mathematical algorithms were programmed into Microsoft Excel creating the Strategic Raw Material Inventory Calculator. Historical data was then collected and used with this unique tool to calculate service levels at current inventory levels as well as optimized inventory levels under various scenarios.

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I would also like to express my thanks to my two thesis advisors, Don Rosenfield and Dan Whitney, who challenged and supported me throughout the project. Their penetrating questions and deep insights helped make this project a great learning experience.

I wish to acknowledge the Leaders for Manufacturing Program for its support of this work. LFM is truly a unique program and I feel blessed to have been able to participate in it. Additionally, I would like to say thanks to my LFM classmates, who I have no doubt will become titans of industry.

Finally and most importantly, I would like to thank my wonderful wife Kamlai. Her patience and support helped me get through a very difficult two years. She makes it all worthwhile.

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Chapter 1 Introduction

This chapter is intended to give the reader an overview of the thesis. It begins by giving an introduction to supply chain management and the role of inventory in a company's supply chain. This initial chapter highlights the problem the thesis addresses and concludes with an outline of the remaining chapters.

1.1 Supply Chain Management and the Role of Inventory

A supply chain is a network of interconnected facilities of diverse ownership with flows of information and materials between them.[1] A company's supply chain encompasses every process and business partner that takes a product from raw material to delivered finished part. As competition in today's globalized markets continues to increase, companies have demanded greater efficiency from their supply chains. As product life cycles continue to shorten, companies have demanded increased flexibility from their supply chains. As customer expectations have continued to rise, companies have demanded higher service levels from all components of their supply chain. Effective management of a company's supply chain has become a key source of competitive advantage for successful businesses.

Inventory is a major focus in the study of supply chain management and is a critical component of most supply chain systems. Manufacturing operations may hold inventory for a variety of reasons. A theoretical minimum level of in-process inventory is necessary to maintain a given process throughput.[2] Inventory is also acquired due to economies of scale or to level production. This thesis focuses on the use of inventory to accommodate uncertainty in a supply chain system. Uncertainty in a supply chain system can result for either uncertainty of demand or uncertainty of supply.

The effective management of inventory to accommodate both uncertainty of demand and uncertainty of supply is key for the successful management of a company's supply chain. The holding of inventory carries its own cost in both operational and financial terms. Therefore the optimization of inventory levels can be a key driver of operational excellence both in terms of achieving a desired service level and in reducing overall costs.

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[1] Anupindi, et al: Managing Business Process Flows
[2] Anupindi, et al: Managing Business Process Flows

1.2 Context and Setting

The research for this thesis was conducted over a six and half month period at Pratt & Whitney, a business unit of the United Technologies Corporation. The author is a participant of the Massachusetts Institute of Technology's Leaders for Manufacturing Program (LFM). The LFM program is a joint program between MIT's School of Engineering, the MIT Sloan School of Management, and numerous industrial partners including the United Technologies Corporation.

1.3 Problem Identification

A main concern for Pratt & Whitney is uncertainty of supply in the titanium raw material supply chain. The production of aerospace grade titanium alloys is concentrated in a relatively small number of producers. The market for these materials has always been cyclical in nature. During periods of high demand, metal producers claim to operate near full capacity utilization. During periods of reduced demand, metal producers struggle to remain profitable. Additionally, the manufacturing process for aerospace grade titanium alloys is capital intensive and does not allow for quick changes in capacity. The combination of these factors often results in extreme uncertainty in Pratt & Whitney's titanium alloy raw material supply chain.

In addition to uncertainty of supply in the titanium raw material supply chain, Pratt & Whitney also must accommodate uncertainty in demand. Pratt & Whitney experiences a variety of rare but disruptive events within the supply chain that affects their raw material requirements. Examples of these disruptive events include customer drop-in orders, manufacturing complications resulting in scrapped material, and planning deficiencies. In order to protect engine and spare part customers from delayed deliveries due to long lead-time raw materials, Pratt & Whitney holds a strategic inventory of various titanium alloy raw materials. This thesis provides a mathematical model that will allow Pratt & Whitney to optimize the amount of material held in their strategic inventory of titanium raw materials.

1.4 Outline of Remaining Chapters

Chapter 2 provides an overview of United Technologies Corporation (UTC) with special emphasis on the Pratt & Whitney division. The material in Chapter 2 provides background information to allow the reader to better appreciate the unique business environment in which Pratt & Whitney's supply chain organization operates. Chapter 2 also provides a brief introduction to Pratt & Whitney's main application for titanium alloys, the gas turbine engine.

Chapter 3 is an overview of titanium and titanium alloys. Specifically, it outlines the main material characteristics of titanium that make it such a vital raw material for the aerospace industry as well as numerous other industries. This chapter also explains the inflexible manufacturing processes involved in the isolation of elemental titanium. Additionally, Chapter 3 details the main types of titanium alloys used at Pratt & Whitney and the various forms they can take.

Chapter 4 provides a comprehensive overview of the titanium metals industry. Factors that could result in uncertain supply for titanium alloy customers are explored. These include an oligopolistic economic environment, the cyclical nature of the industry, limiting U.S. government regulations, and uncertain support from the investment community. Chapter 4 also explores the future of the titanium alloy metals industry. Special emphasis is placed on the current gap between demand and supplier capacity and the causes of this disparity including a cyclical upswing in the commercial aviation market, increased military spending, and new aircraft designs that use a greater proportion of titanium.

Chapter 5 provides an overview of Pratt & Whitney's Strategic Raw Material Inventory and the disruptive events in the supply chain that makes it an essential operations tool. Chapter 5 also describes the modeling of disruptive event arrivals and the creation of the Strategic Raw Material Inventory Calculator. The Strategic Raw Material Inventory Calculator is then used to calculate service levels at current inventory levels as well as new optimized inventory levels.

Chapter 6 uses the Strategic Raw Material Inventory Calculator to perform various scenario analyses. The effect of material lead-time on inventories is explored. Additionally, pooling efficiencies that could result in an overall reduction of inventory are detailed.

Chapter 7 outlines the business process analysis that was conducted during the creation of the Strategic Raw Material Inventory Calculator. This analysis was guided by UTC's ACE Operating System. An ACE Roadmap was created after conducting a Market Feedback Analysis. The business process analysis culminated in the creation of standard work including process maps and the Strategic Raw Material Inventory Release Process Checklist.

Chapter 8 concludes the thesis by summarizing the importance of the Strategic Raw Material Inventory and by summarizing the optimized inventory levels for the Strategic Raw Material Inventory under various scenarios.

Chapter 2 Pratt & Whitney, A United Technologies Company

The objective of this chapter is to give the reader a brief introduction to the United Technologies Corporation with special emphasis on the Pratt & Whitney business unit. This background information will allow the reader to better appreciate the unique business environment in which Pratt & Whitney's supply chain organization operates. This chapter also gives an introduction to Pratt & Whitney's main product and application for titanium alloys: the gas turbine jet engine.

2.1 United Technologies Corporation

United Technologies Corporation (UTC) is a public company traded on the New York Stock Exchange under the ticker UTX. It is a diversified corporation consisting of 7 different business units including Carrier, Hamilton Sundstrand, Otis, Pratt & Whitney, Sikorsky, UTC Fire & Security, and UTC Power. With revenue of over $42 billion in 2005, it is the 43rd largest corporation in America and 20th largest U.S. manufacturer.[3] UTC's diversified portfolio of businesses reaches across the globe and offers a unique opportunity for technological innovation and shared operational excellence. Although the work for this thesis was completed under the auspices of the Pratt & Whitney business unit, it is also applicable at other business units as well as at a corporate level.

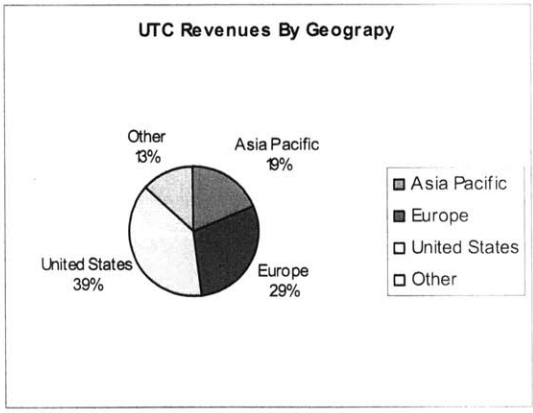

Figure 2.1 UTC Revenues by Geography[4]

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[3] http://utc.com/profile/facts/index.htm ; 19th January, 2007

[4] United Technologies Corporation 2005 Annual Report

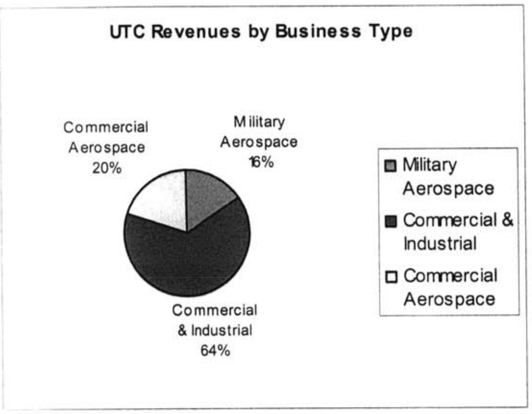

Figure 2.2: UTC Revenues by Business Type[5]

2.2 UTC Business Units

Carrier

Carrier Corporation is one of the world's leading companies for the manufacturing and sales of heating, refrigerating, air conditioning and HVAC systems and products. With revenue of over $12 billion in 2005, it is UTC's largest division in terms of revenue.

Hamilton Sundstrand

Hamilton Sundstrand is a global provider of technologically advanced aerospace and industrial products. It is a major supplier to international space programs as well as both the commercial and military aerospace industries. Over 90% of the world's aircraft contain a Hamilton Sundstrand system.[6]

Otis

Otis is the world's largest manufacturer, installer, and servicer of elevators, escalators, and moving walkways. Founded by the inventor of the "safety elevator", Otis continues to be an

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[5] United Technologies 2005 Annual Report

[6] http://utc.com/units/hamilton.htm; 19th January 2007

innovator in elevator technology. Otis people moving systems can be found in over 200 countries.[7]

Sikorsy

Sikorsky is a world leader in the design and manufacture of advanced helicopters for commercial, industrial, and military uses. As the manufacturer of the world famous Black Hawk helicopter, Sikorsky is a key supplier to the U.S. military as well as over 20 foreign governments.[8]

UTC Fire & Security

UTC Fire & Security provides products and services under the Chubb and Kidde brands. In Security, the business provides integration, installation, monitoring and service of intruder alarms, access control and video surveillance systems. In Fire Safety, UTC Fire & Security manufactures various fire detection, suppression and fire fighting products.

UTC Power

UTC Power is leading the efforts of UTC to meet customers' needs for distributed generation. UTC Power incorporates UTC Fuel Cells, a leader in the production of fuel cells for commercial, space and transportation applications.

Pratt & Whitney

Pratt & Whitney is a world leader in the design, manufacture and support of aircraft engines, gas turbines and space propulsion systems. In 2005, Pratt & Whitney reported an operating profit of $1.4 billion on revenues of $9.3 billion.[9] Pratt & Whitney has over 40,000 employees and 9,000 customers in 180 countries. Currently Pratt & Whitney engines power over 40 percent of the world's passenger aircraft as well as the United States Space Shuttle. Over 30 different armed forces use aircraft powered by Pratt & Whitney engines.[10] Additionally, Pratt & Whitney is a major player in the field of gas turbine power generation.

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[7] http://www.otisworldwide.com/d1-about.html; 30th January 2007

[8] http://utc.com/units/sikorsky.htm; 19th January 2007

[9] United Technologies Corporation 2005 Annual Report

[10] http://www.pw.utc.com/vgn-ext-templating/v/index.jsp?vgnextrefresh=1&vgnextoid=5a5212cb8c6fb010VgnVCM100000881000aRCRD; 19th January 2007

Pratt & Whitney has a history of innovation in the aerospace industry. The first Pratt & Whitney engine, the Wasp, was a technological wonder. It was an air-cooled piston engine whose advantages were immediately apparent over the liquid cooled engines that dominated aviation in the early 1920s. During World War II, Pratt & Whitney engines played a key role for the United States military powering such planes as the Grumman Hellcat and B-24 Liberator.

In 1952, Luke Hobb's of Pratt & Whitney won the prestigious Collier Trophy for "greatest achievement in aviation in America" for his work on the J57, Pratt & Whitney's "homegrown" jet engine. The J57 powered the B-52 Stratofortress placing Pratt & Whitney on the forefront of gas turbine engine design. Pratt & Whitney continues to innovate in the world of aerospace engine design and is the primary engine supplier for the F-35 Joint Strike fight, one of the most advanced airplanes in the world.

2.3 UTC Supply Chain Management

UTC has a long history of innovation in the area of supply chain management. Over the last 10 years, UTC credits working closely with suppliers for $1.5 billion in cost savings.[11] In 2006, UTC won *Purchasing*'s prestigious Medal of Professional Excellence for excellence in supply chain management.

UTC has largely consolidated indirect purchasing at the UTC corporate level. Indirect purchasing refers to all items and services that do not result directly in a UTC finished good. This consolidation, under programs such as UT500, has resulted in substantial savings for every business unit. Alternatively, direct purchasing is largely handled autonomously by each business unit. Direct purchasing refers to all products and services that are directly related to a finished good. Direct purchasing materials tend to have more sophisticated engineering and technical requirements. Titanium alloys always fall in the direct purchasing category. Therefore, Pratt & Whitney largely operates independent of the other UTC business units when making titanium raw material purchasing decisions. There are currently efforts underway to explore possible benefits and limitations to increased cooperation in the purchasing of titanium alloys between UTC business units. The models presented in this thesis can be a valuable tool for quantifying the possible benefits and limitations of such cooperation.

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[11] Teague: "Supply management masters" *Purchasing*, September 2006

2.4 Gas Turbine Engines

Pratt & Whitney is one of the world's largest manufacturers of gas turbine jet engines. There are numerous types of gas turbine engines used in the aerospace industry including turbofan engines and turboprop engines. Although they differ in design, they all function according to the same basic principle of a pressurized gas spinning a turbine.

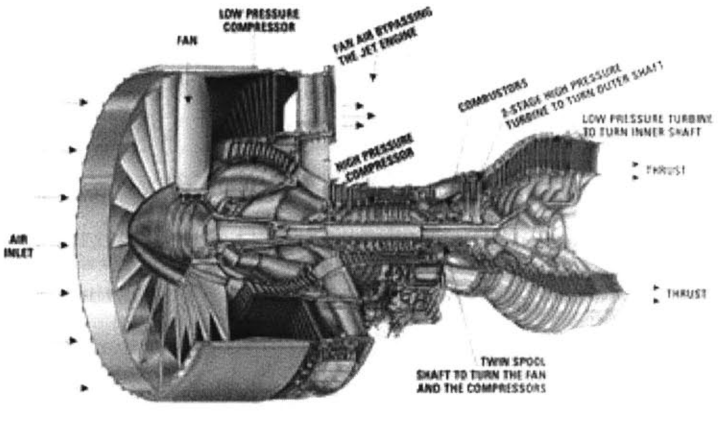

Figure 2.3: Modern Jet Engine: used to power Boeing 777 aircraft. This is a Pratt & Whitney PW4084 turbofan. [12]

Air is drawn into the engine via a fan that is connected by a shaft to the turbine. The air is pressurized by the engine through combustion with a fuel. This combustion process is the main driver of two critical characteristics required by materials used in a gas turbine engine: temperature resistance and strength. Additionally, as with most things that fly, weight is a key consideration. These stringent material requirements result in highly engineered materials being used throughout the engine. Nearly all critical parts on a gas turbine jet engine are composed of either titanium or nickel based super alloys.[13] .

The first jet engines produced in the 1950s contained titanium. Since that time the titanium content has steadily increased. In the early 1960s titanium made up less than 5% of the

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[12] igti.asme.org/resources/articles/intro2gtb.html; 19th January 2007

[13] Leyens and Peters: Titanium and Titanium Alloys

weight of a typical gas turbine engine. By the early 1990's this percentage had increased to over 30%.[14] Initially only compressor blades were manufactured from titanium, but due to steadily increasing engine bypass ratios[15] the large front fan is now often constructed of titanium as well. Due to the unique characteristics of new titanium alloys, the percentage of titanium in gas turbine engines is expected to continue to increase.

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[14] Leyens and Peters: Titanium and Titanium Alloys

[15] An engine bypass ratio is the ratio of fan air to primary air. Primary air travels through the core of the engine where it goes through the compression and combustion stages. Primary air drives the turbines. Fan air bypasses the core of the engine. Fan air provides the majority of forward thrust. In general, gas turbine engine manufacturers attempt to maximize fan air within the design limitations of an engine. See Figure 2.3 for more information.

Chapter 3 Titanium

The objective of this chapter is to give the reader a comprehensive overview of titanium and titanium alloys. The chapter begins with a discussion on the isolation of elemental titanium and the commercial titanium manufacturing process. Special emphasis is placed on the inflexibility of the current manufacturing process and the limited technological advancement over the past 50 years. This chapter also aims to describe the four main titanium alloys used at Pratt & Whitney and the differences between these alloys. The unique characteristics of titanium as compared to other materials are also stressed. The chapter concludes with a discussion on the various material forms of titanium alloys.

3.1 Introduction to Titanium

Titanium was first identified in England by Rev. William Gregor in 1791 and obtained its current appellation in 1795 from the German chemist Martin Heinrich Klaproth. The name derived from the Latin word *titans,* which means earth. It is the ninth most common substance in the earth's crust but is only found bounded to other elements in nature.[16] The most common forms are ilmnenite ($FeTiO_3$) and rutile (TiO_2).[17]

It was not until William Kroll in the late 1940s demonstrated his Kroll Process that pure titanium was able to be extracted in a commercially viable process. Although great sums of money have been spent on research over the last 60 years, nearly all titanium used in metal production is produced via a variant of the basic Kroll Process.

> "According to thermodynamic calculations, alternative processes for direct reduction of titanium oxide to metal (e.g. by electrolytic processes) are believed to be less expensive than the Kroll process. However, the feasibility of alternative processing routes has only been demonstrated on a laboratory scale and not yet in large-scale production."[18]

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[16] Donachie: Titanium A Technical Guide

[17] Lyens and Peters: Titanium and Titanium Alloys

[18] Lyens and Peters: Titanium and Titanium Alloys

> "The history of titanium is replete with efforts focused on reducing the cost of producing titanium to make it a more attractive material alternative, but with relatively limited exception to date, the cost of producing most forms of titanium today has not changed fundamentally since its commercialization over 50 years ago."[19]

Once isolated, the advantages of titanium are immediately apparent. Titanium has a very high specific strength. The density of titanium is only about 60% of that of steel or nickel based super alloys while the tensile strength of titanium alloys are comparable or better than many steel alloys. Additionally, titanium has a remarkable resistance to temperature. Titanium alloys are useful to slightly above 500 C. Titanium is also exceptionally corrosion resistant. It is virtually immune to seawater and exceeds the resistance of stainless steel in most environments. Titanium can be forged or wrought by standard techniques, is castable, and can be processed by means of powder metal technology. Titanium may also be joined by means of fusion welding, brazing, adhesives, and fasteners.[20]

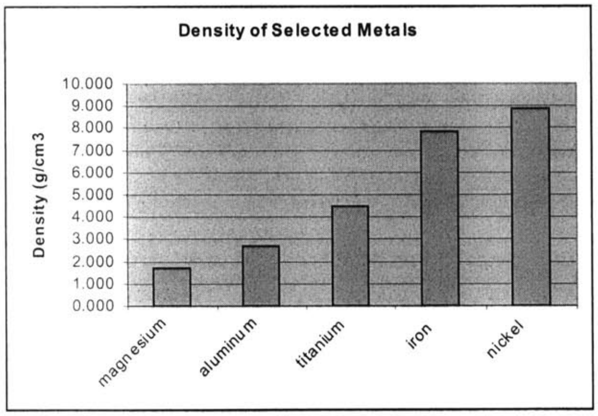

Figure 3.1: Density of Selected Metals

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[19] J. Landis Martin, International Titanium Association 2003 Annual Meeting

[20] Donachie: Titanium A Technical Guide

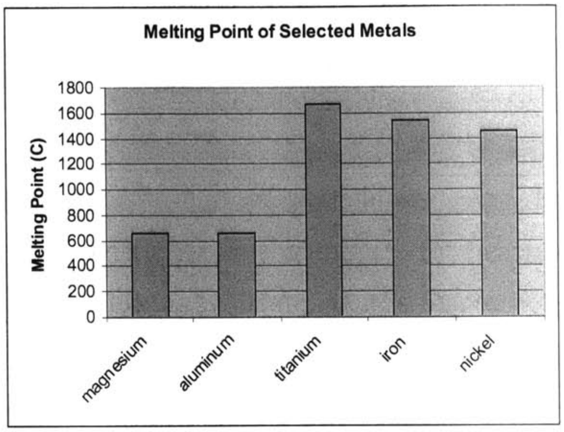

Figure 3.2: Melting Point of Selected Metals

3.2 *Titanium Manufacturing: The Kroll Process*

Most titanium used for metal in the aerospace industry is originally found in rutile (TiO_2) form. The key challenge then becomes how to remove the two oxygen atoms in order to produce pure titanium. The Kroll Process is the standard manufacturing process for accomplishing this feat.

The first step of the Kroll process is to chlorinate the TiO_2 producing titanium tetrachloride ($TiCl_4$). Magnesium is then added, which reacts to form magnesium dichloride and titanium.

$$TiO_2 + 2Cl_2 + C > TiCl_4 + CO_2(CO) \qquad \text{[Purification]}$$

$$TiCl_4 + 2Mg > 2MgCl_2 + Ti \qquad \text{[Metal]}$$

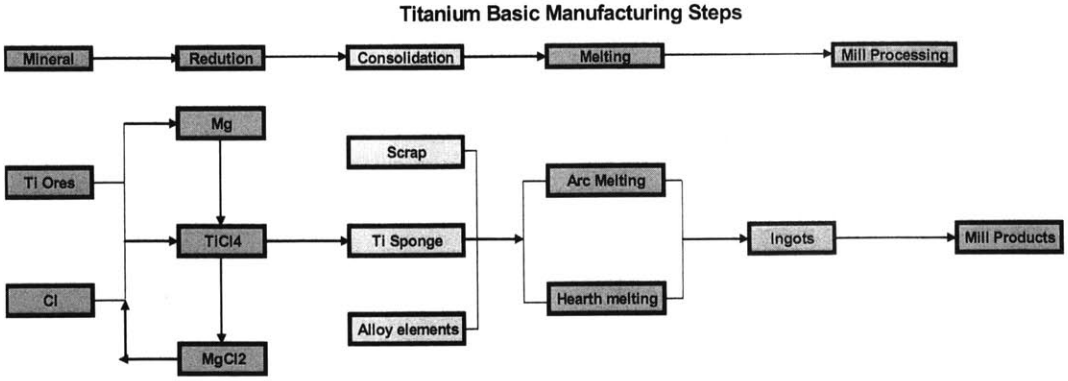

Figure 3.3: Titanium Basic Manufacturing Steps

Although this process is capable of producing 99.9% pure titanium, it has some major limitations that have a crucial impact on the titanium metal industry. First of all, magnesium is a relatively expensive input into the process while not a critical output. Many aspects of a commercial Ti reduction process are concentrated on recycling the $MgCl_2$ by-product. More importantly, the reaction takes a considerable amount of time to complete and the inputs must remain confined in a retort during this period. Therefore, the reduction of Ti from TiO_2 is a batch process as opposed to a continuous process such as the production of steel. Together these attributes of the process make it very difficult for a metal producer to quickly change manufacturing volumes. Learning from past experience, metal producers are very cautious in their decisions to add additional capacity. Titanium metal producers have repeatedly increased capacity in response to anticipated demand and have then been left with excess capacity when programs were canceled or cut back.[21] Additionally once the manufacturing system has begun production, it is very difficult to stop and start it again. This leads to companies attempting to produce a similar amount of material regardless of demand or large step changes in capacity. These factors help to make the production of titanium metal a very cyclical business environment.

3.3 Titanium Sponge and Titanium Alloys

When pure titanium is extracted from its natural occurring compounds such as rutile (TiO_2) it is referred to as titanium sponge. The name "sponge" derives from its porous appearance, which is similar to a sea sponge. The porous nature of the extracted metal is typical of metal that has been produced through the reduction of an oxide.

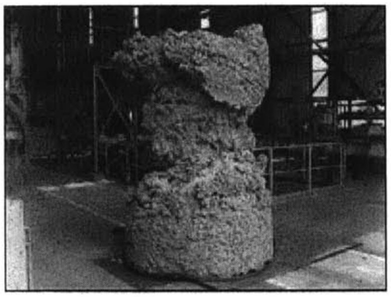

Figure 3.4: Titanium sponge[22]

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[21] USGS: http://minerals.usgs.gov/minerals/pubs/commodity/titanium/stat/; 19th January 2007

[22] http://www.toho-titanium.co.jp/en/products/sponge/html; 19th January 2007

Pure titanium is an allotropic element in that is exists in two crystallographic forms: alpha and beta. The alpha form has a hexagonal close packed crystal structure while the beta has a body centered cubic crystal structure. In order to obtain the desired material characteristics, pure titanium sponge is alloyed with various elements. The alloying elements are classified as either alpha or beta stabilizers.

Pratt & Whitney uses four main types of titanium alloy: Ti 6-4, Ti 6-2-4-2, Ti 6-2-4-6, and Ti 8-1-1. The major metallurgical difference between these materials is the proportional amount of titanium, aluminum, vanadium, tin, zirconium, and molybdenum. Aluminum, tin, and zirconium are considered alpha stabilizers while molybdenum and vanadium are beta stabilizers. The properties and manufacturing characteristics of titanium alloys are extremely sensitive to small variations in both alloying and residual elements. The complexity of the titanium alloy manufacturing operations adds considerably to the cost of titanium.[23]

MATERIAL	AL	MO	SN	TI	V	ZR
Ti-6-2-4-2	0.06	0.02	0.02	0.86	0	0.04
Ti-6-2-4-6	0.06	0.06	0.02	0.82	0	0.04
Ti-6-4	0.06	0	0	0.9	0.04	0
Ti-8-1-1	0.08	0.01	0	0.9	0.01	0

Figure 3.5: Percentage of Elements in Different Titanium Alloys

3.4 Titanium Material Forms

The path from raw material to a finished titanium part for a gas turbine engine can be divided into 6 main stages: raw material, titanium sponge, titanium alloy ingot, mill product, raw material part, and finished machined part.

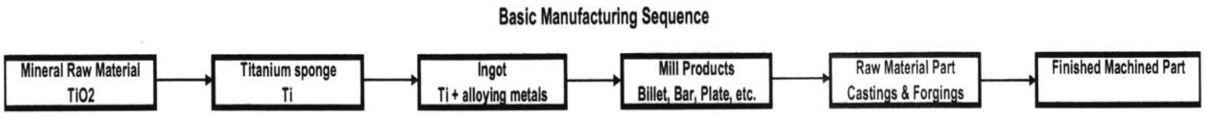

Figure 3.6: Titanium Components Basic Manufacturing Sequence

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[23] Kalpakjian and Schmid: Manufacturing Engineering and Technology

An ingot is the end product of the consolidation and melting stages of the material manufacturing process. It is produced by melting titanium sponge, alloying elements, and scrap together. Once again one of the key characteristics of this process is that it is a batch process. Therefore the size of the ingot will depend on the size of the furnace used to melt the input material. Ingots can vary in size from 6,000 lbs up to 20,000 pounds. For the most part, the size of an ingot for any given titanium alloy from a specific metal producer is consistent. For example, an ingot of Ti-6-2-4-6 from the Titanium Metals Corporation is always 14,000 lbs +/- 500 lbs.

Figure 3.7: Titanium Ingot[24]

Mill products include billet, bar, plate, sheet, strip, extrusions, tube, and wire. Mill products are ingots that have been further processed through forging and rolling operations. Mill processing is a key contributor to the final material properties.

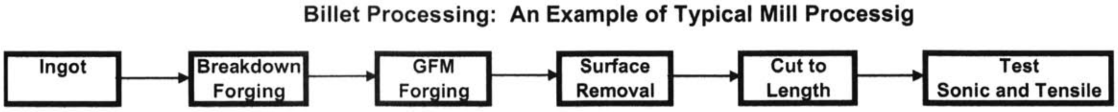

Figure 3.8: Billet Processing: An Example of Typical Mill Processing

Whereas Pratt & Whitney uses 4 basic types of titanium alloy, the number of different types of mill products is significantly greater. For example billet is usually classified by its

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[24] http://www.china-ti.com/html/ingots.html; 19th January 2007

diameter. Pratt & Whitney currently uses 15 different billet diameters ranging from 4" to 15". Each billet diameter can be one of any of the four different types of titanium alloy thus leading to a total of 60 different possibilities. Pratt & Whitney experiences a similar explosion of forms for bar, wire, and plate mill products.

Figure 3.9: Titanium Mill Products[25]

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[25] http://www.titanium.com/titanium/barbill.cfm; 19th January 2007

Chapter 4 The Titanium Alloy Metals Industry

The objective of this chapter is to give the reader a comprehensive overview of the titanium alloy metals industry. Special emphasis is placed on the limitations within the industry that could result in uncertain supply for titanium alloy customers.

4.1 Main Players in the Titanium Alloy Metals Industry

The titanium alloys metal industry is a traditional oligopoly where a small number of firms account for most or all of total production. An oligopolistic market exists in both the production of titanium sponge as well as titanium alloys. In both cases the oligopolistic market is a result of substantial positional competitive advantages including a large minimum efficient scale as well as large barriers to entry including the need to subject the product to extensive testing procedures in order for it to be approved for usage. There are only 4 companies capable of producing aerospace grade titanium alloys on a large scale. They are the Titanium Metals Corporation (TIMET) , RTI International Metals Company (RTI), Allegheny Technologies (ATI), and the Russian company VSMPO. Figure 4.1 shows the relative capacity of the major U.S. titanium metal producers.

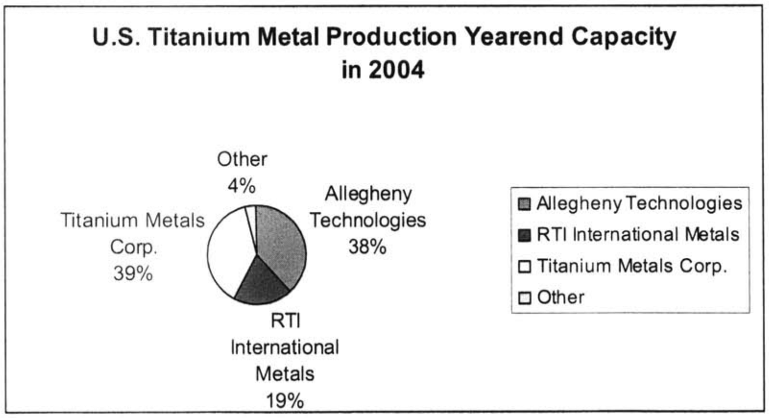

Figure 4.1: U.S. Titanium Metal Production Yearend Capacity in 2004[26]

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[26] U.S. Geological Survey Minerals Yearbook - 2004

4.2 Foreign Supply and the Berry Amendment

VSMPO is widely considered to be the world's largest producer of both titanium mill products and titanium sponge with a capacity approaching the combined capabilities of the three main U.S. manufacturers.[27] Although priced competitively, VSMPO materials can not be used in all applications due to U.S. government regulations.

The Berry Amendment was originally created in 1941 in order to protect the U.S. industrial base during periods of adversity or war. In 1973 Congress added a key provision called the specialty-metals clause. This addition required that titanium as well as various other metal alloys used by U.S. defense contractors be produced in the U.S. The Berry Amendment effectively bans U.S. companies from using VSMPO sourced titanium on products manufactured for the U.S. Department of Defense, thus greatly reducing the available supply base for many titanium components.[28]

4.3 Cyclical Nature of the Titanium Metals Industry

> "The cyclical nature of the commercial aerospace industry has been the principal driver of the historical fluctuations in the performance of most titanium companies." [29]

> "The cyclical nature of the industries in which our customers operate causes demand for our products to by cyclical, creating uncertainty regarding profitability." [30]

Perhaps the defining characteristic of the titanium metals industry is its cyclicality. Over the past 20 years, the titanium industry had cyclical peaks in titanium mill products in 1989, 1997, and 2001 and cyclical lows in 1983, 1991, 1999, and 2003.[31] Figure 4.2 shows the apparent titanium sponge consumption in the United States as reported by the United States Geological Survey. On eight different occasions titanium sponge consumption has dropped by over 25% in a single year.

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[27] American Metals Market: "VSMP Ponders the Next Move"; 10th October 2005

[28] CRS Report for Congress: The Berry Amendment, 2005

[29] Titanium Metals Corporation 2005 Annual Report

[30] Allegheny Technologies 2005 Annual Report

[31] Titanium Metals Corporation 2005 Annual Report

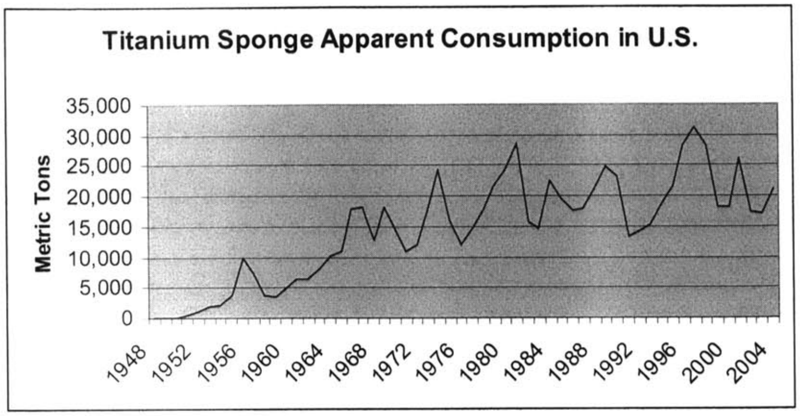

Figure 4.2: Titanium Sponge Apparent Consumption in U.S.[32]

The cyclicality of the industry is also evidenced by examining the price of titanium sponge over both the long and short term. The extreme fluctuations in both consumption and pricing makes planning major capital investment very difficult for titanium producers.

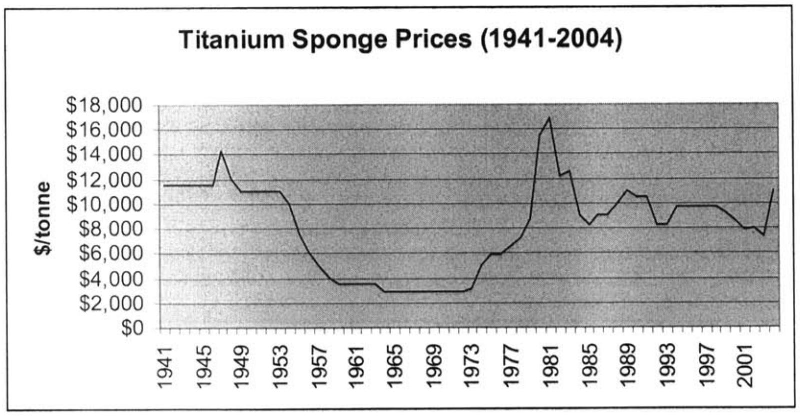

Figure 4.3: Titanium Sponge Prices 1941-2004[33]

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[32] United States Geological Survey (http://minerals.usgs.gov/ds/2005/140/titanium.xls)
[33] United States Geological Survey (http://minerals.usgs.gov/ds/2005/140/titanium.xls)

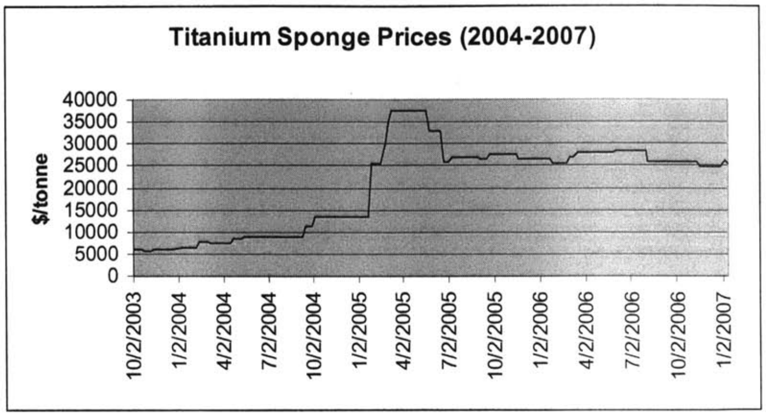

Figure 4.4: Titanium Sponge Prices 2004-2007[34]

Additionally, the stock performance of the major publicly traded titanium metal producers indicate a very cyclical business environment. During periods of peak demand, titanium metal producing companies often see a substantial increase in their stock prices. During periods of limited demand, they often struggle to stay solvent. These large swings in the fortunes of titanium metal producers are a large contributor to the uncertain supply environment during periods of reduced titanium demand.

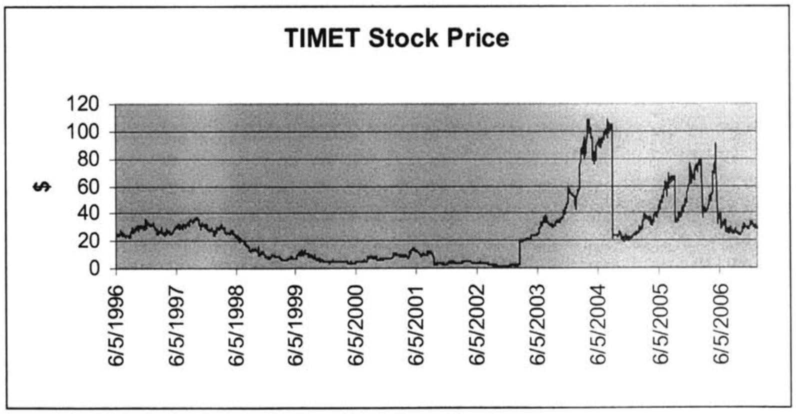

Figure 4.5: Timet Historical Stock Price

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[34] www.metalprices.com ; 19th January 2007

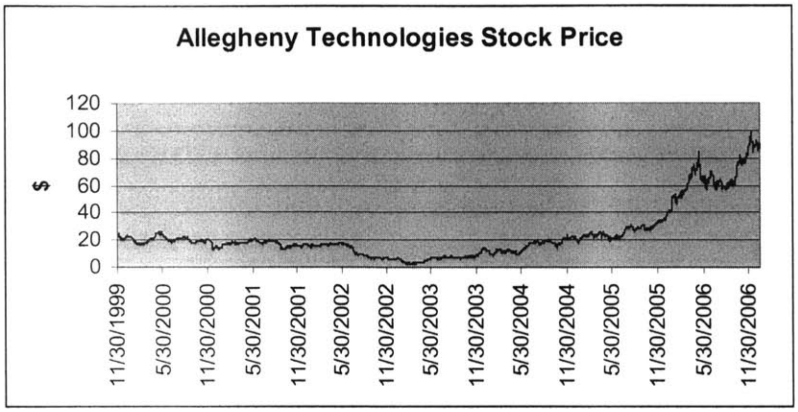

Figure 4.6: Allegheny Technologies Historical Stock Price

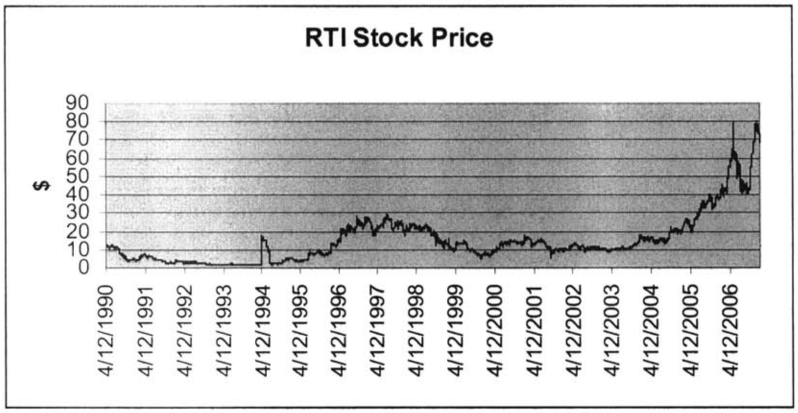

Figure 4.7: RTI Historical Stock Price

4.4 Future of the Titanium Metals Market

The market for titanium is largely driven by the aerospace industry. It is estimated that 65% of all titanium sponge produced in the world is used for aerospace applications.[35] There are three main business trends in the aerospace industry that will result in a very tight titanium market for the foreseeable future: a cyclical up swing in the commercial aviation industry, new airplane designs that use comparably more titanium, and continued demand from the U.S. military due to new product programs and high capacity utilization of current equipment.

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[35] United States Geological Survey January 2006 Report

Additionally, non-aerospace applications for titanium are expected to increase and contribute to an increase in demand for titanium.

The cyclicality of the commercial aviation industry is a major contributor to the cyclicality of the titanium industry. The cyclicality of the commercial aviation industry is clearly evidenced by examining the historical large jet aircraft deliveries .

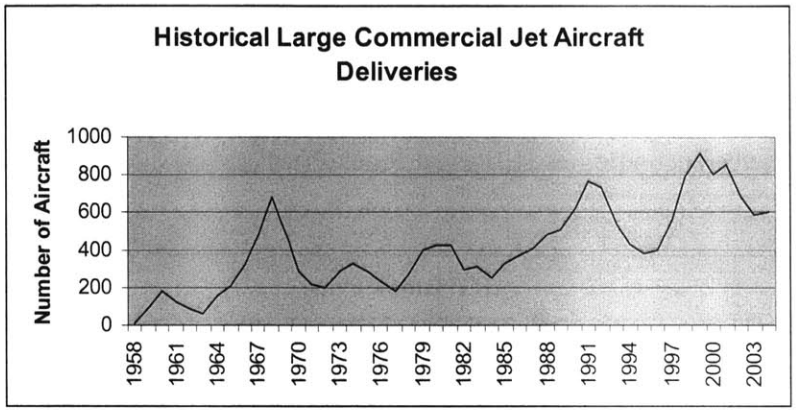

Figure 4.8: Historical Large Commercial Jet Aircraft Deliveries[36]

Large commercial jet aircraft deliveries hit a historical peak in 1999. In the beginning of 2000 a series of events began to unfold that would drastically reduce the demand for commercial aircraft. These events include the sudden drop in value of the NASDAQ stock exchange beginning in March 2000, an economic recession that began in March 2001, the terrorist attacks in New York City on September 11, 2001, and the SARS epidemic. After several years of dampened demand, aircraft deliveries began to once again increase in 2004. In 2005 both Boeing and Airbus received a record number of orders.[37] Most commercial aerospace companies indicate in their 2005 annual reports that they expect the commercial aerospace industry rebound to continue. The January 2006 forecasts from The Airline Monitor, a leading aerospace publication, confirm this prediction.

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[36] www.speednews.com/lists; 19th January 2007

[37] Titanium Metals Corporation 2005 Annual Report

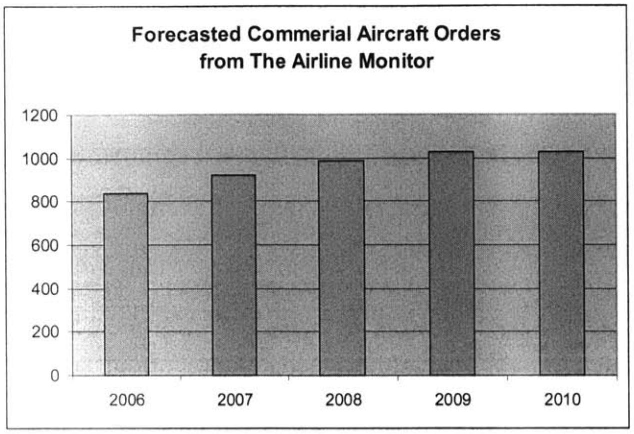

Figure 4.9: Forecasted Commercial Aircraft Orders[38]

In addition to the cyclical upswing in the commercial aviation market, the leading commercial aviation companies Boeing and Airbus have developed all new aircraft that will fundamentally change the dynamics of the titanium industry. Specifically, new aircraft designs are using an increased proportion of titanium. Over 20% of the weight of the new Boeing 787 will be titanium. This is a considerable increase as compared to 8% on the Boeing 777.[39] With 555 seats on two separate levels, the Airbus A380 is the largest commercial aircraft in production. It uses approximately 76 metric tons of titanium in its production. Airbus' existing twin aisle aircraft, the A340, uses only 25 metric tons of titanium.[40]

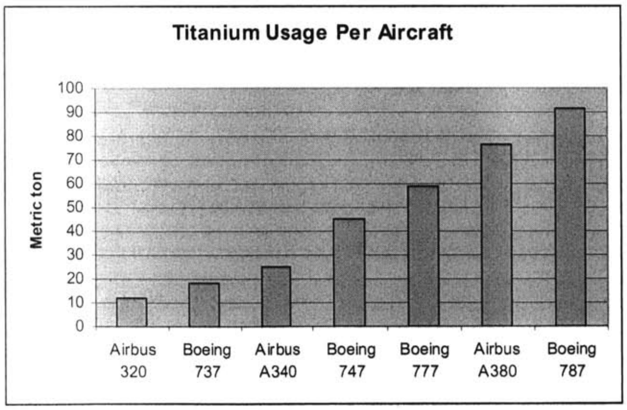

Figure 4.10: Titanium Usage Per Aircraft[41]

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[38] Titanium Metals Corporation 2005 Annual Report

[39] Flight International: "Metal High Hits Hard" (http://www.flightglobal.com/articles/2006/05/16/206643/metal-high-hits-hard.html); 22nd January 2007

[40] Titanium Metals Corporation 2005 Annual Report

[41] Titanium Metals Corporation 2005 Annual Report

In addition to the commercial aviation industry, the military aviation industry has a large impact on the state of the titanium industry. In fact military aerospace programs were the first to utilize titanium on a large scale. In the late 1980s titanium shipments to the military aerospace sector peaked before declining in the early 1990s due to the end of the Cold War. The importance of the military market to the titanium industry has once again increased due to extended military activities in Afghanistan and Iraq and is expected to continue to increase as defense spending continues to rise.[42] Titanium is also a key input material for new aircraft programs including the F/A-22 Raptor and the F-35 Joint Strike Fighter, which are forecasted to increase production in the coming years.

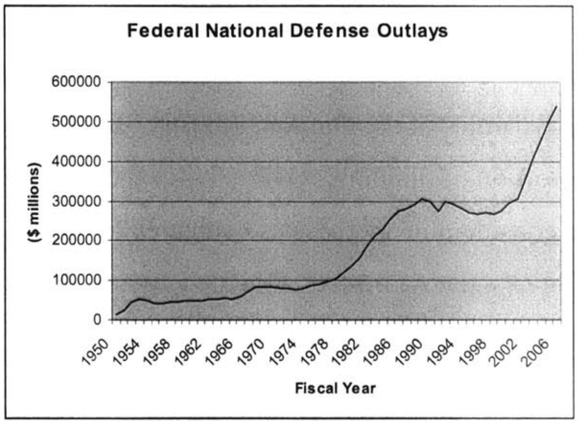

Figure 4.11: Federal National Defense Outlays[43]

In addition to the traditional aerospace market for titanium, there has been a concentrated effort by the titanium industry to expand the use of titanium in other industries. In particular, titanium metal producers have focused efforts on increasing consumption in less-cyclical industries.

Due to titanium's exceptional compatibility with the human body and advancement in medical technology, titanium is increasingly being used in the medical field. The metal

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[42] Titanium Metals Corporation 2005 Annual Report

[43] http://www.dod.mil/comptroller/defbudget/fy2007/fy2007_greenbook.pdf; 22th January 2007

components in the first artificial heart were largely manufactured of titanium. Additionally, most hip implants as well as bone fracture plates and screws are made of titanium.[44]

In addition to the aerospace and medical industries, titanium is often used in applications where corrosion resistance is needed. These applications include automotive, chemical processing, power generation, architecture, as well as the sports and leisure industry. Currently many professional golfers including Tiger Woods use golf clubs made principally of titanium.[45] Although emerging markets for titanium represent only 4% of the 2005 total industry demand, it is expected to achieve double-digit growth rates over the next several years.[46]

4.5 Expansion in the Titanium Metals Industry

> "We are taking major steps to help meet the growing demand for titanium products."[47]
>
> Timet 2005 Annual Report

> "Another key to growth is surging demand for our products. The principal driver of the demand surge for titanium, our core product, is the record growth in commercial aerospace."[48]
>
> RTI International Metals Inc. 2005 Annual Report

> "The outlook in our High Performance Metals segment is robust for our titanium and titanium alloys and for our nickel-based super alloys. Demand from customers exceeds our current capacity."[49]
>
> Allegheny Technologies 2005 Annual Report

The titanium industry is currently in a state of expansion. The major producers are experiencing demand in excess of their current capacity. In response to this business environment, each of the major producers have announced new capital investments in capacity

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[44] Leyens and Peters: Titanium and Titanium Alloys

[45] http://www.tigerwoods.com/defaultflash.sps; 22nd January 2007

[46] Titanium Metals Corporation 2005 Annual Report

[47] Titanium Metals Corporation 2005 Annual Report

[48] RTI International Metals Inc. 2005 Annual Report

[49] Allegheny Technologies 2005 Annual Report

over the last three years. This barrage of expansion announcements is a clear indicator of a major shift in demand for titanium as well as the current constraints on titanium manufacturing capacity.

In May 2005, TIMET announced a plan to expand their titanium sponge capacity in Hendersen, Nevada. This expansion, which will take over two years to complete, will increase TIMET's sponge capacity by approximately 47%. In April 2006, TIMET announced another plan to expand their titanium melting capacity by over 8,500 metric tons. This capacity is not scheduled to come on-line until 2008.

ATI is also pursuing an aggressive expansion policy. In June 2006 ATI announced plans to build a greenfield titanium sponge facility capable of producing 24 million pounds of titanium sponge. This new facility, scheduled to be completed near the end of 2008, will compliment a previously planned expansion of their Albany, OR facility.

RTI has also made recent expansion announcements. In May 2006 RTI announced two separate expansion projects valued at $35 million and $43 million respectively for their titanium processing capabilities.

This recent storm of expansion announcements indicates a very tight titanium alloy market. As demand has begun to outstrip available capacity, titanium customers have seen a dramatic increase in quoted lead-times for titanium ingots. In the fourth quarter of 2003, a spot market purchase of a titanium ingot could expect an 11 week lead-time to delivery. By the second quarter of 2006 the lead-time had increased to 60 weeks. These long lead-times should continue until the titanium producers have brought their schedule expansions on line.

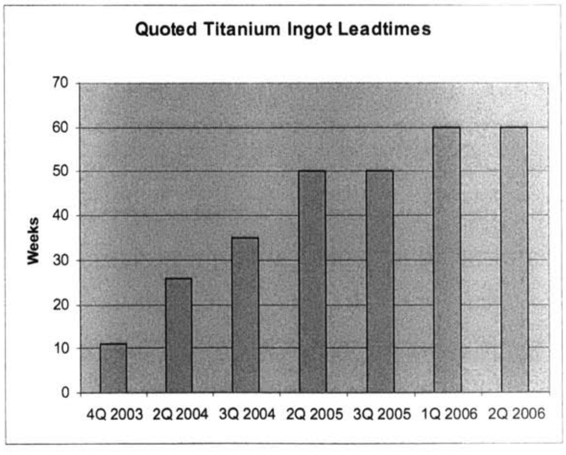


Figure 4.12: Quoted Titanium Ingot Lead-times

4.6 Conclusion: Titanium and the Titanium Metals Industry

Gas turbine jet engines are highly engineered machines that operate at very high pressures and temperatures. The materials used in their construction must meet very stringent requirements and once approved are very difficult to substitute. Titanium has several key characteristics including temperature resistance and a very high strength-to-weight ratio that make it an essential raw material in the construction of gas turbine jet engines.

Although titanium is widely found in the earth's crust, it is never found in its pure elemental form. Usually it is bound to oxygen in the form of rutile or oxygen and iron in the form of ilmnenite. The dominant manufacturing process for extracting pure titanium, the Kroll Process, has basically remained unchanged since its discovery in the late 1940s. The Kroll Process is a batch process that limits the flexibility of titanium metal producers and is a major contributor to the cost of titanium alloys.

The titanium industry consists of a relatively small number of large producers. Due to a large minimum efficient scale and extensive customer approval processes, it is a very difficult industry for new entrants. Additionally, the U.S. Berry Amendment limits the ability of the world's largest titanium producer, the Russian company VSMPO, to meet the demands of U.S. aerospace customers. The titanium industry is an extremely cyclical industry whose fluctuations are largely dictated by the commercial and military aerospace industries.

Currently demand in the titanium industry is in excess of available capacity. The recent increase in demand is a result of a cyclical upswing in the commercial aviation industry, new airplane designs that use substantially more titanium than older designs, increased military demand due to extended U.S. military engagements in Iraq and Afghanistan, and a concerted effort by titanium industry to diversify into non-aerospace industries. As a result of a fundamental shift in demand, all of the major titanium producers have recently announced expansion plans. Most of these expansion plans require at least two years before becoming fully operational.

These factors combine to make the current titanium market a very difficult place for titanium customers such as Pratt & Whitney. The required lead-time for an ingot of titanium on the spot market has grown from 11 weeks at the end of 2003 to 60 weeks at the beginning of 2006. This incredibly tight raw material market has severely limited the flexibility of Pratt &

Whitney. A gas turbine jet engine producer has an opportunity to gain a distinct competitive advantage over their competitors by creating a strategic plan to accommodate the tight titanium raw material market.

Chapter 5 Disruptive Events and the Strategic Raw Material Inventory

The objective of this chapter is to give the reader an overview of Pratt & Whitney's Strategic Raw Material Inventory. Special emphasis is placed on defining disruptive events in the supply chain that make this inventory necessary. The arrival of these events is modeled using a Poisson Process. Furthermore, the arrival and size of the events are modeled using a Compound Poisson Process. The associated algorithms were program into Microsoft Excel to create the Strategic Raw Material Inventory Calculator, a powerful tool for inventory optimization.

5.1 Disruptive Events in the Supply Chain

> "Companies are increasingly vulnerable to high-impact/low-probability events. The risks grow daily as global supply lines stretch, competition stiffens around the globe, customers demand faster responses and more choice at lower cost, and political instability takes its toll worldwide."
> Yossi Sheffi and James B. Rice Jr, "A Supply Chain View of the Resilient Enterprise"

Pratt & Whitney uses a sophisticated enterprise resource planning (ERP) system in order to determine material requirements throughout its supply chain. This system does an excellent job of forward planning with a known demand. Additionally, embedded within the system are standard processes to assist the entire Pratt & Whitney supply chain react to normal demand fluctuations and manufacturing yield variability. Unfortunately, the system is not helpful in accommodating large disruptions in the supply chain. Additionally, as previously discussed in Chapter 4, the raw material supply base is not always able to effectively react to large unplanned demand fluctuations due to high capacity utilization in an oligopolistic market and inflexible manufacturing processes.

Despite considerable resources devoted to forecasting, Pratt & Whitney experiences disruptive events in its supply chain. These relatively rare but very disruptive events can be classified into three main categories: customer drop-in orders, manufacturing complications resulting in scrapped material, and major planning deficiencies.

The manufacturing of new jet engines is a well planned process. For the most part, new engine demand is known well in advance. As a derivative of airplane sales, production plans are often set a year in advance. On the other hand, spare part demand can be both volatile and difficult to predict. Many factors contribute to spare part demand including aircraft utilization and changes in maintenance schedules. It is not uncommon for Pratt & Whitney to receive an order for spare parts from a customer with a due date that does not respect the required raw material lead-time. Additionally, it is not uncommon for Pratt & Whitey to win a new contract only after committing to delivering in a timeframe that does not respect the required raw material lead-time. In the past, Pratt & Whitney had two main options available to deal with these situations. The first is to simply disappoint the customer and deliver the parts when material becomes available. There are some obvious drawbacks to this approach. Alternatively, Pratt & Whitney could work with the relevant members of the supply chain and rearrange the schedule. For example, some part deliveries could be delayed in order to make material available for the new order. This approach was very common and had some serious side effects. The main problem was that a single disruptive order could ripple throughout the supply chain and cause smaller yet significant disruptions on multiple orders. Often the root cause of the secondary issues was not properly traced back to the original disruptive drop-in order.

Although customer drop-in orders are by far the most common type of disruptive event in the Pratt & Whitney supply chain, manufacturing complications resulting in scrapped material can also lead to a raw material shortage. Although the manufacturing processes take into account normal yield variability, on rare occasions a major complication occurs that results in a large amount of scrapped material. These rare events are incredibly disruptive for Pratt & Whitney's raw material supply chain. As the source of the disruption is internal as opposed to originating at a customer, Pratt & Whitney is more willing to try high risk solutions in an attempt to meet customer needs. Although sometimes successful, often times a simple lack of raw material results in the failure of even the most heroic of recovery attempts.

In addition to customer drop-in orders and manufacturing complications, planning deficiencies are sometimes the cause of material shortages. The root cause of these errors is most often a human input error or a major Pratt & Whitney forecasting error. Although advances in information technology have helped to reduce these errors, when they occur they are particularly disruptive.

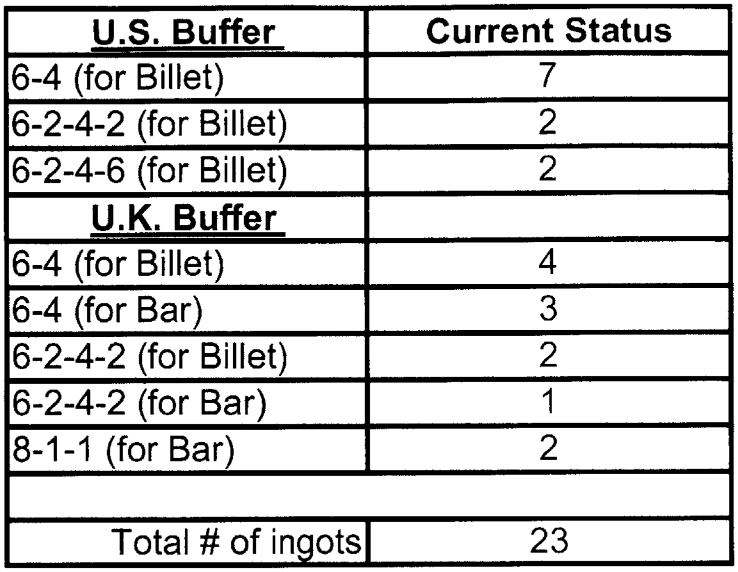
5.2 Strategic Raw Material Inventory

In response to tight raw material market conditions and the arrival of rare but disruptive events, Pratt & Whitney decided in 1998 to begin purchasing a strategic inventory of various titanium raw materials. This inventory is meant to accommodate large but relatively rare disruptive events including customer drop-in orders, large manufacturing complications, and major planning deficiencies. It is not meant to accommodate relatively small fluctuations in material demand. Small disruptions including normal variability in the manufacturing processes can be accommodated through inventory held at upstream casting and forging operations or through specialty metal distributors. It is also important to note that this material is not intended to be a hedge against material price fluctuations. The sole purpose is to allow Pratt & Whitney access to raw material when otherwise it would not be available in a suitable timeframe.

The strategic raw material buffer was created in cooperation with Pratt & Whitney's raw material suppliers. In fact, the metal producers are perhaps the greatest benefitters from this inventory. In the past, they were often called upon to produce materials in order to accommodate disruptive events that were out of their control. The new strategic raw material buffer took a major source of variability out of their demand requirements. The original size and configuration was based on the perceived requirements of Pratt & Whitney as well as the operations and capabilities of the metal producers.

5.3 Strategic Raw Material Inventory Categories

There are eight main categories in the titanium strategic raw material inventory. These categories are differentiated by three factors: alloy type (Ti 6-4, Ti 6-2-4-2, Ti 6-2-4-6, and Ti 8-1-1), location (United States or United Kingdom), and final form (billet or bar). The current inventory target levels are summarized in Figure 5.1.



U.S. Buffer	**Current Status**
6-4 (for Billet)	7
6-2-4-2 (for Billet)	2
6-2-4-6 (for Billet)	2
U.K. Buffer	
6-4 (for Billet)	4
6-4 (for Bar)	3
6-2-4-2 (for Billet)	2
6-2-4-2 (for Bar)	1
8-1-1 (for Bar)	2
Total # of ingots	23

Figure 5.1: Strategic Raw Material Inventory Levels

5.4 Modeling Event Arrivals with a Poisson Process

Once again it is important to note that the strategic raw material inventory is only intended to accommodate the arrival of rare but disruptive events in the supply chain. It is not intended to be used for normal and smaller demand variation. The arrival of these disruptive events is both rare and stochastic and is not best modeled as a traditional Gaussian distribution. A large and complex combination of random factors must simultaneously occur in order for a disruptive material shortage to occur. Additionally, many of the root causes occur inside Pratt & Whitney's customers' operations thus their arrival at Pratt & Whitney is random in nature.

In order to model the effect of these disruptive events their arrival was simulated by a Poisson Process, which stipulates that the time between arrivals in exponentially distributed. The use of the Poisson Process is very common in operations research and supply chain modeling. Examples of phenomenon commonly modeled as a Poisson random variables include customers arriving at a store, accidents occurring on a certain highway, earthquakes, and emission of radioactive processes.[50]

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[50] Olofsson: Probability, Statistics, and Stochastic Processes

The Poisson Process is a counting process for discrete events.[51] A process $\{N(t), t >= 0\}$ must meet three main criteria in order to be considered a Poisson Process with an arrival rate of λ:

i) $N(0) = 0$

ii) The process has independent increments

iii) The number of events in any interval of length t is Poisson distributed with mean $\lambda*t$. That is, for all s, t>=0:

$$\mathbf{P\{N(t+s) - N(s) = n\} = e^{-\lambda t} * ((\lambda*t)^n / n!)}$$ [52]

The first criterion simply states that the counting of the arrivals starts at t=0, which is certainly true in the analysis of the arrival of disruptive events in Pratt & Whitney's raw material supply chain. The second criterion can be directly verified by examining our process. The arrival of a disruptive event leading to a material shortage is a discrete event and there exist an arrival time interval *dt* such that only one arrival can occur. Furthermore, the arrival of an event is independent of the time the last arrival occurred. The third criterion can be verified by examining historical data.

Through careful examination of accounting records, inventory reports, and past communications between Pratt & Whitney and their metal suppliers; a history of the arrival of disruptive events affecting the raw material supply chain was created. Figure 5.1 through 5.8 show pictorial representations of the arrival of requests for the different strategic raw material inventories.

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[51] Ross: Introduction to Probability Models

[52] Ross: Introduction to Probability Models. Note there are other treatments of a Poisson Process (including Devore: Probability and Statistics for Engineering and the Sciences) that express the assumptions in terms of a zero probability of two events arriving in a sufficiently small interval. The approaches are equivalent.

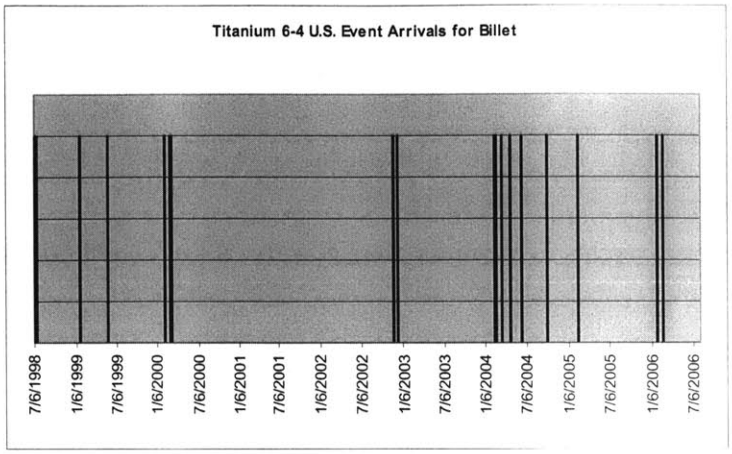

Figure 5.2: Titanium 6-4 U.S. Event Arrivals for Billet

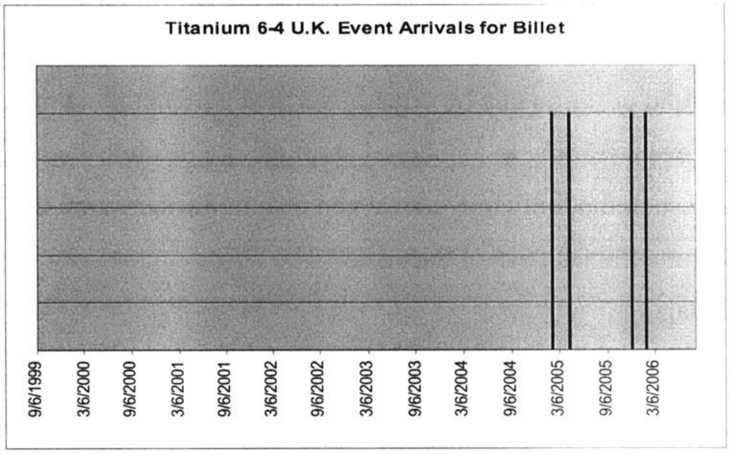

Figure 5.3: Titanium 6-4 U.K. Event Arrivals for Billet

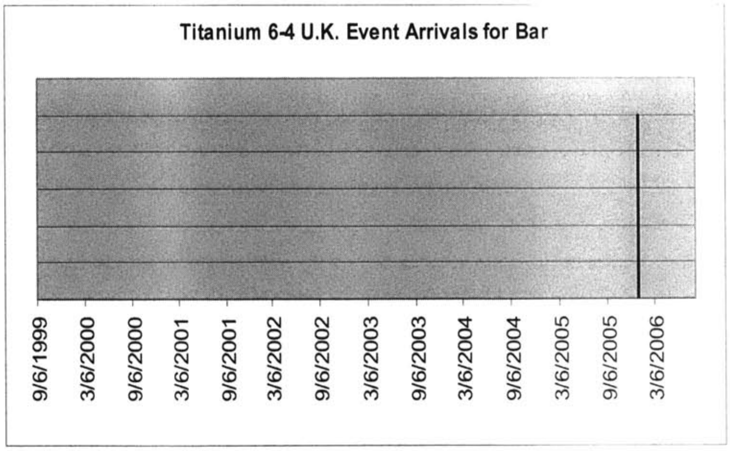

Figure 5.4: Titanium 6-4 U.K. Event Arrivals for Bar

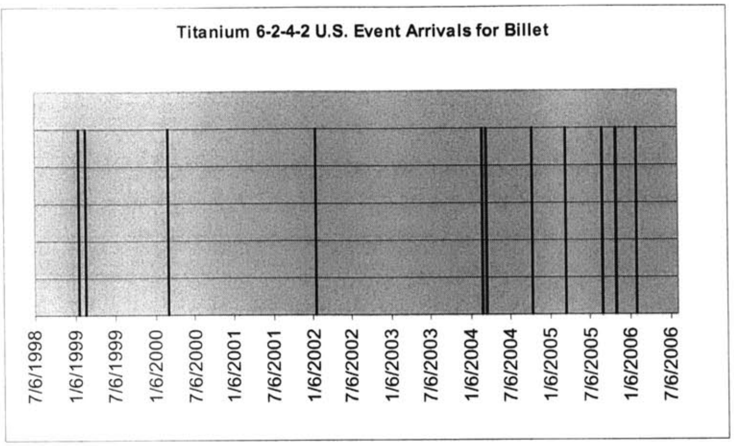

Figure 5.5: Titanium 6-2-4-2 U.S. Event Arrivals for Billet

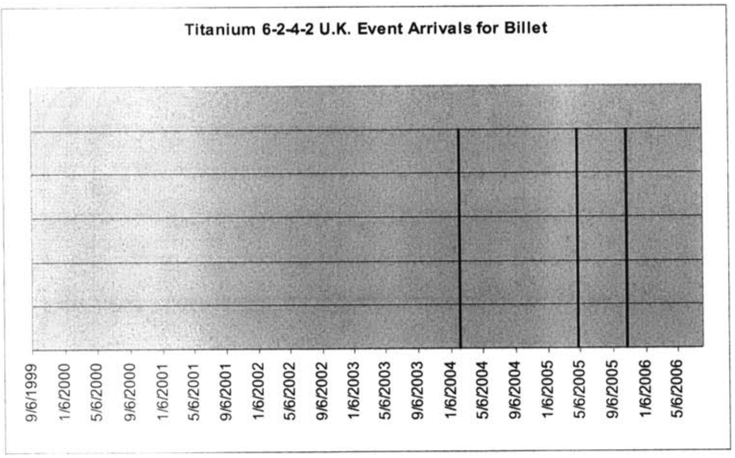

Figure 5.6: Titanium 6-2-4-2 U.K. Event Arrivals for Billet

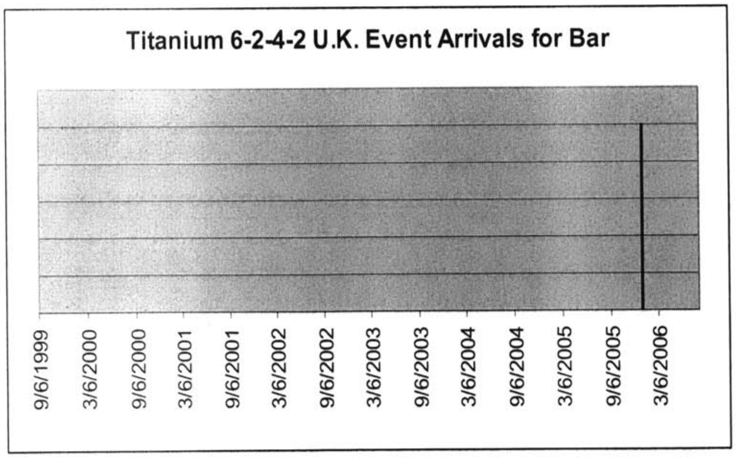

Figure 5.7: Titanium 6-2-4-2 U.K. Event Arrivals for Bar

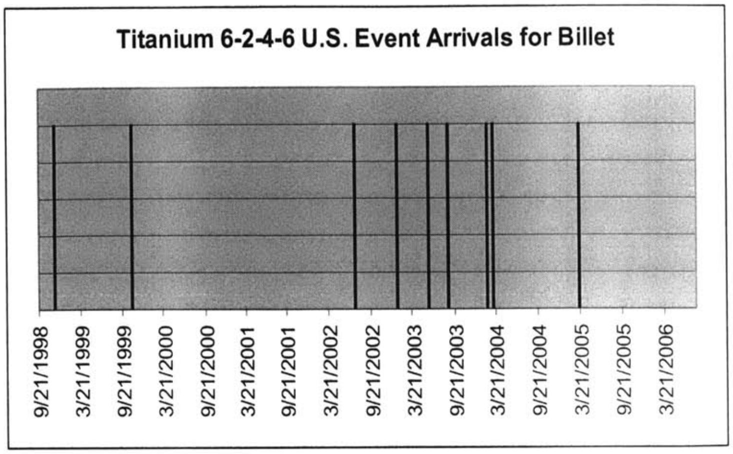

Figure 5.8: Titanium 6-2-4-6 U.S. Event Arrivals for Billet

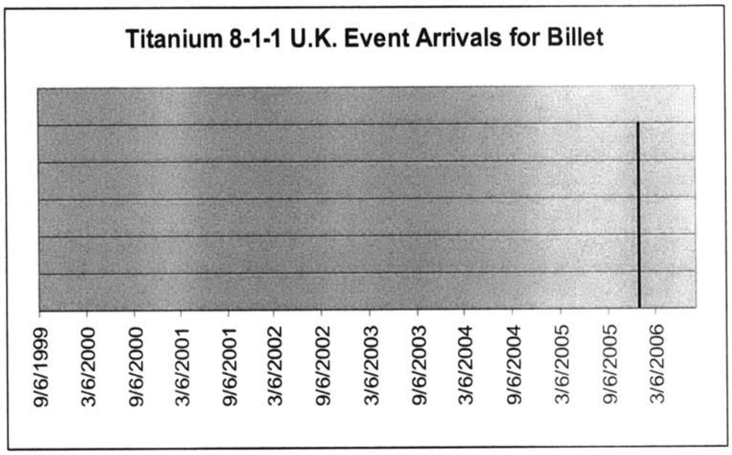

Figure 5.9: Titanium 8-1-1 U.K. Event Arrivals for Billet

A comparison of the historical observed data to the expected outcome of a Poisson Process is exhibited in Figure 5.10. In all inventory categories, the expected number of arrivals given by a Poisson Process defined by an arrival rate of λ closely replicates the observed arrival rate as determined through the examination of historical records.

Ti 6-4 U.S. Billet Inventory: Observed vs. Expected Event Arrivals

Number of weeks with n events	Observed	Observed %	Poisson Expected (λ=0.0426 events/week)
0	405	95.74%	95.83%
>=1	18	4.26%	4.17%

Ti 6-4 U.K. Billet Inventory: Observed vs. Expected Event Arrivals

Number of weeks with n events	Observed	Observed %	Poisson Expected (λ=0.0110 events/week)
0	358	98.90%	98.90%
>=1	4	1.10%	1.10%

Ti 6-4 U.K. Bar Inventory: Observed vs. Expected Event Arrivals

Number of weeks with n events	Observed	Observed %	Poisson Expected (λ=0.00276 events/week)
0	361	99.72%	99.72%
>=1	1	0.28%	0.28%

Ti 6-2-4-2 U.S. Billet Inventory: Observed vs. Expected Event Arrivals

Number of weeks with n events	Observed	Observed %	Poisson Expected (λ=0.0260 events/week)
0	412	97.40%	97.43%
>=1	11	2.60%	2.57%

Ti 6-2-4-2 U.K. Billet Inventory: Observed vs. Expected Event Arrivals

Number of weeks with n events	Observed	Observed %	Poisson Expected (λ=0.00829 events/week)
0	359	99.17%	99.17%
>=1	3	0.83%	0.83%

Ti 6-2-4-2 U.K. Bar Inventory: Observed vs. Expected Event Arrivals

Number of weeks with n events	Observed	Observed %	Poisson Expected (λ=0.00276 events/week)
0	361	99.72%	99.72%
>=1	1	0.28%	0.28%

Ti 6-2-4-6 U.S. Billet Inventory: Observed vs. Expected Event Arrivals

Number of weeks with n events	Observed	Observed %	Poisson Expected (λ=0.0218 events/week)
0	403	97.82%	97.84%
>=1	9	2.18%	2.16%

Ti 8-1-1 U.S. Billet Inventory: Observed vs. Expected Event Arrivals

Number of weeks with n events	Observed	Observed %	Poisson Expected (λ=0.00276 events/week)
0	361	99.72%	99.72%
>=1	1	0.28%	0.28%

Figure 5.10: Comparison of Observed Versus Expected Event Arrivals

5.5 *Chi-square Goodness-of-Fit Test*

A chi-square goodness-of-fit test is used to test if a sample of data came from a population with a specific distribution.[53] In the case of modeling the arrival of disruptive events requiring material from the strategic raw material inventory, the chi-square goodness-of-fit test provides a useful tool for testing the observed data to the expected output of a Poisson process as exhibited in Figure 5.10.

The chi-square goodness-of-fit test is applied to data that has been binned or put into classes. This is very convenient for a discrete distribution such as the Poisson distribution.[54] One of the key considerations when using a chi-square goodness-of-fit test is the need for sufficient data. For best results there should be a minimum of three bins or classifications each with a minimum of five data points.[55] Due to the relative scarcity of data regarding the strategic raw material inventory, each individual inventory category was combined into a single group where an event was defined as any situation where material from the strategic raw material inventory was required. Therefore, a single underlying event could result in the need for more than one type of titanium alloy. The combination of inventory categories is clearly acceptable due to the superposition properties of a Poisson Process.[56]

In order to achieve the minimum of five data points in three different bins, the data was classified into the following categories.

Bin 1: no event arrivals in given month
Bin 2: one event arrival in given month
Bin 3: two or more event arrivals in given month

Historical records for a 98 month period reveal 68 events for Bin 1, 23 events for Bin 2, and 7 events for Bin 3. It should be noted that Bin 3 consists of four two-event months, two three-event months, and one four-event month. Once again in order to achieve a minimum of 5 data points in each bin, the data was combined into a single bin of 7 data points and defined as two or more events in a given month.

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[53] Devore: Probability and Statistics for Engineering and the Sciences

[54] Alternative tests for continuous distributions include the Anderson-Darling and Kolmogorov-Smirnov goodness-of-fit tests.

[55] Devore: Probability and Statistics for Engineering and the Sciences

[56] Olofsson: Probability, Statistics, and Stochastic Processes. Two Poisson processes with rate of $\lambda 1$ and $\lambda 2$ can be superimposed into a single Poisson process with rate $\lambda 1 + \lambda 2$.

The null hypothesis for this test is that the observed data follows a Poisson process. The alternative is that the data does not follow a Poisson process.

H_0 : Data follows Poisson process.
H_a : Data does not follow Poisson Process.

Test Statistic: $\chi^2 = \sum_{i=1}^{k} (O_i - E_i) / E_i$

where O_i is the observed data and E_i is the expected outcome from a Poisson Process.

Test Procedure:

if $\chi^2 >= \chi^2_{\alpha, k-1}$ reject H_o
if $\chi^2 <= \chi^2_{\alpha, k-1-m}$ do not reject H_o

χ^2 degrees of freedom = k -1 → 3-1 = 2 , where k is the number of classes
χ^2 degrees of freedom = k -1 - m → 3-1-1 = 1
where k is the number of classes and m is the number of estimated parameters[57]

significance level $\alpha = 0.05$

$\chi^2_{0.05,2} = 5.992$
$\chi^2_{0.05,1} = 3.843$[58]

Poisson $\lambda = [(68*0) + (23*1) + (4*2) + (3*2) + (1*4)] / 98 = 0.4183$

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[57] In this case only the arrival rate of a Poisson process (λ) is estimated from the data.
[58] Devore: Probability and Statistics for Engineering and the Sciences.

	Expected probability	Expected Number	Observed Number	O-E	(O-E)^2 / E
0	65.81%	64.50	68	3.50	0.190
1	27.53%	26.98	23	-3.98	0.588
2	5.76%	5.64	4	x	x
3	0.80%	0.79	2	x	x
4	0.08%	0.08	1	x	x
5	0.01%	0.01	0	x	x
>=2	6.65%	6.52	7	0.48	0.035

0.814 **Chi-square**

Figure 5.11 Chi-square calculations

Conclusion:

Since 0.814 is less than 3.843 there is no evidence to suggest that the data does not follow a Poisson distribution.

Overall the chi-square goodness of fit test confirms what can be intuitively deduced from Figure 5.10. Namely that the Poisson process does an excellent job of replicating the arrival of disruptive events for the strategic raw material inventory.

5.6 *Event Arrival Probability Distribution*

One of the benefits of utilizing the algorithms associated with the Poisson Process is the ability to easily create a probability distribution. In the case of the Strategic Raw Material Inventory, it is very easy to calculate the probability of a certain number of events occurring in a given time frame by utilizing the Poisson equation:

$$\mathbf{P\{N(t+s) - N(s) = n\} = e^{-\lambda t} * ((\lambda * t)^{n} / n!)}$$

For example, events leading to a shortage of Ti 6-4 raw material in the U.S. arrive according to a Poisson Process at a rate $\lambda = 0.0426$ events/week. Therefore we can calculate the probability of any number of events occurring in a given time period. Figure 5.12 displays the probability distribution for the number of events in a 4 week period for the Titanium 6-4 U.S. for Billet inventory.

Ti 6-4 Billet Inventory in the U.S.
λ = 0.0426 events/week
Probability Distribution for a 4 Week Period

Number of Events (N)	P(N)	Cumulative Probability
0	84.348%	84.348%
1	14.357%	98.705%
2	1.221%	99.927%
3	0.0693%	99.996%
4	0.00295%	99.999%
5	0.00010%	100.00000%

Figure 5.12 Probability Distribution of Ti 6-4 U.S. Billet Event Arrivals

For instance there is an 84.348% probability of 0 events occurring in any given four week period, a 14.357% probability of 1 event occurring in any given four week period, and a 1.221% probability of 2 events occurring in a four week period.

$P(Z=0) = 84.348\%$
$P(Z=1) = 14.357$
$P(Z=2) = 1.221$

Additionally one can build a cumulative probability distribution. In the above example, there is an 84.358% probability of 0 events, a 98.705% probability of 1 or fewer events occurring in any give four week period, and a 99.927% probability or 2 or fewer events occurring in any given four week period

$P(Z<=0) = 84.348\%$
$P(Z<=1) = 98.705\%$
$P(Z<=2) = 9.927\%$

The mean number of events for this Poisson Process can be calculated as follows:

$E[N(t)] = \lambda * t$
$E[N(4)] = 0.0426$ events/week * 4 weeks = 0.1704 events

The variance of a Poisson Process is equal to the mean and in the above example is 0.1704 events for a four week period.

5.7 *Modeling Event Arrivals and Size with a Compound Poisson Process*

The Poisson Process does an excellent job of modeling the arrival of disruptive events, yet this is not completely descriptive of the entire Strategic Raw Material Inventory process. Each of these events can also vary in size depending on the order requirements. The order size is itself an independent and identically distributed random variable. Therefore, the entire process can be best modeled as a Compound Poisson Process where $\{N(t), t>=0\}$ is the arrival of disruptive events following a Poisson Process and $\{Y_i, i>=t\}$ is a family of independent and identically distributed random variables indicating the size of the event.

$$X(t) = \sum_{i=1}^{N(t)} Y_i$$

Inventory in the raw material strategic buffer is held in ingot form. Therefore the size of the arrivals can be thought of in terms of the number of ingots required to satisfy the requirements of a disruptive event. The distribution of the event size can be determined by examining historical data, which revealed the possibility of one, two, three, or four ingot events.

As previously described, it is very easy to create a probability distribution of the number of *arrivals* in any given time period. Unfortunately, in general for an arbitrary distribution of conditional size given an event there is no equivalent closed form solution for the Compound Poisson Process that will allow for the construction of the probability distribution of the number of *ingots* required during a given timeframe. The mean and variance of a Compound Poisson Process can be calculated as follows:

$$E[X(t)] = \lambda*t*E[Y]$$
$$Var[X(t)] = \lambda*t*E[Y^2]$$

Although very useful in many applications, the mean and variance of the process is not sufficient to determine a complete probability distribution.

In order to create a probability distribution for the number of *ingots* required to satisfy the arrival of disruptive events in Pratt & Whitney's raw material supply chain, one can view the size of the event as a conditional probability. Given the arrival of an event, there is a probability, p_i, that it is a one, two, three, or four ingot event. This conditional probability allows one to build a probability distribution of the number of required ingots by summing the feasible sets of events that can lead to a certain number of ingots.

m_i = number of i-ingot events
p_i = conditional probability of i-ingot event

$\Sigma\, i * m_i = Z$

$$P(Z) = \sum_{\text{Feasible sets of } m_i} \prod_{i} \frac{e^{-\lambda p_i}(\lambda p_i)^{m_i}}{m_i!}$$

In order to determine the feasible sets for Z ingots, one must determine the number of different event combinations that could lead to Z ingots being required. In the case of the strategic raw material inventory, it was observed that one, two, three, or four ingot events are possible. Therefore the probability of zero, one, two, etc. ingots being required during a defined period of time is as follows:

P(Z=0) = P(0 one-ingot events)*P(0 two-ingot events)*P(0 three-ingot events)*P(0 four-ingot events)

P(Z=1) = P(1 one-ingot event)* P(0 two-ingot events)*P(0 three-ingot events)*P(0 four-ingot events)

P(Z=2) = P(2 one-ingot events)* P(0 two-ingot events)*P(0 three-ingot events)*P(0 four-ingot events) + P(0 one-ingot events)*P(1 two-ingot event)* P(0 three-ingot events)*P(0 four-ingot events)

P(Z=3) = P(3 one-ingot events)* P(0 two-ingot events)*P(0 three-ingot events)*P(0 four-ingot events) + P(1 one-ingot event)* P(1 two-ingot events)*P(0 three-ingot events)*P(0 four-ingot events) + P(0 one-ingot events)*P(0 two-ingot events)*P(1 three-ingot events)*P(0 four-ingot events)

P(Z=4) = P(4 one-ingot events)*P(0 two-ingot events)*P(0 three-ingot events)*P(0 four-ingot events) + P(2 one-ingot events)*P(1 two-ingot events)*P(0 three-ingot events)*P(0 four-ingot events) + P(0 one-ingot events)*P(2 two-ingot events)*P(0 three-ingot events)*P(0 four-ingot events) + P(1 one-ingot events)*P(0 two-ingot events)*P(1 three-ingot events)*P(0 four-ingot events) + P(0 one-ingot events)*P(0 two-ingot events)*P(0 three-ingot events)*P(1 four-ingot events)

P(Z=5) = P(5 one-ingot events)*P(0 two-ingot events)*P(0 three-ingot events)*P(0 four-ingot events) + P(3 one-ingot events)*P(1 two-ingot events)*P(0 three-ingot events)*P(0 four-ingot events) + P(1 one-ingot events)*P(2 two-ingot events)*P(0 three-ingot events)*P(0 four-ingot events) + P(2 one-ingot events)*P(0 two-ingot events)*P(1 three-ingot events)*P(0 four-ingot events) + P(0 one-ingot events)*P(1 two-ingot events)*P(1 three-ingot events)*P(0 four-ingot events) + P(1 one-ingot events)*P(0 two-ingot events)*P(0 three-ingot events)*P(1 four-ingot events)

P(Z=6) = P(6 one-ingot events)*P(0 two-ingot events)*P(0 three-ingot events)*P(0 four-ingot events) + P(4 one-ingot events)*P(1 two-ingot events)*P(0 three-ingot events)*P(0 four-ingot events) + P(3 one-ingot events)*P(0 two-ingot events)*P(1 three-ingot events)*P(0 four-ingot events) + P(2 one-ingot events)*P(2 two-ingot events)*P(0 three-ingot events)*P(0 four-ingot events) + P(1 one-ingot events)*P(1 two-ingot events)*P(1 three-ingot events)*P(0 four-ingot events) + P(0 one-ingot events)*P(3 two-ingot events)*P(0 three-ingot events)*P(0 four-ingot events) + P(0 one-ingot events)*P(0 two-ingot events)*P(2 three-ingot events)*P(0 four-ingot events) + P(2 one-ingot events)*P(0 two-ingot events)*P(0 three-ingot events)*P(1 four-ingot events) + P(0 one-ingot events)*P(1 two-ingot events)*P(0 three-ingot events)*P(1 four-ingot events)

P(Z=7) = P(7 one-ingot events)*P(0 two-ingot events)*P(0 three-ingot events)*P(0 four-ingot events) + P(5 one-ingot events)*P(1 two-ingot events)*P(0 three-ingot events)*P(0 four-ingot events) + P(4 one-ingot events)*P(0 two-ingot events)*P(1 three-ingot events)*P(0 four-ingot events) + P(3 one-ingot events)*P(2 two-ingot events)*P(0 three-ingot events)*P(0 four-ingot events) + P(2 one-ingot events)*P(1 two-ingot events)*P(1 three-ingot events)*P(0 four-ingot events) + P(1 one-ingot events)*P(0 two-ingot events)*P(2 three-ingot events)*P(0 four-ingot events) + P(0 one-ingot events)*P(2 two-ingot events)*P(1 three-ingot events)*P(0 four-ingot events) + P(3 one-ingot events)*P(0 two-ingot events)*P(0 three-ingot events)*P(1 four-ingot events) + P(1 one-ingot events)*P(1 two-ingot events)*P(0 three-ingot events)*P(1 four-ingot events) + P(0 one-ingot events)*P(0 two-ingot events)*P(1 three-ingot events)*P(1 four-ingot events)

P(Z=8) = P(8 one-ingot events)*P(0 two-ingot events)*P(0 three-ingot events)*P(0 four-ingot events) + P(6 one-ingot events)*P(1 two-ingot events)*P(0 three-ingot events)*P(0 four-ingot events) + P(5 one-ingot events)*P(0 two-ingot events)*P(1 three-ingot events)*P(0 four-ingot events) + P(4 one-ingot events)*P(2 two-ingot events)*P(0 three-ingot events)*P(0 four-ingot events) + P(3 one-ingot events)*P(1 two-ingot events)*P(1 three-ingot events)*P(0 four-ingot events) + P(2 one-ingot events)*P(3 two-ingot events)*P(0 three-ingot events)*P(0 four-ingot events) + P(2 one-ingot events)*P(0 two-ingot events)*P(2 three-ingot events)*P(0 four-ingot events) + P(1 one-ingot events)*P(2 two-ingot events)*P(1 three-ingot events)*P(0 four-ingot events) + P(0 one-ingot events)*P(4 two-ingot events)*P(0 three-ingot events)*P(0 four-ingot events) + P(0 one-ingot events)*P(1 two-ingot events)*P(2 three-ingot events)*P(0 four-ingot events) + P(4 one-ingot events)*P(0 two-ingot events)*P(0 three-ingot events)*P(1 four-ingot events) + P(2 one-ingot events)*P(1 two-ingot events)*P(0 three-ingot events)*P(1 four-ingot events) + P(0 one-ingot events)*P(2 two-ingot events)*P(0 three-ingot events)*P(1 four-ingot events) + P(1 one-ingot events)*P(0 two-ingot events)*P(1 three-ingot events)*P(1 four-ingot events) + P(0 one-ingot events)*P(0 two-ingot events)*P(0 three-ingot events)*P(2 four-ingot events)

P(Z=9) = P(9 one-ingot events)*P(0 two-ingot events)*P(0 three-ingot events)*P(0 four-ingot events) + P(7 one-ingot events)*P(1 two-ingot events)*P(0 three-ingot events)*P(0 four-ingot events) + P(6 one-ingot events)*P(0 two-ingot events)*P(1 three-ingot events)*P(0 four-ingot events) + P(5 one-ingot events)*P(2 two-ingot events)*P(0 three-ingot events)*P(0 four-ingot events) + P(4 one-ingot events)*P(1 two-ingot events)*P(1 three-ingot events)*P(0 four-ingot events) + P(3 one-ingot events)*P(3 two-ingot events)*P(0 three-ingot events)*P(0 four-ingot events) + P(3 one-ingot events)*P(0 two-ingot events)*P(2 three-ingot events)*P(0 four-ingot events) + P(2 one-ingot events)*P(2 two-ingot events)*P(1 three-ingot events)*P(0 four-ingot events) + P(1 one-ingot events)*P(4 two-ingot events)*P(0 three-ingot events)*P(0 four-ingot events) + P(0 one-ingot events)*P(3 two-ingot events)*P(1 three-ingot events)*P(0 four-ingot events) + P(5 one-ingot events)*P(0 two-ingot events)*P(0 three-ingot events)*P(1 four-ingot events) + P(3 one-ingot events)*P(1 two-ingot events)*P(0 three-ingot events)*P(1 four-ingot events) + P(1 one-ingot events)*P(2 two-ingot events)*P(0 three-ingot events)*P(1 four-ingot events) + P(2 one-ingot events)*P(0 two-ingot events)*P(1 three-ingot events)*P(1 four-ingot events) + P(0 one-ingot events)*P(1 two-ingot events)*P(1 three-ingot events)*P(1 four-ingot events) + P(1 one-ingot events)*P(0 two-ingot events)*P(0 three-ingot events)*P(2 four-ingot events)

This approach is equivalent to the traditional usage of a Compound Poisson Process where one conditions on the total number of events.

m_i = number of i-ingot events
p_i = conditional probability of i-ingot event

$\Sigma\, i*m_i = Z$

$$P(Z) = \sum_{\text{Feasible sets of } m_i} \prod_{i} \frac{e^{-\lambda p_i}(\lambda p_i)^{m_i}}{m_i!}$$

$$P(Z) = \sum_{\text{Feasible sets of } m_i} \frac{e^{-\lambda(\Sigma p_i)}\, \lambda^{\Sigma m_i}\, \Pi\, (p_i)^{m_i}}{\prod_{i} m_i!}$$

But $\Sigma p_i = 1$ and we can condition on j where j is defined as: $j = \Sigma\, m_i$.

$$P(Z) = \sum_{j=1}^{Z} \sum_{\text{Feasible sets of } m_i} \frac{e^{-\lambda}\, \lambda^{\Sigma m_i}\, \Pi\, (p_i)^{m_i}}{\prod_{i} m_i!}$$

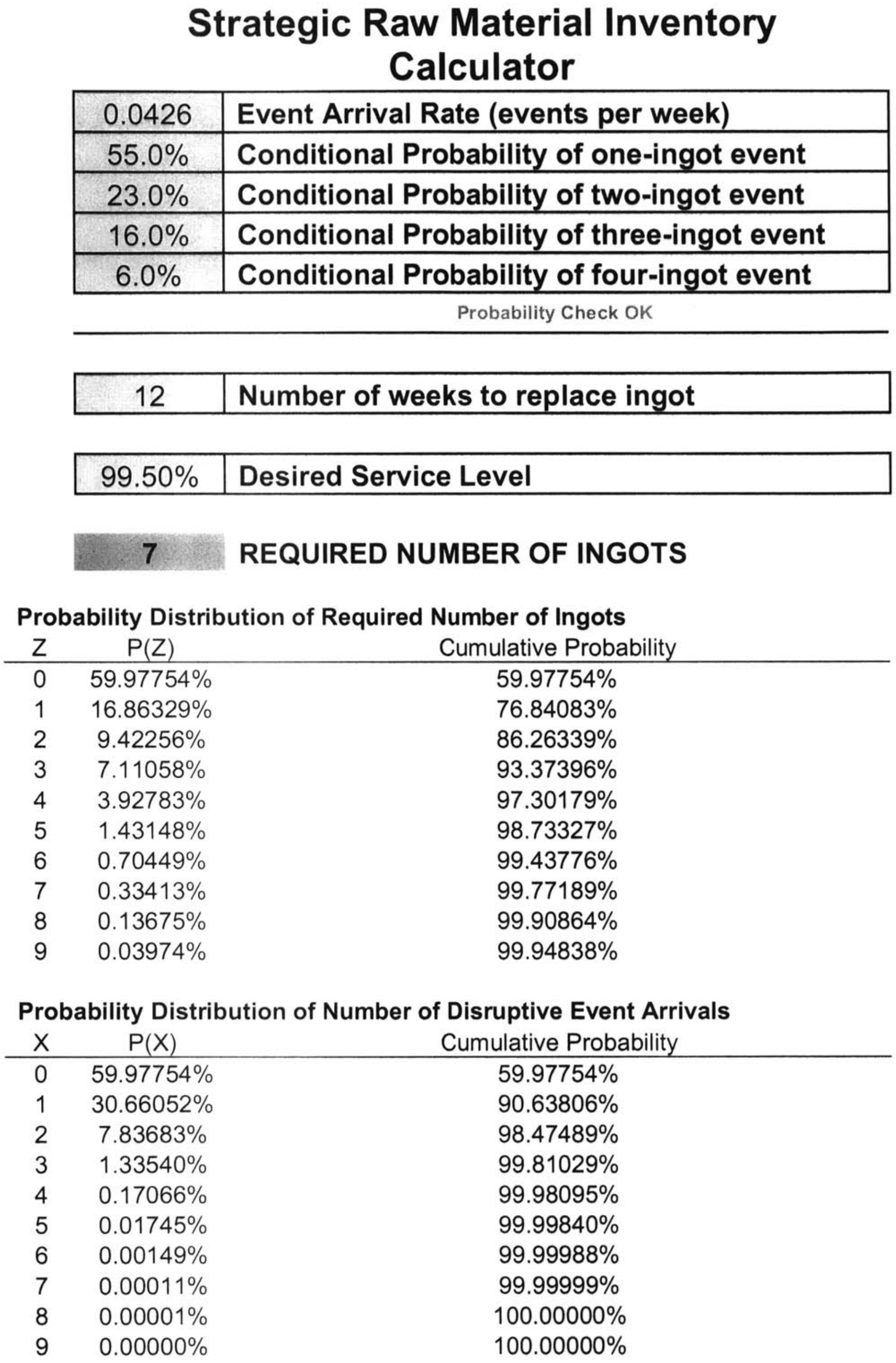
$$P(Z) = \sum_{j=1}^{Z} \sum_{\text{Feasible sets of } m_i} \frac{e^{-\lambda} \lambda^j \Pi (p_i)^{m_i}}{\prod_i m_i!}$$

$$P(Z) = \sum_{j=1}^{Z} \frac{e^{-\lambda} \lambda^j}{j!} \sum_{\text{Feasible sets of } m_i} j! \prod_i \frac{(p_i)^{m_i}}{m_i!}$$

5.8 Strategic Raw Material Inventory Calculator

In order to determine the optimum inventory levels required to satisfy the arrival of rare but disruptive events in the raw material supply chain, the Compound Poisson Process conditional probability algorithms were programmed into Microsoft Excel. This created a unique tool that can be used to calculate optimal inventory levels. There are seven inputs into the model. They are as follows: event arrival rate, conditional probability of an one-ingot event, conditional probability of a two-ingot event, conditional probability of a three-ingot event, conditional probability of a four-ingot event, the required lead-time to replace an ingot, and the desired service level. Figure 5.13 shows an example calculation with the Strategic Raw Material Inventory Calculator.

The cells highlighted in yellow are the seven input cells. The cell highlighted in green is the model output cell. Given the inputs and utilizing the Compound Poisson algorithms previously described, the green cell displays the number of ingots required to achieve the specified service level. Additionally, the probability distributions of both the event arrivals as well as the required number of ingots are displayed below the green output cell. These distributions are very useful for understanding the marginal benefits and marginal costs of increasing or decreasing inventory. For instance in the example illustrated in Figure 5.13, one can determine that with an inventory of 7 ingots the service level is 99.77189%. If the inventory is reduced to 6 ingots the service level would be 99.43776%. If the inventory was increased to 8 ingots the service level would be 99.90864%.



Strategic Raw Material Inventory Calculator

0.0426	Event Arrival Rate (events per week)
55.0%	Conditional Probability of one-ingot event
23.0%	Conditional Probability of two-ingot event
16.0%	Conditional Probability of three-ingot event
6.0%	Conditional Probability of four-ingot event

Probability Check OK

12	Number of weeks to replace ingot

99.50%	Desired Service Level

7	REQUIRED NUMBER OF INGOTS

Probability Distribution of Required Number of Ingots

Z	P(Z)	Cumulative Probability
0	59.97754%	59.97754%
1	16.86329%	76.84083%
2	9.42256%	86.26339%
3	7.11058%	93.37396%
4	3.92783%	97.30179%
5	1.43148%	98.73327%
6	0.70449%	99.43776%
7	0.33413%	99.77189%
8	0.13675%	99.90864%
9	0.03974%	99.94838%

Probability Distribution of Number of Disruptive Event Arrivals

X	P(X)	Cumulative Probability
0	59.97754%	59.97754%
1	30.66052%	90.63806%
2	7.83683%	98.47489%
3	1.33540%	99.81029%
4	0.17066%	99.98095%
5	0.01745%	99.99840%
6	0.00149%	99.99988%
7	0.00011%	99.99999%
8	0.00001%	100.00000%
9	0.00000%	100.00000%

Figure 5.13: Strategic Raw Material Inventory Calculator

5.9 Service Level at Current Inventory Levels and Optimized New Levels

The creation of the Strategic Raw Material Inventory Calculator provides an analytical tool that can be used to determine the service level achieved at the current inventory levels. Once again a careful examination of accounting records, inventory reports, and past communications between Pratt & Whitney and their metal suppliers was undertaken in order to produce a comprehensive history of the arrival of disruptive events in the raw material supply chain as well as the size of the events. Figure 5.14 summarizes the results of the current service level analysis using this historical data.

Inventory Category	Arrival Rate (events/week)	P(1-ingot event)	P(2-ingot event)	P(3-ingot event)	P(4-ingot event)	Material Replacement LT (weeks)	Current Inventory(# of ingots)	Current Service Level
6-4 U.S. Billet	0.04260	55%	23%	16%	6%	12	7	**99.77%**
6-2-4-2 U.S. Billet	0.02600	73%	27%	0%	0%	12	2	**97.93%**
6-2-4-6 U.S. Billet	0.02180	77%	23%	0%	0%	12	2	**98.68%**
6-4 U.K. Billet	0.01100	75%	0%	25%	0%	12	4	**99.93%**
6-4 U.K. Bar	0.00276	0%	0%	100%	0%	12	3	**99.95%**
6-2-4-2 U.K. Billet	0.00829	67%	33%	0%	0%	12	2	**99.74%**
6-2-4-2 U.K. Bar	0.00276	100%	0%	0%	0%	12	1	**99.95%**
8-1-1 U.K. Bar	0.00276	0%	100%	0%	0%	12	2	**99.94%**

Figure 5.14 Service Levels at Current Inventory Levels

This inventory is considered to be strategic in nature and therefore the intent as determined by management is to achieve over a 99.5% service level. The analysis indicates that with the current configuration two inventory categories may have an unacceptable level of risk: 6-2-4-2 U.S. for Billet and 6-2-4-6 U.S. for Billet. At the same time, inventory levels for 6-4 U.K. for Billet could be reduced and still achieve a 99.5% service level. Figure 5.15 summarizes the current inventory levels and minimum inventory levels required to achieve a 99.5% service level.

Inventory Category	Current Inventory	Optimized for 99.5% Service Level
6-4 U.S. Billet	7	7
6-2-4-2 U.S. Billet	2	4
6-2-4-6 U.S. Billet	2	3
6-4 U.K. Billet	4	3
6-4 U.K. Bar	3	3
6-2-4-2 U.K. Billet	2	2
6-2-4-2 U.K. Bar	1	1
8-1-1 U.K. Bar	2	2

Figure 5.15: Optimized Inventory Levels Under Current Configuration

It should be noted that the current service level analysis used only historical data for the computation of event arrival rate and conditional probabilities of number of ingots per event. Therefore it was assumed that historical data is an acceptable indicator of future demand. Although generally true unless a fundamental change is the business dynamics has occurred or the data are especially scarce, this assumption is not a requirement. The advantage of the Strategic Raw Material Inventory Calculator is the ability to vary the inputs. Therefore forecasted data can easily be used in place of historical data. An analysis utilizing historical data is always useful as a base of comparison as will be shown in the next section regarding sensitivity analysis.

Chapter 6 Scenario Analysis with the Strategic Raw Material Inventory Calculator

The purpose of this chapter is to exhibit the power of the Strategic Raw Material Inventory Calculator in performing various scenario analyses. Model levers including material lead-times are tested to show their effect on overall inventory levels. Additionally, Little's Law is used to determine average wait time in the Strategic Raw Material Inventory. Finally, the power of pooling efficiencies is explored, which details possible inventory reduction opportunities.

6.1 Sensitivity Analysis: Material Lead-Time

The benefit of creating a mathematical model that replicates the behavior of the arrival of disruptive events in the raw material supply chain is the ability to change the input variables and understand the effect. One of the key considerations regarding the Strategic Raw Material Inventory is the material replacement lead-time. Material replacement lead-time for the Strategic Raw Material Inventory is negotiated with the metal suppliers on a contract by contract basis. The previous analysis assumed a lead-time of 12 weeks for the replacement of an ingot. Due to the increased volatility of the metal markets this may increase in the future. The Strategic Raw Material Inventory Calculator can be used to determine the effect of lengthening and shortening the material replacement lead-time. Figure 6.1 is a summary of the number of ingots required to achieve a 99.5% service level assuming a 4 week lead-time, an 8 week lead-time, a 12 week lead-time, a 16 week lead-time, a 20 week lead-time, and a 24 week lead-time.

Inventory Category	4 Week LT	8 Week LT	12 Week LT	16 Week LT	20 Week LT	24 Week LT
6-4 U.S. Billet	4	6	7	8	8	9
6-2-4-2 U.S. Billet	2	3	4	4	4	5
6-2-4-6 U.S. Billet	2	3	3	4	4	4
6-4 U.K. Billet	3	3	3	4	4	4
6-4 U.K. Bar	3	3	3	3	3	3
6-2-4-2 U.K. Billet	2	2	2	2	3	3
6-2-4-2 U.K. Bar	1	1	1	1	1	1
8-1-1 U.K. Bar	2	2	2	2	2	2
Total	**19**	**23**	**25**	**28**	**29**	**31**

Figure 6.1: Material Lead-time Sensitivity Analysis

If an ingot of material can be replaced in 4 weeks, overall inventory could be reduced by six ingots. Alternatively, if lead-time extends to 24 weeks six additional ingots will be required to achieve the same service level. It should be noted that material replacement lead-time is just one of the inputs used to determine optimum inventory levels. Therefore when lead-time doubles, inventory levels do not necessarily double. For those categories where events arrive at a very low rate, increased material lead-times have little effect on required inventory levels.

6.2 *Little's Law Analysis*

Little's Law shows the fundamental relationship between inventory, throughput, and average flow time for a stable process.[59] It states that the average inventory in a system is equal to throughput multiplied by average flow time.

Average Inventory(I) = Throughput(R) x Average Flow Time (T)

Although a simple formula, Little's Law is a powerful tool in examining the Strategic Raw Material Inventory. Since the inventory was originally put into place over eight years ago, it is safe to assume that the process is stable. Additionally, as previously discussed, through a careful examination of accounting records, inventory reports, and past communications between Pratt & Whitney and their metal suppliers; a history of throughput and average inventory was created. Therefore using Little's Laws it is possible to determine the average flow time of an ingot in the Raw Material Strategic Inventory.

Inventory Category	Avg Time Ingot in Buffer (months)	Average Inventory	Average Demand (per month)	Current Inventory Targets
6-4 U.S. Billet	19.6	5.78	0.295	7
6-2-4-2 U.S. Billet	18.5	2.44	0.132	2
6-2-4-6 U.S. Billet	15.1	1.62	0.107	2
6-4 U.K. Billet	56.2	3.71	0.066	4
6-4 U.K. Bar	86.4	2.85	0.033	3
6-2-4-2 U.K. Billet	41.1	1.81	0.044	2
6-2-4-2 U.K. Bar	95.2	0.95	0.010	1
8-1-1 U.K. Bar	86.6	1.90	0.022	2

Figure 6.2: Little's Law Analysis

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[59] Anupindi, et al: Managing Business Process Flows

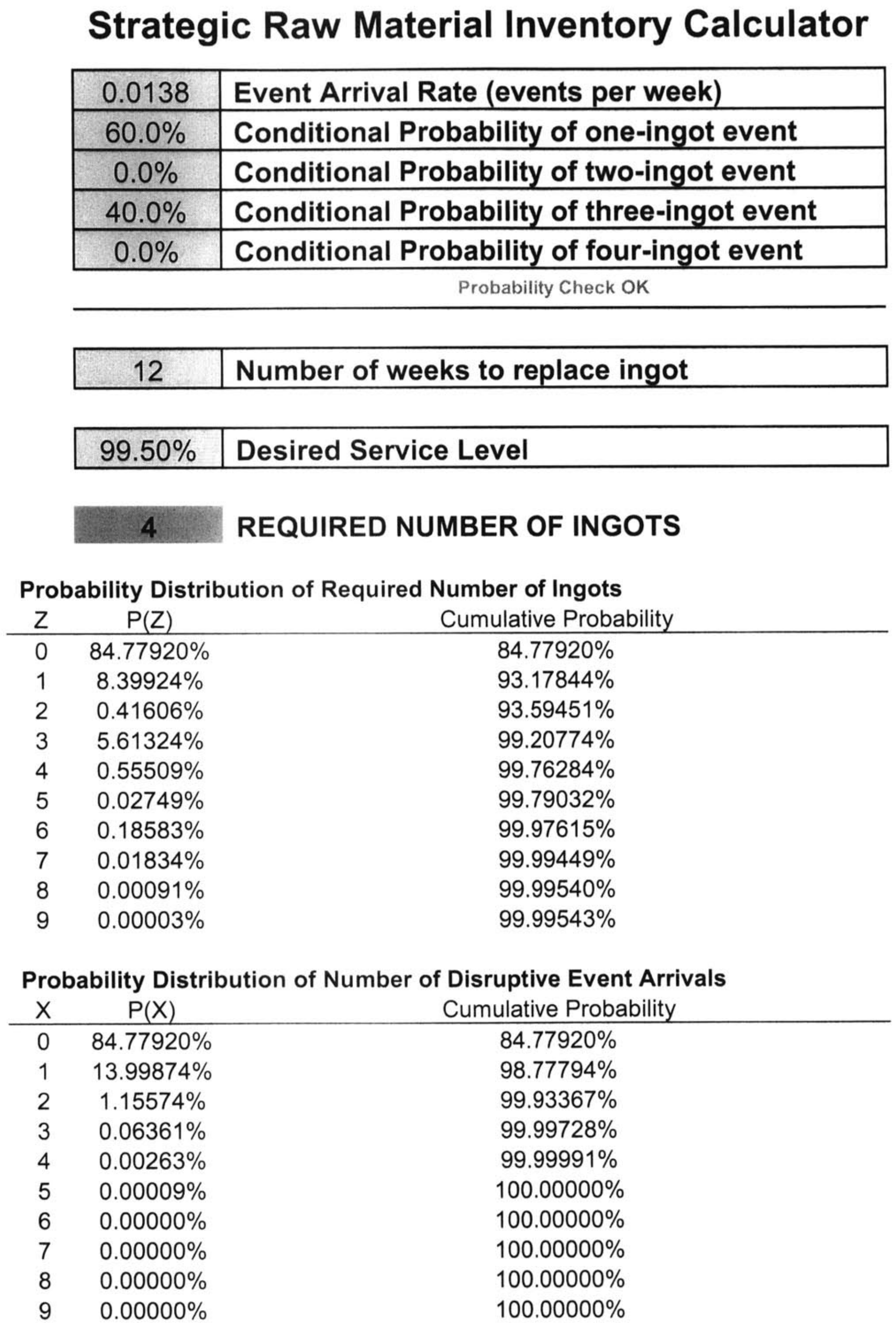
Little's Law does an excellent job of quantifying the same information contained in Figures 5.1 through 5.8. Namely, that some buffer inventory categories are not used very often while others are consistently utilized. This conclusion naturally leads to the next section on possible pooling efficiencies.

6.3 Pooling Efficiencies: Billet and Bar

The Strategic Raw Material Inventory Calculator allows a user to examine different scenarios that could lead to a reduction of inventory. For instance the material for 6-4 U.K. for Billet and 6-4 UK for Bar is very similar. The basic chemistry is exactly the same. The main difference is the number of times the material is melted to ensure the homogeneity of all of the alloying elements. An ingot intended to be used for billet is melted three times while an ingot intended to be used for bar is melted only two times. Although engineering would first need to approve any material substitution, it may be possible to use a common inventory for both 6-4 U.K. for Billet and 6-4 U.K. for Bar. The Strategic Raw Material Inventory Calculator can be used to quantify the possible reduction of inventory.

Arrival rate for 6-4 U.K. for Billet: $\lambda 1 = 0.0110$ events/week
Arrival rate for 6-4 U.K. for Bar: $\lambda 2 = 0.00276$ events/ week
Arrival rate for combined inventory: $\lambda\text{total} = \lambda 1 + \lambda 2 = 0.01376$
Conditional Probability of 1-ingot event: 60%
Conditional Probability of 2-ingot event: 0%
Conditional Probability of 3-ingot event: 40%
Conditional Probability of 4-ingot event: 0%

The current inventory target for 6-4 U.K. Billet is four ingots while the current inventory target for 6-4 U.K. Bar is three ingots. Previously, it was discovered that an inventory target of three ingots and three ingots respectively would be sufficient to achieve the desired service level. Figure 6.3 shows the Strategic Raw Material Inventory Calculator results for the proposed combined inventory category.



Strategic Raw Material Inventory Calculator

0.0138	Event Arrival Rate (events per week)
60.0%	Conditional Probability of one-ingot event
0.0%	Conditional Probability of two-ingot event
40.0%	Conditional Probability of three-ingot event
0.0%	Conditional Probability of four-ingot event

Probability Check OK

12	Number of weeks to replace ingot

99.50%	Desired Service Level

4	REQUIRED NUMBER OF INGOTS

Probability Distribution of Required Number of Ingots

Z	P(Z)	Cumulative Probability
0	84.77920%	84.77920%
1	8.39924%	93.17844%
2	0.41606%	93.59451%
3	5.61324%	99.20774%
4	0.55509%	99.76284%
5	0.02749%	99.79032%
6	0.18583%	99.97615%
7	0.01834%	99.99449%
8	0.00091%	99.99540%
9	0.00003%	99.99543%

Probability Distribution of Number of Disruptive Event Arrivals

X	P(X)	Cumulative Probability
0	84.77920%	84.77920%
1	13.99874%	98.77794%
2	1.15574%	99.93367%
3	0.06361%	99.99728%
4	0.00263%	99.99991%
5	0.00009%	100.00000%
6	0.00000%	100.00000%
7	0.00000%	100.00000%
8	0.00000%	100.00000%
9	0.00000%	100.00000%

Figure 6.3: 6-4 U.K. Billet and Bar Inventory Calculation

Using historical data, we can see that the combined inventory would only require 4 ingots to achieve a 99.5% service level as opposed to the previous optimal of 6 ingots. Therefore a 33% reduction in inventory could be accomplished with pooling efficiencies.

A similar billet and bar pooling efficiency can be calculated for 6-2-4-2 U.K. for Billet and 6-2-4-2 U.K. for Bar.

Arrival rate for 6-2-4-2 U.K. for Billet: $\lambda 1 = 0.00829$ events/week

Arrival rate for 6-2-4-2 U.K. for Bar: $\lambda 2 = 0.00276$ events/ week

Arrival rate for combined inventory: $\lambda\text{total} = \lambda 1 + \lambda 2 = 0.01105$

Conditional Probability of 1-ingot event: 75%

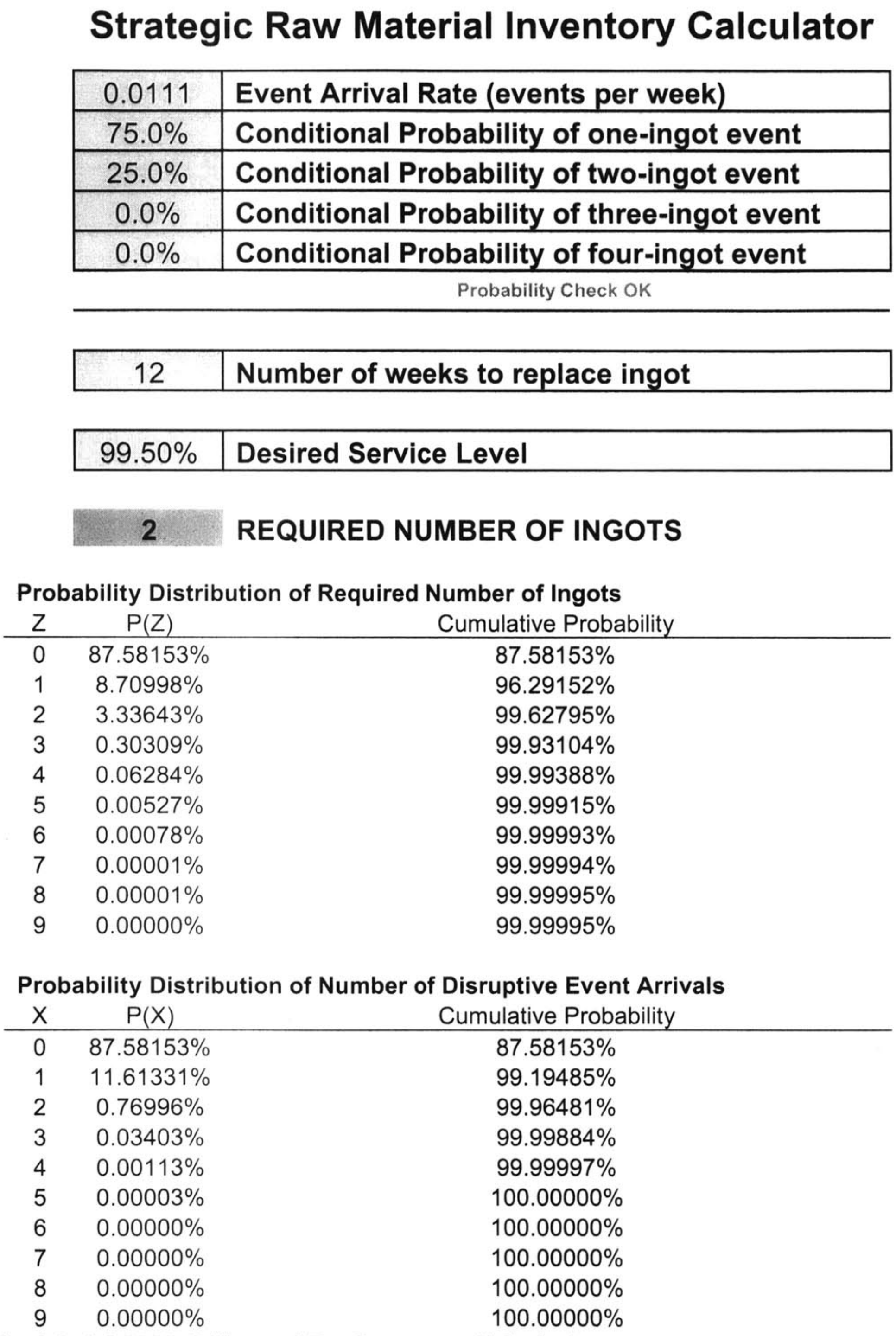
Conditional Probability of 2-ingot event: 25%

Conditional Probability of 3-ingot event: 0%

Conditional Probability of 4-ingot event: 0%

Currently the optimal inventory level for 6-2-4-2 U.K. for Billet is two ingots while the optimal level for 6-2-4-2 U.K. for Bar is one ingot. The Strategic Raw Material Inventory Calculator in Figure 6.4 shows a combined inventory of only two ingots would be required if the inventories were combined. This represents a 33% reduction in inventory.

Overall pooling efficiencies associated with combining billet and bar inventories could yield an overall inventory reduction of 3 ingots or 13%. It should be noted that such a change would need to go through an extensive engineering approval process before being implemented. Yet the Strategic Raw Material Inventory Calculator is a powerful tool in determining possible benefits from pooling efficiencies and can be used to justify the cost of additional funding for the engineering approval process.



Strategic Raw Material Inventory Calculator

0.0111	**Event Arrival Rate (events per week)**
75.0%	**Conditional Probability of one-ingot event**
25.0%	**Conditional Probability of two-ingot event**
0.0%	**Conditional Probability of three-ingot event**
0.0%	**Conditional Probability of four-ingot event**

Probability Check OK

12	**Number of weeks to replace ingot**

99.50%	**Desired Service Level**

2	**REQUIRED NUMBER OF INGOTS**

Probability Distribution of Required Number of Ingots

Z	P(Z)	Cumulative Probability
0	87.58153%	87.58153%
1	8.70998%	96.29152%
2	3.33643%	99.62795%
3	0.30309%	99.93104%
4	0.06284%	99.99388%
5	0.00527%	99.99915%
6	0.00078%	99.99993%
7	0.00001%	99.99994%
8	0.00001%	99.99995%
9	0.00000%	99.99995%

Probability Distribution of Number of Disruptive Event Arrivals

X	P(X)	Cumulative Probability
0	87.58153%	87.58153%
1	11.61331%	99.19485%
2	0.76996%	99.96481%
3	0.03403%	99.99884%
4	0.00113%	99.99997%
5	0.00003%	100.00000%
6	0.00000%	100.00000%
7	0.00000%	100.00000%
8	0.00000%	100.00000%
9	0.00000%	100.00000%

Figure 6.4: 6-2-4-2 U.K. Billet and Bar Inventory Calculation

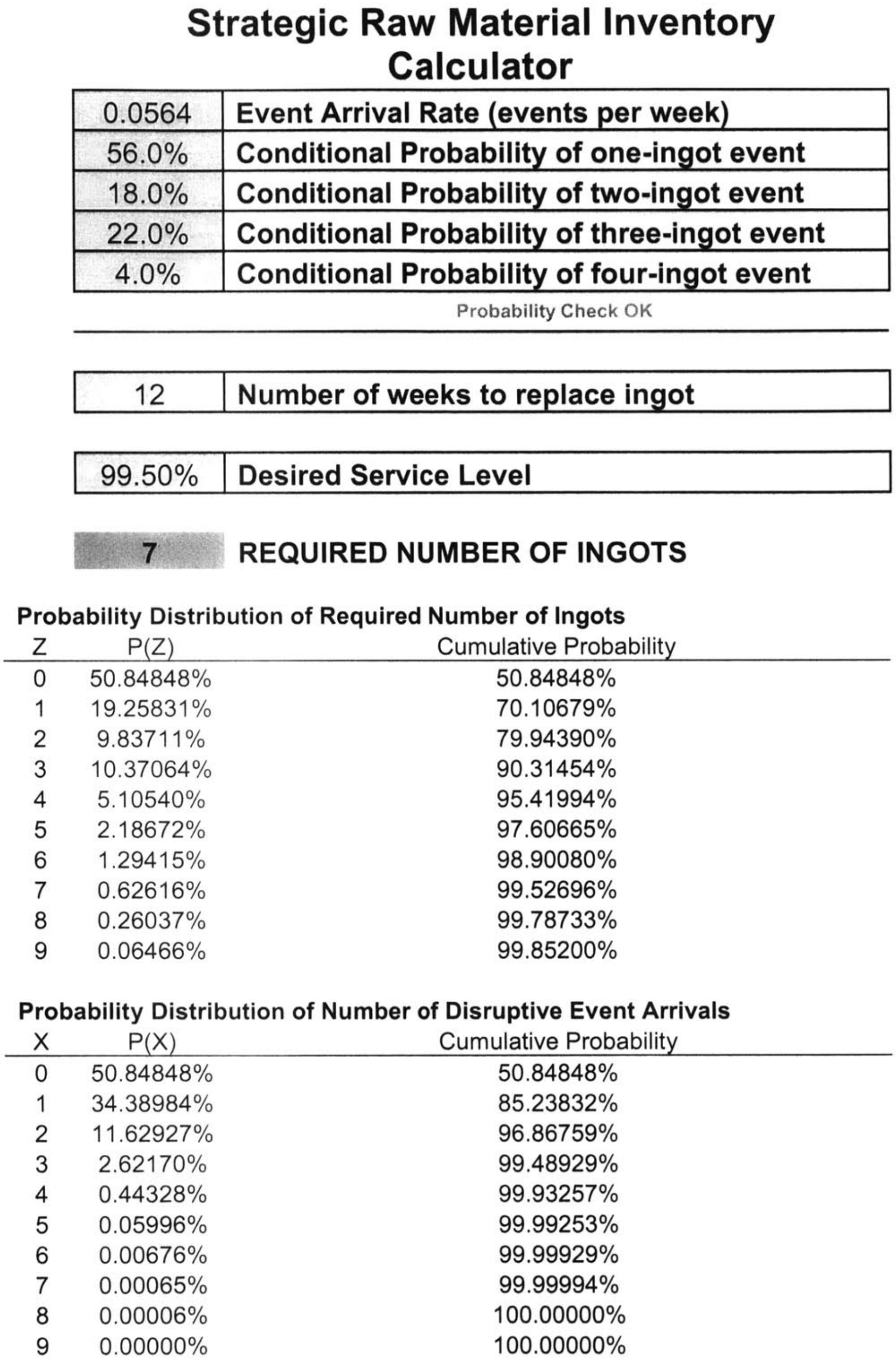
6.4 Pooling Efficiencies: U.S. and U.K.

In addition to pooling efficiencies obtained by combining materials with different final form requirements, it may also be possible to take advantage of pooling efficiencies by combining geographies. Whereas combining inventories with different final form requirements will require extensive engineering review, combining inventories in different geographies will require new business processes. In particular, material lead-time requirements as well as metal producer capabilities will need to be carefully examined. That said, the Strategic Raw Material Inventory Calculator allows a user to first examine the potential benefits of pooling efficiencies.

Ti 6-4 is held in three different forms with two inventories in the U.K. and one inventory in the U.S. The current optimal inventory consists of a total of 16 ingots: seven ingots in the U.S. for billet and 3 ingots in the U.K. for each billet and bar final form. Figure 6.5 shows the optimal inventory calculation for an inventory category that combines all three inventories with the following inputs.

Arrival rate for 6-4 U.S. for Billet: $\lambda 1 = 0.0426$ events/week
Arrival rate for 6-4 U.K. for Billet: $\lambda 2 = 0.011$ events/ week
Arrival rate for 6-4 U.K. for Bar: $\lambda 3 = 0.00276$ events/week
Arrival rate for combined inventory: $\lambda\text{total} = \lambda 1 + \lambda 2 + \lambda 3 = 0.05636$
Conditional Probability of 1-ingot event: 56%
Conditional Probability of 2-ingot event: 18%
Conditional Probability of 3-ingot event: 22%
Conditional Probability of 4-ingot event: 4%

The overall inventory requirements of the combined categories is 7 ingots in order to achieve a 99.5% service level. This is a reduction of 9 ingots or 56%. Once again it is important to note that the combined inventories would require a different business process. In particular, one would first need to determine if the additional material lead-time associated with shipping material from the U.S. to the U.K. would be acceptable.



Strategic Raw Material Inventory Calculator

0.0564	**Event Arrival Rate (events per week)**
56.0%	**Conditional Probability of one-ingot event**
18.0%	**Conditional Probability of two-ingot event**
22.0%	**Conditional Probability of three-ingot event**
4.0%	**Conditional Probability of four-ingot event**

Probability Check OK

12	**Number of weeks to replace ingot**

99.50%	**Desired Service Level**

7	**REQUIRED NUMBER OF INGOTS**

Probability Distribution of Required Number of Ingots

Z	P(Z)	Cumulative Probability
0	50.84848%	50.84848%
1	19.25831%	70.10679%
2	9.83711%	79.94390%
3	10.37064%	90.31454%
4	5.10540%	95.41994%
5	2.18672%	97.60665%
6	1.29415%	98.90080%
7	0.62616%	99.52696%
8	0.26037%	99.78733%
9	0.06466%	99.85200%

Probability Distribution of Number of Disruptive Event Arrivals

X	P(X)	Cumulative Probability
0	50.84848%	50.84848%
1	34.38984%	85.23832%
2	11.62927%	96.86759%
3	2.62170%	99.48929%
4	0.44328%	99.93257%
5	0.05996%	99.99253%
6	0.00676%	99.99929%
7	0.00065%	99.99994%
8	0.00006%	100.00000%
9	0.00000%	100.00000%

Figure 6.5: Geography Pooling Efficiencies Calculation

Chapter 7 Business Process Analysis Utilizing the ACE Operating System

The purpose of this chapter is to give the reader an overview of the ACE Operating System at UTC. The work done on the Strategic Raw Material Inventory was guided by the principles of the ACE Operating System.

7.1 ACE Operating System

"Every day, in almost every country in the world, customers define our competitive excellence when they decide to buy our products and services or those of a competitor's. Similarly, investors define our competitive excellence when they choose to invest in us or in another company. Only by offering superior value to both customers and investors will our company continue to grow and prosper. Therefore, our quest for competitive excellence has no end."

ACE mission statement[60]

One of the core values that permeates throughout United Technologies is a commitment to the ACE Operating System. ACE is an acronym for Achieving Competitive Excellence and is based on three foundations. The first is the philosophy on competitive excellence based on the teachings of Yuzuru Ito, a quality guru who refined his ideas at Japan's Matsushita Electric. The second foundation is a rigorous system that helps UTC identify and solve problems, improve processes, and eliminate waste. The third foundation is the competence, commitment, and involvement of the entire organization.[61]

ACE at UTC involves all employees from the CEO to the employees on the shop floor. George David, the CEO of UTC, credits the ACE operating system in helping deliver the phenomenal improvements in productivity that UTC has achieved over the last 10 years. In fact, he sites the "powerful repetitive discipline" of ACE for more than half of UTC's gains in shareholder value during his tenure.[62] The ACE Operating System was formalized in 1996 and includes an assortment of tools commonly associated with Japanese lean manufacturing

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[60] http://www.utc.com/profile/quality/index.htm 24th February 2007
[61] http://www.utc.com/profile/quality/index.htm 24th February 2007
[62] The Chief Executive: "George David steps out", May 2005

techniques including standard work, total productive maintenance, value stream mapping, 6S, market feedback analysis, and relentless root cause analysis.

In simplest terms, ACE is the way Pratt & Whitney runs their business. It begins with soliciting feedback from the customer. This feedback brings focus on what Pratt & Whitney needs to improve in order to bring greater value to the customer. Most importantly, ACE allows the customer to define quality. With a clear definition of quality, ACE then focuses on process improvement with the mantra "Right the First Time". Yet ACE is not simply about process efficiency. It is also meant to "nurture good hearts, good minds, and the total involvement of the organization". ACE stresses simple, visual approaches to process improvement and is data driven. Data is used to discover problems, guide solutions, and validate improvements.

7.2 Market Feedback Analysis and an ACE Roadmap

The optimization of the Pratt & Whitney Strategic Raw Material Inventory provided an excellent opportunity to extend the ACE Operating System into the Raw Material Commodity Management group. The ACE Operating System begins with customer feedback. Customers define both value and quality.

In order to obtain feedback from the customers of the Strategic Raw Material Inventory, the Market Feedback Analysis (MFA) tool was used. This tool is a standard method of capturing customer feedback followed by a performance gap analysis. The available resources included the z-Telligence web-based system, on online solution for capturing, reporting, analyzing, and managing survey data[63]. Utilizing this system, a survey was designed and distributed to all of the customers of the Strategic Raw Material Inventory, both within the Raw Material Commodity Management group and beyond. A copy of the MFA questions can be found in the appendix.

The results of the MFA were used to create an ACE roadmap. An "As Is – To Be" diagram was created. This diagram can also be found in the appendix. There were two main performance gaps identified. The first centered around confusion of exactly what types of events qualify for use of the Strategic Raw Material Inventory. For example, how can a commodity manager distinguish between a normal variation in the business system and a rare but disruptive event? The second performance gap identified through the MFA was the absence of a set of

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[63] http://www.markettools.com/web_solutions/ztelligence.php 24th February 2007

standard procedures for releasing material from the Strategic Raw Material Inventory. This led to confusion about exactly how to receive material including what issues need to be addressed and what steps should be taken.

7.3 Defining a "Rare But Disruptive Event" and the Strategic Raw Material Inventory Release Process Checklist

One of the key considerations in the analysis of the Strategic Raw Material Inventory is defining what qualifies as a rare but disruptive event. This is vitally important for several reasons. First, a clear definition will allow potential users to quickly decide if a situation warrants removing material from the Strategic Raw Material Inventory. Secondly and perhaps a bit more subtle, the calculations using the Strategic Raw Material Inventory Calculator assume a consistent definition of a rare but disruptive event.

The manager of the Pratt & Whitney Industry Analysis Group historically controls and audits the Strategic Raw Material Inventory. Therefore it is largely at this manager's discretion, subject to senior management approval, to approve or reject a request for material from the Strategic Raw Material Inventory. In order for the optimization model to be accurate, the historic average arrival rate must be consistent. Consistency can only be achieved with a uniform definition of what types of events qualify. However, it is worth noting that the Strategic Raw Material Inventory Calculator is a robust tool in this regard as long as a conscious decision has been made to expand or contract the mandate of the Strategic Raw Material Inventory. In the case where a conscious decision has been made to loosen or tighten event qualifying requirements, new forecasted data can simply be used.

In order to educate potential customers about types of events that qualify for a release from the Strategic Raw Material Inventory a process checklist was created. A copy of the Strategic Raw Material Inventory Release Process Checklist can be found in the appendix. In addition to giving potential users insight into the decision making process of the manager of the Industry Analyst Group, the checklist is also a valuable tool for helping the manager achieve consistency as well as collect and track new data that can drive continuous improvement.

7.4 Process Checklist and Relentless Root Cause Analysis

Embedded within the Strategic Raw Material Release Process Checklist is one of the principle tools of the ACE Operating System: relentless root cause analysis (RRCA). RRCA is the rapid and persistent pursuit of the fundamental breakdown or failure of a process, which, when resolved prevents a recurrence of the problem. The execution of RRCA utilizes a unique methodology called DIVE. DIVE is an acronym for Define, Investigate, Verify, and Ensure. It is a powerful tool in fully understanding and distinguishing the arrival of rare but disruptive events in a supply chain.

The "Define" aspect of DIVE concentrates on understanding and defining the problem. Basic questions associated with this first step include:

1. Why are we working on this problem (in terms of dollars and time)?
2. What type of problem do we have?

In regards to the Strategic Raw Material Inventory, the "Define" step is a unique opportunity to consistently collect valuable new data that can be used for continuous improvement efforts in the future. Such data includes: beginning destination of material, final destination of material, material specification, material final form, and final form characteristics such as billet diameter, weight, and number of ingots. During the "Define" step, information regarding part numbers should be collected as well as at which program the problem is originating. This information will allow the Industry Analysis Group to identify historical trends.

The "Investigate" portion of the checklist concentrates on identify the underlying cause of the disruption. It is during this phase of the process where the Industry Analysis Group can identify the root cause of the problem as either a customer drop-in order, manufacturing complication, planning deficiency, or perhaps some new classification.

The "Verify" portion of the DIVE methodology focuses on confirming the root cause of the problem. It is important that during this phase of the process that all stakeholders are notified and understand the problem. Once again this is a valuable opportunity to collect additional data including the relevant mill response as well as the reaction of various functional groups within the Pratt & Whitney organization.

The final step of the DIVE methodology is "Ensure". It is during this phase that one endeavors to implement a mistake proof solution and control plan. By successfully completing the "Ensure" step, future instances of the same problem can be eliminated.

The Strategic Raw Material Inventory Release Process Checklist is also a valuable tool for educating potential customers. It gives potential customers keen insight into the approval process of the Industry Analysis Group. Additionally, the checklist provides a standard procedure for collecting important data that can be used for continuous improvement efforts.

7.5 Standard Work and Process Mapping

With the Strategic Raw Material Inventory Release Process Checklist as a guide, the next step along the ACE journey was the development of a set of standard work. Whereas the checklist was created to help educate potential customers on what types of events qualify for a release from the Strategic Raw Material Inventory, standard work and process mapping is meant to solve the second performance gap as identified through the market feedback analysis, namely confusion about how to actually get material released.

By definition, business process standard work is a consistent approach to activities. The object is to ensure that everyone performs a consistent and repeatable process. Standard work allows everyone to have a mutual understanding of the required effort. Additionally, it provides a known base for continuous improvement.

The creation of standard work began with identifying the key services of the Strategic Raw Material Inventory. These include: reception of a release request, decision process, acceptance process, rejection process, and restocking process. The appendix contains a copy of the Level 1 process map.

After creating a Level 1 overview of the entire process, standard work procedures were created for each step. A copy of the Reception of a Release Request from the Strategic Raw Material Inventory standard work is also in the appendix. A similar standard work was created for each step. The Level 2 Process Maps are also contained in the appendix.

The creation of Standard Work and Level 1 and Level 2 Process Maps serve two main purposes. First, they can be used to educate potential customers of the inventory on minimum requirements and what must be done to receive material. Secondly, the creation of the process maps gave the Industry Analysis Group a valuable opportunity to fully explore the release process. The lessons learned through the creation of the process maps will help ensure consistency in the process and satisfied internal customers.

Chapter 8 Conclusion

Titanium has numerous unique characteristics that make it an essential input in the manufacture of gas turbine engines. Its high strength-to-weight ratio, corrosion resistance, and resistance to high temperatures make substitution very difficult. Although it is one of the most abundant elements in the earth's crust, it is only found bound to other elements. The dominant manufacturing process for extracting pure titanium, the Kroll Process, is a time consuming batch process that greatly increases the cost of titanium and severely limits the flexibility of titanium metal producers to react to changes in demand.

The titanium metals industry is an oligopoly with large barriers to entry. It is largely driven by the aerospace industry and is subject to severe cyclicality. This cyclicality puts a severe strain on industry firms during periods of low demand and has resulted in cautious capacity expansion during periods of high demand.

Demand in the titanium industry has increased dramatically over the past few years. This upswing in demand is evidenced by the recent increase in the price of titanium and is a result of both cyclical factors and fundamental changes in the industry. Cyclical factors include a recovery of the commercial aviation industry following a downturn in the early 2000s as well as protracted U.S. military engagements. Fundamental changes include new airplane designs by both Boeing and Airbus that use a substantially greater amount of titanium as compared to previous designs and a concerted effort by the titanium metal producers to diversify into non-aerospace industries.

Pratt & Whitney holds a strategic inventory of titanium alloy raw materials. The basic question posed to the author when beginning the project was: In light of the tight supply market, can you tell us how well covered Pratt & Whitney is in regards to our strategic titanium inventory? In order to develop insights, a comprehensive review of titanium inventory and accounting records was conducted and a history of disruptive events requiring titanium was created. These relatively rare but disruptive events were found to arrive according to a Poisson Process. Furthermore, event arrivals and size were effectively modeled as a Compound Poisson Process. The Strategic Raw Material Inventory Calculator was created in order to determine current service levels. The full results can be found in Chapter 5 and are summarized in Figure 8.1.

Inventory Category	Current Inventory(# of ingots)	Current Service Level
6-4 U.S. Billet	7	**99.77%**
6-2-4-2 U.S. Billet	2	**97.93%**
6-2-4-6 U.S. Billet	2	**98.68%**
6-4 U.K. Billet	4	**99.93%**
6-4 U.K. Bar	3	**99.95%**
6-2-4-2 U.K. Billet	2	**99.74%**
6-2-4-2 U.K. Bar	1	**99.95%**
8-1-1 U.K. Bar	2	**99.94%**

Figure 8.1 Current Service Levels

Inventory decisions are often made by comparing the cost of holding inventory as compared to the cost of a stock out. This calculation has been purposely left out of this thesis due to confidentiality concerns. Instead, as a strategic inventory meant to cover rare but disruptive events, a management mandated service level of 99.5% was used. Under this consideration, one can see that the current inventory levels are sufficient in most cases with the exception of 6-2-4-2 U.S. Billet inventory and 6-2-4-6 U.S. Billet inventory. Additionally, in the case of 6-4 U.K. Billet, a reduced inventory could still meet the 99.5% service level. Figure 8.2 summarizes these results.

Inventory Category	Current Inventory(# of ingots)	Optimized for 99.5% Service Level
6-4 U.S. Billet	7	7
6-2-4-2 U.S. Billet	2	4
6-2-4-6 U.S. Billet	2	3
6-4 U.K. Billet	4	3
6-4 U.K. Bar	3	3
6-2-4-2 U.K. Billet	2	2
6-2-4-2 U.K. Bar	1	1
8-1-1 U.K. Bar	2	2

Figure 8.2 Optimized Inventory Levels

The Strategic Raw Material Inventory Calculator also allows one to examine various scenarios. Chapter 6 shows the effect of material lead-time on inventory levels. This is a very important consideration as the quoted lead-time of material has increased substantially over the past year.

In addition to the material lead-time analysis, the Strategic Raw Material Inventory Calculator was used to examine the possible benefits of pooling efficiencies. Two different scenarios were examined. The first was combining billet and bar inventories. It is important to note that although such a combination seems possible, this thesis did not fully explore all the technical issues that may arise in such a combined inventory. Instead, it is meant to simply show the possible benefits of the pooling efficiencies. By combing the 6-4 U.K. for Billet inventory and the 6-4 U.K. for Bar inventory, total inventory could be reduced by 2 ingots or 33%. Additionally, by combining the 6-2-4-2 U.K. for Billet inventory and 6-2-4-2 U.K. for Bar inventory, total inventory could be reduced by one ingot or 33%.

Pooling efficiencies between the U.S. and U.K. were also explored. It should be noted that in order for the inventories to be combined, a full examination of the possible side effects would be in order. Regardless, the Strategic Raw Material Inventory Calculator is a powerful tool to show the possible benefits of this pooling efficiency. By combining the 6-4 U.S. for Billet, 6-4 U.K. for Billet, and 6-4 U.K. for Bar; total inventory could be reduced by 9 ingots or 56%.

One of the key considerations in the administration of the Strategic Raw Material Inventory is deciding when to classify an event as a rare but disruptive event that warrants use of the Strategic Raw Material Inventory. In order to better ensure consistency in the administration of material requests, the tools in Pratt & Whitney's ACE Operating System were used. Market feedback was first solicited. The feedback was used to create standard work and business processes that assist potential users in understanding the decision making process. Finally, the Strategic Material Buffer Release Process Checklist was created. This powerful tool can be used to ensure a consistent approach to material requests. Additionally, the checklist provides a consistent forum for additional data collection that can be used for further continuous improvement projects.

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Appendix

Pratt & Whitney ACE Achieving Competitive Excellence

Strategic Material Buffer
Market Feedback Analysis #1

1. Do you know that P&W holds a strategic buffer of Ti and Ni raw materials?

1	2	3	4	5
Completely unfamiliar		Vaguely familiar		Completely understand

2. Do you understand the intent and purpose of the Ti and Ni Strategic Material Buffers?

1	2	3	4	5
Completely unfamiliar		Vaguely familiar		Completely understand

3. Do you understand the formal process followed for releasing material?

1	2	3	4	5
Completely unfamiliar		Vaguely familiar		Completely understand

4. Do you understand the lead-times that are involved with a material release?

1	2	3	4	5
Completely unfamiliar		Vaguely familiar		Completely understand

5. Do you understand the different types of materials that are held in the buffers?

1	2	3	4	5
Completely unfamiliar		Vaguely familiar		Completely understand

6. Do you understand the form of the material in the strategic buffer?

1	2	3	4	5
Completely unfamiliar		Vaguely familiar		Completely understand

7. Do you understand the quantity of material held in the strategic buffers?

1	2	3	4	5
Completely unfamiliar		Vaguely familiar		Completely understand

8. Do you understand the pricing mechanisms for material released from the buffer?

1	2	3	4	5
Completely unfamiliar		Vaguely familiar		Completely understand

9. Do you believe that buffer material will be available when absolutely needed?

1	2	3	4	5
No		Not sure		Yes

10. What other questions do you have concerning the Ti and Ni Strategic Material Buffers?

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Strategic Material Buffer Release Process

AS IS → **TO BE**

Problem Definition **Problem Solution**

1.	No standard work exists	Need to understand and document current processes, which will serve as baseline for continuous improvement efforts	ACE standard work
2.	No business metrics exist	Identify relevant business metrics, which will serve as tools in measuring continuous improvement success	Clear business metrics that are tracked in order to identify opportunities and celebrate success
3.	Customers have limited understanding of release requirements	Clearly identify customers, solicit feedback, and develop tools	Customer list and MFA
4.	Need to quantify required inventory levels	Create model using historical data that can be used to forecast	Inventory Calculation Model

Strategic Material Buffer Release Process
Checklist

Request Date: ____________

Requester: ____________

Facsimile # : ____________
(if applicable)

Completed by: ____________

I. Strategic Buffer Initial Questions

1. Does the requester understand that the buffer is intended as a strategic reserve of last resort with all releases subject to senior management approval?

YES NO

2. Does the requester realize and accept that material released from buffer is sold at "market prices"?

YES NO

Note:
If requester is on LTA contract, "market price" is LTA price
otherwise "market price" is open market price

3. Does the requester realize and accept the required lead-time to process buffer ingots?

YES NO

Current contractual "target" lead-times:

Timet
Billet = 8 weeks
Bar = 12 weeks
HFB = 14 weeks

Allvac
Billet/Bar = 5 weeks
Reroll Bar = 10 weeks

Material Required By Date: ____________

4. Does the requester realize and accept that a quantity of material equal to an entire ingot's yield must be purchased?

YES NO

Note:
Average ingot yields

U.S.

6-4	9,800 lbs
6-2-4-2	7,000 lbs
6-2-4-6	9,800 lbs

U.K.

6-4 billet	4,900/9,800
6-4 bar	4,900
6-2-4-2 billet	4,900
6-2-4-2 bar	4,900
8-1-1	4,900

II. Relentless Root Cause Analysis (RRCA) using DIVE

Define

5. What are the material requirements?

A. Vendor Destination ____________
B. Material Specification ____________
C. Billet or bar input ____________
D. Diameter ____________
E. Weight ____________
F. # of Ingots ____________
Notes:

6. What are the parts driving the request? (include both raw material and finished part numbers)

7. What programs are impacted and to what dollar level? (e.g. sales dollars, penalties, etc.)

Investigate

8. What is the root cause of the shortage?

drop-in spares
scrapped material
planning deficiency
other:
Complete details:

9. Is there any opportunity to push out the schedule or otherwise manage customer requirements?

Verify

10. What other avenues have you exhausted to find material?

Mills (Timet, RTI, Allvac, VSMPO, Carpenter, Special Metals)
Metal distributors
other:

Person(s) contacted and date of contact:

11. Has P&W Industry Analyst and/or commodity management contacted mills to verify material shortage?

12. Has P&W Industry Analyst and/or commodity management contacted relevant P&W organization to verify situation?

Program
Commodity Management
Purchasing
other:

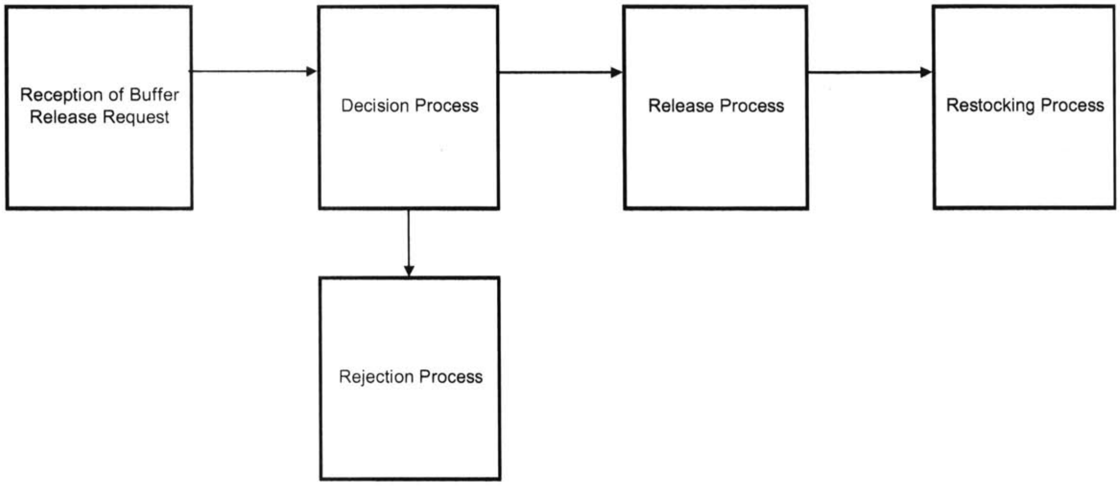
Ensure

13. What steps are be taken to avoid similar situation in the future?

14. What checks are in place to ensure actions have been completed successfully?

Level 1 Process Map

Strategic Buffer Material Release Process



Process Name
Reception of Strategic Raw Material Inventory Release Request

What is new?
This is the first revision of the standard work for the Reception of Strategic Raw Material Inventory Release Request Process

Purpose
To establish a clear methodology for the reception of a request for release from the Strategic Raw Material Buffer

Scope
This methodology is used for both the Ti and Ni buffers.

Crictical Data
Emailed Buffer Release Requests should be sent to: karl.hafner@pw.utc.com
Karl Hafner, P&W Industry Analysis can also be reached at: 860-557-1046

Process Champion & Owner
Karl Hafner, Pratt & Whitney Industry Analyst is owner of this process.

Definitions

The Raw Material Strategic Buffer was created by P&W in 1998 in order to assist P&W and our suppliers in acquiring raw material for customer orders that do not respect the necessary lead-times of the input materials

Buffers for Ti based materials are held at TIMET
Buftfers for Ni based materials are held at ALLVAC

Process Overview
See Level 1 And Level 2 Process Maps located at for complete overview of process

Level 2 Process Map: Strategic Raw Material Inventory Release Process