

# Leveraging Manufacturing Process Capability in Integrated Product Development

by

**Charles E. Hix**

B. S., Mechanical Engineering,  
Colorado State University (1986)

M. S., Aeronautics and Astronautics  
University of Washington (1990)

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

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and  
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**Eric B. Kittleson**

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Signature of Author \_\_\_\_\_  
Sloan School of Management  
Department of Mechanical Engineering  
May 8, 1998

Signature of Author \_\_\_\_\_  
Sloan School of Management  
Department of Mechanical Engineering  
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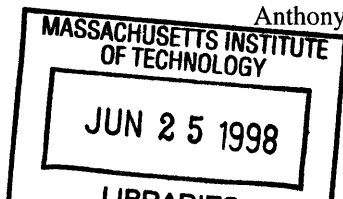
Certified by \_\_\_\_\_  
Donald B. Rosenfield, Thesis Advisor  
Sloan School of Management

Certified by \_\_\_\_\_  
Charles H. Fine, Thesis Advisor  
Sloan School of Management

Certified by \_\_\_\_\_  
David E. Hardt, Thesis Advisor  
Department of Mechanical Engineering

Accepted by \_\_\_\_\_  
Lawrence S. Abeln, Director of Master's Program  
Sloan School of Management

Accepted by \_\_\_\_\_  
Anthony T. Patera, Acting Chairman, Departmental Committee on Graduate Students  
Department of Mechanical Engineering





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## **Abstract**

The focus of this research is to identify a means to acquire and use information about manufacturing process capability to improve product, process and supply chain designs decisions in integrated product development (IPD). The IPD process is often hampered by the lack of access to useful information about manufacturing process capabilities. Often, manufacturing representatives bring only unsubstantiated personal experience to IPD decision-making because data-based manufacturing process information is inaccessible. Even when manufacturing information is accessible, it often lacks credibility because the underlying manufacturing processes are not in a state of statistical control. Either of these situations can cause IPD decisions to be dominated by other concerns, most often product performance, to the detriment of manufacturability. The result is expensive rework of the product and process as well as delay of production. The lack of access to process capability information prevents IPD from realizing the achievable levels of cost, quality and time to market.

This document proposes a two-element plan for elevating the performance of IPD decision-making. These elements are a manufacturing process improvement and control program, and a process capability information system. Process improvement and control is identified as a key factor in establishing the necessary credibility of process capability information required to promote its use in the IPD process. Current literature and case studies are used to support the design and use of a feature-based process capability information system. The intent of such a system is demonstrated and the issues surrounding its implementation and maintenance are discussed. The combined effect of the two elements is better decisions, leading to more manufacturable products and therefore to lower costs, higher quality and less development time.

Thesis Advisors: Donald B. Rosenfield, Sloan School of Management, Senior Lecturer  
Charles H. Fine, Sloan School of Management, Associate Professor  
David E. Hardt, Department of Mechanical Engineering, Professor





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## LFM Class of 1998

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From Charlie Hix:

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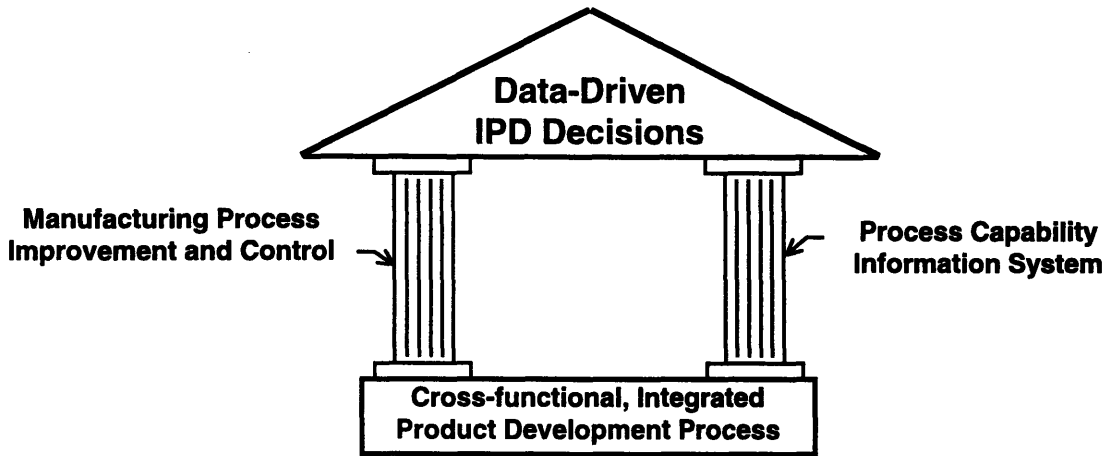
# 1. Introduction

The title of this document, *Leveraging Manufacturing Process Capability in Integrated Product Development*, suggests an improvement to product development through the use of manufacturing process capability information. This is the intent. Cross-functional, concurrent engineering processes, such as integrated product development (IPD), have been in widespread use for over a decade and offer substantial improvements over previous functional, serial development processes. Methodologies for controlling manufacturing process variation, such as the use of statistical process control and root cause analysis, are also tried and true. What then, is new on these topics? This document contends that the answer to this question lies in the intersection of the two. This intersection is information - information about the capability of the manufacturing process. The product development process uses information about customer needs and technological capabilities to define solutions. Process variation improvement and control methods use information gathered from manufacturing processes to improve the quality of the product. The connection is the need for, and the availability of, manufacturing process capability information. The contribution of this document is to suggest how such information can be made accessible by an information system and made use of in IPD to substantially improve the cost, quality and time to market for manufactured products. Integrated product development is about making decisions. These decisions are about what the product is, what manufacturing processes will be used and who will perform them<sup>1</sup>. Figure 1.1 is presented to illustrate how IPD, process improvement and control methods and information technology come together to enable data-driven decisions.

The foundation and pillars of Figure 1.1 represent the three important elements this document contends must be in place to support the goal of data-driven IPD decisions. First, an effective IPD process must be in use. Critical to establishing a strong IPD process is the creation of a cross-functional team environment composed of qualified team members from the appropriate functional disciplines - most notably manufacturing and engineering.

---

<sup>1</sup> As described in Section 1.3.2, this document adopts the three-dimensional definition of IPD suggested by Fine (i.e., integrated product, process and supply chain design).



**Figure 1.1: Data-Driven IPD Decisions Conceptual Model**

Second, manufacturing processes and their variation must be understood and under control. This is established through effective process improvement and control methods<sup>2</sup>. Such methods include measurement systems to collect and analyze process data to identify problems and implement improvements.

Third and finally, a vehicle in the form of an information system must be in place to provide IPD participants access to manufacturing process capability information. Many companies have collected and stored data in databases, however, accessibility and usability (clarity and presentation of data/information) become fundamental barriers to use.

The conceptual model of Figure 1.1 serves as a guide to the ideas presented in this document. This model will be referenced frequently to reiterate the connection between various concepts and the following two-part hypothesis of this document.

### ***1.1 Thesis Hypothesis***

This document has a two-part hypothesis relating to the linkage between manufacturing process capability information and IPD. This hypothesis ties directly to the conceptual model above and assumes the existence of an IPD process (i.e., the foundation of the conceptual model is in place).

---

<sup>2</sup> Several approaches to process improvement and control are presented in Appendix H.

- The first part of the hypothesis is that the existence of a structured method for monitoring and controlling manufacturing process variation is critical to making manufacturing process capability information credible for use in IPD decision making. In other words, the issue of information credibility is a critical determinant of the degree to which process capability information is used. This is the first pillar of the Figure 1.1 structure.
- The second part of the hypothesis is that a properly-constructed information system can provide access to manufacturing process capability information and thereby enable high quality product, process and supply chain design decisions (i.e., data-driven IPD decisions). This information system is the second pillar of Figure 1.1.

The benefits of data-driven IPD decisions were previously stated as lowered costs, improved quality and reduced time to market. This is the premise of the hypothesis and is not explicitly proven herein. Rather, logic in the form of a system dynamics analysis of the product development process together with findings from literature and case studies will be relied on to support the hypothesis and the associated benefits. The system dynamics analysis is based on interview data collected from managers and engineers during the research period.

It is significant to note that the contention that manufacturing process capability information is an important factor in IPD decisions, but not the only factor. Customer needs, regulatory requirements and business objectives are also important factors in any product development process. These requirements must be combined and balanced in order to reach the optimal solution. Nor is the intent of this document to imply product designs should be limited by existing manufacturing process capabilities. Rather, all available information should be used to identify gaps between process capabilities and proposed product designs such that the gaps can be closed earlier rather than later. These gaps may be dealt with by design changes, process improvements or source selection. The leverage is in being able to make these decisions early in the product development process when the associated costs are much less.

In summary, the hypothesis of this document is that process improvement and control methods, in combination with a properly designed information system, enable data-driven

decisions that lead to better and cheaper products faster. The methodology used to evaluate this hypothesis is logic and will be addressed in Section 1.4.

## **1.2 Background Information**

This document is based on two parallel six-month research internships, one by each author, conducted at United Technologies Corporation - Pratt & Whitney from June to December, 1997. Although the examples and data presented in this document come from Pratt & Whitney, the intent is to be general. The authors believe the hypothesis, findings and recommendations of this document apply to a broad range of manufacturing companies.

Manufacturing companies have a common interest in driving down manufacturing costs, improving quality and reducing the time required to bring new products to market in order to remain competitive. An example of how company executives view this issue is illustrated by the following quote from Karl Krapek, President of Pratt & Whitney<sup>3</sup>:

“Engineering now offers the largest opportunity for cost reduction. Eighty-five percent of the cost of our products is driven by the way we design them, set specifications and quality requirements, and select materials. We must simplify our designs, increase commonality across engine families, and more closely match engineering requirements to what we are able to produce.”

This document focuses on the need to “more closely match engineering requirements to what [manufacturing is] able to produce.” This view is held by many manufacturing companies today. Many of these companies are working feverishly to improve the cost, quality and time to market performance of the product development process. Matching engineering requirements to manufacturing capabilities is one way to reach these objectives. However, the coupling between product development and manufacturing goes deeper than this. Chapter 2 presents a system dynamics analysis to explore this coupling and to lay the argument for validating the hypothesis. The remainder of this chapter presents definitions of key terms used throughout this document and describes the structure of the chapters and appendices.

---

<sup>3</sup> Pratt & Whitney, *Mid-Thrust HPC CIPT and North Berwick Product Center Engineering - Information Management Kaizen Event*, (Compression Systems Component Center internal document, March 1997).

## 1.3 Key Definitions

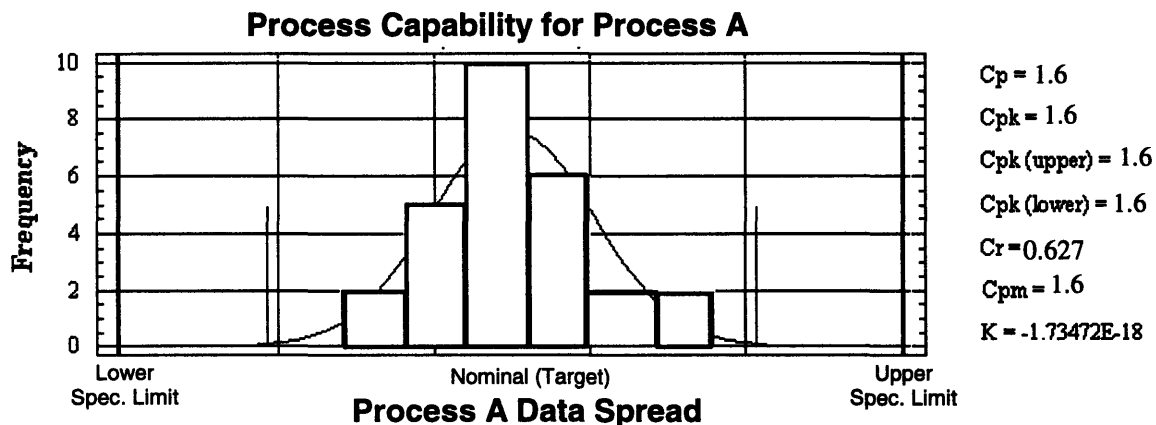
The terms *process capability* and *integrated product development (IPD)* both have a number of different meanings depending on the situation, the functional organization and even the company in which they are discussed. Definitions of these terms are included below to clarify their meanings in the context of this document.

### 1.3.1 PROCESS CAPABILITY

To capture all of the aspects of manufacturing process capability addressed in this document, we adopt a broad definition. This definition has three components that are necessary to fully define the capability of a process, namely *Statistical*, *Contextual* and *Competency*. Each of these components are discussed below. From this point forward, references to *process capability information* are meant to include all three components.

#### 1.3.1.1 Statistical Component

The statistical component of process capability refers to the numeric and visual representation of the ability of a process to produce a part characteristic<sup>4</sup> to a target value within given specification limits. The numeric representation will be primarily discussed in terms of the Process Capability Index,  $C_{pk}$ , while the visual representation will



**Figure 1.2: Process Capability Visual Display**

normally take the form of a histogram presenting the distribution of actual measurements of a part characteristic produced by the process (see Figure 1.2). While this provides

<sup>4</sup> Per the American Society of Mechanical Engineers, *Dimensioning and Tolerancing*, ASME Y14.5M, 1994, a feature is defined as “The general term applied to a physical portion of a part, such as a surface, pin, tab, hole, or slot.”

some of the basics behind the meaning of process capability, it is important to understand that in this document a “process” is defined to be the operation performed to produce a single part characteristic, rather than the broader definition where a process is a series of operations performed to transform an incoming part or raw material into a desired interim or final form (and may involve producing a number of part characteristics). Figure 1.2 provides one example of process capability information; additional visual displays of the statistical component of process capability are presented in Chapter 4.

#### **1.3.1.2 Contextual Component**

The contextual component of process capability describes the conditions under which the statistical characterization of the process is valid. This component would include such information as machine states, material input states, and tooling and fixture definitions. A combination of text and diagrams may be used to describe this information. Examples of the contextual component are provided in Chapter 4.

#### **1.3.1.3 Competency Component**

The competency component of process capability describes what the process or source is able to accommodate. This information may include limitations on materials, machine states, or part geometry, as well as preferred or standard practices or configurations. The competency component may be thought of as a set of all possible process operating conditions and design configurations (i.e., the set of all possible contextual points). Significant value is added to the competency component when information is included about how this broad set of possibilities may be narrowed to the preferred process conditions and design configuration. Again, as noted for the statistical and contextual components, text and diagrams may be used to represent this information. Examples of the competency component are provided in Chapter 4.

### **1.3.2 INTEGRATED PRODUCT DEVELOPMENT**

In this document *integrated product development* (IPD) refers to the concurrent design of the product, process and supply chain by a cross-functional team. The concurrent design of the product and process has often been referred to as *concurrent engineering* or *integrated product and process development* (IPPD). The more comprehensive definition

of IPD used in this document, which includes supply chain design, is defined by Fine<sup>5</sup> as three-dimensional concurrent engineering (3DCE). Fine asserts current IPD processes can be improved by integrating the design of the supply chain with that of the product and process. This three-dimensional definition is adopted in this document because the hypothesis of data-driven decisions based on process capability information applies to supplier evaluation and selection as well as to product and process design.

## **1.4 Thesis Structure and Methodology**

As mentioned earlier, the visual model presented in Figure 1.1 serves as a guide to the structure of this document. Each chapter addresses one or more elements of this model.

**Chapter 2** describes the dynamics of the product development process through the use of two system dynamics models. These models illustrate how the foundation of an IPD process and the supporting pillars of a process improvement and control and a process capability information system are required to support the goal of data-driven IPD decision-making. The intent of this chapter is to validate the hypothesis.

**Chapter 3** presents information to support the development of such a process capability information system. This supporting information is presented in two forms. First, literature on IPD-focused information systems and process capability improvement and control practices is reviewed to identify best practices for promoting data-driven IPD decision-making.

Second, case studies are used to illustrate the realities surrounding the issues of (1) process variation improvement and control and (2) process capability information feedback. These case studies are drawn from the authors' on-site research at Pratt & Whitney. The key issues identified in the case studies are used to support the development of the process capability information system presented in Chapter 4.

**Chapter 4** describes the user requirements, design structure and utilization framework of a feature-based, process capability information system. A detailed hypothetical example is included in this chapter for illustrative purposes.

---

<sup>5</sup> Charles Fine, *Clockspeed: Winning Industry Control in the Age of Temporary Advantage*, (to be published by Perseus Books, Fall 1998).

**Chapter 5** reiterates the thesis hypothesis, summarizes how the hypothesis is validated and provides recommendations relating to the design, implementation and maintenance of a process capability information system and points to areas for further research.

**Appendices** are included to provide specific background on Pratt & Whitney (Appendices A through E), detailed case studies (Appendices F & G) and a description of some approaches to process improvement and control (Appendix H).



## 2. Dynamics of the Product Development Process

### 2.1 Introduction

The purpose of this chapter is to describe the problem this document is intended to address and identify the logic used to validate the hypothesis introduced in Chapter 1. The problem is that the existing applications of IPD have been insufficient to ensure the product design has a high level of manufacturability. Said differently, manufacturability is often neglected or readily traded in order to achieve product performance requirements. The hypothesis of this document proposes that process capability improvement and control methods and process capability feedback, via an information system, enable data-driven IPD. That data-driven IPD decisions will result in higher quality, lower cost products faster is the premise of this hypothesis. The field of System Dynamics is used in this chapter to examine the problem and the validity of the hypothesis as well as to illustrate the premise.

System Dynamics enables the behavior of complex systems to be investigated by the use of models and simulation of the causal relationships, feedback and delays associated with the flow of information in such systems (see Forrester<sup>1</sup> and Senge<sup>2</sup>). This technique is useful for viewing the inherent interconnectedness of the product development process and manufacturing. To begin, one must first establish the cause and effect relationships between important parameters in the product realization system (i.e., IPD and manufacturing). The authors turned to the experience and intuition of engineers and managers at Pratt & Whitney to identify these relationships. The relationships are then combined to establish causal loops in which feedback from a downstream process affects inputs to an upstream process. The interviews at Pratt & Whitney produced causal loop models for two distinctly different manifestations of IPD. These models are presented in Figures 2.1 and 2.2.

The intent of this section is to address issues that are generally applicable. Although the models which are presented were developed with the help of Pratt & Whitney, they

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<sup>1</sup> Jay Forrester, *Industrial Dynamics* (Portland OR: Productivity Press, 1961).

<sup>2</sup> Peter Senge, *The Fifth Discipline, The Art and Practice of the Learning Organization* (New York: Doubleday, 1990).

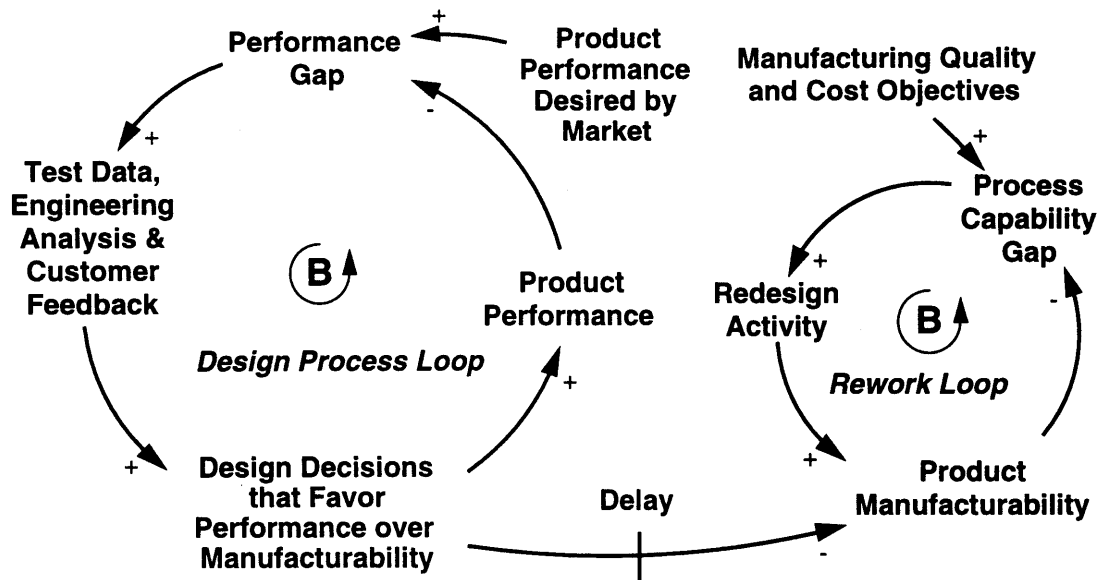
are not intended to be reflective of only Pratt & Whitney. Discussions with managers at Pratt & Whitney and other LFM member companies, LFM fellows and MIT faculty indicate that the issues presented by this section exist in many manufacturing firms today.

The models presented in this section represent near extremes. The first model assumes the capability of manufacturing processes is not well understood and that little process capability information is available for use in the IPD process. The second model shows the near-ideal situation, where systems are in place to both improve and control process capability and provide feedback of this information for use in making better decisions in the IPD environment (i.e., in the context of the foregoing chapter, the foundation and pillars are in place to support data-driven IPD decision-making).

## ***2.2 IPD without Process Capability Feedback***

Although the IPD process is based on cross-functional teams, many companies have found that designs emerging from these teams have not reached the desired balance between product performance and manufacturability. Product performance continues to drive the dominant set of requirements in many companies. Manufacturing is thereby left to struggle with some difficult design features and incapable processes (Appendix D provides detail on these issues for the specific case of Pratt & Whitney). The following analysis illustrates the situation where information about manufacturing process capability is ineffectively represented or unavailable to the IPD process.

Figure 2.1 was constructed to illustrate the dynamics which may be causing design decisions to favor product performance over manufacturability. The authors were able to simplify the IPD process to a model containing two feedback loops: a *Design Process Loop* and a *Rework Loop*. The following discussion examines the inner workings and the interaction of these loops.



**Figure 2.1: Performance-Driven IPD Process Model<sup>3</sup>**

### 2.2.1 THE DESIGN PROCESS LOOP

The *Design Process Loop* represents the design process where companies attempt to define and satisfy customer requirements. This loop begins with the demand of the market for a product with some level of performance (*Product Performance Desired by Market*). For example, Pratt & Whitney feels the market effect in the form of demands (from airlines and airframe manufacturers) for greater engine thrust, lower fuel consumption and better reliability. The *Performance Gap* is established by the difference between the *Product Performance Desired by Market* and the *Product Performance* level of existing products. The existence of a *Performance Gap* causes companies to seek information in the form of customer feedback, testing and analysis. This information then becomes the input, or the requirements set, for product, process and supply chain decisions. The loop attempts to create a design embodying the requirements set. In the absence of manufacturing process capability information and the presence of credible information from product performance analysis and testing, the overall requirements set

<sup>3</sup> Causal loop models are interpreted as follows: Arrows indicate the relationship between parameters. A “+” indicates that an increase in the first parameter causes an increase to occur in the second. A “-” indicates an inverse relationship. The “B” inside a loop symbol denotes a balancing loop. Balancing loops exhibit the behavior where a change in a system parameter creates a feedback condition that tends to drive the parameter back to its initial condition (also termed *goal seeking behavior*). “Delay” indicates the effect on a downstream parameter is delayed after a change in the first parameter occurs.

tends to be biased towards product performance. This results in *Design Decisions that Favor Product Performance Over Manufacturability*.

The *Design Process Loop* attempts to close the *Performance Gap*. Any shortfall in *Product Performance* relative to the *Product Performance Desired by Market* creates a *Performance Gap*. The existence of a gap causes additional data to be gathered from analyses, tests and customers. This data becomes the new requirements set and the basis for design actions. The loop continues to move the design towards a performance level corresponding with the demand of the market until the design is finally released to production.

The output of the *Design Process Loop* is a design embodying inherent levels of *Product Performance* and *Product Manufacturability*. The inherent level of *Product Manufacturability* depends on the existing process capabilities and in this model is not well-known until production begins. The start of production marks the end of the *Design Process Loop* and the start of the *Rework Loop*. The delay between these loops simulates the effect of not knowing the level of *Product Manufacturability* until production begins.

### **2.2.2 THE REWORK LOOP**

The *Rework Loop* attempts to correct the deficiencies of the *Design Process Loop* with regard to *Product Manufacturability*. When a design is completed and released to production, manufacturing attempts to meet the design specifications. This occurs without much difficulty where the design of the product and process have been well integrated. However, where the product and process were designed without knowledge of process capability, a *Process Capability Gap* develops between the actual and desired levels of manufacturing process capability. The actual process capability is represented by the *Product Manufacturability*. The desired level of process capability is represented by the *Manufacturing Quality and Cost Objectives*. The existence of a *Process Capability Gap* causes manufacturing and engineering to undertake *Redesign Activity* in order to reduce the *Process Capability Gap*. The *Redesign Activity* may include changes to the product and/or process designs to increase *Product Manufacturability*. In some cases, the company may decide to live with the situation by effectively decreasing the *Manufacturing Quality and Cost Objectives*. The *Rework Loop* attempts to make up for

the shortcomings of the original *Design Process Loop* - albeit with greater cost, delay and less effectiveness.

The *Rework Loop* is costly, given to delay and often unable to overcome the failure of the *Design Process Loop* to balance between performance factors and manufacturability. Rework is a symptom of a development process that has failed to adequately align the product design requirements and the manufacturing process capability. Whitney<sup>4</sup> describes how as much as 80% of the cost of a product is determined in the design and that the cost of making late changes is magnified. Ulrich & Eppinger<sup>5</sup> discuss how when a design is created without much regard for manufacturability, the overall costs, quality and time-to-market can suffer substantially. The cost comes in the form of redesign, rework, scrap and increased inspections. The cost of late design changes is magnified as a result of the interdependencies inherent in the product and process - a single change will often necessitate changes in many other areas. These costs and quality issues can be reduced by increasing the degree to which the design requirements and manufacturing process capabilities are in harmony.

The *Rework Loop* also symbolizes delay. Production ramp-up is delayed because the existence of a process capability gap effectively reduces production capacity. Rather than producing sellable product or improving capabilities, the manufacturing resources must be tapped to rework, repair or reproduce product and redesign the process. Capacity is also consumed by scrap. In some cases, production may be stopped entirely while problems are corrected. Delays represent an inefficient use of resources and a reduced or delayed presence in the market.

The redesign effort is also subject to delay. Changes may be required to items with long lead times such as raw material and capital equipment. Manufacturing is often forced operate under sub-optimal conditions while waiting for improvements.

### **2.2.3 CONCLUSIONS FROM THE FIRST MODEL**

The key finding from interviews with engineers and managers at Pratt & Whitney is that the information available to the integrated product teams (IPT's) often lacks manufacturing process capability content and this asymmetry causes performance

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<sup>4</sup> Daniel Whitney, "Manufacturing by Design", *Harvard Business Review*, 1988.

requirements to be favored over manufacturability. One may ask why this process capability information is unavailable or underutilized given that manufacturing is often well-represented on IPT's. The reasons for this are four-fold:

- The information is not easily accessible.
- The information is incomplete.
- The information lacks credibility.
- The information is ignored because the impact of doing so is delayed.

Examples of each of these reasons exist at Pratt & Whitney. On the first point, as described in Appendix D, Pratt & Whitney collects and stores a large amount of data, but the organization of this data, and the systems in which it is stored, are not conducive to access for the purposes of IPD. For example, measurement data of engine part geometry is recorded as a function of part number, serial number and other tracking numbers arbitrarily assigned by a manufacturing engineer (see Appendix D). Thus, when an IPD team wants to find data on similar parts they are faced with an unfriendly database structure. In some cases, the data may only be recorded as “good” versus “no good” making analysis almost impossible.

Secondly, incomplete data is also a barrier to balanced design decisions. In the case of Pratt & Whitney, a great deal of measurement data already exists. However, this data is of limited usefulness unless the conditions under which it is valid are understood (i.e. machine feed rates, speeds, tooling, material, etc.). This information is the *contextual* component of process capability defined in Chapter 1. Information about process limitations and the preferences and standard practices of the manufacturing source are also not typically well communicated. This is the *competency* component of process capability and is critical for conducting concept feasibility studies early in the IPD process and for identifying and documenting best practices. The case study of the Product Cell Capability Catalogue in Appendix G demonstrates the sort of contextual and competency information that can be captured in a process capability information system. The *contextual* and *competency* components are critical to IPD decisions because they

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<sup>5</sup> Karl Ulrich and Steven Eppinger, *Product Design and Development* (New York: McGraw Hill, 1995).

allow statistical data to be better utilized and facilitate the transfer of learning both within manufacturing and from manufacturing to the IPD environment. The framework of Chapter 4 illustrates how such information can be used in IPD decision-making.

The third reason process capability information is not utilized in IPD is its lack of credibility. IPT's traditionally have a large amount of information at their disposal to promote and substantiate performance requirements. This information comes from tests, analysis and customers. These are credible sources to design engineers. Engineers use sophisticated modeling tools and test methods to investigate the performance of a design and to check this performance against the objective. Often, the same engineer who designs the product will also have involvement in the test or analysis work. These investigations generate substantial amounts of credible information that is readily accessible to IPD decision-makers. Many of the managers and engineers interviewed believe this high quality performance data overwhelms what little process capability data the IPD team may have and causes product performance to be optimized with little regard for manufacturability.

Credibility can also be an issue when manufacturing possesses the information but is unable to convince engineering that it is a reliable indicator of process capability. As argued in Chapter 3 and Appendix F, the credibility of the statistical data hinges on the rigor with which it was gathered and the degree to which the underlying process is under control. This dependence on rigor is the basis for the assertion of this document that a process capability improvement and control program is a necessary pillar of data-driven IPD. With process improvement and control programs, such as described in Chapter 3, Appendix C and Appendix H, manufacturing is driven to collect and analyze process data and to establish means by which process variation will be reduced and controlled. These efforts result in a deeper and credible understanding of the capability of a process.

The fourth reason why process capability information is not effectively used in IPD stems from the delay between the *Design Process Loop* and the *Rework Loop*. As described in the foregoing section, the *Design Process Loop* iterates to close the *Performance Gap* without knowledge of the resultant level of *Product Manufacturability*. Once manufacturing begins, the real manufacturability of the product becomes known.

The delay between the decision and the resultant effect may serve to diminish the impact of low levels of manufacturability in the minds of the IPD decision-makers. Moreover, the burden associated with the *Rework Loop* often falls more heavily on manufacturing than on engineering. Hayes, Wheelwright and Clark<sup>6</sup> describe how, in some companies, a functional discipline, such as engineering, can come to dominance and thereby enforce decisions that are sub-optimal for the whole of the company. Discussions with many managers at Pratt & Whitney and Boeing support that this is often the case in the aerospace industry. Thus, IPD may fail to appropriately address manufacturability because the burden is delayed and somewhat shifted to the less dominant function. The next section presents an IPD environment in which such a condition can be alleviated through the use of process capability information.

### ***2.3 IPD with Process Capability Feedback - Data-Driven IPD***

The second model in this analysis is different from the first in that it includes a dedicated process capability feedback mechanism. This model illustrates the premise that data-driven IPD, that is IPD decisions made with the benefit of process capability information, result in higher quality, lower cost products in less time. This model represents the other end of the spectrum where design decisions are optimized with respect to product performance and manufacturability.

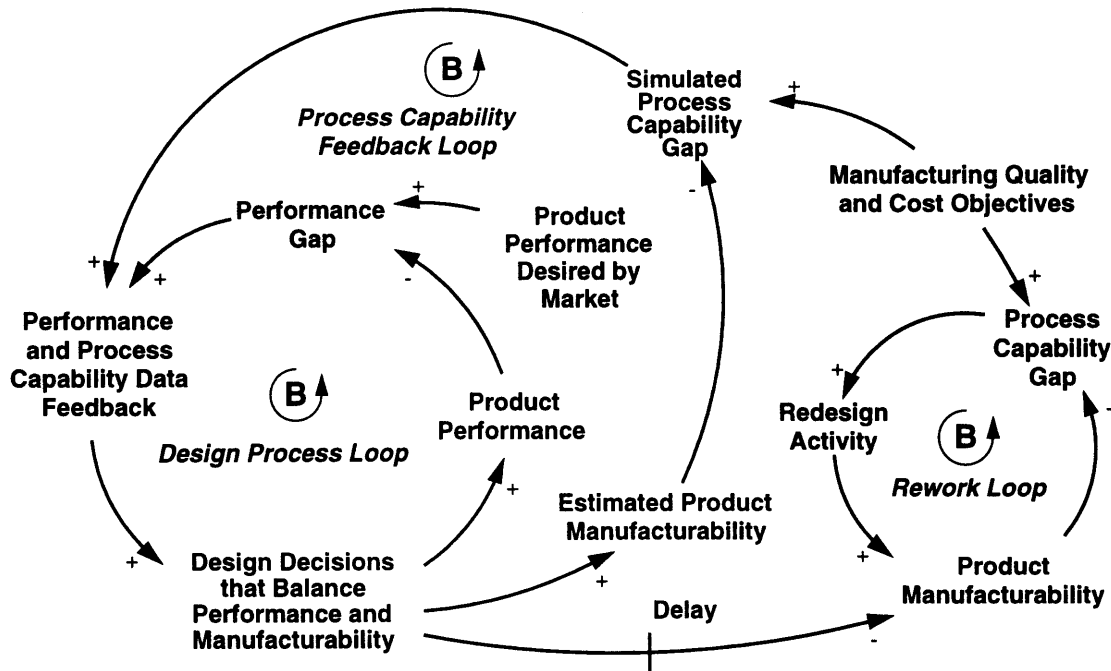
#### **2.3.1 DESIGN PROCESS AND PROCESS CAPABILITY FEEDBACK LOOPS**

Figure 2.2 shows the IPD process with the addition of process capability information feedback. This feedback, manifested in an information system, is represented by the *Process Capability Feedback Loop*. This loop allows IPD teams to access process capability information to determine an *Estimated Product Manufacturability*. The *Estimated Product Manufacturability* and the *Manufacturing Quality and Cost Objectives* combine to give a *Simulated Process Capability Gap*. Since the *Process Capability Loop* is a balancing loop its effect is to minimize the *Simulated Process Capability Gap*. The interaction of the *Process Capability Loop* and the *Design Process Loop* is to form a balanced set of requirements shown as *Performance and Process Capability Data*

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<sup>6</sup> Robert Hayes, Steven Wheelwright and Kim Clark, *Dynamic Manufacturing - Creating the Learning Organization* (New York: Free Press, 1988).





**Figure 2.2: Data-Driven IPD Process Model**

*Feedback.* This balanced set of requirements serves to drive *Design Decisions that Balance Performance and Manufacturability.* In other words, the combined effect of the two balancing loops is to produce designs with a higher relative level of *Product Manufacturability* while concurrently seeking to adhere to product performance objectives.

### 2.3.2 REWORK LOOP

The *Rework Loop* still exists in this model, but has significantly less impact than in the first model. Designs emerging from the two-loop IPD process have a higher level of *Product Manufacturability.* This results in a smaller *Process Capability Gap* and therefore less *Redesign Activity.* The *Rework Loop* still performs a valuable function to compensate for unforeseen circumstances or errors in the IPD process.

### 2.3.3 CONCLUSIONS FROM THE SECOND MODEL

The potential benefits of making better decisions early in the product development process can be substantial. As described in the Section 2.2, significant and avoidable costs are associated with redesigning the product and process once production has begun.

Process capability feedback weakens the expensive *Rework Loop* by helping to eliminate changes for reasons of manufacturability.

The impact of the delay between design actions and production (i.e., when actual manufacturability is determined) is greatly diminished by process capability feedback. Using information about process capabilities from products already in production allows IPT's to simulate the manufacturability of a given design concept just as testing and analysis techniques allow performance to be simulated. Thus, design concepts can be evaluated for compliance to performance requirements and manufacturability requirements simultaneously. Therefore, knowing the impact of design decisions on manufacturability is no longer delayed until the start of production. This allows changes to be made in the design process when the relative cost and schedule impact is significantly less. Moreover, the entire IPT can more easily be held responsible for manufacturability. This reduces dominance by performance requirements and shifts the burden of manufacturability onto the core IPT.

## **2.4 The Premise of Data-Driven IPD Decisions**

Logic would suggest that providing more complete information and instituting incentives to use this information will result in better decisions. To the degree that IPT's are provided with process capability information and held accountable for manufacturability, the manufacturability of designs should improve. If this is true, then the amount of rework or redesign activity occurring after the start of production should be less. Intuition supports that more manufacturable designs are higher in quality, lower in cost and faster to market. Whitney<sup>7</sup>, Wheelwright and Clark<sup>8</sup>, Youssef<sup>9</sup> and Feng<sup>10</sup> substantiate this intuition. Thus, logic supports the premise that data-driven IPD increases quality, reduces cost and speeds product realization.

The manufacturing learning curve is a useful means of illustrating the cost saving potential of data-driven IPD. Figure 2.3 shows per unit manufacturing cost as a function

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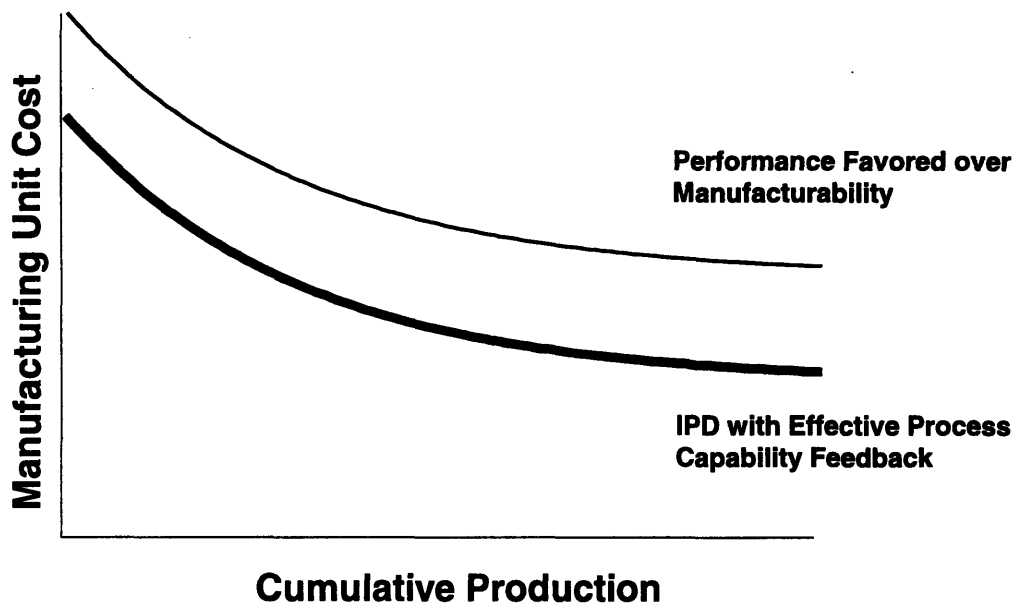
<sup>7</sup> Whitney, *op. cit.*

<sup>8</sup> Steven Wheelwright and Kim Clark, *Revolutionizing Product Development* (New York: Free Press, 1992).

<sup>9</sup> Mohamed Youssef, "Design for Manufacturing and Time-to-Market - Part 2: Some Empirical Findings", *International Journal of Operations & Production Management*, 1995.

<sup>10</sup> Chang-Xue Jack Feng, "Design of Tolerances in Agile Manufacturing", (Ph.D. dissertation, University of Iowa, 1995).

of cumulative production for the situation represented by each of the two system dynamics models. Note that the lower curve is the case where effective process capability feedback exists. Per the previous discussion, this curve starts at a lower per-unit cost. This is the effect of a more manufacturable design. Then, as production continues, both situations experience cost reductions as learning occurs. The potential savings between the two situations is the area between the two learning curves. Making better decisions early in the product development process has enormous leverage on profitability via lower manufacturing costs and faster time-to-market.



**Figure 2.3: Manufacturing Learning Curve**

Intuition might suggest that the *Rework Loop* would eventually drive the upper and lower curves together, however, an important effect is the cost associated with running the *Rework Loop*. Design changes after the start of production are more expensive than those made up-front in IPD. Whether these changes are made up-front through the use of process capability information or after the start of production via the *Rework Loop*, the isolated per-unit cost benefit is essentially the same. Thus, changes made by the *Rework Loop* cost more but deliver the same benefit and therefore have a longer pay-back period. Thus, companies using the *Rework Loop* approach can be expected to forego some

changes that data-driven IPD companies would make (up-front in IPD). This suggests that the two curves will never meet.

## **2.5 Validation of the Hypothesis**

The hypothesis of this document is that process improvement and control methods and a process capability information system, if well-implemented, will enable data-driven IPD decisions. The previous discussion validated the premise. However, validation of the hypothesis does not stem from the same argument. Rather, proof of the hypothesis relies on the argument that if the deficiencies of the IPD process portrayed in Figure 2.1 are addressed, then the IPD process of Figure 2.2 can result. In other words, does the introduction of process improvement and control and a process capability information system (i.e., the pillars of data-driven IPD) address the four deficiencies of the first model? The following discussion supports that this is the case.

***The information is not easily accessible:*** This deficiency is addressed directly by the second pillar - a process capability information system. A well-constructed information system can make process capability information readily available to IPT's. This is a simple statement, but not a simple task. Chapter 3 reviews the current literature on this subject and presents case studies to identify the requirements of such a system. Chapter 4 describes and demonstrates an information system designed to these requirements.

***The information is incomplete:*** This problem is addressed by the information system content. Chapter 1 introduced the concept of the three components of process capability. Chapter 3 expands on this concept and shows why each component is critical to IPD decisions. Chapter 4 describes and demonstrates an information system designed to provide complete information about process capability to the IPD process.

***The information lacks credibility:*** This issue is addressed by the process improvement and control pillar. Chapter 3 explains how the credibility of information is low when the variation of a manufacturing process is out of control. Furthermore, Chapter 3 lays out the benefits of the detailed understanding of the process that comes from formal process improvement and control efforts. Controlling and understanding the variation in a manufacturing process allows manufacturing engineers to confidently and credibly make statements about process capability in the IPD environment.

*The information is ignored because the impact of doing so is delayed:* This point is addressed by the information system. Chapter 4 presents a framework to illustrate how process capability information on products currently in production can be made readily available to estimate the manufacturability of future designs. In this way, IPT's can simulate process capability and make adjustments in product and process design before either are committed to production.

## **2.6 Applications to Supply Chain Design**

Although the design of the supply chain is not explicitly addressed in the system dynamics models, this dimension of IPD is also dependent on an understanding of process capability. Moreover, important interactions exist between the product, the process and the supply chain such that design decisions should be addressed together. For these reasons the framework presented in Chapter 4 includes supply chain issues as potential areas for use of process capability information.

Critical decisions such as make-buy and source selection occur early in the product development process and depend on assessments of supplier process capability. Increasing pressure to shorten the time-to-market is tending to push companies to make these decisions even earlier. Appendix E describes some aspects of the supply chain strategy being implemented at Pratt & Whitney. This strategy, known as Day One Sourcing, has critical supply chain design decisions made earlier in the development process. Such strategies increase the risk that low quality decisions will be made unless actions are taken to improve the information available to the decision makers. Pratt & Whitney addresses this issue with formalized criteria. One of the criteria is process capability information.

The use of process capability information in supply chain design can be extended beyond determining where and who should make a particular part or assembly. By reviewing process capability information, engineers and source planners can begin to identify source development needs. For instance, which process technologies are becoming incapable due to increasingly tighter design requirements? Which process technologies are nearing production readiness? Which sources (internal or external) are in need of capital investment? The framework of Chapter 4 suggests how process

capability information can be used to address these questions and lower the risk associated with making supply chain decisions earlier in the development process.

## **2.7 Summary**

Many manufacturing companies today use a cross-functional team based product development process such as IPD to seek more balance between product performance and manufacturability. However, as illustrated by the system dynamics models presented in this chapter, this good intention has been hampered by the lack of access to complete, credible and timely information about manufacturing process capability. This handicap has prevented IPD from reaching its potential.

The critical success factors for addressing this handicap are the presence of a process capability improvement and control program and a well-designed process capability information system. These factors form the pillars of data-driven IPD decision-making. In the next chapter, current literature and case studies are reviewed for examples of process capability feedback in IPD and to illustrate the importance of process capability improvement and control. Chapter 4 then presents an integrated approach for achieving process capability information feedback in IPD.

## **3. Supporting Information**

### ***3.1 Introduction***

The system dynamics models of the development process presented in Chapter 2 identified the need for credible process capability information and an effective means of access to the information in order for companies to design lower cost, higher quality products in less time. In this chapter, information from literature reviews and case studies is presented to identify how companies are addressing process improvement and control and process capability feedback (i.e., the pillars of data-driven IPD). This information is relied on in Chapter 4 to develop the requirements for a process capability information system and in Chapter 5 to support recommendations about the design, implementation and maintenance of such a system.

### ***3.2 Process Improvement and Control***

#### **3.2.1 LITERATURE REVIEW**

A summary of several process improvement and control programs either currently used in industry or discussed in publications is provided in this section. The programs studied include Total Quality Management (TQM), Six Sigma, Redefining a Process in 14 Steps, Software Failure Analysis, and Process Certification. More details on these programs can be found in Appendix H.

##### **3.2.1.1 Fundamental Themes in the Literature**

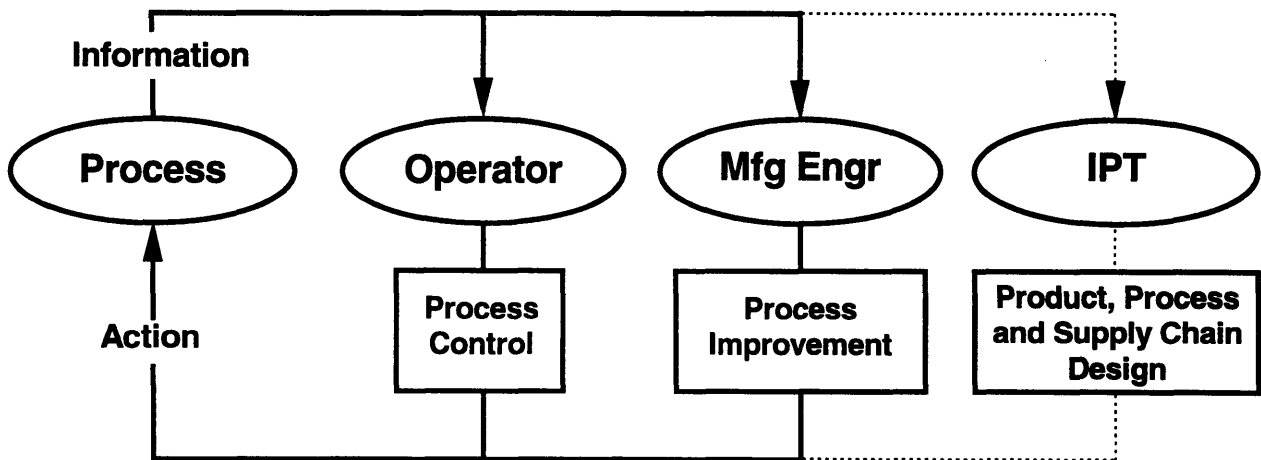
Many process improvement programs have been developed and are used within both the service and manufacturing sectors. While the details and scope of these programs vary, they generally have a common approach toward process improvement and control. The basic steps in this common approach are:

1. Documentation of the Current Process Flow
2. Collection of Performance Data on the Current Process
3. Identification of Possible Sources of Variation in the Process
4. Root Cause Analysis of the Most Probable Sources of Process Performance Problems
5. Implementation of Process Improvements
6. Collection of Performance Data on the Improved Process
7. Institutionalization of the Improved Process

Within these steps there is typically some iteration between Steps 4, 5 and 6. Step 7 plays an important role in preventing the process from decaying back toward its original state. Another

common theme is the attention to certain prerequisites necessary for a successful process improvement effort. These prerequisites typically include upper management support, effective communication of goals and process improvement tool training. These programs are usually difficult to get started, but with these elements in place and subsequent evidence of improvement they take root and lead to substantial and continued improvements.

While there is a great deal of literature on process improvement and control, and within this literature process capability data plays an important role in driving continued improvements, there is little explicit mention of using process capability data in the IPD process. As illustrated in Figure 3.1 below, information from manufacturing processes is used by operators to maintain process control, and by manufacturing engineers to work on process improvements, however, in many cases this information is not used by IPT's. Figure 3.1 also represents the increasing degree of difficulty in accessing data from the manufacturing process the farther removed one is from the process. Operators have first hand access to the data as it is created. Manufacturing engineers work with the operators to identify opportunities for process improvement, and often maintain their own area specific database (find a means to access their area specific data from a



**Figure 3.1: Critical Feedback Loops**

common database). Unfortunately, IPT's generally do not have easy access to the more company-wide process capability information required to make effective decisions.



### **3.2.1.2 Literature Review Conclusions**

The conclusions drawn by the authors from the review of the programs noted above is that process improvement and control efforts are key in establishing efficient manufacturing and critical to enabling process capability feedback in IPD. Process improvement and control plays a critical role in establishing the credibility of process capability information and thereby promoting its use in the IPD process for three primary reasons:

- Process improvement and control reduces variation. Processes subjected to rigorous variation reduction efforts perform nearer to their potential capability than they would without such efforts. Thus, estimates of process capability (such as achievable tolerances) have increased credibility.
- Process improvement and control stabilizes the process. Control of variation necessitates control of important process inputs and control variables. Such control ensures that process capability information taken yesterday is valid today and tomorrow (excepting that capability may be improving due to ongoing efforts). This provides increased confidence that process capability information on existing products is a valid (credible) basis for design decisions on new products.
- Process improvement and control results in a deeper understanding of process variation. These methods require operators and manufacturing engineers to identify, analyze and address the causes of variation. This work affords the participants a detailed knowledge of the process and its inherent capabilities and limitations. This knowledge can be powerful information in negotiating decisions with design engineers in the IPD environment.

These three reasons establish the importance of the first pillar of data-driven IPD. The following case study review demonstrates each of these concepts through real examples of process improvement and control.

### **3.2.2 CASE STUDY REVIEW**

The process improvement and control case studies discussed in this section are based on the on-site research conducted on Pratt & Whitney's Process Certification program. Details of the case studies on the Pierce Press, Surface Grind and Counterbore processes can be found in Appendix F. Participation by one of the authors in the application of Pratt & Whitney's ten step Process

Certification program<sup>1</sup> (see Table 3.1 below for a listing of the ten Process Certification steps) provided an opportunity to see first hand how first establishing an understanding of process flows, followed by a detailed analysis of the process physics, lays the groundwork for process improvement and ultimately process control. The rigorous Process Certification gave manufacturing representatives more credible ground to stand on in design discussions than they had before the certification effort began.

**Table 3.1: Process Certification Steps**

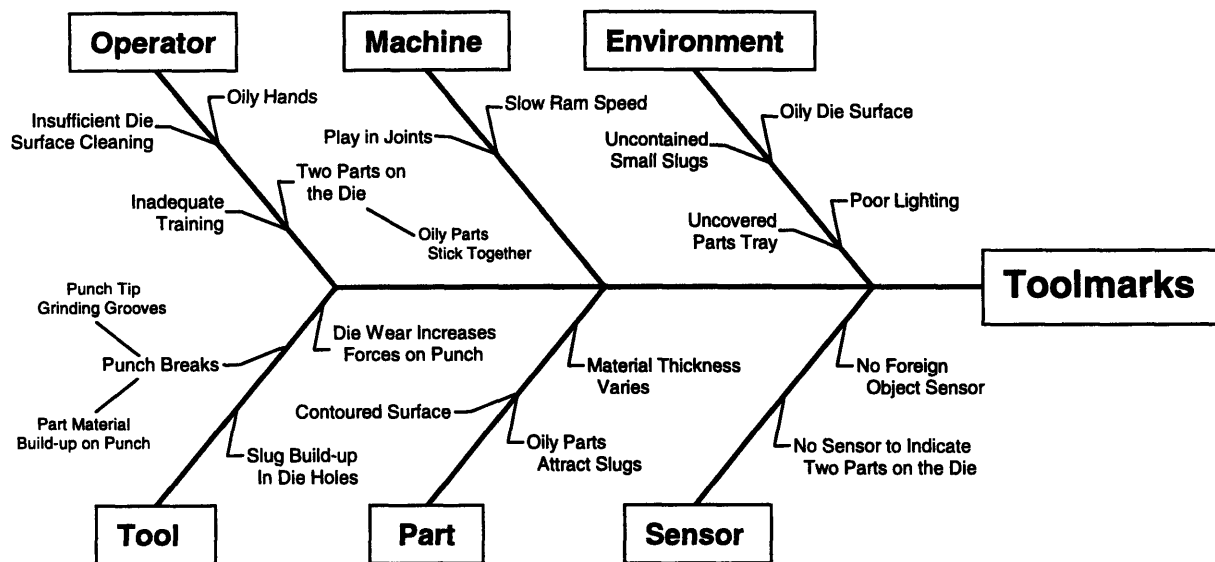
<b>Process Mapping</b>	<ol style="list-style-type: none"> <li>1. Team Formation</li> <li>2. Process Flow Charts</li> <li>3. Process Baseline</li> <li>4. Process Output Prioritizing</li> </ol>
<b>Process Improvement</b>	<ol style="list-style-type: none"> <li>5. Cause and Effect Diagram</li> <li>6. Root Cause Analysis</li> <li>7. Process Improvement Verification</li> </ol>
<b>Process Control</b>	<ol style="list-style-type: none"> <li>8. Control Plan</li> <li>9. Documentation</li> <li>10. Certification</li> </ol>

The detailed analysis of the Pierce Press process presented in Appendix F provides some indication of the rigor with which the processes are scrutinized during the certification effort. Figure 3.2 provides a simple illustration of how the Cause and Effect diagram was used to document and clarify the relationship between toolmark defects and their potential causes. The certification ultimately led to (1) the ordering of a small high velocity press which is more suitable for the required piercing operations (and does not require the parts to be coated with oil to promote proper piercing) and (2) the ordering of higher quality, less expensive punches.

In the case of the Surface Grind process, verification that gages used to measure part characteristics provide both repeatable and reproducible measurements<sup>2</sup> was demonstrated to be an important step in certifying the process as a whole, since unchecked gages can result in good parts identified as defective and vice versa. And finally, in the Counterbore case study, the analysis of process output data using data displays was illustrated as an effective means by which to develop a better understanding of the process physics and lead to generating ideas for

<sup>1</sup> Refer to Appendix C for a step-by-step review of the ten steps of Process Certification.

<sup>2</sup> Gage Repeatability and Reproducibility (Gage R&R) is defined in Appendix C.



**Figure 3.2: Cause and Effect Diagram for Toolmarks**

substantial process improvement. An important element in the control of each of these processes is the control plan which, along with periodic audits, is used to maintain the Process Certification gains, and thus maintain the credibility of the process capability information.

A key message from these case studies is that with process information the organizations were able to appreciate the physics of each process and make the appropriate corrections. Before information was available and reviewed, the organizations did not have a quantified understanding of what their process capabilities really were, nor would they have known what actions would have been needed to make significant improvements.

Another message is that by archiving the information collected for the purposes of process improvement and control, the information can also serve another purpose later - use in IPD. This information will now be available for future part and process design studies. More is also known about the process based on the analysis and documentation completed during the certification effort, providing a richer context for the information. The missing link between the creation and improvement of this credible process capability information, and its use in IPD decision-making, is an effective process capability information system. An example of one such system, the Product Cell Capability Catalogue, is included in the case study presented in the next section.

## **3.3 Process Capability Feedback**

### **3.3.1 LITERATURE REVIEW**

This section reviews the literature on the subject of process capability feedback. Certain fundamental themes and conclusions are drawn from the literature. These conclusions are used to support the development of the process capability information system described in Chapter 4.

#### **3.3.1.1 Fundamental Themes in the Literature**

The literature contains many examples of attempts to bring automated assessment of manufacturability into the IPD environment. Some of these examples describe successful systems that are in use today. Others describe visions of future systems. Some focus on narrow problems such as the manufacturability of electronic component placement on printed circuit boards (Nagel<sup>3</sup>). Others attempt to address a wide range of manufacturing processes (Gadh et al.<sup>4</sup>). Many attempt to integrate computer aided design (CAD) systems with process planning and manufacturability assessment tools. Few, if any, of these tools are actual process capability feedback systems in the true sense. Most rely on heuristics or rules to determine manufacturability. The authors found no literature on the subject of feedback of actual data from the shop floor to the IPD environment. Discussions with managers from other LFM member companies and with MIT faculty identified that many industrial companies are working on plans for such systems, although few have reached implementation. The authors suspect the literature on actual feedback systems will begin to surface as these efforts continue.

Although the available literature is slightly different from the topic of process capability feedback, the concepts are similar and many ideas cross-over. The process-specific attempts at determining manufacturability appear to be the most successful. Of these, Boothroyd-Dewhurst is the most widely known. This software package focuses on the design for manufacturing (DFM) of injection molded plastic parts. Lewis<sup>5</sup> provides a review of this tool. The literature also contains many references on DFM tools in the electronic printed circuit board

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<sup>3</sup> Greg Nagler, "Sustaining Competitive Advantage in Product Development: A DFM Tool for Printed Circuit Assembly", Master's Thesis, Massachusetts Institute of Technology, Leaders for Manufacturing Program, 1996.

<sup>4</sup> R. Gadh, et al., "Knowledge Driven Manufacturing Analysis from Feature-Based Representations", *Concurrent Engineering*, American Society of Mechanical Engineers, 1993.

<sup>5</sup> Gordon Lewis, "Swap Guestimates for Accurate Estimates", *Machine Design*, November 6, 1997.

industry (see Goering<sup>6</sup> and Nagler<sup>7</sup> for examples). Most of these tools address manufacturability using certain key parameters specified by the designer (e.g., number of components on a circuit board) to identify unfeasible situations or to estimate the cost of manufacture. Wheelwright & Clark<sup>8</sup>, Hayes<sup>9</sup>, Dissinger & Magrab<sup>10</sup>, and Liou & Riff<sup>11</sup> describe process-specific systems for gear design, three-axis machining, powder metal and die design applications, respectively. These tools appear to be successful where the rules or heuristics are well codified.

In contrast, the generalized (i.e., non-process technology specific) approaches are still in their infancy. Lu & Modi<sup>12</sup>, Gadh et. al.<sup>13</sup>, Kamrani<sup>14</sup>, Kamrani<sup>15</sup>, Dong et. al.<sup>16</sup>, Candadai et. al.<sup>17</sup> and Geiger & Dilts<sup>18</sup> describe such systems. These systems generally involve a feature-based or group technology (GT) based approach and the use of a database of manufacturability information (knowledge base). Features and GT allow the similarities of specific portions of the product geometry to be exploited for determining manufacturability of the overall product. This is done by defining a set of features from which the complete product is constructed (i.e., holes, slots, pins, pockets, etc.). Rules are then written to define the level of manufacturability for each

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<sup>6</sup> Richard Goering, "Manufacturability is Taking Center Stage", *Electronic Engineering Times*, July 28, 1997.

<sup>7</sup> Nagler, *op. cit.*

<sup>8</sup> Steven Wheelwright and Kim Clark, *op. cit.*

<sup>9</sup> C. Hayes, "P<sup>3</sup>: A Manufacturing Planner that Reasons About Efficient Plans to Achieve Positional Tolerance Specifications", *Concurrent Product and Process Engineering*, American Society of Mechanical Engineers MED Vol. 1/DE Vol. 85, 1995.

<sup>10</sup> Thomas Dissinger and Edward Magrab, "A Fully Integrated Design-for-Manufacture System for Powder Metallurgy", *Concurrent Product Design*, American Society of Mechanical Engineers, DE Vol. 74, 1994.

<sup>11</sup> Shuh-Yuan Liou and Richard Riff, "DFM Design Advisor", *Concurrent Product Design*, American Society of Mechanical Engineers, DE Vol. 74, 1994.

<sup>12</sup> Wen Lu and Ronak Modi, "Feature-Based Design in an Integrated CAD/CAM System for Manufacturability of Machined Prismatic Parts", *Concurrent Product Design and Environmentally Conscious Manufacturing*, American Society of Mechanical Engineers, DE Vol. 94/MED Vol. 5, 1997.

<sup>13</sup> Gadh et. al., *op. cit.*

<sup>14</sup> Ali Kamrani, "An Integrated Knowledge-Based System for Product Design Feasibility and Manufacturability Analysis", *Computers and Industrial Engineering*, Vol. 31, No. ½, 1996.

<sup>15</sup> Ali Kamrani, "GD&T Classification Impact on Integrated Product and Process Design", *Proceedings of the 1995 4<sup>th</sup> Industrial Engineering Research Conference*, 1995.

<sup>16</sup> Jian Dong et. al., "Feature-Based Interactive Manufacturability Assessment with Process Flow Charts", *Concurrent Product and Process Engineering*, American Society of Mechanical Engineers MED Vol. 1/DE Vol. 85, 1995.

<sup>17</sup> A. Candadai et. al., "A Group Technology-Based Variant Approach for Agile Manufacturing", *Concurrent Product and Process Engineering*, American Society of Mechanical Engineers MED Vol. 1/DE Vol. 85, 1995.

<sup>18</sup> Theodore Geiger and David Dilts, "Automated Design to Cost: Integrating Costing into the Design Decision", *Computer-Aided Design*, Vol. 28, No. 6/7, 1996.

of these simpler geometric forms. The level of manufacturability of the overall product is then estimated by combining each of the individual feature estimates.

The generalized manufacturability assessment systems have a typical architecture. This architecture begins with the CAD environment. Here a digital model of the product is created either by conventional means or by selecting features from a feature library. This model is then converted for input into the manufacturability assessment module. In the conventional case, this involves feature extraction whereby the model is divided up into features by a feature recognition scheme. The manufacturability module then determines the inherent level of manufacturability of each feature by applying the rules or heuristics from the knowledge base. The intent of the manufacturability module is to automate the function normally performed by a manufacturing engineer. In fact, Lu & Modi<sup>19</sup> state the intent is that “manufacturability can be determined automatically from a design part without human *interference*...[emphasis added].” The specifics of how such a knowledge base is constructed, what it contains, and how or if the performance of the such system has been validated is left largely undiscussed. The majority of each article is spent describing the CAD system architecture surrounding the knowledge base. Including the references cited here, the authors were unable to locate information on any generalized system that is in use and proven.

### **3.3.1.2 Literature Review Conclusions**

Three conclusions regarding process capability feedback are drawn from the literature review:

- The notion of features and/or the use of group technology (GT) appears to add significant value to a process capability or design for manufacturing (DFM) system. Features and GT take advantage of similarities. Similar geometric features may be produced by the same or similar manufacturing processes. Thus, if a complicated design can be decomposed into a relatively small number of standard features, heuristics can be applied to determine the manufacturability of the overall part. Features and GT also appear to have the potential to enable more efficient communication between CAD, computer aided manufacturing (CAM) and DFM systems. Libraries of standardized features can speed CAD model construction and allow for the easy interpretation of geometry manufacturability by DFM systems. The literature suggests this capability is on the horizon.

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<sup>19</sup> Lu and Modi, *op. cit.*

- The difficulty in codifying DFM rules has limited the success of DFM tools to specific process technologies. The ability of a manufacturing engineer to review a design and identify problems or opportunities for improvement is difficult to simulate except in cases of limited complexity. The successful DFM tools appear to be those that are focused on a single process technology (e.g., injection molding, printed circuit board design and die design) where robust rules have been developed. Consequently the general-purpose attempts at automating manufacturability assessment (i.e., those tools intended to address multiple and complex process technologies as opposed to those focused on a one simple process technology) seem to be years away if possible at all. The volume of literature in this area suggests that the CAD/CAM industry is committed to pursuing this capability.
- An implication of the second conclusion is that the optimum approach for companies with multiple, complex process technologies is to seek process capability feedback, but avoid large-scale development of a “black-box” manufacturability assessment system. Developing a black-box to replace the manufacturing engineer is a tall order. Rather than trying to codify and automate the manufacturing engineer’s experience and decision-making ability into a knowledge base, the best approach may be to develop an information system to serve the manufacturing engineer and thereby enable him/her to drive better decisions. This is the intent of the information system symbolized in Chapter 1 by the second pillar of data-driven IPD. The purpose of Chapter 4 is to describe the requirements of such a system.

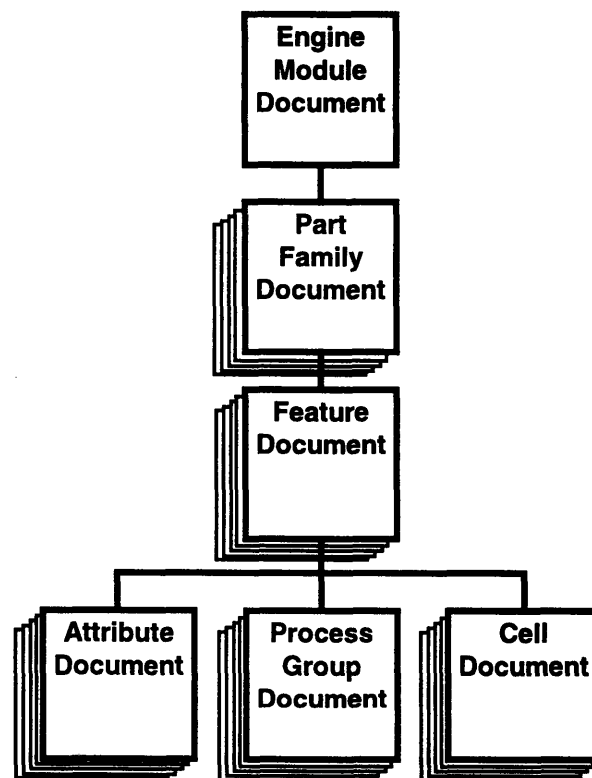
### **3.3.2 CASE STUDY REVIEW**

The process capability data collection and feedback case study presented in this section was derived from on-site research at Pratt & Whitney. This section briefly describes and summarizes the key findings from the North Berwick Product Cell Capability Catalog case presented in Appendix G and from the description of the “IPD of the Future” process capability information system presented in Appendix D.

#### **3.3.2.1 Product Cell Capability Catalog**

During the research period, the North Berwick Product Center of Pratt & Whitney was implementing a process capability information system known as the Product Cell Capability Catalogue (PC<sup>3</sup>). The intent of this system was to act as a means to communicate important information about part manufacturability from the production plant in North Berwick, Maine to

the design engineers in East Hartford, Connecticut. As described in detail in Appendix G, a web-based system of documents was used to collect and display both textual and graphical information about process capability. This information was collected on a part-family basis and arranged by part feature, attribute, process and manufacturing cell in a series of documents as shown in Figure 3.3. The term *attribute* is synonymous with *characteristic* and represents a dimension or other measurable aspect of a feature. The content of the PC<sup>3</sup> was guided by templates shown in Appendix G, but was largely determined by negotiations between the manufacturing engineers and design engineers responsible for the each part family.



**Figure 3.3: PC<sup>3</sup> Documents**

By the end of the research period, the PC<sup>3</sup> was nearly finished but had yet to be tried in IPD. Notwithstanding, the PC<sup>3</sup> case offers several key findings related to the development and implementation of a process capability information system. The following points summarize the findings discussed in Appendix G:

***Important Structural and Content Requirements:***

- The structure of the process capability information system should be consistent with the product architecture and the arrangement of the manufacturing environment. This enables



users to more easily navigate the system. The organization of the PC<sup>3</sup> mirrors the product architecture (i.e., modules, part families, features and attributes) as well as the arrangement of the manufacturing facilities (i.e., Business Unit, cell and process group). This is an intuitive arrangement of the information from the viewpoints of the design engineer and manufacturing engineer.

- The system should link manufacturing process capability to the product at the characteristic (attribute) level. Manufacturing process capability is only meaningful in direct reference to a specific characteristic and the specific process that produced it. Early on, the architects of the PC<sup>3</sup> attempted to define process capability at the feature level. However, this was found to be impossible since a feature can be composed of many characteristics, each of which may be produced to unique tolerances by different processes.
- The system should encompass all three components of process capability: statistical, contextual and competency. The PC<sup>3</sup> system content is strong in terms of contextual and competency components. Process descriptions are included and machine limitations are described. A key area for improvement of the PC<sup>3</sup> is statistical content. The statistical component lacks rigor because of the unavailability of a statistical process data collection and analysis infrastructure. This forced manufacturing engineers to estimate the achievable tolerances for many characteristics using gut feel experience (see Appendix G for detail).
- The system should make use of a well-constructed dictionary of feature and characteristic nouns. As mentioned earlier, the content of the PC<sup>3</sup> was determined largely by the individual negotiations between manufacturing engineers and design engineers associated with each part family. As such, the terms negotiated for features and characteristics were inconsistent across part families. The architects of the PC<sup>3</sup> recognized this and initiated an effort to develop a standard list of nouns.
- The architects of the system should consider how to balance the needs of local and global users. Local users are people associated with a specific part family or cell who use the PC<sup>3</sup> to look up specific information. These users tend to search the system in a vertical manner (e.g., up and down the same part family). The PC<sup>3</sup> accommodates these searches well. However, global users want to identify best practices and this requires searching across part families and cells (i.e., horizontally). For example, global users may want to investigate all the processes used to manufacture slots and therefore would like to be able to search the system

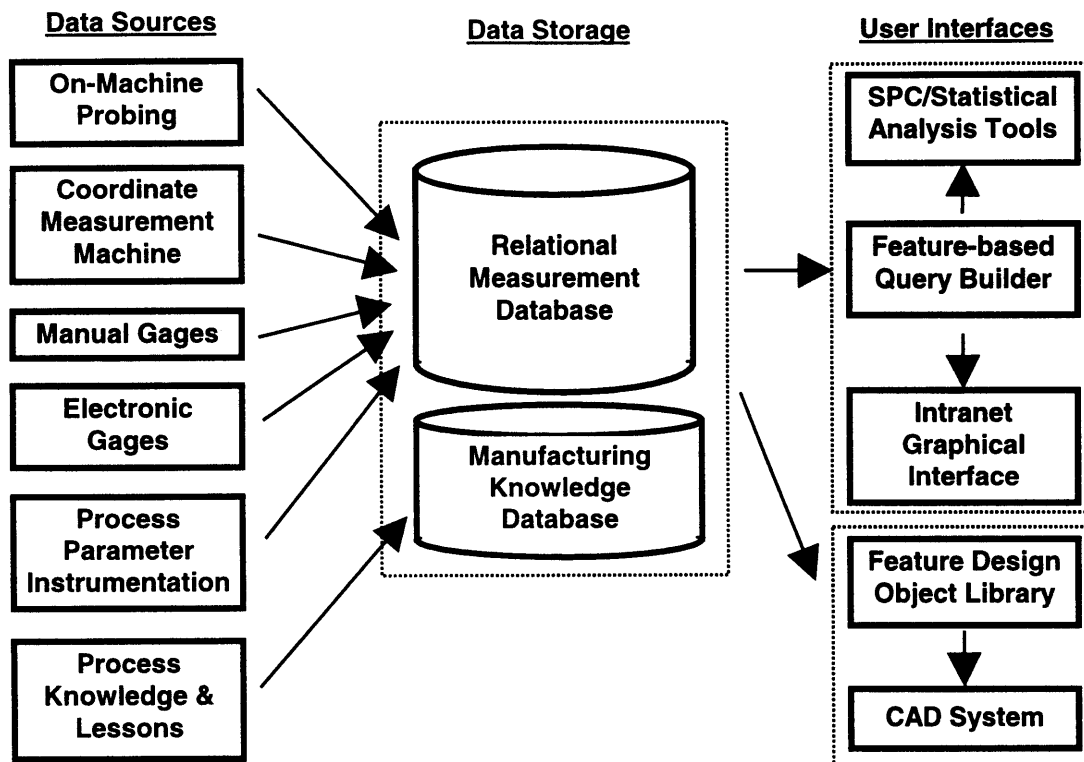
using a feature-based query. The PC<sup>3</sup> did not include the functionality to enable such searches.

***Critical Success Factors:***

- Cross-functional participation in the construction of the system is critical. Both engineering and manufacturing must jointly own the system and concur on the content. This is a strength of the PC<sup>3</sup>. Joint ownership is believed to be a critical success factor to ensuring the use of the information system by IPT's and the maintenance of the information content by manufacturing.
- Management commitment is critical to successful implementation. Significant resources are required to construct such a system. The use and maintenance of such a system takes commitment from the leadership of the engineering and manufacturing communities.
- Information technology is critical to implementation. The successful deployment of the PC<sup>3</sup> was largely a result of the existence of an information system infrastructure. This suggests that the development of the infrastructure should precede the implementation of a process capability information system.

**3.3.2.2 IPD of the Future Process Capability Information System**

IPD of the Future is a strategic vision of the Chief Manufacturing Engineer at Pratt & Whitney that is intended to improve the effectiveness and efficiency of manufacturing engineers in the IPD environment. The goals of IPD of the Future are lower per unit manufacturing costs and shorter IPD cycle time. The use of information technology to facilitate process capability feedback is a key component of this strategy. Specifically, IPD of the Future seeks to create an information system to collect, store and retrieve process capability data on a part feature basis. Appendix D provides a detailed description of this system. The basic structure of the system is composed of data sources, one or many relational databases and a suite of user interfaces (see Figure 3.4). The data gathered by the system are primarily measurements of part geometry (i.e., feature/characteristic positions and tolerances) and some process parameters (i.e., machine feeds and speeds). Much of this instrumentation already exists and is used for part inspection and process control. The database(s) would store the data and associate each piece of data with the appropriate feature and characteristic descriptors. This database structure is chosen to allow feature-based queries by users. Again, measurement databases already existed, but lacked the



**Figure 3.4: IPD of the Future Process Capability Information System**

feature associations. The user interfaces would serve operators, manufacturing engineers and IPT's with the feature-based capability primarily for the IPT's. By the end of the on-site research, the manufacturing engineer interface was in evaluation and the others were under development.

Another component of the IPD of the Future information system is the Manufacturing Knowledge Database. This component is intended to become a library for manufacturing engineers to record and share important information such as lessons learned and the results of interesting studies or tests. This component of the system was still in the initial concept phase by the end of the research period and thus no detail is provided herein.

The IPD of the Future information system design provides another example of a process capability information system for use in IPD. This system has many of the same benefits and challenges already described for the PC<sup>3</sup> system (for instance, both systems required the development of a feature/characteristics dictionary). However, two notable strengths of the IPD

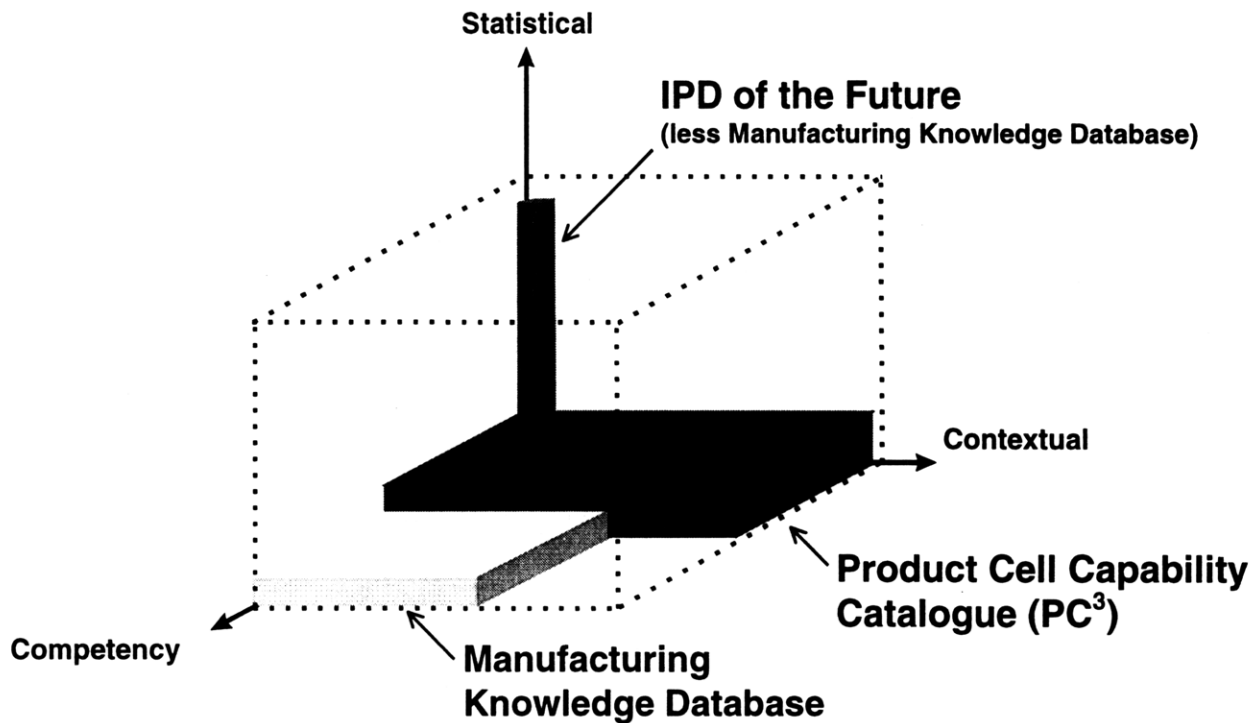
of the Future system relate to content and structure and suggest the following requirements for a process capability information system:

- The system should provide access to real-time statistical data. What the North Berwick PC<sup>3</sup> lacked was high quality statistical data. The IPD of the Future system plan includes the rationalization and connection of all measurement databases into one system. Thus, a user could conceivably access any part measurement data recorded anywhere in the company. This includes data from machine tools, coordinate measurement machines, hand-held gages or any other means by which part measurement data is gathered. By including instrumentation of process parameters, Pratt & Whitney plans to provide users with access to information about the states of machines and facilities. This information is valuable to both manufacturing engineers and machine maintenance engineers.
- The system should allow for easy querying across part families, features, processes and manufacturing sources. The planned feature-based query capability promised to allow both global users and local users to tailor searches of the database to their specific needs. Recall that global users tend to search across part families (horizontally) whereas local users tend to search within a part family (vertically). The notion of features provides the ability to accommodate both such queries. This is an advantage over the vertical structure of the North Berwick PC<sup>3</sup>.

### **3.3.2.3 Information Systems Content Comparison**

The approaches to process capability feedback discussed above can be compared on the basis of content. The authors found the three components of process capability (introduced in Chapter 1) to be useful dimensions for such a comparison. Figure 3.5 shows how the Pratt & Whitney systems compare on these dimensions in a qualitative sense. Note that the Manufacturing Knowledge Database has been broken out as a separate system.

As illustrated in the figure, each of the systems possess advantages over the others in terms of content. The IPD of the Future measurement data collection system is high in statistical content, but lacks other components. The PC<sup>3</sup> is low in statistical content, but is relatively high in the other areas. The Manufacturing Knowledge Database is a library of lessons learned and therefore would primarily be focused on competency information. This representation suggested to the authors that an integrated approach of the three systems would better meet users' needs and



**Figure 3.5: Information Systems Content Comparison**

potentially reduce redundancy of effort and infrastructure. This recommendation was made to Pratt & Whitney.

### **3.4 Summary**

Literature and several case studies were reviewed in this chapter to provide background on process capability improvement and control as well as to identify important requirements for process capability feedback that will be used to support the recommendations of this document.

The process capability improvement and control literature shows many examples of programs which are fundamentally similar. The case studies demonstrate that process improvement and control increases the credibility of process capability information because it:

- Reduces process variation,
- Stabilizes the process,
- Provides a deeper understanding of the process and associated causes of variation.

The IPD literature was found to contain no examples of process capability information feedback systems. The literature was found to contain examples of heuristic-based manufacturability systems. These systems were examined for ideas that might be applied to a

process capability (feedback) information system. These ideas are used in Chapter 4 to develop the information system described therein.

The North Berwick and “IPD of the Future” case studies identified important requirements and critical success factors for a process capability information system. The requirements relate to content and structure and help form the basis for the information system described in Chapter 4. The critical success factors address some important challenges of implementing and maintaining a process capability information system and are the basis for some of the recommendations discussed in Chapter 5.

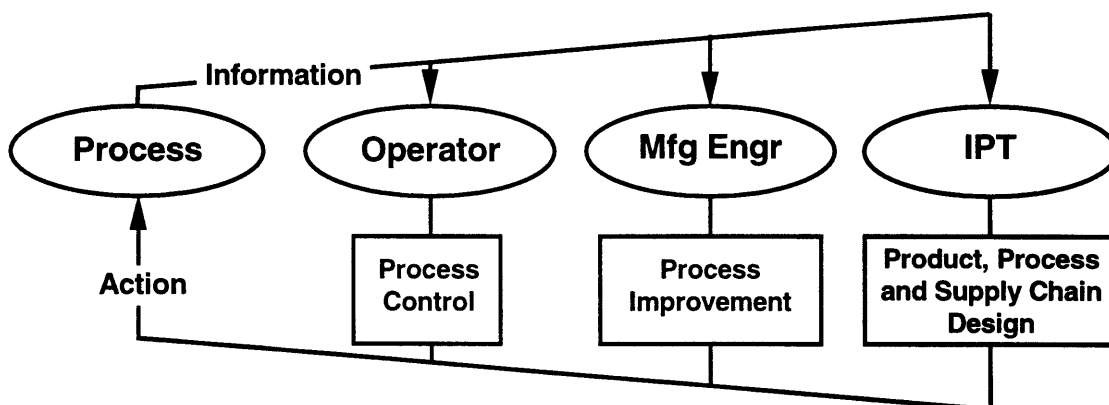
## 4. Information System Design for Improved IPD

### 4.1 Introduction

This chapter discusses the design of a process capability information system and its use in IPD decision making. First, the high-level requirements for such a system are presented from the users' points of view. Second, certain system architectural considerations arising from the users' requirements are discussed relative to the structure of data association and a database query builder. Third, a framework designed to illustrate how manufacturing information can be used to facilitate better decision making throughout the product, process and supply chain development process is explained. Finally, a feature-based design decision example is presented to demonstrate the use of an information system designed to provide feedback of process capability information into the IPD process.

### 4.2 Users and User Requirements

Through research at Pratt & Whitney, the authors found the primary users of process capability to be operators, manufacturing engineers and Integrated Product Teams (IPT's). The core members of an IPT are typically manufacturing engineers, design engineers and source planners. Figure 4.1 illustrates the relationship between users and their needs for process capability information. This model is similar to the model presented in Chapter 3, only here a solid line to IPT's is used to represent the added strength of this feedback loop in the presence of an information system designed to serve as the avenue for IPT's to access process capability information for making data-driven decisions. Also, the funnel shape is used to represent the increasing information breadth. While there is some discussion on the information system



**Figure 4.1: Feedback Loops for Primary Users**

requirements of operators and manufacturing engineers below, as mentioned in Chapter 3 the primary focus of this chapter will be on the information system design elements required to fulfill the needs of IPT's.

As discussed in Chapter 3, operators are generally interested in accessing process data in real-time so disturbances can be detected and the appropriate action can be taken before scrap, rework or repair is necessary. The data of interest to the operators tends to be what is captured in the statistical component of process capability, since they already have a certain understanding of the contextual and competency components from working directly with the process.

Manufacturing engineers, when not in the IPD environment, are generally looking to process capability information to help identify opportunities for process improvement. In this case, manufacturing engineers expressed the desire to be able to access the statistical, contextual and competency components of process capability for cross-process comparison.

In the IPD environment, design engineers, manufacturing engineers and source planners are interested in all three components of process capability and desire access to information from all candidate processes and sources to promote effective decision-making. Such decisions include tolerance allocation and material, feature geometry, process and source selections.

In addition, these user groups have specific database querying requirements corresponding to their use of process capability information. These requirements must be considered in the design of the information system. Operators need a simple data query screen to help them quickly pull up statistical data for the specific process of interest. Manufacturing engineers need a more powerful querying system to help them access process capability information not only on their local processes, but also on similar processes across the company. And finally, the IPT's will need a comprehensive, feature-based query builder to enable team members to determine the best process to produce a given characteristic and assess the existing process capability relative the what is required to meet product performance objectives. An integrated information system must be designed to meet this full range of querying needs.

### ***4.3 Data Association and Database Query Structure***

Data association can be looked at in terms of group technology and key characteristics. These concepts provide insights relative to how a process capability database might best be organized.



Per Hyer<sup>1</sup>, group technology (GT) is the concept of recognizing and exploiting similarities. Hyde<sup>2</sup> attempted to define GT more precisely and found that it has come to mean many different things (e.g., cellular manufacturing, design standardization, manufacturing process standardization). In the context of this document, GT provides the idea that process capability information should be accessible on the basis of similarity; similarity in product architecture/geometry and similarity in manufacturing process. This gives rise to the idea of using features as a way to associate the capability of manufacturing processes to the appropriate components of product geometry (see Kamrani<sup>3</sup> and Appendix A). Key characteristics (KC's) is a method of translating the important, or key, product system level requirements into the detail part requirements at the characteristic level and then associating these requirements to the manufacturing process. This method is described by Lee & Thornton<sup>4</sup> and Boeing<sup>5</sup> and is illustrated later in this chapter (using Figure 4.5). By combining the elements of GT and KC's as described above, a feature-based process capability database can be established and serve as the structure for a process capability information system. This structure will allow users to easily navigate through the system to access the information they need. The feature-based structure of the process capability database and query builder is presented in the following sections. In this feature-based structure, two models are used to associate elements of process capability information with the product architecture and the process infrastructure: a part family-based model and a process-based model.

#### **4.3.1 PART FAMILY-BASED MODEL**

A part family-based model establishes the “parent-child” relationship (i.e., the relationship between part feature and the part characteristic). These relationships are established all the way through the product architecture (see Figure 4.2). An example of a part family-based model is the ability to look at a characteristic, such as diameter, associated with a feature, such as a hole,

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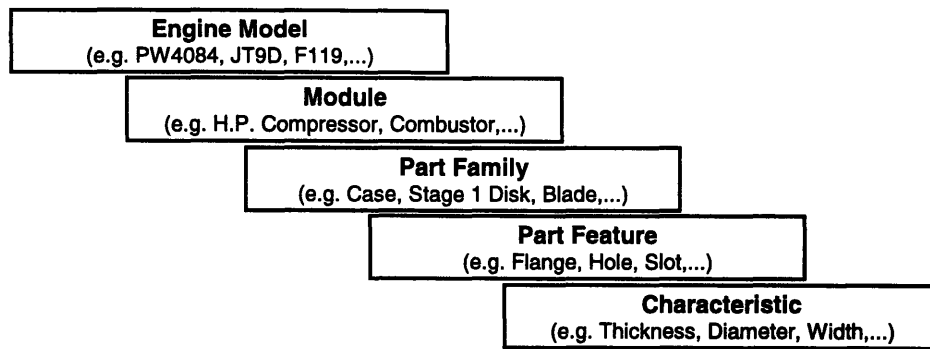
<sup>1</sup> Nancy L. Hyer. ed., *Capabilities of Group Technology* (Dearborn, MI: Society of Manufacturing Engineers, 1987).

<sup>2</sup> William F. Hyde, *Improving Productivity by Classification, Coding, and Data Base Standardization* (New York: Marcel Dekker, Inc., 1981).

<sup>3</sup> Ali K. Kamrani, “An Integrated Knowledge-based System for Product Design Feasibility and Manufacturability Analysis” (*Computers and Industrial Engineering*, Oct. 1996).

<sup>4</sup> Don J. Lee and Anna C. Thornton, “The Identification and Use of Key Characteristics in the Product Development Process” (*Proceedings of the 1996 ASME Design Engineering Technical Conferences and Computers in Engineering Conference*).

<sup>5</sup> The Boeing Company, *Hardware Variability and Control* (Boeing internal document).

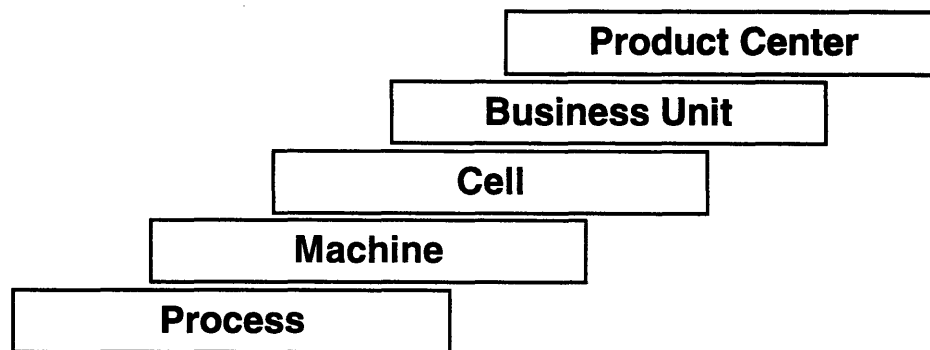


**Figure 4.2: Part Family-Based Model**

associated with a part family, such as a case. As shown in Figure 4.2, using this model a user can navigate through the product architecture to pull up all information tied to the specific characteristic of interest.

#### **4.3.2 PROCESS-BASED MODEL**

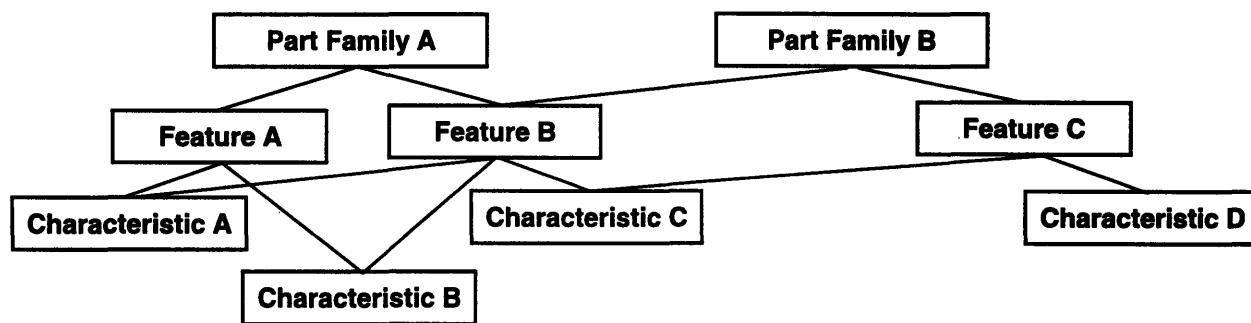
Another helpful way to organize process capability information is to use a process-based model. The organization of Pratt & Whitney manufacturing facilities shown in Figure 4.3 below illustrates what is meant by a process-based model. This model shows how each manufacturing process can be associated with particular machine, cell, unit and plant. This model allows manufacturing engineers and IPT's to sift and sort by process capability information by process type and machine type as well as by organizational structures.



**Figure 4.3: Process-Based Model**

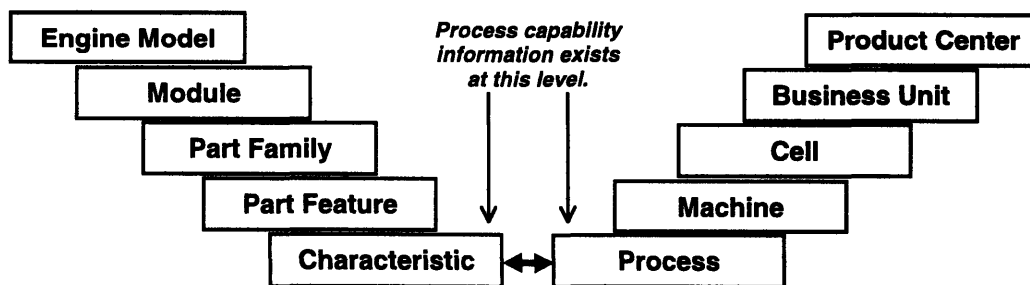
Figures 4.2 and 4.3 are not meant to imply a hierarchical structure. Rather, the actual information structure is relational such as shown in Figure 4.4 below. The power of this relational structure is the recognition that certain features exist in multiple part families and certain characteristics exist in multiple features. This structure makes it possible for users to

search across different part families for common feature information and even across different features for common characteristic information. For example, if an IPT is designing a slot, they can get process capability information on all of the many slot manufacturing processes in use (e.g., milling, broaching, grinding, etc.). This structure is typical of a relational database. An object-oriented database structure could also be used, however, the benefits of such a structure are beyond the scope of this document. From the user's perspective, the relational structure provides a useful way to think about the inherent structure of process capability information.



**Figure 4.4: Relational Structure of a Feature-based System**

As shown in Figure 4.5, a connection can be made between the part family-based and process-based models at the Characteristic-Process levels. This forms a structure that is seen in the North Berwick Process Cell Capability Catalog (described in Chapter 3 and Appendix G) and in the Boeing AQS/HVC systems (Design/Build Trees) discussed by Lee and Thornton<sup>6</sup>. This connection allows users to search up and down both sides of the “V” within a single information system.



**Figure 4.5: Part Family and Process-Based Models Connection**

<sup>6</sup> Lee and Thornton, *op. cit.*

## 4.4 Utilization Framework

This section describes a framework designed to illustrate how process capability information can be used in the IPD process. This framework assumes the existence of a three-dimensional IPD process (i.e., product, process and supply chain design are integrated).

The structure of the framework shown in Figure 4.6 contains three important elements. First, the five phases of the IPD process are identified to distinguish how process capability information can be used at different times in a development program. Second, the relevant source of process capability information is indicated for each of the five IPD process phases. Early in the development process (*Concept Development* through *Detail Design*) product, process and supply chain design decisions are based on process capability information for existing part designs. This information provides guidelines for making decisions related to the new part design. Later (during *Testing & Refinement* and *Production*), the process capability information retrieved comes from the new processes actually producing the new parts. This information is used to guide product and process refinement decisions to adapt to any unforeseen

Program Phase →	Concept Development	System Design	Detail Design	Testing & Refinement	Production
Relevant Source of Information →	Real-time Upload of Existing Part Information			Real-time Upload of New Part Information	
<b>Use of Statistical and Contextual Information</b> →	Process technology development needs identification Potential process and source identification Capital planning (source infrastructure)	Source evaluation and selection (make/buy) Process evaluation and selection Envelope tolerance assignment	Process parameter specification (machine states) Tooling selection Characteristic tolerance assignment Inspection plan development	Process capability verification Part and process refinement In-process and end item inspection	Process capability monitoring, statistical process control Process improvement Source planning for added capacity In-process and end item inspection
<b>Use of Competency Information</b> →	Potential process and source identification Capital planning (source infrastructure) Product concept feasibility studies Production strategy feasibility evaluation	Source evaluation and selection (make/buy) Process evaluation and selection Keep competency under consideration as product and process designs evolve		Keep competency under consideration as product and process designs evolve	

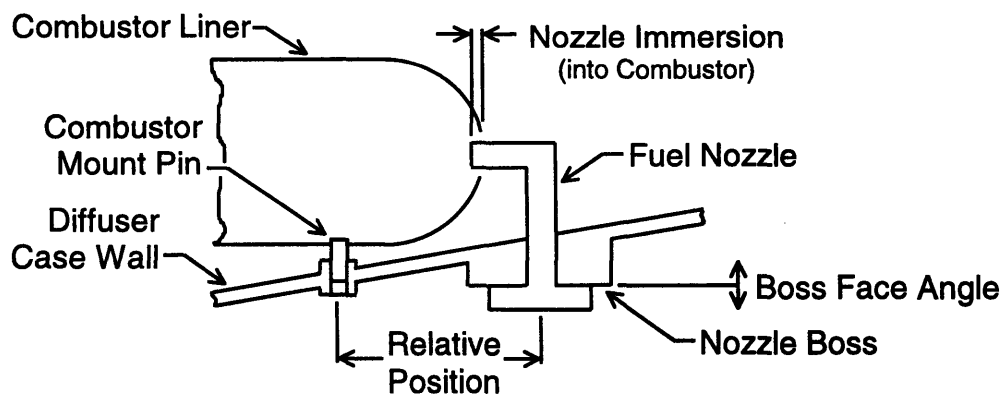
Figure 4.6: Process Capability Utilization Framework

conditions as well as to facilitate continuous improvement. Finally, along the left side of the framework the types of process capability information are broken out into two groupings to help illustrate the uses for different types of information.

This framework shows how different types of process capability information can be used at each of the different phases of the development process. The next section presents a hypothetical example to illustrate how a process capability information system can be used to guide decisions in the IPD process. While the example presented focuses on “characteristic tolerance assignment” noted in the *Detail Design* phase of the utilization framework, it is meant to illustrate just one of many possible examples of how process capability information can be used in the development process.

#### 4.5 Information System Demonstration

The intent of this section is to demonstrate how a design engineer and a manufacturing engineer might use a process capability information system for improved IPD decision making. This will be done using two scenarios. First, a design decision scenario in an environment lacking access to credible process capability information is described. This is followed by a contrasting scenario where a process capability information system is used to drive better design decisions. Both scenarios discussed are based on a hypothetical design decision involving the interaction between the fuel nozzle, the diffuser case and the combustor of a turbine engine. These scenarios are hypothetical, but were developed based on real life design considerations with the help of Pratt & Whitney engineers. The basic geometry important to the nozzle/combustor design decision discussed in this section is shown schematically in Figure 4.7.



**Figure 4.7: Fuel Nozzle and Combustor Interface Geometry**

The key performance characteristic in this example is *nozzle immersion*. If the nozzle protrudes too far into the combustor, the nozzle may oxidize and require premature replacement. On the other hand, if *nozzle immersion* is insufficient, fuel spray may contact the *combustor liner* and reduce combustor durability. A firm design requirement is never to allow negative immersion (the nozzle tip is outside of the combustor liner). The two characteristics which affect *nozzle immersion* are (1) *relative position* (the position of the *combustor mount pin* relative to the fuel *nozzle boss* hole) and (2) the *boss face angle*.

#### **4.5.1 INFORMATION DEFICIENT DECISION-MAKING SCENARIO**

This scenario begins with the design engineer explaining the key performance characteristics to the manufacturing engineer in an effort to drive for tight tolerances on *relative position* and *boss face angle*. The manufacturing engineer counters with an explanation of the overall manufacturing process capability based on gut feel knowledge of the process and recent inspection records written to address problems on *relative position* and the *boss face angle* for diffuser cases currently in production. The design engineer points out that new design requires tighter control on *nozzle immersion* to meet the performance requirements. The manufacturing engineer recalls that the process seems to be handling the current design requirements well, and there have been relatively few recent inspection records on these items. Lacking disconfirming data, the manufacturing engineer commits to meeting the tighter tolerances.

Once production begins, the manufacturing engineer finds that although manufacturing is still able to meet the *relative position* requirement (even under the tightened tolerance), manufacturing has numerous problems attempting to meet the *boss face angle* tolerance. The manufacturing engineer first investigates the *boss face angle* problem and then meets with the design engineer to ask for the angle tolerance to be opened up to alleviate the rework and potential part scrap activity. After some discussion, the design engineer agrees to open the angle tolerance a little, but not as much as the manufacturing engineer originally requested.

With the new angle tolerance manufacturing is still able to avoid a *negative immersion* condition, however, nozzle tip durability has been compromised to some degree because additional *nozzle immersion* is allowed. In relaxing the *boss face angle* tolerance, the design engineer has traded off some nozzle tip life in exchange for reduced rework and scrap. Even with this trade-off, manufacturing is still required to perform some rework since the new angle tolerance is still beyond the process capability. Under this scenario there is both a sub-optimal

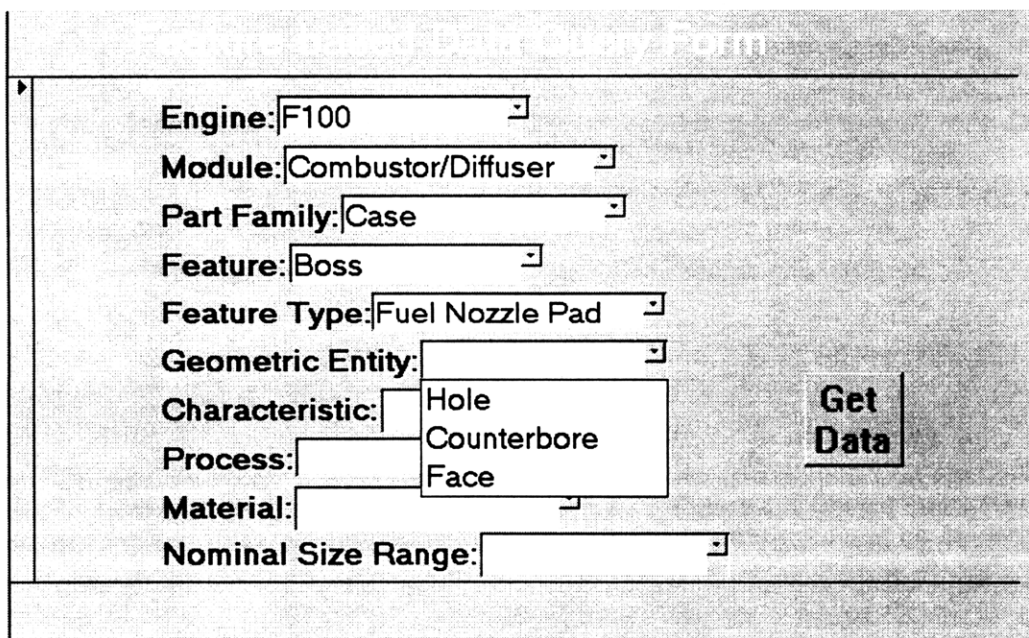
performance condition and costly rework activity. This slow and costly feedback loop is filled with inefficiencies and delays. The inability of the process to produce the features on the new part is not perceived until the new part enters production, and by that time costly product and process redesign work is required to reduce the impact of the sub-optimal condition.

#### 4.5.2 INFORMATION SUPPORTED DECISION-MAKING SCENARIO

In contrast to the scenario described above, decisions supported by credible process capability information can lead to more desirable results. This demonstration describes the use of a feature-based query builder to pull-up the information required for certain characteristics, walks through the information screens retrieved, and discusses how the information can be used to drive more effective design decisions using the hypothetical example introduced above.

##### 4.5.2.1 Query Builder Use

A view of the query builder used to access the desired information from the database is shown in Figure 4.8. The authors developed this query builder using Microsoft Access. The screen shown is for the query builder option an IPT would select to proceed with a feature-based query. Other options might be available for operators and manufacturing engineers to allow them to pull-up more simplified query screens to access specific process data for process control and process



The screenshot shows a window titled "Feature-Based Querying Form". It contains several input fields, each with a dropdown arrow on the right:

- Engine: F100
- Module: Combustor/Diffuser
- Part Family: Case
- Feature: Boss
- Feature Type: Fuel Nozzle Pad
- Geometric Entity: (empty)
- Characteristic: (dropdown menu open showing "Hole", "Counterbore", and "Face")
- Process: (empty)
- Material: (empty)
- Nominal Size Range: (empty)

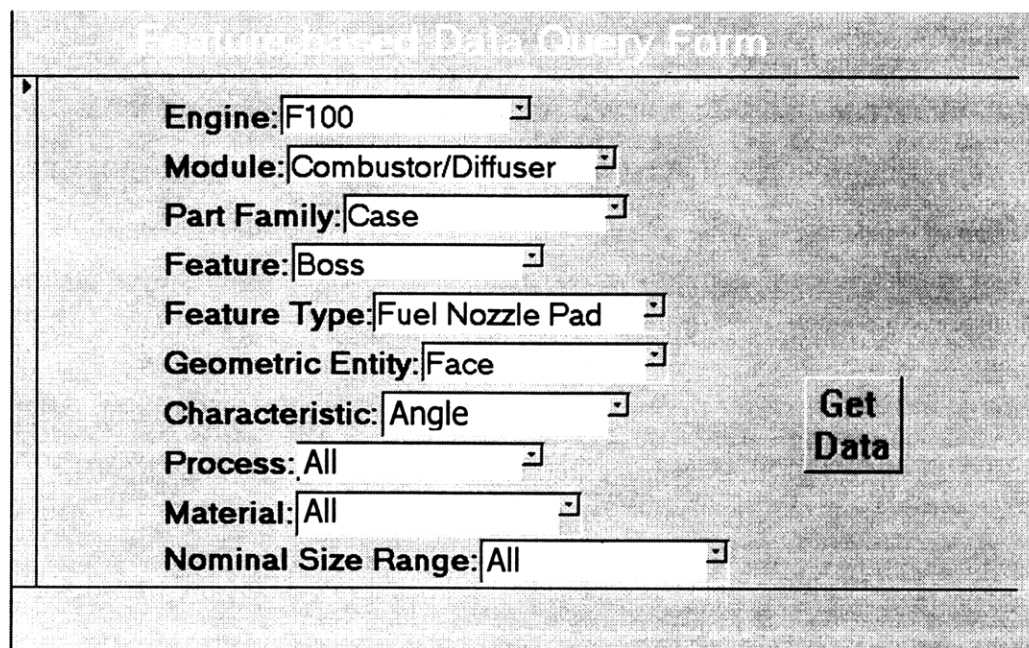
To the right of the input fields is a button labeled "Get Data".

Figure 4.8: Feature-Based Querying Screen

improvement. The focus of this section is on a feature-based query builder for IPT use.

Pull-down menus at each level (i.e. Engine, Module, etc.) are used to narrow down the data search. The users also have the option of conducting a broader data search by selecting less specific options such as “All” processes or “All” sizes as shown in Figure 4.9. Menu levels of Feature Type and Geometric Entity were added to create menu lists of manageable size. Also, menu levels of Material, Process and Nominal Size Range were added based on user input.

Once the user has completed the required fields on the query screen, the “Get Data” button is selected to initiate information retrieval from the database. The information screens retrieved using the query builder are discussed below.



The image shows a screenshot of a software interface titled "Feature-based Data Query Form". The form contains several pull-down menus for selecting search criteria. The selected values are: Engine: F100, Module: Combustor/Diffuser, Part Family: Case, Feature: Boss, Feature Type: Fuel Nozzle Pad, Geometric Entity: Face, Characteristic: Angle, Process: All, Material: All, and Nominal Size Range: All. A "Get Data" button is located to the right of the "Process" and "Material" fields.

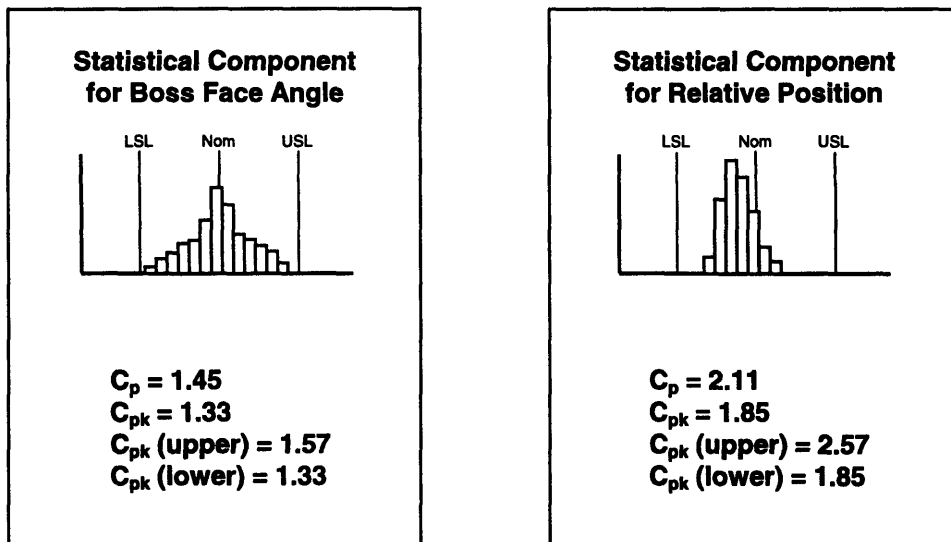
Field	Selected Value
Engine	F100
Module	Combustor/Diffuser
Part Family	Case
Feature	Boss
Feature Type	Fuel Nozzle Pad
Geometric Entity	Face
Characteristic	Angle
Process	All
Material	All
Nominal Size Range	All

**Figure 4.9: Completed Querying Screen**

#### 4.5.2.2 Process Capability Information Screens

Three different types of information screens corresponding to the three components of process capability (Statistical, Contextual and Competency) are retrieved from the database. Figure 4.10 shows statistical information screens for the two characteristics of interest in the hypothetical example introduced earlier in this chapter. In addition to the histogram and process capability indices shown below, a run chart may be available for certain characteristics.

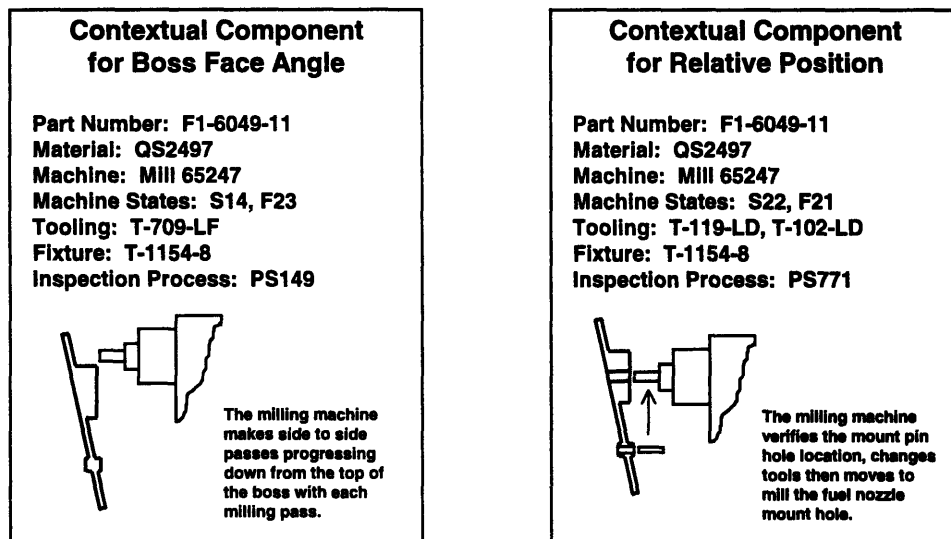




**Figure 4.10: Statistical Information Screens**

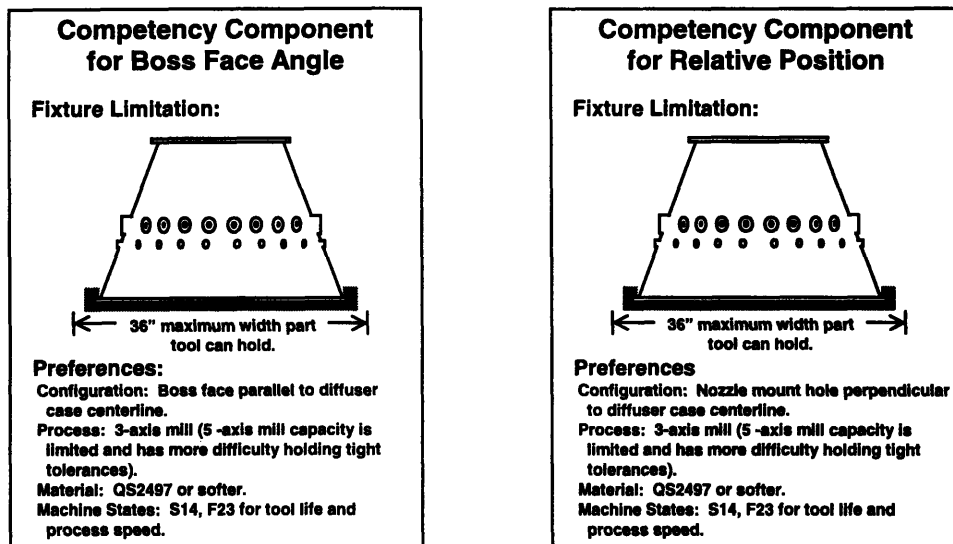
The information screens shown above would not be retrieved by the same query and pulled up in such a side-by-side format, however, by conducting separate queries in different windows, this side-by-side display could be generated for convenient information review.

Figure 4.11 illustrates the type of contextual information retrieved for the characteristic specified in the information query. In addition to the textual information, a diagram is included to provide a visual representation of the context under which the characteristic is produced.



**Figure 4.11: Contextual Information Screens**

Finally, Figure 4.12 presents process competency information such as machine limitations and operating preferences. Here again, a diagram is included to convey information more clearly than would be the case in simply providing a written description.



**Figure 4.12: Competency Information Screens**

#### 4.5.2.3 Making Better Design Decisions

The hypothetical design negotiation scenario is quite different when design and manufacturing engineers have a process capability information system at their disposal. In this scenario, the manufacturing engineer walks through the query builder with the design engineer to specify the information for the query. Once the information screens are retrieved, they can begin to confidently negotiate design tolerances and make data-driven decisions.

As the design engineer explains the need to tighten tolerances for the new design, the manufacturing engineer points out that the process capability for the *boss face angle* (shown on the Statistical Information screen) is just marginally meeting the company established  $C_{pk}$  goal of 1.33. However, by looking at the process capability for the *relative position* between the combustor mount pin and the fuel nozzle mount hole, the manufacturing engineer explains that there is some room to tighten the tolerance of this characteristic.

The manufacturing engineer also points out some additional details about the manufacturing process by paging to the Contextual Component screen. The information provides the context under which the statistical information is valid. The combination of textual and graphical information presented on the screen makes it possible for the design engineer to develop a better understanding of the process capability and how it relates to the design decisions under consideration.

In addition, paging to the Competency Information screen opens another window into the process. In this example, as shown in Figure 4.12, it is easy to see that as diffuser case diameters grow with the market requirements for larger engines, at some point (i.e., when the diameter exceeds 36 inches) new fixturing will have to be developed. The preferences noted also help guide the design engineer to alter what might have been arbitrary decisions to decisions focused on making the product easier to manufacture. While the example screen shows only a fixture limitation and a few manufacturing preferences, actual Competency Information screens would typically include a more extensive set of limitations and preferences for the IPT to page through.

In contrast to the earlier scenario where the *boss face angle* tolerance and nozzle tip life were traded-off against one another, in this scenario the information system makes a “trade-on” possible - allowing the *boss face angle* tolerance to stay in alignment with the process capability while at the same time maintaining the desired nozzle tip life. In fact, the design negotiation may even provide the incentive for the manufacturing engineer to improve the relative position process to center the data more closely around the nominal value. There may still be some issues to resolve when production of the new design begins, however, manufacturing is in a much better position under this scenario than they were in the information deficient scenario. Again, as mentioned earlier, while the example presented above focused on “characteristic tolerance assignment”, it is meant to illustrate just one of many possible examples of how process capability information can be used in the development process.

## **4.6 Summary**

There are three primary groups of process capability information users. Operators use such information for process control. Manufacturing engineers use it for process improvement. And IPT's use it for product, process and supply chain design. To meet all of their requirements a process capability information system must have an architecture that allows the users to navigate through the information in the database to access what they need. Such a design can be satisfied by incorporating part family-based and process-based models. A framework and simple example were included to illustrate how certain types of information can be used at different phases of the IPD process.

This chapter presented the key elements of an information system designed for use in the IPD environment were presented. The next, and final, chapter provides a summary of issues covered, important recommendations, and some thoughts on where further research may be focused.



## **5. Summary and Recommendations**

This intent of this final chapter is to provide (1) a summary of the issues presented in this document; (2) recommendations on the design, implementation and maintenance of a process capability information system; and (3) some thoughts on areas for further research. The summary reiterates the main issues covered in each chapter. The recommendations extend directly from many of the conclusions and key findings discussed in earlier chapters. The final section suggests the following areas for further research: studying the implementation and use of a process capability information system, identifying best practices through benchmarking, and extending process capability feedback to explore variation risk assessment.

### **5.1 Thesis Summary**

Chapter 1 laid the groundwork for this document by first introducing the conceptual model of a well-functioning IPD process (the foundation) built onto by an effective process improvement and control program and an easy-to-use process capability information system (the pillars) to support data-driven IPD decisions. This conceptual model symbolizes the two-part hypothesis of this document restated below:

- The existence of a structured method for monitoring and controlling process variation is critical to making manufacturing process capability information credible for use in IPD decision-making.
- A properly constructed information system can provide access to manufacturing process capability information and thereby enable high quality product, process and supply chain design decision-making in the IPD environment.

Also, the use of the term process capability was defined to consist of three components: statistical, contextual and competency. Integrated product development was defined in a broad sense as the concurrent design of product, process and supply chain design - also referred to as 3-D Concurrent Engineering.

Chapter 2 presented the logic behind this hypothesis. Two models representing the system dynamics of development processes were used to demonstrate the effectiveness of the IPD process with and without significant use of process capability information. The first model illustrated how product, process and supply chain design decisions made in the absence of process capability information results in costly product and process redesign activity. The

second model explained how the accessibility and use of process capability information make it possible to make effective product, process and supply chain design decisions which result in the benefits of products that are of lower cost, higher quality and require less time to bring to market. In addition, four reasons to explain why process capability information is underutilized in IPD decision-making, namely that information is (1) not easily accessible, (2) incomplete, (3) lacks credibility and (4) ignored (since the impact of ignoring the information is delayed), were discussed in terms of how they could be addressed by implementing a process improvement and control program and a process capability information system.

Chapter 3 provided information in the form of literature reviews and case studies on process improvement and control and process capability feedback to support the hypothesis and its underlying logic. From these reviews and case studies a number of conclusions and key findings were identified and discussed in terms of their utility in defining an effective process capability information system.

Finally, Chapter 4 discussed the primary users of process capability information and what their requirements implied about the design of a process capability information system. Also, Chapter 4 introduced a framework to illustrate how different types of process capability information can be used in the various phases of the development process. The chapter culminated with a demonstration on the use of a feature-based process capability information system through a hypothetical IPD decision-making example.

The material presented in this document lead up to the demonstrated use of a feature-based process capability information system. The following section provides recommendations on the design, implementation and maintenance of such a system.

## ***5.2 Recommendations***

The recommendations of this document stem from the conceptual model introduced in Chapter 1. At a high level, the advice is to implement and integrate a rigorous process improvement and control program and a well-constructed process capability information system to achieve data-driven IPD. The following discussion outlines the detailed recommendations relative to the design, implementation, and maintenance of a process capability information system and how such a system should be integrated with process improvement and control.

### 5.2.1 INFORMATION SYSTEM DESIGN

The following elements are recommended design requirements for an information system designed to facilitate the feedback of high quality process capability information into the IPD process:

- **Populate the system with information covering all three components of process capability - statistical, contextual and competency.**

Throughout this document the three components of process capability have been described as valuable for IPD decision-making. The *statistical* component shows the capability of the process to meet specified targets and tolerances. The *contextual* component documents the states of important process parameters and enables valid statistical comparisons between processes and design configurations. The *competency* component communicates what is possible and what is preferred. Together these three components provide a more complete view of process capability. This view enables IPT's to make data-driven decisions and thereby produce designs at lower cost, higher quality and in less time.

- **Develop a database structure that takes advantage of similarities in the product architecture and the manufacturing environment.**

The notions of features and group technology are often used to organize product design information in the CAD environment and to arrange manufacturing facilities. The reason is to allow similarities to be exploited. This reason also applies in the arena of a process capability information system. By searching on a specific feature or process, engineers can locate alternate design and processing approaches. Best practices can be located more easily. The product architecture and the arrangement of the manufacturing environment is tangible and intuitive to design engineers and manufacturing engineers. Structuring the database to take advantage of these arrangements will allow users to easily formulate queries to find the desired information.

- **Develop the database structure and query builder together based on user input.**

The database of a process capability information system is only useful if users are able to access the desired information. The database and query builder must be consistent and must recognize the querying needs of the users. Interviews should be used to establish these querying needs before database or query builder structures are finalized. These

needs should be examined to determine the ways in which users think about finding process capability information. Such interviews conducted at Pratt & Whitney gave rise to the first recommendation and thereby helped formulate a preliminary database and query structure.

- **Access statistical process capability information in real-time.**

Unless the process capability information provides an accurate depiction of the capability of the current process, the IPT will not be able to make well-informed decisions. One critical step to providing accurate information is to include a direct link to the statistical process capability information. This real-time access to statistical information also provides the information system with an added element of credibility over a system that has only a generic estimate of statistical process capability information based on an out-of-date, single-point-in-time assessment.

- **Establish a set of standardized terminologies.**

The shop floor and engineering often have different terminologies for features and characteristics. In addition, geometrically similar/identical features may have different names from cell to cell, plant to plant, or part family to part family. The ideal scenario is to develop one standard dictionary of part features and characteristics that works for everyone and is mutually exclusive and collectively exhaustive. However, this may not always be possible. Some redundancy in terms may be necessary to translate between different user communities. In such cases a *thesaurus* of feature and characteristic terms should be developed. This will allow the information system to translate the language of those who input the process capability information into the language of those who wish to access the information.

### **5.2.2 INFORMATION SYSTEM IMPLEMENTATION**

The following recommendations address issues that were found or expected to arise in the implementation of a process capability information system:

- **Implement (or continue) an enterprise-wide process improvement and control program which stretches manufacturing to understand and control process variation.**

As discussed throughout this document, information credibility plays a critical role in promoting the use of an information system. Processes subjected to rigorous variation



reduction efforts perform nearer to their potential capability than they would without such efforts. In turn, estimates of process capability (such as achievable tolerances) have increased credibility. Such control ensures that process capability information taken from today's products and processes is valid for design of tomorrow's products and processes. Process improvement and control efforts also result in a deeper understanding of process variation. These factors can be powerful information to a manufacturing engineer negotiating design decisions with design engineers in the IPD environment. The degree to which the existence of a process improvement and control program is known throughout the company and the supply base increases the credibility that will be placed on process capability information brought to the IPD environment.

- **Institutionalize the requirement to utilize the process capability information system for all IPD decision-making.**

No information system can be effective unless it actually gets used. Unless the appropriate incentives are in place to encourage IPT's to use process capability information, the level of product manufacturability is unlikely to increase with the addition of an information system. One approach to promote the use of a process capability information system is to require an estimate of product manufacturability at critical junctures in the IPD process. Such requirements can be added to the gate pass-through criteria of a stage-gate design process.

- **Allocate resources to design and implement the information system.**

The creation of a process capability information is a non-trivial undertaking in a large company. Information technology infrastructure must be in place or be put in place. Gathering the information to populate the system requires the involvement of the manufacturing engineers, operators and technicians with intimate knowledge of the process. Design engineers must also be involved to ensure that the information content addresses the design community as well. Such joint participation also engenders joint ownership and encourages use of the system. Allocating the resources to undertake these efforts is a necessary first step.

- **Tie the collection of information to populate the information system to the company process improvement and control program.**

As pointed out earlier, a rigorous process improvement and control program requires manufacturing engineers and others to collect and analyze process capability data and to become familiar with the causes of process variation. Thus, synergy exists between process improvement and control and efforts to collect content for a process capability information system.

- **Employ the method of Key Characteristics to focus resources.**

Equal attention to all features and characteristics will waste scarce resources. Many part characteristics are not critical to either product performance or manufacturability. Efforts to populate a process capability information system should focus on the critical characteristics - the Key Characteristics.

### **5.2.3 INFORMATION SYSTEM MAINTENANCE**

The following recommendations address the issues of maintaining the credibility and content of a process capability information system:

- **Make maintenance of the information system part of each department's yearly performance goals.**

An incentive must be in place to ensure that the content of the information system remains up-to-date and of high quality. If this is not so, the credibility of the system will be undermined. The recommendation is to include the maintenance of the information system content in the mutually agreed to performance goals for the appropriate departments. This should include both design and manufacturing engineering to further encourage joint ownership of the information.

- **Establish a system to capture and incorporate process capability information changes.**

In line with the recommendation above, there needs to be a systematic approach for revising the information system content. Information about changes in process capability information need to be collected and incorporated into the system. The existing content of the system needs to be periodically audited. Revisions to the content also need to be agreed to by both the design engineering and manufacturing communities. Companies should develop and institutionalize systematic means to accomplish these tasks.

These recommendations constitute the high-level requirements for enabling data-driven IPD. By instituting process improvement and control and a process capability information system based on these requirements, companies can elevate current IPD performance to a new level. This level is one where the benefits of lower cost, higher quality and faster product design are reached through better informed product, process and supply chain design decisions. The authors' research suggests that these recommendations will lead to the benefits. In the final section of the document, suggestions for further research into this assertion and other applications of process capability feedback is explored.

### **5.3 Further Research**

In this document the authors have hypothesized an approach for improving the quality of IPD decisions through the use of process capability information. This hypothesis led to the formulation of a plan, which although logically supported, has yet to be evaluated in a real IPD environment. Therefore, the first suggested area for further study is to measure the effectiveness of a process capability information system during an actual development program. This would enable the recommendations on design, implementation and maintenance to be evaluated for completeness and validity. This effort would also allow the hypothesis to be explicitly tested.

In discussions with MIT faculty, the authors have learned of a number of large companies attempting to develop process capability feedback for IPD. This provides the opportunity for further study in benchmarking. The objective of such work should be to discover and generalize the best methods of design, implementation and maintenance of a process capability information system.

Another area for research is to extend process capability feedback to enable the impact of process variation to be assessed in the IPD environment. Process capability feedback allows variation to be accommodated in the design. That is to say, the design of the product and the process can be matched. However, assessment of the impact of such variation on the performance of the complete product remains a challenge. Thornton<sup>1</sup> proposes a tool that uses estimates of process variation at the piece-part characteristic level to model the behavior product-level performance. The integration of a this tool and a process capability information system would allow IPT's to quickly determine the impact of decisions such as tolerance allocation and

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<sup>1</sup> Anna C. Thornton, "Quantitative Selection of Variation Reduction Plans".

process selection and to undertake changes to mitigate the risks associated with variation.

Further work should attempt to define the requirements for such an arrangement and to measure its utility.

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# Appendix A

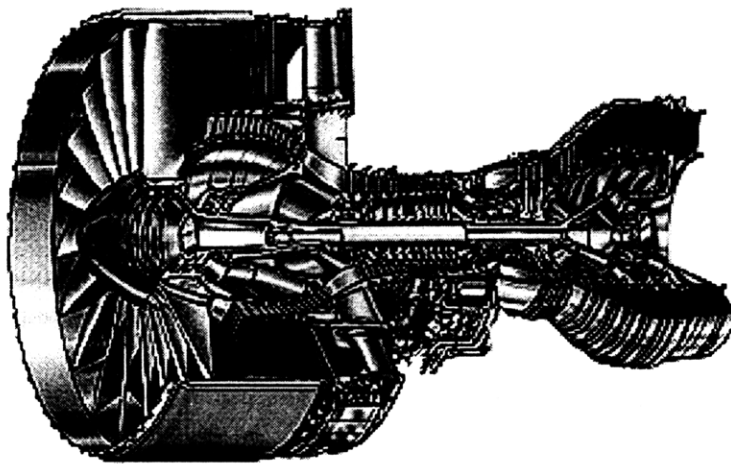
## Pratt & Whitney Products

### ***Introduction***

This section provides a short description of the product architecture and manufacturing environment at Pratt & Whitney.

### ***Pratt & Whitney Product Overview***

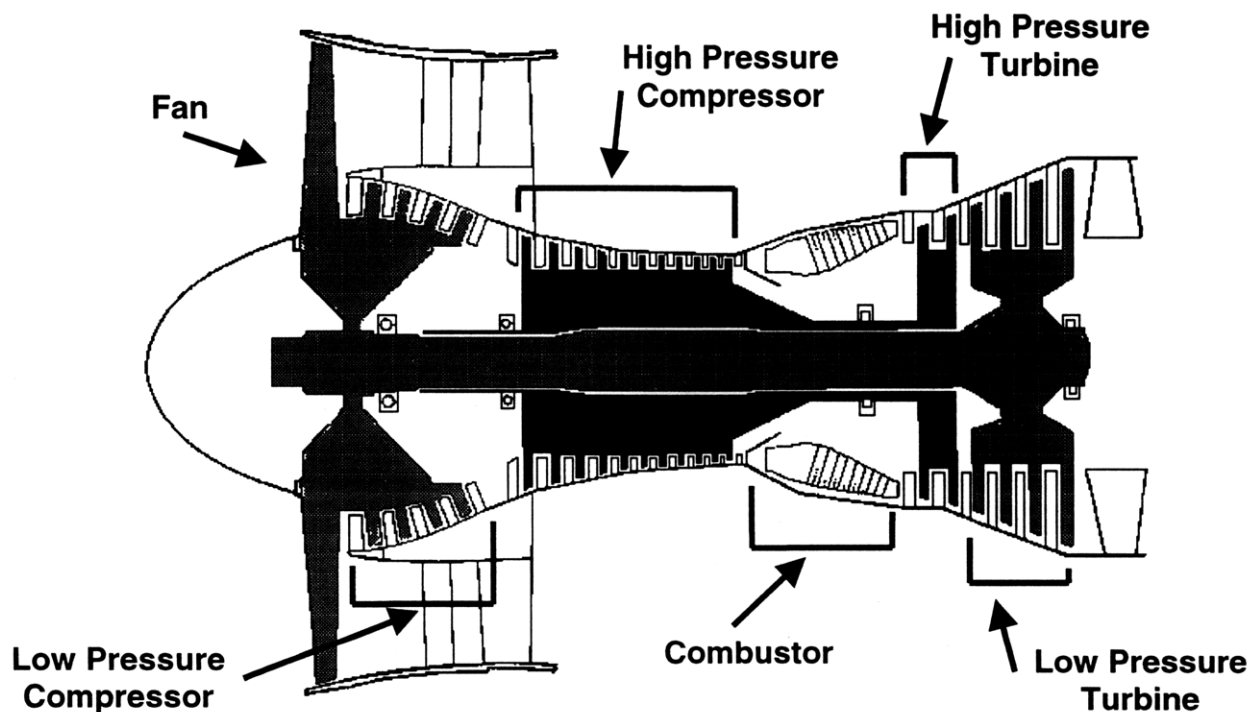
The principal products of Pratt & Whitney are gas turbine engines used for aircraft propulsion. Pratt & Whitney produces several models of engines (as well as engine replacement parts) for a wide variety of commercial and military airplanes and helicopters. The engines currently in production consist of several models of turbofan, turbopropeller, and in the case of helicopters, turboshaft engines. Figure A.1 shows an example of a the large PW4084 turbofan engine used to power the Boeing 777 airplane. Pratt & Whitney also produces a smaller number of gas turbines for stationary power generation, marine propulsion and aircraft auxiliary power applications as well as rocket engines for space propulsion applications.



**Figure A.1: Cutaway View of a Commercial Turbofan Engine**

The turbofan engine comprises the majority of the engine models in production at Pratt & Whitney. Turbofan engines are characterized as having a relatively large axial compressor

(termed a fan) which is driven, via a turbine, by the gas stream of the core gas turbine engine. Figure A.2 shows a simplified schematic of a turbofan engine. Generally, the rotors of the core engine and fan share the same axis of rotation but are mechanically independent, thereby forming what is known as a two-spool engine. The core engine is composed of a compressor (high pressure), combustor and turbine (high pressure) and referred to as the high-pressure spool. The fan, low pressure compressor and low pressure turbine form the low-pressure spool. A significant portion of the air processed by the fan is bypassed around the core engine to improve propulsive efficiency. The gas streams exiting the fan and core engine are expanded through a nozzle to produce thrust. In military engines, the nozzle system may also include an augmentor (afterburner) which increases thrust by re-heating the gas stream prior to the nozzle. Kerrebrock<sup>1</sup> and Rolls Royce<sup>2</sup> discuss gas turbine engines in more detail.



**Figure A.2: Schematic Diagram of a Two-Spool Turbofan Engine**

<sup>1</sup> Jack L. Kerrebrock, *Aircraft Engines and Gas Turbines* (Cambridge, MA: MIT, 1977).

<sup>2</sup> Rolls Royce, *The Jet Engine* (Great Britain: Rolls Royce, plc., 1986).

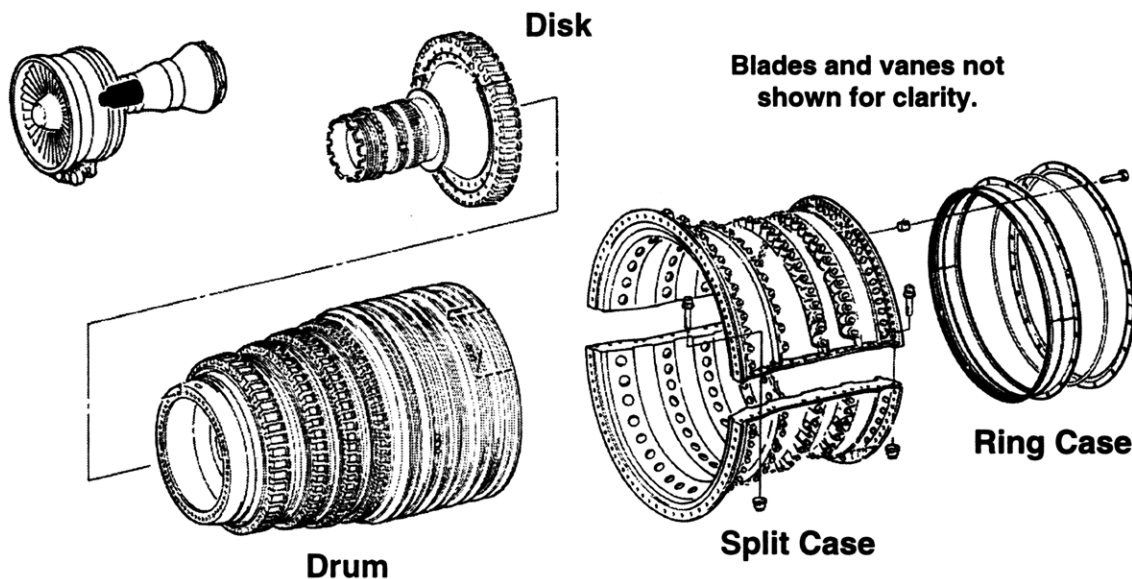


## PRODUCT ARCHITECTURE

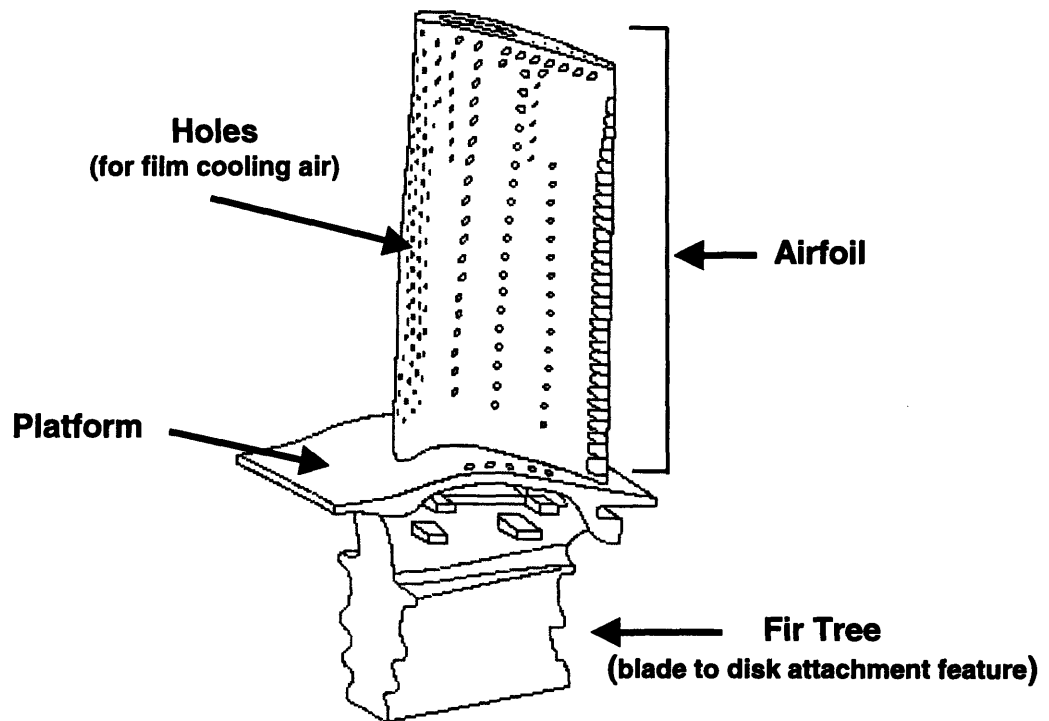
Turbofan engines share a great deal in terms of architecture. This similarity is useful in structuring the process capability information system described in Chapter 4 and gives rise to the notion of feature-based process capability.

Turbofan engines tend to have a module architecture where the six major modules are the fan, low pressure compressor, high pressure compressor, combustor, high pressure turbine and low pressure turbine (as shown in Figure A.2). Of these, the combustor is unique in that it contains only stationary parts (primarily a liner, inside which combustion occurs, and a structural case). The remaining five modules contain rotating equipment (turbomachinery) and have many architectural similarities. Sometimes a seventh module is defined to contain accessories and external components such as gearboxes, tubes, pumps, etc.

Each turbomachine module is composed of a rotating assembly and a stationary assembly. The rotating assembly is made of one or more disks or drums to which airfoils, also known as blades, are attached. The stationary assembly tends to be made of a structural case to which bearing supports and airfoils, also referred to as vanes, are attached. Figure A.3 shows an example of a high pressure compressor rotor and case. Figure A.4 shows an individual turbine blade. Anti-friction bearings support the rotating assemblies from the structure of the stationary assemblies.



**Figure A.3: High Pressure Compressor Rotor and Case Assemblies**



**Figure A.4: View of a Cooled Turbine Blade**

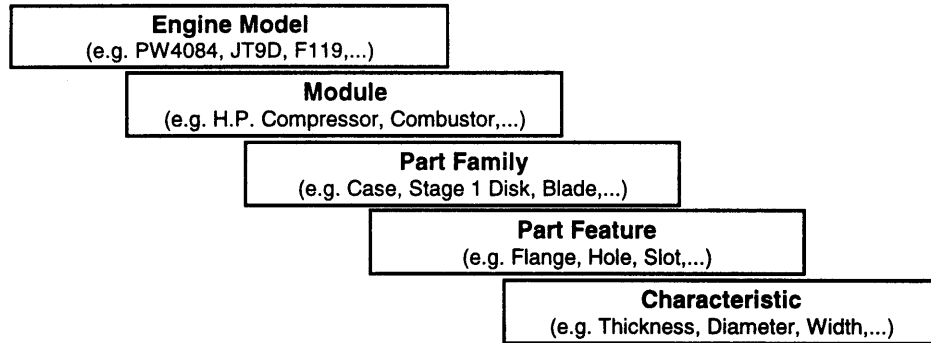
The part types that make up the assemblies just described tend to be grouped into part families which share similar architecture and function. For example, almost all turbine disks have slots for blade attachment as do most compressor and fan disks. Cases tend to have circumferential flanges at both ends and bosses for services such as oil and air. Blades and vanes have airfoil sections. This similarity gives rise to part families, where a family is a group of parts with similar function and similar geometric features<sup>3</sup> (e.g. cooled turbine blades).

This similarity also supports a product architecture decomposition model of the form shown in Figure A.5. This model begins at the engine model and progressively decomposes the product into modules, part families, part features and finally individual characteristics<sup>4</sup>. At the feature level it is possible to define geometric primitive features which exist in many part families. For example, most part families contain parts with holes. The use of geometric primitives reduces the proliferation of feature definitions and eases the problem of coding and classifying the data.

<sup>3</sup> Per the American Society of Mechanical Engineers, *Dimensioning and Tolerancing*, ASME Y14.5M, 1994, a feature is defined as "The general term applied to a physical portion of a part, such as a surface, pin, tab, hole, or slot."

<sup>4</sup> A characteristic is defined herein as a measurable attribute of a part feature such as a dimension (size or position), surface finish requirement, hardness condition, etc..

An enhanced version of this product decomposition model is used in Chapter 4 to organize process capability information for subsequent product feature-based queries.



**Figure A.5: Product Architecture Decomposition Model**

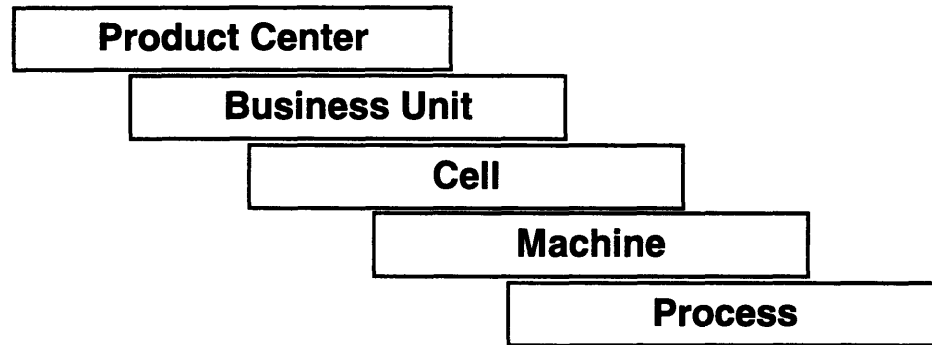
### ***Manufacturing Environment***

Pratt & Whitney manufacturing facilities have a grouped cellular arrangement to take advantage of the product architecture similarities discussed above. Four Product Centers are organized to manufacture four groupings of similar part families: Cases, Rotors and Shafts, Turbine Airfoils and Compressor Airfoils. The Cases Product Center and the Rotors and Shafts Product Center are located in Middletown, Connecticut. The Turbine Airfoils Product Center is in North Haven, Connecticut. The Compression System Product Center is in North Berwick, Maine. In addition, the General Machining Product Center in East Hartford, Connecticut manufactures machined parts which do not fit well into any of the other four Product Centers.

Each Product Center is organized into Business Units which tend to manufacture one or more specific part families. With some exceptions, Business Units are subdivided into cells which are groups of machines (or work stations) that manufacture a specific subset of individuals part from the part family.

The subdivision of Business Units is based on the manufacturing process. Cells might be formed to take advantage of part designs which do and do not lend themselves to automation. In other instances, cells are formed for each of the alternative processing technologies (e.g. turbine blades baffles which have laser drilled holes versus those which have holes made by electro-discharge machining). The cellular arrangement could also be based on the size ranges or materials of the parts in the part family. For instance, large fan cases are machined in a different cell than small fan cases.

This arrangement of manufacturing facilities at Pratt & Whitney suggests a hierarchical model of the form shown in Figure A.6. Note that this model accommodates the situation where that a single machine may perform more than a single type of manufacturing process. For example, a milling machine could be used for drilling and milling. The Process level in this model equates to the Micro Process defined in Appendix C. This model, together the product decomposition model can be used to structure a process capability information system.



**Figure A.6: Organization of Pratt & Whitney Manufacturing Facilities**  
**Summary**

This appendix has provided a brief description of the product architecture and manufacturing environment at Pratt & Whitney. The product architecture and manufacturing process models described herein are useful for organizing information in a process capability information system.

# Appendix B

## Achieving Competitive Excellence Initiatives

### ***Introduction***

This section is provided as an example of how a Process Improvement and Control Program (in this case, Process Certification, which is discussed below) has been integrated with other complementary initiatives at an actual company, namely Pratt & Whitney.

Within manufacturing at Pratt & Whitney a key continuous improvement strategy is called Achieving Competitive Excellence<sup>1</sup>, or as it is more commonly referred to, simply “ACE”. ACE in its simplest form is a three year strategy, but it is actually structured for maintaining gains and continuing improvement well into the future. It is not only directed at improving performance, but also at bringing about a cultural change that instills a sense of ownership within every employee on the shop floor. The structure of this “three year” strategy is best illustrated through a high level description of the ACE Goals.

### ***ACE Goals - Bronze, Silver, Gold***

The Bronze, Silver and Gold level descriptions represent increasingly challenging goals established for every manufacturing Business Unit within Pratt & Whitney for the years 1997, 1998 and 1999, respectively. Each of these the Business Unit goals are further broken down into seven initiatives which are described in the next section.

The Bronze, Silver and Gold levels all have goals within each of the seven initiatives. The Bronze and Silver level goals are critical stepping stones towards reaching Gold. For example, within the Process Certification initiative, the Bronze level goal is to certify the processes which are responsible for 80% of the scrap, throughput losses and lost opportunities within each Business Unit. Subsequently, the Silver level goal focuses on the processes which are responsible for 80% of the remaining scrap, throughput losses and lost opportunities. And finally, the Gold level goal is to complete the effort by certifying the rest of the processes. The next section provides a short description of each of the seven ACE initiatives.

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<sup>1</sup> Pratt & Whitney, *Achieving Competitive Excellence* (Pratt & Whitney internal document).

## **THE SEVEN INITIATIVES**

Each of the seven ACE initiatives listed in Table B.1 has its own set of Bronze, Silver and Gold levels. The goals for each of the initiatives work in conjunction with each other for the overall benefit of the company.

**Table B.1: ACE Initiatives**

- **5S / Visual Factory**
- **Total Productive Maintenance (TPM)**
- **Quality Control Process Charting (QCPC)**
- **Mistake Proofing**
- **Set-up Standardization**
- **Standard Work**
- **Process Certification**

A brief overview of the seven initiatives is provided in the following paragraphs by means of a short description along with an accompanying table of the associated Bronze level requirements checklist. In order for a Business Unit to reach the Bronze level each item on the checklist for every initiative must be completed, with one exception noted for 5S / Visual Factory below.

### **5S / VISUAL FACTORY**

The 5S / Visual Factory initiative focuses on establishing and maintaining a clean and well organized Business Unit. This goes well beyond just simple cleaning. It drives the Business Unit to higher levels of performance by establishing better practices and visual indicators for the work cell status and operations. In the 5S / Visual Factory Bronze level checklist shown in Table B.2, the first nine items (left column) are mandatory. Each Business Unit is then allowed to select three out of the last seven items, for a total of twelve items required to reach the Bronze level.

**Table B.2: 5S / Visual Factory Bronze Checklist**

- |  |  |
|--|--|
| ✓ <b>Weekly Checklists Used</b>                      | ▫ <b>Cell and Workstations In/Out Marked</b>               |
| ✓ <b>Aisles Marked, Clear and Clean</b>              | ▫ <b>Operator Skill Matrix Maintained</b>                  |
| ✓ <b>Documents Controlled per ISO 9000</b>           | ▫ <b>Tools, Gages, etc. Locations Labeled</b>              |
| ✓ <b>Cell Status Board in Place</b>                  | ▫ <b>Shadow Trays in Place</b>                             |
| ✓ <b>Takt Time Clock Visible</b>                     | ▫ <b>Floor Markings in Place</b>                           |
| ✓ <b>Electrostatic Discharge Protection in Place</b> | ▫ <b>Cell Production/People Displays in Place</b>          |
| ✓ <b>Gauss Checks Completed</b>                      | ▫ <b>Walls, Columns, Ceilings, Fans and Lighting Clean</b> |
| ✓ <b>Machines and Area Clean</b>                     |  |
| ✓ <b>Leak Free Plan Completed</b>                    |  |

## **TOTAL PRODUCTIVE MAINTENANCE (TPM)**

Total Productive Maintenance drives to keep machines up and running when they are needed for production. Seemingly simple measures like conducting daily walkarounds (walking around the machine to check items such as fluid levels and leaks, as well as looking for any potential problems which may be developing) allows the Business Unit to catch many small problems before they become major and lead to machine downtime and lost production capacity.

In line with the daily walkarounds are the scheduled maintenance shutdowns. These shutdowns follow an established schedule which allows the Business Unit to plan for the machine to be out of service, such that a comprehensive check and repair of the machine can be completed with virtually no loss of production capacity.

Again, as in the 5S / Visual Factory initiative, visual effects such as the Activity Board used to display current information on TPM progress and the PM Schedule used to display upcoming and completed machine maintenance, provide every employee easy access to information on the TPM efforts of the Business Unit.

### **Table B.3: Total Productive Maintenance Bronze Checklist**

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- ✓ **Enhanced Training Complete and Documented**
- ✓ **Daily Walkarounds Conducted**
- ✓ **Initial Cleaning and Inspection of 75% of Machines**
- ✓ **Preventative Maintenance (PM) Schedule Developed**
- ✓ **Sustained +/- 15% Date Adherence to PM Schedule**
- ✓ **Activity Board Current Data**
- ✓ **Minimum Planned/Unplanned Downtime of 25%**
- ✓ **Top Three Downtime Issues Reduced by 50%**
- ✓ **Machine Failure Analysis Displayed**
- ✓ **Machine Capability Study Completed on 75% of Machines**
- ✓ **25% of Machines Use Less than 25% of Part Tolerance**
- ✓ **Formal Log Out / Tag Out Training Documented**
- ✓ **Lock Out / Tag Out Procedures Followed**
- ✓ **Minimum Overall Equipment Effectiveness of 50%<sup>2</sup>**
- ✓ **Spare Parts List**
- ✓ **Weekly Cell Shutdowns Conducted**

---

<sup>2</sup> OEE is determined using the equation  $(RT-SU-BD-MS-QR)/RT$  where RT is the total time the machine should be available to run (taking into consideration what shifts are operated and the time for meetings and lunch breaks), SU is the time used for machine set-ups, BD is unplanned downtime due to breakdowns, MS is for miscellaneous stoppages when the operator is not running the machine, and QR is the calculated time wasted producing defective parts. The equation above is derived from the more commonly referred to OEE equation  $(AV)(PE)(RQ)$  where AV is Availability, PE is Performance Efficiency and RQ is the Rate of Quality.

## **QUALITY CONTROL PROCESS CHARTING (QCPC)**

Quality Control Process Charting focuses on the identification of any stoppages or delays found in the process. These stoppages and delays are more commonly referred to as turnbacks. The operators play a critical role in QCPC, since they work directly with the process and therefore are in the best position to identify turnbacks and their potential causes.

The data collected by the operator increases the operator's awareness problems in process and allows the Business Unit to allocate resources for process improvement activity to the processes which will provide the greatest gain.

### **Table B.4: Quality Control Process Charting Bronze Checklist**

- ✓ **Enhanced Training Complete and Documented**
- ✓ **Data Collected Daily at Workstations**
- ✓ **Pareto of Highest Identified Processes Displayed**
- ✓ **Project Plan for Corrective Action Displayed**
- ✓ **Success Stories Displayed**
- ✓ **Top Five Turnback Issues Reduced by 50%**

## **MISTAKE PROOFING**

The Mistake Proofing initiative drives the Business Unit to prevent defects from occurring by implementing changes which preclude mistakes from taking place. Redesigning a fixture so that it will only allow a part to be located in a certain orientation, or changing a computer program to limit the range of a cutter on a milling machine are two examples which illustrate how simple changes can help prevent potentially costly problems from occurring.

The philosophy behind this initiative is that there are always opportunities to mistake proof processes in a Business Unit, one just needs to continue to look for them. This philosophy is backed up by the Bronze Checklist requirement that four improvements are implemented each month.

### **Table B.5: Mistake Proofing Bronze Checklist**

- ✓ **Training Complete and Documented**
- ✓ **Four Improvements Implemented per Month**
- ✓ **Record of Implementations Maintained**



## **SET-UP STANDARDIZATION**

Set-up Standardization efforts look at such concepts as driving internal time to external time, and eliminating set-up adjustments. Internal time is considered to be set-up time which could be used for production. External time is considered to be time which is used while production is taking place and is not counted in the actual set-up time. An example of driving internal time to external time is retrieving the fixture for the next set-up while the machine is running.

Eliminating adjustments is a key element in set-up time reduction. Time wasted screwing nuts onto bolts can easily be eliminated by installing quick release (or quarter turn) attachments. Time wasted aligning cutters to a different fixture can easily be eliminated by standardizing all fixtures such that no realignment is required.

In addition, although the use of tools is to be avoided whenever possible, when tools are required they should be well organized and within easy reach. Senselessly wasting time looking for tools can always be avoided. This simple concept falls right in alignment with the 5S / Visual Factory initiative.

### **Table B.6: Set-up Standardization Bronze Checklist**

- ✓ **Training Complete and Documented**
- ✓ **Baseline Set-up Times Reduced by 50%**

## **STANDARD WORK**

Standard Work concentrates on collecting information on each operation required to produce a part such as the order in which the operations must take place, and how long each operation takes to complete (including a breakdown of manual time, automatic time and walk time between operations). With this information, the Business Unit determines how to arrange work cells, how work should be allocated among operators, and how work should be reallocated to react to changing customer demand.

### **Table B.7: Standard Work Bronze Checklist**

- ✓ **Kaizen Event Held**
- ✓ **Simplified Work Instructions Completed**
- ✓ **Standard Work Combination Sheets in Database**

## PROCESS CERTIFICATION

The Process Certification initiative drives each Business Unit to analyze each process (beginning with 20% of the processes for the Bronze level) and implement changes required in order to meet high standards of performance, namely a process capability index ( $C_{pk}$ ) of at least 1.33 and a Defects per Million (DPM) level of no greater than 63. The method used to analyze each process is broken up into ten steps which are shown in Table B.8 below. A detailed review of the Process Certification initiative and these ten steps is provided in Appendix C.

**Table B.8: Process Certification Steps**

<b>Process Mapping</b>	1. Team Formation 2. Process Flow Charts 3. Process Baseline 4. Process Output Prioritizing
<b>Process Improvement</b>	5. Cause and Effect Diagram 6. Root Cause Analysis 7. Process Improvement Verification
<b>Process Control</b>	8. Control Plan 9. Documentation 10. Certification

Process Certification is a systematic approach to variation reduction. By reviewing each step in the process and identifying all sources of variation, the Business Unit can implement changes which both eliminate variation in the process and are cost effective.

A key to the success of Process Certification is the Control Plan. The Control Plan pulls together all of the issues required to keep the process in control and at the same time pulls together all of the ACE initiatives. Refer to the example provided in Appendix C to see how the Control Plan integrates each of the ACE initiatives in order to keep the process under control.

**Table B.9: Process Certification Bronze Checklist**

- ✓ **Training for All Team Members Completed**
- ✓ **Milestones Developed**
- ✓ **20% of Processes Certified (Ten Steps Applied)**
- ✓ **Process Certification Status Displayed**
- ✓ **Gage R&R Studies Completed for Processes Certified**
- ✓ **Top Five External Suppliers Displayed**

# Appendix C

## Process Certification Initiative

### Introduction

This section provides an overview of Process Certification<sup>1</sup>; the initiative which Pratt & Whitney has implemented to address process improvement and control. This overview is presented as a sort of “How To” guide, and is intended to provide supporting information and background for the Process Certification case studies presented in Appendix F.

The Process Certification initiative drives each Business Unit to analyze its processes and implement changes required to reach the high standards of performance attained by achieving a process capability index<sup>2</sup> ( $C_{pk}$ ) of at least 1.33 and a Defects per Million opportunities (DPM) level of no greater than 63. Process Certification is broken into the ten steps listed in Table C.1. below. A description of the ten steps is provided in the next section.

**Table C.1: Process Certification Steps**

<b>Process Mapping</b>	1. Team Formation 2. Process Flow Charts 3. Process Baseline 4. Process Output Prioritizing
<b>Process Improvement</b>	5. Cause and Effect Diagram 6. Root Cause Analysis 7. Process Improvement Verification
<b>Process Control</b>	8. Control Plan 9. Documentation 10. Certification

### The Ten Steps

The ten steps of Process Certification shown in Table C.1 are split up into three basic groups. Steps 1 to 4 fall into the Process Mapping grouping in which the groundwork for Process

<sup>1</sup> Pratt & Whitney, *Process Certification* (Pratt & Whitney internal document).

<sup>2</sup> For more information on process capability indices see: Dr. Madhukar Joshi, “Reporting Process Capability, Everything You Always Wanted to Know, Many Things You Might Not Want to Hear”, *IEEE/SEMI Int’l Semiconductor Manufacturing Science Symposium*, 1993.

Certification is put in place by establishing a solid team and collecting essential information about the process under review. Steps 5 to 7 fall into the Process Improvement grouping in which the details of the process are actually analyzed and changes are implemented. And finally, steps 8 to 10 fall into the Process Control grouping in which the new process is institutionalized and formally certified. An overview of each of the ten steps is included in the following pages.

### **STEP 1 - TEAM FORMATION**

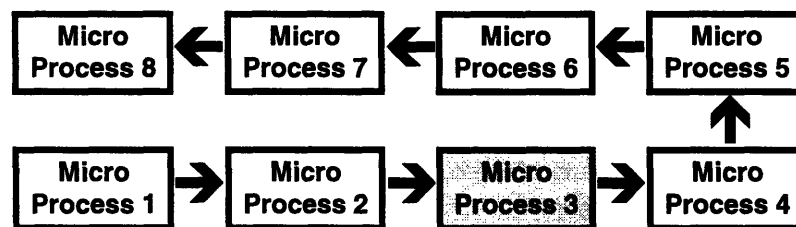
Team formation is an important step for laying a solid foundation and plays a critical role in the success of the Process Certification effort. It is important to have both a supportive manager in the role of the Coordinator and a motivated Team Leader. In addition, good representation from Engineering, Operations (the actual operator who performs the process is preferred), Maintenance, Quality Assurance and Statistical help to drive out effective results.

### **STEP 2 - PROCESS FLOW CHARTS**

With a solid team in place, the focus turns to the actual process. The team reviews part processing documents and walks through the work area to establish the Macro and Micro Process Flow Charts which are discussed below.

#### **Macro Process Flow**

The Macro Process Flow is developed (see Figure C.1) to illustrate how the micro process<sup>3</sup> which is to be certified (Process 3 in this example) fits into the overall flow of processes performed to create a part. The processes in Figure C.1 are shown in the most efficient counter-clockwise cellular arrangement, however, the specific process flow should be shown in an arrangement representative of the actual layout since it could be a source of variation. As the Process Certification effort proceeds it is important to have a clear understanding of the upstream and downstream processes.

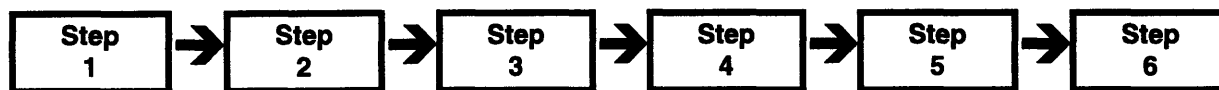


**Figure C.1: Macro Process Flow Example**

<sup>3</sup> A micro process is one of potentially many processes that can be performed on a particular machine.

## Micro Process Flow

The Micro Process Flow is developed by documenting each step completed as the process is performed (see Figure C.2). First hand observation of each step as it is performed is essential. Simply talking to the operator about the process steps almost always leads to missing key issues about the process which can be easily be identified if the time is taken to go through the process step by step.



**Figure C.2: Micro Process Flow Example**

### STEP 3 - PROCESS BASELINE

Once the process flows are documented and understood, the team must collect data from the process. Three types of data are required: the Gage Repeatability and Reproducibility (Gage R&R), Dimensional and Attribute.

#### Gage R&R Data

Data for the Gage R&R study must be collected for each part and entered into the Gage R&R Data Collection form shown in Figure C.3. To complete the Gage R&R study, the information on the top row of the form must be entered along with the data for Operators A and B (generally only two operators are used for this study). Both operators use the same two parts when they collect the five readings for each part. The consistency of the measurements within each set of part data (looking down the columns) drives the gage repeatability calculation, while the consistency of the measurements between sets of part data as measured by the different operators for the same part (e.g., Part 1) drives the gage reproducibility calculation. These calculations are then combined to give the overall Gage R&R, termed Percent of Tolerance Consumed by Measurement Variability as shown at the bottom of Figure C.3.

In order to certify the process, the Gage R&R must be under 20%; however, for a process with a Gage R&R between 10% and 20% there must be a plan in place to achieve a Gage R&R which is below 10%. When the Gage R&R is confirmed, or improved, to be under 20%, the team can begin collecting dimensional data.

Gage No.	Serial No.	Tolerance	Trials	Parts	Operators	Date
			5	2	2	
	Operator A		Operator B		Operator C	
	Part 1	Part 2	Part 1	Part 2	Part 1	Part 2
Gage Reading	1					
	2					
	3					
	4					
	5					
Repeatability (Gage Variation)				Reproducibility (Operator Variation)		
Pct. of Tolerance Consumed by Gage			Pct. of Tolerance Consumed by Operators			
Total Measurement System Variation						
Pct. of Tolerance Consumed by Measurement Variability						

**Figure C.3: Gage R&R Data Collection Form<sup>4</sup>**

### Dimensional Data

Dimensional data must be collected for the part characteristics on which actual measurements are taken. These part characteristics must have a nominal dimension and upper and lower specification limits. For Process Certification, dimensional data from a minimum of 25 parts (to provide a representative spread of the data) is required to calculate the  $C_{pk}$ . As noted in the introductory comments, the requirement for a process to be certified is a  $C_{pk}$  of 1.33 or greater.

### Attribute Data

Attribute data must be collected for each part. Attribute data is part defect data that is collected for which there is not an actual measurement taken. For example, data collected from a go/no-go gage or the presence or absence of a tool mark. For Process Certification, attribute data from a minimum of 100 parts (to provide a representative sample of data) is required to calculate the DPM. As noted in the introductory comments, the requirement for a process to be certified is a DPM of 63 or less.

<sup>4</sup> Source: Pratt & Whitney Gage R&R software program.

#### STEP 4 - PROCESS OUTPUT PRIORITIZING

After the baseline data has been collected, the team evaluates this data in order to determine the areas on which they should concentrate their efforts. Here the Pareto diagram (see example in Figure C.4) is often useful to highlight the top defect occurrences, identify where in the process the most scrap is created, or even determine the most common reasons for machine downtime.

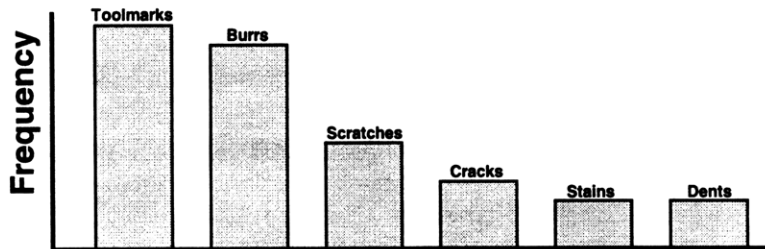


Figure C.4: Pareto Diagram of Defects

#### STEP 5 - CAUSE AND EFFECT DIAGRAM

Once the team has established what should be addressed first, the possible causes of the problem, or effect, must be determined. An effective way to capture the possible causes is via the use of the Cause and Effect (or Ishikawa, or Fishbone) diagram like the one shown in Figure C.5.

There are many variations on what categories are actually used on the Cause and Effect diagram; however, the important thing to keep in mind is that whatever categories are used, they help capture the sources of variation in the process. Also, it is often necessary to branch off from the first possible cause limbs to capture other possible causes.

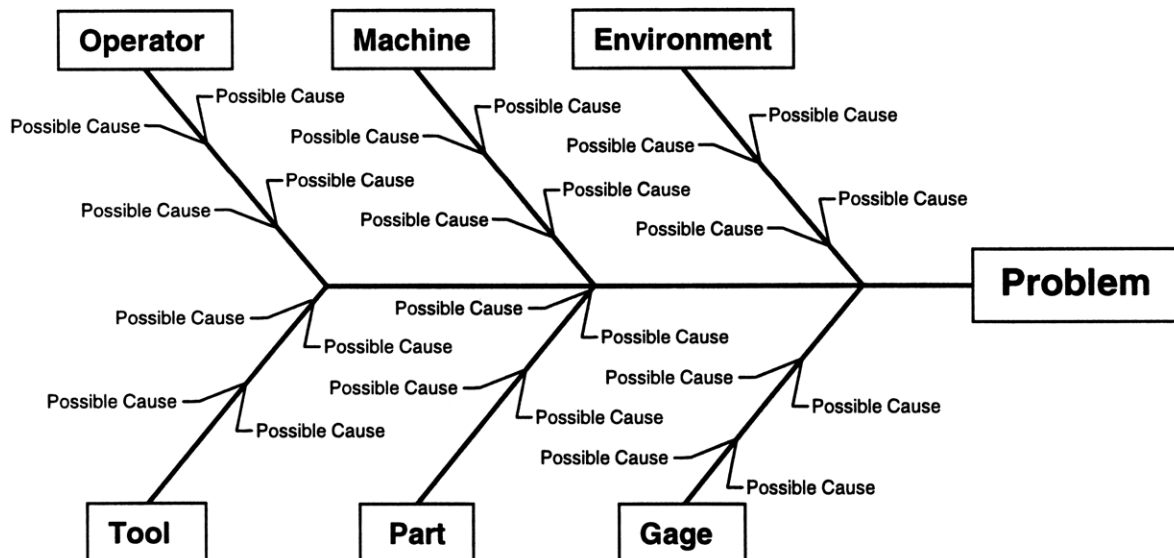


Figure C.5: Cause and Effect Diagram

## STEP 6 - ROOT CAUSE ANALYSIS

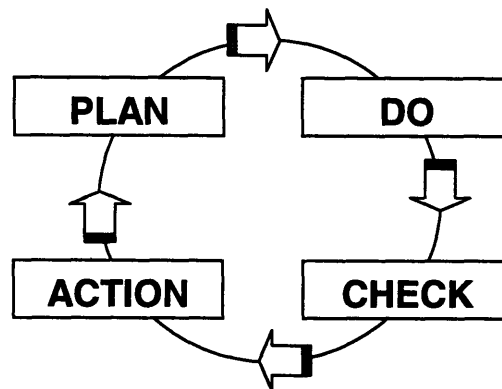
Using the Cause and Effect diagram, the baseline data and the process flow information, the team must identify which possible cause is most likely the greatest contributor to the problem under review. The identified possible cause is then subjected to a root cause analysis. At this point additional investigation may be necessary to answer a series of “Whys” as illustrated in Table C.2. In the past this has often been referred to as the Five Whys, since answering the question “Why?” five times typically lead to getting to the root cause.

**Table C.2: Getting to the Root Cause**

<b>Possible Cause is PC.</b>		
1. Why does PC occur?	☞	Due to A.
2. Why does A occur?	☞	Due to B.
3. Why does B occur?	☞	Due to C.
4. Why does C occur?	☞	Due to D.
5. Why does D occur?	☞	Due to E.
<b>Root Cause is E.</b>		

## STEP 7 - PROCESS IMPROVEMENT VERIFICATION

After identifying the root cause, the team must establish and implement a process improvement plan. The tool used to accomplish this is the Plan-Do-Check-Action Improvement Cycle shown in Figure C.6.



**Figure C.6: Plan-Do-Check-Action Improvement Cycle**

In this cycle, a plan to eliminate the root cause is developed. The plan is then implemented on a test basis. The results are checked to determine whether or not the root cause was eliminated, and the process meets all of the certification criteria ( $Gage\ R\&R \leq 20\%$ ,  $C_{pk} \geq 1.33$ ,  $DPM \leq 63$ ). If the root cause has been eliminated and the process meets all of the certification criteria the changes are formally institutionalized as part of the process.



If the root cause has not been eliminated a new plan must be established and the cycle repeats. However, if the root cause has been eliminated, but the process still does not meet the certification criteria, another root cause must be identified (repeat Step 6) and eliminated. Iterations of Steps 6 and 7 are completed until the process meets all of the certification criteria.

### STEP 8 - CONTROL PLAN

After successfully improving the process to meet the certification criteria, the team must establish a Control Plan for the process. The Control Plan contains information about the critical elements in the process such as the machine, operator, gage, tooling and part, which must be followed in order to ensure the process continues to meet the certification criteria over time. The Control Plan takes the form of simple one page chart (see the sample Control Plan in Figure C.7) to make it easy for those both within and outside the Business Unit to understand the important

<b>Workstation:</b> _____		<b>Cell:</b> _____		<b>Approval:</b> _____		
<b>Audit Frequency:</b> _____		<b>Owner:</b> _____		<b>Date:</b> _____		
<b>What</b>	<b>KPP</b>	<b>Settings</b>	<b>Who</b>	<b>How</b>	<b>Where</b>	<b>When</b>
<b>Machine</b>	Preventative Maintenance	As specified on Maintenance Sheets	Maintenance	Follow PM Documentation	Workstation	Semiannually
	Daily Walkarounds	As specified on Walkaround Sheets	Operators	Follow Daily Walkaround Sheets	Workstation	Daily
<b>Operator</b>	Communication between Shifts	Inform next shift of process variations	Operators	Review Rainbow chart and QCPC form	Workstation	Daily
	Communication with Inspection	Inform operators of process variations	Inspectors	In-line Inspection of every 25 <sup>th</sup> part	Workstation	Every parts lot
	Machine Cleaning	As specified in 5S and TPM standards	Operators	Clean as needed to meet standards	Workstation	During weekly 5S shutdown
	Operator Training	Meet minimum skill requirements	Cell Leader	Use established procedures	Where arranged	As required
	Work Instructions	As specified in Work Instructions	Operators	Follow Work Instructions	Workstation	Every part
<b>Gage</b>	Gage Calibration	As specified in Gage Standard procedures	Gage Standard	Follow Gage Standard procedures	Gage Standard office	Calibration due date
	Gage R&R	Maintain Gage R&R $\leq 10\%$ of part tolerance	Operators	Take readings and calculate Gage R&R	Gage table	Calibration due date
<b>Tooling</b>	Die Surface	Maintain die surface to Die Standards	Die Makers	Follow Die Standard procedures	Die Room	Check die surface after each parts lot
<b>Part</b>	QCPC	As specified on QCPC forms	Operators	Fill out QCPC form and analyze results	Workstation	Daily
	$C_{pk}$	Maintain $C_{pk} \geq 1.33$	Operators	Track data using Rainbow chart	Gage table	Every parts lot
	Yield	Maintain $DPM \leq 63$	Operators	Fill out QCPC form and calculate DPM	Workstation	Daily

**Figure C.7: Sample Control Plan**

elements. However, there is a great deal of supporting documentation behind the Control Plan that actually serves as the mechanism for controlling the process.

For each of the critical elements of the process (the “What” in Figure C.7) Key Process Parameters (KPP), along with the corresponding details, namely “Settings”, “Who” is responsible, and “How”, “Where” and “When” the action should be accomplished, are included. The simplicity and comprehensiveness of the Control Plan promotes success.

### **STEP 9 - DOCUMENTATION**

In preparation for the formal certification of the process, the team must compile all of the data and information gathered during the Process Certification effort and document all of the work completed. This documentation also clearly defines how the improved process, along with the Control Plan and its supporting documentation, will produce defect free results.

### **STEP 10 - CERTIFICATION**

When Steps 1 to 9 have been completed the certification package for the process, which is essentially a compilation of the information generated in Steps 1 to 9, is submitted to the Product Center Process Certification Focals for review. The package is then passed on to the Product Center Continuous Improvement Manager for final sign-off.

### **THE IMPORTANT “11<sup>th</sup>” STEP**

Process Certification doesn’t end with the certification package sign-off. In order to maintain the gains of Process Certification the certified process is periodically audited (typically at six month intervals).

### ***Summary***

Process Certification provides a structured approach to reducing process variation and developing capable processes. Simple practices such as observing the operator perform the process combined with the use of proven tools such as Cause and Effect diagrams and Improvement Cycles can lead teams to achieve remarkable results. Process Certification not only provides the direct benefits such as drastically reduced (or eliminated) rework and scrap, but also establishes a foundation of capable processes that generate reliable data that can be used for further improvement. Through a common understanding, in Manufacturing, Engineering and other functional organizations, of what a “certified process” really means, process capability data can be used for greater benefits in product, process and supply chain development.

# Appendix D

## Integrated Product Development (IPD) at Pratt & Whitney

### ***Introduction***

This section provides an overview of the Integrated Product Development (IPD) process in use at Pratt & Whitney and describes an associated information system strategy known as “IPD of the Future”. The description of the Pratt & Whitney IPD process is provided as general background. The section on IPD of the Future describes a process capability information system which serves as a case study for this thesis.

IPD at Pratt & Whitney has a narrower scope than that described elsewhere in this document. At Pratt & Whitney, IPD includes product and manufacturing process design but typically excludes supply chain design. Appendix E describes some important aspects of the Pratt & Whitney supply chain design process.

Information presented in this section was derived from Pratt & Whitney IPD documentation<sup>1</sup>, interviews with engineers and managers at Pratt & Whitney, and the experience of the author who was privileged to have attended many meetings of a functioning Integrated Product Team.

### ***IPD Process Basics***

Integrated Product Development (IPD), also known as Concurrent Engineering, is the business process whereby the development of the product is concurrent and integrated with development of the associated manufacturing processes. Per Ulrich and Eppinger<sup>2</sup>, Concurrent Engineering uses cross-functional teams to carry out product and process designs in an integrated way. These teams are typically composed of representatives from Engineering, Manufacturing, Marketing, Quality Assurance and a variety of other functions such as Purchasing, Product Support and Finance. The membership evolves through the life cycle of the project, but generally centers around a core group of individuals who have direct accountability for the deliverables of the team

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<sup>1</sup> Pratt & Whitney, *Operating Guidelines for Integrated Product Development at Pratt & Whitney*, (Pratt & Whitney internal document, June 4, 1992).

<sup>2</sup> Karl T. Ulrich and Steven D. Eppinger, *Product Design and Development*, (New York: McGraw Hill, Inc., 1995).

(often these would be individuals from Engineering, Manufacturing and Marketing). See Ulrich and Eppinger<sup>3</sup> for a more extensive description of typical product development teams.

### ***The IPD Process at Pratt & Whitney***

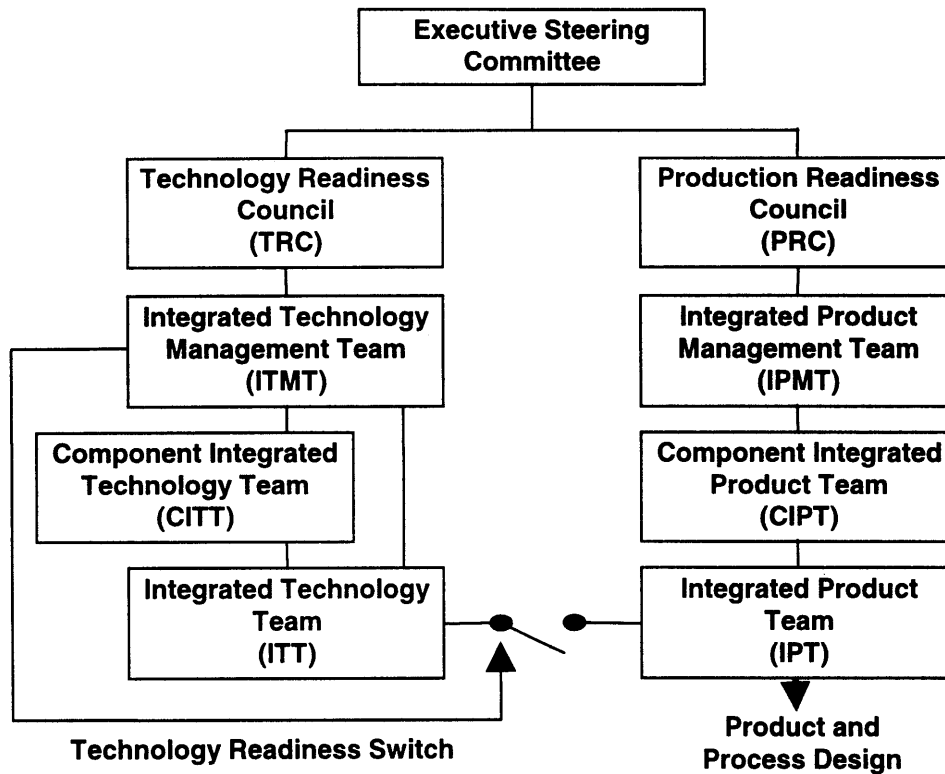
A structured Integrated Product Development (IPD) process has been formally in place at Pratt & Whitney since 1990. The ownership of this process resides with the office of the Executive Vice President of Technical. The IPD process is given structure by a set of operating guidelines<sup>4</sup>. These guidelines define the goals of IPD and the roles of the supporting functional organizations as well as the membership, organization, responsibilities and authority of the various teams that carry out the process.

The stated goals of IPD are to: “create products which meet customers’ requirements and fulfill Pratt & Whitney’s business objectives; achieve technology readiness consistent with program requirements; reduce lead time between design concept and product maturity; and ensure that engineering requirements, manufacturing processes, and customer support requirements are compatible.” Alignment with these goals is administered through a hierarchy of cross-functional teams. Figure D.1 shows the overall structure of this hierarchy.

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<sup>3</sup> *Ibid.*

<sup>4</sup> Pratt & Whitney, *Operating Guidelines for Integrated Product Development at Pratt & Whitney*, (Pratt & Whitney internal document, June 4, 1992).



**Figure D.1: IPD Process Organization at Pratt & Whitney**  
(simplified from Pratt & Whitney<sup>5</sup>)

The IPD process is headed by the Executive Steering Group. This team is composed of the top leadership of Pratt & Whitney and establishes product and business strategy. The Executive Steering Group has approval responsibility for engine program launch, technology initiatives and partnership agreements. Below this level IPD is divided into two segments: the Technology Readiness and Advanced Programs branch and the Product Readiness branch. Each of these branches, particularly the Production Readiness branch, has an organization that mirrors the modular product architecture that typifies an aircraft gas turbine engine (see Appendix A).

### **TECHNOLOGY READINESS AND ADVANCED PROGRAMS**

The Technology Readiness and Advanced Programs branch is responsible for oversight of technology development and determines when such technology has reached sufficient maturity to be ready for production development. This part of IPD is headed by the Technology Readiness Council (TRC) which is composed of vice presidential or director level management from disciplines such as Engineering, Manufacturing and Research.

<sup>5</sup> *Ibid.*

Below the TRC are three levels of cross-functional teams. These levels are, from top to bottom, Integrated Technology Management Teams (ITMT), Component Integrated Technology Teams (CITT) and Integrated Technology Teams (ITT). Each of these levels is responsible for an increasingly focused aspect of a new technology.

The ITMT is responsible for technology development at the program level (engine program or generic technology program). CITT's are used to manage the development of a technology that is specific to a particular engine component (i.e. turbine, compressor or combustor). ITT's are the lowest level in this structure and are the actual teams of engineers, scientists and technicians working to carry out technology development. ITT's might be overseen by an ITMT, if working on a generic technology project, or by a CITT, if developing a component-specific technology.

### **PRODUCTION READINESS**

In much the same way that the TRC oversees technology development, the Product Readiness Council (PRC) is responsible for product development. The PRC is a vice presidential team representing such functions as Engineering, Manufacturing, Purchasing and Finance. Pratt & Whitney has established two PRC's, one for each major product market segment: Government Engines and Space Propulsion (GESp) and Commercial Engine Business (CEB). Each of these PRC's is headed by the vice president of the respective market segment.

Beneath the PRC are three levels of cross-functional teams: Integrated Product Management Teams (IPMT), Component Integrated Product Management Teams (CIPT) and Integrated Product Teams (IPT). IPMT's generally have product development responsibility for an entire engine program. CIPT's manage the development of specific engine components and report to an IPMT. Following the product decomposition, IPT's are responsible for the development of a part or assembly within a particular component and report to the appropriate CIPT.

The IPT is the heart of the IPD process at Pratt & Whitney. IPT's are generally formed at the launch of an engine program and continue through initial production. IPT's are usually composed of representatives from Engineering, Manufacturing (may include one or more suppliers), Purchasing, and Product Support. On occasion a customer representative associated with an airline, an airframe manufacturer, government agency or armed service may be included.

The prime responsibility of the IPT is to develop a product and process design such that the requirements flowed down from the IPMT and CIPT are satisfied. These requirements take the

form of engineering data such as temperatures, pressures, physical envelope, etc. as well as cost and schedule. Such system and component level requirements are defined by the IPMT and CIPT's based on customer requirements, government regulations and Pratt & Whitney business objectives. When such requirements cannot be satisfied, the IPT's role is to elevate these issues to the CIPT or IPMT for reconsideration at the system level.

## RESULTS

Pratt & Whitney has seen significant benefits as a result of adopting an IPD process<sup>6</sup>. The literature also contains many other examples<sup>7</sup> of how IPD has proven to be superior to the previous sequential development process. Prior to IPD, completely engineered product definition was “thrown over the wall” for manufacturing engineers and operators to struggle with in production. IPD has resulted in higher initial product quality and lower manufacturing cost. Aerospace firms such as Pratt & Whitney had a history of favoring product performance over manufacturability (or cost). These days are gone. IPD has helped Pratt & Whitney to reduce costs and improve quality by giving manufacturing a stronger voice in product development.

Although IPD is a significant improvement, there remain at least three recurring problems expressed by practitioners of IPD at Pratt & Whitney:

- Information describing the capabilities of manufacturing processes is difficult to obtain.
- Manufacturing process designs are not standardized resulting in unnecessary cost, complexity, and lost learning.
- Product designs are often optimized to the pre-production or prototype manufacturing processes rather than to the volume production process.

***Manufacturability information is difficult to obtain.*** One Pratt & Whitney Engineering manager indicated that as much as 75% of the IPT member engineers' time is spent searching for information. During the detail design phase much of this search is for manufacturability information. Often times this search is unsuccessful and IPT members must rely on the “gut feel” of the manufacturing engineers. This sort of information is frequently much less effective than the more accessible, highly credible performance data available from testing, analysis and field experience. The result of this imbalance between manufacturability and performance

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<sup>6</sup> James P. Womack and Daniel T. Jones, *Lean Thinking: Banish Waste and Create Wealth in Your Corporation*, (New York: Simon and Schuster, 1996), page 165.

<sup>7</sup> The references of Chapter 3 provide other accounts of the benefits of IPD.

related information has tended to drive designs that favor product performance (over manufacturability). This in turn has caused significant and costly redesign activity during initial production. Another Pratt & Whitney Engineering manager stated that as much as 30% of Class II engineering changes<sup>8</sup> are for manufacturability reasons

***Manufacturing design is not standardized.*** Process designs are typically developed based on the design of similar parts already in production or based on the experience of the individual manufacturing engineer. This results in a proliferation of processes for producing similar features. A Pratt & Whitney manager stated that a review of processes for making similar holes revealed at least six significantly different processes in use. This proliferation is adverse because the most cost effective processes are not always chosen, many more configurations of cutting tools must be in inventory, and because of learning that is lost when manufacturing engineers are reassigned to other areas.

***Product design is not optimized to the volume production process.*** As described in Appendix A, the life cycle of an engine program is such that there is generally a requirement for a few engine sets of hardware for test purposes followed by a delay before production ramp-up. This situation means that different manufacturing sources are often used for pre-production and production. The difficulty comes from the fact that it is usually the pre-production source that dominates that manufacturing representation on the IPT. The result is a product design that requires engineering changes to be cost effectively manufactured at the production source

The following section, “IPD of the Future” (IPDoF), and Appendix E, Sourcing at Pratt & Whitney, discuss two strategies that Pratt & Whitney is implementing to address these issues. IPDoF chiefly deals with the availability of manufacturability information and process standardization. Day One Sourcing addresses the failure to optimize designs for the production source.

### ***“IPD of the Future”***

The office of the Chief Manufacturing Engineer at Pratt & Whitney has undertaken a series of initiatives to improve the IPD process. This set of initiatives has come to be known as “IPD of the Future” (IPDoF). IPDoF aims to improve the product development process by capturing

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<sup>8</sup> Engineering Changes are design revisions that occur after the release of the basic part design. Class II changes are generally considered minor changes and have been described as not affecting fit, form or function.



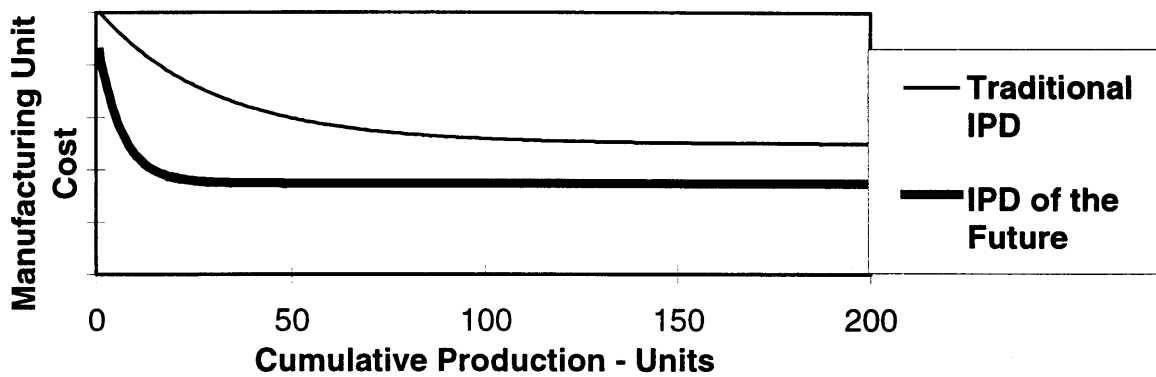
manufacturing process capability information for use by IPT's, by standardizing the methods used by manufacturing engineers and by improving certain business processes that affect IPD. This section devotes attention to the process capability information system aspect as this is the research topic.

The vision of IPDoF is that design decisions must be driven by manufacturing data ("Data-Driven IPD"). As pointed out previously, IPT's are often confronted with a difficult search when trying to find information about the manufacturing process capability and yet often have ready access to engineering data and field experience. As discussed previously, this situation is believed to result in design decisions that favor performance over manufacturability. IPDoF aims to correct this tendency by providing an information system that will collect, analyze and display process capability data for use by IPT's. Before discussing this information system in detail we shall describe the goals that Pratt & Whitney have set out relative to IPDoF.

#### **GOALS FOR IPD OF THE FUTURE:**

##### **"Learned Out by 25"**

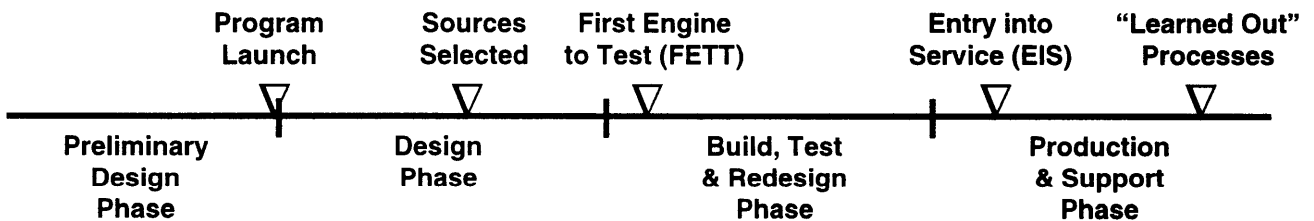
Learned Out By 25 is defined in the context of the manufacturing learning curve (see Figure D.2). The first aspect of the definition is that new parts must be introduced so as to reduce the initial unit cost. The second aspect is that a reduction in unit cost over time (i.e. the learning) must occur rapidly so that unit costs will essentially reach the final asymptotic value by the time that the 25<sup>th</sup> production unit has been manufactured. As shown in Figure D.2, Pratt & Whitney has traditionally experienced a learning curve that takes 100 or more engines worth of production to reach the "learned out" unit cost. "Learned Out by 25" challenges the IPT's to do a better job of designing for manufacturing up-front and to quickly respond to issues that arise once production has started. Note that the area between the two curves of Figure D.2 represents cost savings.



**Figure D.2: “Learned Out by 25” Goal of IPD of the Future**

**Reduced IPD Flow Time**

The second goal of IPDoF is to reduce the time required to take an engine design from the time of program launch to the time at which the first engine enters service with the customer (Entry Into Service -EIS). Figure D.3 shows some key milestones in the life cycle of a typical engine program. Traditionally, major engine programs have required 60 months from program launch to EIS. The goal Pratt & Whitney has set for future programs is 30 months from launch to EIS. This goal is comparable to the goals adopted by other aerospace firms such as Boeing and GE and Boeing.

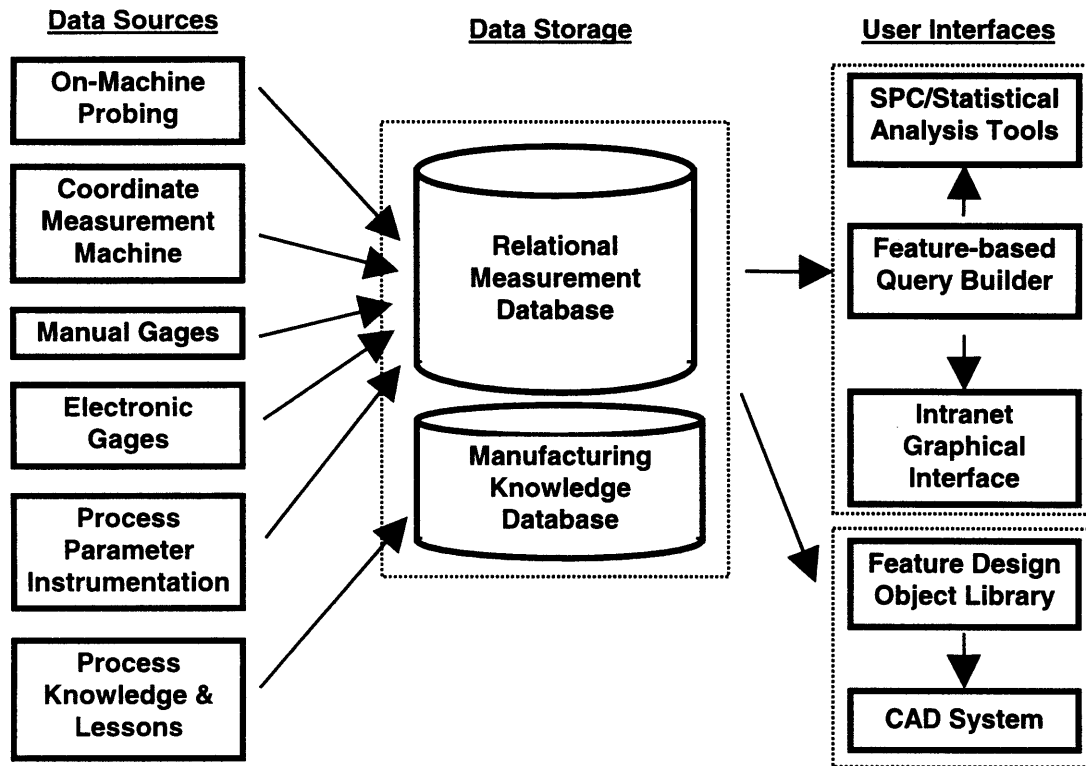


**Figure D.3: Typical Engine Program Life Cycle**

**Information Technology Strategy**

The use of information technology is a key strategy of IPDoF. To meet the goals described in the foregoing sections IPDoF must enable engine parts to be designed faster and with far fewer changes required for production. Having manufacturing process information within the easy reach of the IPT’s is considered to be the means to these ends. Figure D.4 is a schematic of the information system which Pratt & Whitney is constructing to make this information available to

the IPD process. Following this schematic is a description of the data sources, data storage and user interface elements of this system.



**Figure D.4: IPD of the Future Process Capability Information System**

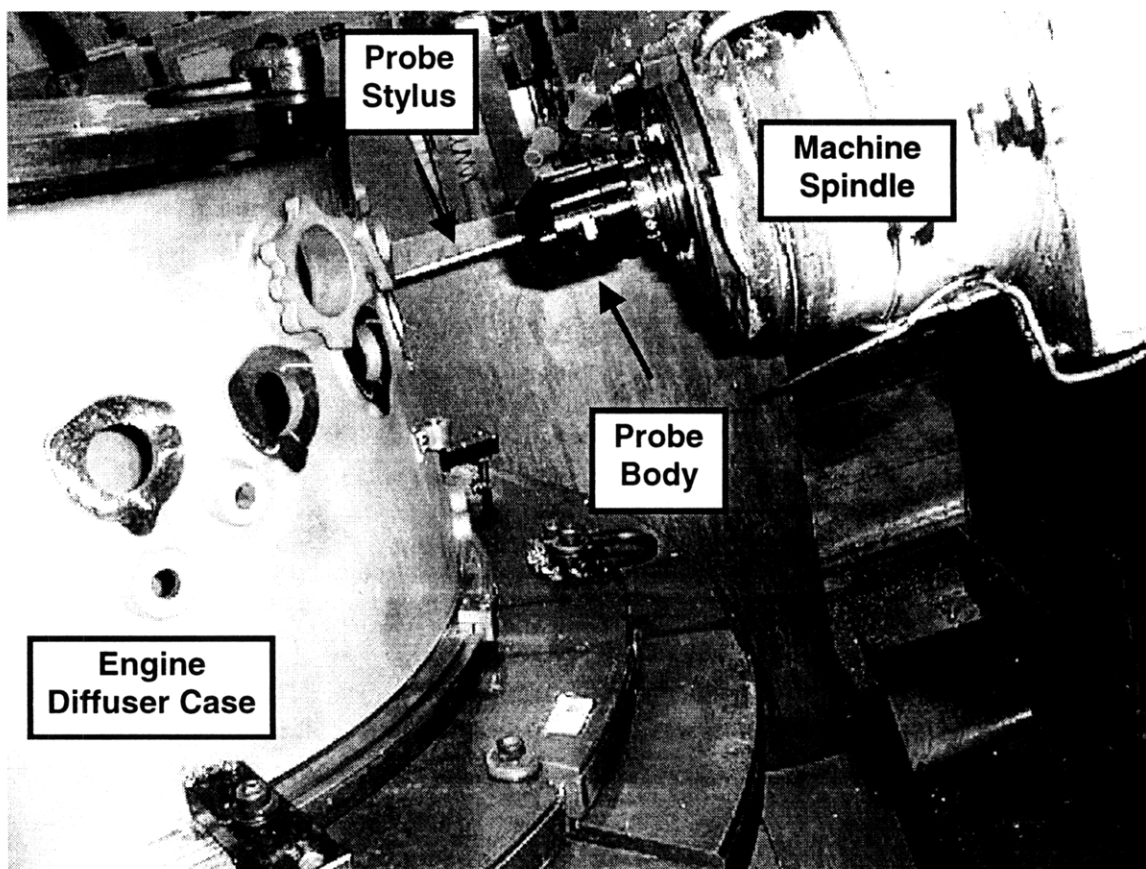
## DATA SOURCES

The information to be gathered by this system is of two different types. One type is the statistical data gathered from measurements of actual parts or from monitoring critical process parameters. This data comes from the shop floor via the upper five sources shown in Figure D.4. The second type of information is knowledge about manufacturing processes which resides in a variety of places including in the minds of experienced manufacturing engineers. This information input is depicted as Process Knowledge in the figure.

### On-Machine Probing

The first source of statistical data is On-Machine Probing. This technique uses the machine tool itself as a measurement device. A touch sensitive probe located on the machine tool is used to make measurements (size or position) of the part being processed or of the setup (fixture

location, cutting tool length, etc.). Figure D.5 shows an example of this means of data collection. Probing can be added to the Computer Numeric Control (CNC) program of the machine so that measurements are automatically taken of each part. These measurements may be done prior to the first operation, between operations and on the completed part. Pratt & Whitney uploads this data to a database over an electronic network. The measurements that are generally probed are finished part dimensions specified by the engineering digital model (or blueprint) and certain in-process measurements of interest for process control. Pratt & Whitney and others have been using probing more and more to collect data and to reduce the need for separate post-process inspections. Christensen<sup>9</sup> et. al. provide a more detailed description of the use of on-machine probing.



**Figure D. 5: Example of On-machine Probing**  
(A Milling Machine Probing an Engine Diffuser Case Boss)

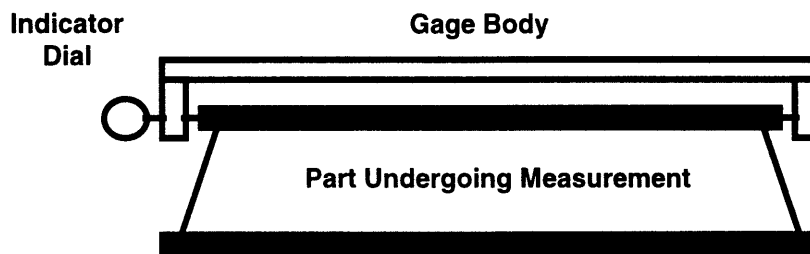
<sup>9</sup> Naomi G. Christensen, Lane D. Harwell, and Andrew Hazelton, *Laboratory Directed Research and Development Final Report: Intelligent Tools for On-Machine Acceptance of Precision Machined Components*, Sandia Report SAND96-2329 UC-906, (Sandia National Laboratories, February 1997).

## Coordinate Measurement Machines

The second data source is Coordinate Measurement Machines (CMM). This means of data collection is similar to on-machine probing in that a touch sensitive probe is used to make size and position measurements of an article at specified locations. The key difference is that the CMM is a separate device from the machine tool and is used only for inspection. As with probing, the data gathered by a CMM can often be uploaded directly into a database. Pratt & Whitney generally uses CMM's for finished part inspection, where on-machine probing is not available, as well as to periodically check other means of inspection.

## Manual Gages

The third source of data collection is manual gages. As the name implies this means uses hand-held or bench-top gages to make measurements (see Figure D.6). The data is then recorded by the operator and later entered into the database via a computer interface. This means of data collection is often the least desirable due to errors that can occur in reading the gage or during data entry.



**Figure D.6: Manual Gage Measurement of a Flange Diameter**

## Electronic Gages

The fourth source is electronic gages. This is similar to the manual gage method except that the gage is outfitted with a transducer that converts the gage reading directly into an electronic signal. An electronic link relays the gage signal to a database via an electronic link (hardwire or radio frequency). This type of data collection is becoming more prevalent at Pratt & Whitney as manual gages are being converted to electronic form.

## Process Parameter Instrumentation

The fifth source of data collection is Process Parameter Instrumentation. This is a broad category of which includes data that tends to be internal to the process and, in general, other than measurements of part geometry. Examples of this data are heat treatment furnace temperatures and times, machine tool feeds and speeds, bonding press pressures, etc. This sort of data is

collected primarily for process control. Transducers located on the process equipment acquire this information for subsequent manual or automatic recording.

### **Manufacturing Knowledge**

The sixth and final data source is Manufacturing Knowledge. This is the textual and graphical information about manufacturing processes that is referred to as the *competency* component of process capability. This information can include process critical settings or recipes, manufacturing trade factors (e.g., relative cost versus surface finish requirement), and other manufacturing related learning. Currently this information is difficult to retrieve and maintain owing to the fact that it resides in a variety of places such as manuals, handbooks and in many cases only in the memories of the experienced individuals in the organization. The intent is to capture and organize critical information from across the organization to form a resource for manufacturing engineers who are designing future processes or troubleshooting existing ones. If successful this tool will help to standardize manufacturing processes on the designs that have proven most capable and cost efficient. There remain significant issues regarding how to format and organize this information as well as how to provide incentives for people to collect and maintain this information. At the time of writing, Pratt & Whitney has yet settle these issues. Appendix G describes another approach underway at Pratt & Whitney to collect some manufacturing knowledge into a Lotus Notes™<sup>10</sup> database.

### **DATABASE**

Pratt & Whitney is considering an Oracle™<sup>11</sup> relational database to warehouse the information gathered from the aforementioned data sources. Currently, measurement data at Pratt & Whitney is stored in a variety of databases (VAX based, PC based and mainframe). Pratt & Whitney is also planning to use a Lotus Notes™ document database to collect and store knowledge information. The intent is that all of these databases will be migrated to or accessed through the Oracle™ database. The precise architecture and content of this Oracle™ database has not been finalized at time of writing. However, certain requirements regarding structure and content have been settled and are discussed below.

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<sup>10</sup> Lotus Notes is a registered trademark of Lotus Development Corporation.

<sup>11</sup> Oracle is a registered trademark of Oracle Corporation.

## **Feature-Based Structure**

The primary structural requirement of the database is based on the notion of a feature. A feature is some aspect of a part that is typically described by a set of characteristics<sup>12</sup>. For instance, defining a hole as a feature leads to quantities such as position (x, y, z), diameter, length, and surface finish becoming some of the appropriate characteristics. As described in Appendix A, the architecture of gas turbine engines decomposes into features that tend to be similar in form (geometry) and tend to be created by comparable manufacturing processes. The primary intent of the feature-based construct is that powerful insight can be gained by comparing the manufacturing capabilities to produce a given feature across part families, machine tools, manufacturing cells, plants, suppliers, etc. For instance, a manufacturing engineer faced with designing a process to produce a feature, say a pattern of flange holes in a compressor case, will be able to begin down-selecting to the optimum process design by comparing the capabilities of flange hole producing processes in use across the entire enterprise (and possibly the supply base). From the IPT standpoint, engineers designing a feature will be able to confidently specify design tolerances that are manufacturable or to identify early on when a more capable process is needed. Chapter 4 provides several detailed examples of how such feature-based comparisons can be used in IPD.

## **Information Content and Associativity**

The database must contain enough information to capture certain unique relationships in order for meaningful feature-based queries to be made. Each entry of measurement data must be related to both a characteristic<sup>13</sup> and the specific manufacturing process step which created it. Each characteristic must in turn be related to a feature, part family, engine component module and so on. Each manufacturing process operation must be related to a specific machine (or group of machines), manufacturing cell, business unit and plant<sup>14</sup>. The database existing at Pratt & Whitney already contains much of this information. What is missing are the characteristic and feature identifiers for each element of data. These identifiers are needed if data is to be extracted

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<sup>12</sup> See Appendix A for further explanation of features and characteristics.

<sup>13</sup> A characteristic is a measurable attribute of a feature associated with a single engineering drawing requirement (i.e. a single dimension). See Appendix A for additional detail.

<sup>14</sup> Appendix A provides a description of the organization of Pratt & Whitney manufacturing into Product Centers, Business Units and cells.

on a feature basis<sup>15</sup> using standard feature and characteristic nouns (e.g., hole diameter). Pratt & Whitney intends to develop a standard dictionary of nouns to serve as these identifiers. Additional discussion of this dictionary is provided in Appendix G.

Appendix A discusses two models that can be used to represent the associativity of this data. One model captures the unique relationship between a measured characteristic and the product architecture (feature, part family, module and engine model). The other model captures the relationship between a process and the factory infrastructure (machine, cell, unit, plant).

## **USER INTERFACES**

Three sorts of user interfaces are planned for this system: an SPC/statistical analysis interface, a textual/graphical intranet interface and a feature-based Computer Aided Design (CAD) library.

### **SPC/Statistical Interface**

The statistical interface is included to conduct analysis of the measurement data collected from the five shop floor data sources. This interface will allow real-time SPC or process capability studies to be conducted. During the research period, Pratt & Whitney was evaluating several statistical software analysis packages for this interface.

The statistical interface depends on a query builder to extract the desired dataset from the database. As depicted, Pratt & Whitney intends to develop a feature-based query builder to perform this function. The prototype detailed in this document includes such a feature-based query builder.

### **Intranet Interface**

A combination of a Lotus Notes™ and the Pratt & Whitney intranet has been proposed as a means to access textual and graphical information contained in the database. Lotus Notes™ could be used to construct and populate a series of documents which could then be navigated and viewed over the company intranet using a web browser such as Netscape™. This combination of Lotus Notes™, the intranet and Netscape™ has been used successfully elsewhere in Pratt & Whitney. Appendix G describes one such application.

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<sup>15</sup> In the Pratt & Whitney data system, measurements of individual characteristics are uniquely identified by five parameters: Part Number, Part Serial Number, Operation Number, MQI/IMS Number and Channel Number. The Operation Number, MQI/IMS Number (which identifies a process step) and Channel Number (which identifies an individual measurement taken in that process step) tend to be arbitrarily assigned. This arbitrary assignment makes feature-based comparison across part families or processes very difficult.



The statistical interface, query builder and intranet interfaces are shown surrounded by a dashed line in Figure D.4 to symbolize the objective that the user applications appear as one integrated interface.

### **Feature-Based CAD Library**

The third interface planned for this system is a library of standard feature models. This library would be accessed through a CAD system such as Unigraphics<sup>TM16</sup>. Unigraphics<sup>TM</sup> is the CAD system used by Pratt & Whitney to create digital models that define the engineering configuration of parts and assemblies. The intent of this library is to facilitate faster and higher quality creation of digital models. The library will provide engineers with standard feature geometry which may be combined to develop the model of a complete part or assembly.

The feature models are intended to include more than just standard geometry. The plan is that a standard “tool kit” consisting of CNC program routines, cutting tool definition, and fixture design information will be associated with each feature model. It is also intended that the feature models will have pre-assigned tolerances that are within the current process capability. The objective is that this library will allow rapid creation of models that are “guaranteed” producible.

### **Summary**

This appendix has described the IPD process used at Pratt & Whitney as well as the initiative known as IPD of the Future. Integral to IPD of the Future is the notion of manufacturing process capability feedback. The information system described in this appendix is as an example of how such feedback might be implemented.

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<sup>16</sup> Unigraphics<sup>TM</sup> is a trademark of Electronic Data Systems, Inc.



# Appendix E

## Source Planning at Pratt & Whitney

### ***Introduction***

The purpose of this section is to describe certain aspects of the supply chain design process at Pratt & Whitney in order to show the applicability of a manufacturing process capability information system to source selection decisions. Some basic characteristics of the Pratt & Whitney supply chain are described, followed by a discussion of past and current source selection processes. The primary resource for this information has been interviews at Pratt & Whitney<sup>1</sup>.

### ***Characteristics of the Supply Chain***

Aircraft engines are complex machines with correspondingly complex supply chains. Engine parts range from twelve foot diameter fan containment cases to tiny compressor blades to microprocessor-based controls. The raw materials used range from aluminum to Kevlar®<sup>2</sup> to heat-resistant superalloys. Technologies include turbine blades cast as single crystals and which operate in engine gas stream temperatures that exceed the material melting point.

Such complexity suggests that a great deal of an engine might be purchased as it would be difficult for one firm to be highly competent in all the diverse manufacturing technologies required. In fact, roughly 70% of the cost of a typical engine is purchased from suppliers. In all, Pratt & Whitney has approximately 600 suppliers providing items ranging from raw material forgings to finished components. Some of these suppliers are other large companies. Some are small “mom and pop” machine shops located near Pratt & Whitney facilities. Many suppliers used by Pratt & Whitney also supply competitors such as General Electric and airframe manufacturers such as Boeing. Some suppliers have leverage since Pratt & Whitney represents a small segment of their overall business<sup>3</sup>. Lead times on purchased items, particularly certain raw

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<sup>1</sup> Especially: Interview with Robert Lepine, Pratt & Whitney, Fall 1997.

<sup>2</sup> Kevlar® is a registered trademark of E. I. Du Pont de Nemours and Company.

<sup>3</sup> For example, titanium suppliers have recently found considerable business outside the aerospace industry with the popularity of titanium sports equipment such as golf clubs.

material inputs, can approach two years. These facts support the assertion that supply chain design at Pratt & Whitney is an important and non-trivial undertaking.

Aircraft engines are also extremely expensive products to develop necessitating relationships that further affect the supply chain. An all new engine can cost nearly \$1B to bring to market. Engine programs also tend to be somewhat risky since the break-even point is typically ten or more years in the future and depends heavily on the sale of replacement parts. It is not uncommon for engines to be sold below manufacturing cost with the intent that the annuity due to the ongoing sale of parts will eventually return a profit<sup>4</sup>.

### ***Supplier Relationships***

There tend to be three types of relationships or commitments that Pratt & Whitney forms with suppliers: partnerships or joint ventures, offset or market access, and conventional purchase agreements.

Engine manufacturers often seek partnerships or joint ventures to offset some of this risk and expense discussed previously. These partnerships typically involve suppliers, but may also include competitors. Such commitments are generally based on a fixed percentage of the engine (program revenue and hardware responsibility) being allocated to each of the participants.

A second type of supplier commitment is offset or market access. When engines are sold outside the United States the purchaser or associated government may require that some amount of the engine be sourced locally or that some other offsetting investment be made. This is known as offset. A slightly different variation is market access. This is when the engine manufacturer proactively establishes an international agreement with a supplier in the hope that access will be gained to the engine market in the supplier's home country<sup>5</sup>.

Beyond these types of commitments, supplier relationships tend to be more conventional and based on either long or short term commitments. Long term agreements are made with preferred suppliers who possess capabilities that are known to be world class. Such suppliers generally have capabilities not held by Pratt & Whitney. Short-term relationships tend to be made to meet temporary business needs such as limited production runs or when additional capacity is needed.

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<sup>4</sup> Karl Krapek, President of Pratt & Whitney, presentation to Pratt & Whitney summer MBA program, August 1997.

<sup>5</sup> Peter Fera, "Developing a Cost-based Decision Process for International Outsourcing in the Aircraft Industry", (Master's Thesis, Massachusetts Institute of Technology, Leaders for Manufacturing Program, May 1998).

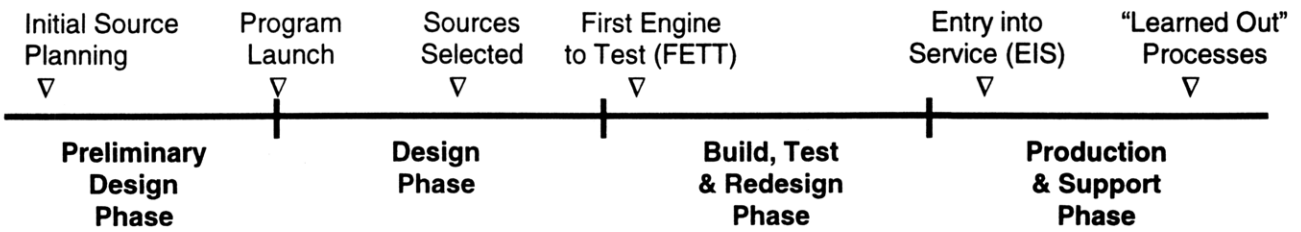
## ***Source Planning Process***

Prior to the 1980's the source selection process at Pratt & Whitney was much less complicated. Pratt & Whitney was more integrated and there were few partnerships. During the 1980's Pratt began to outsource certain part families in an effort to retain only those parts for which there was a compelling motivation - such as retention of a unique manufacturing competence. Pratt & Whitney also began to establish risk/revenue sharing partnerships with major suppliers. These developments were not necessarily consistent. Some partners were allowed to select the parts that they wished to supply. This "cherry picking" resulted in a very diverse product mix at some suppliers.

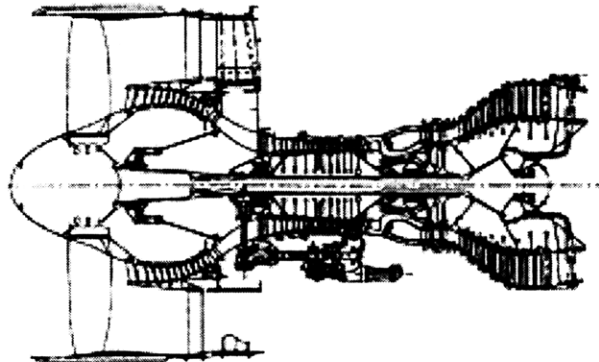
Beginning in the late 1980's Pratt & Whitney began establishing partnerships based on a rationalization strategy known as Centers of Excellence. Under this policy partners were given responsibility for entire modules (see Appendix A for a definition of module) or part families based on their manufacturing and engineering competencies. The Centers of Excellence policy addressed the lack of an overarching sourcing strategy that led to cherry picking, however, there remained several other issues that have recently been addressed. These other issues and the associated actions taken by Pratt & Whitney are discussed following a description the of the previous source selection process.

### **SOURCE SELECTION PROCESS OF THE PAST**

On past programs the source selection process began just prior to program launch (see Figure E.1). At this time source planning and engineering would start by identifying major parts from a cross-sectional drawing of the proposed engine concept (see Figure E.2). From this review, approximately 150 part types, consisting of about 400 part numbers, would be identified. Each of these parts would then be assigned either to a Pratt & Whitney Business Unit (and referred to as "make" parts) or, in a nonspecific way, to the supply base (and termed "buy" parts). The criterion for these assignments was left to the experience of the source planners. In addition, the assignment applied only to the volume production. Development (or prototype) hardware was handled separately. With regard to "buy" parts, the supplier was often not selected until sometime later during the detail design phase.



**Figure E.1: Typical Engine Program Life Cycle**



**Figure E.2: Engine Cross-Section<sup>6</sup>**

The process just described led to several problems. Source decisions were not made based on formalized criteria. As a result, decisions were based on the information known to an individual source planner although better or more comprehensive information was available elsewhere in the enterprise.

Supplier selection also did not occur until late in the design process. This hampered the intent of IPD since the representation of the production source on the appropriate IPT was delayed such that many decisions would have already occurred resulting in cost and schedule impact when alterations were necessary.

IPT's also tended to pay attention to the needs or capabilities of the development manufacturing process over those of the production source. This occurred because the source decisions for production were handled separately from development and generally occurred later (especially if the part was to be purchased). As a result, design decisions tended to optimize on

<sup>6</sup> Dimensions and drawing callouts have been removed.

the development manufacturing process rather than the production process. Thus, when the part was introduced into production, a flurry of activity could typically be expected as part design and process design changes were rushed through to address producibility problems.

Another effect of late decisions is that the production supplier could miss out on the learning opportunity associated with development manufacturing. Thus, the cost reductions associated with manufacturing learning would be lost.

The overall effect of these problems was higher manufacturing costs and delay. The delay directly affects the time required to bring a new engine to market in volume. The effect of higher manufacturing unit costs tends to persist since considerable (and sometimes prohibitive) expense must be incurred to alter a design once production has begun.

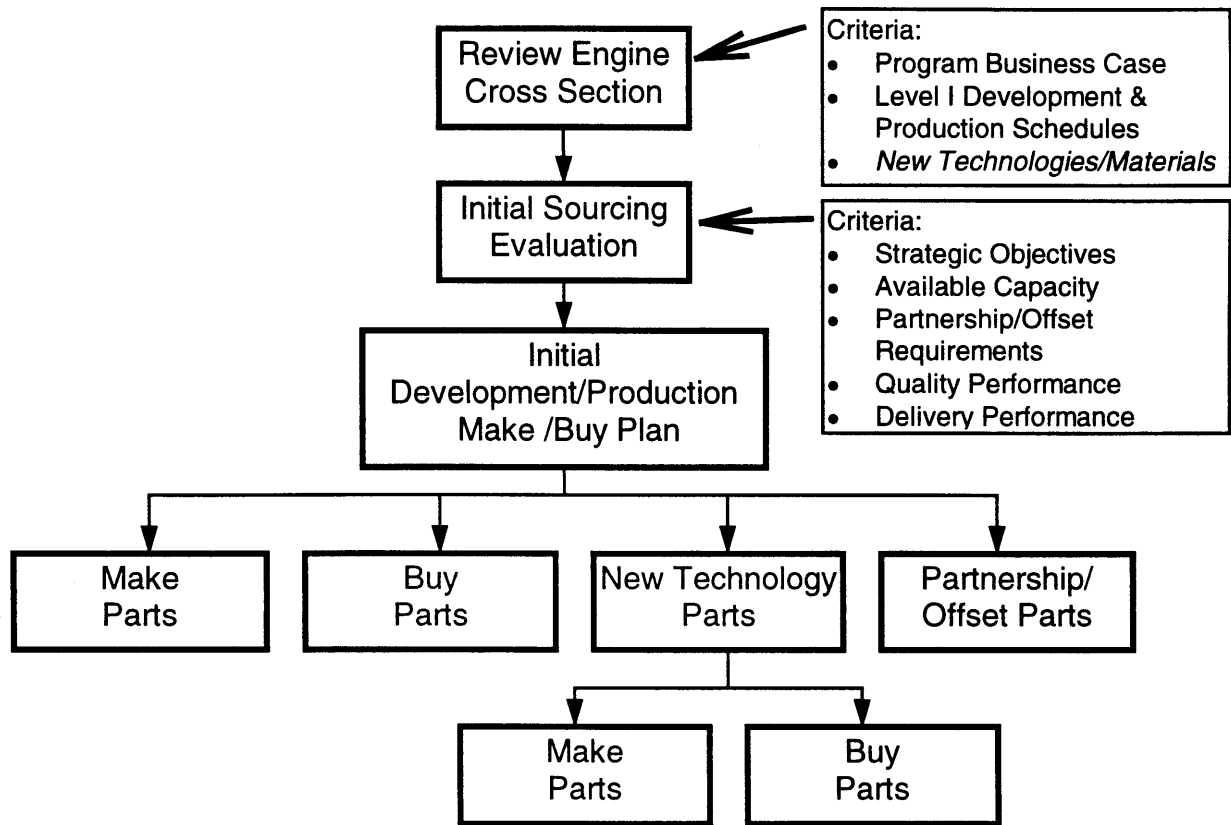
### **SOURCING PROCESS OF TODAY: DAY ONE SOURCING**

Pratt & Whitney developed the Day One Sourcing process for the GP7000 engine program in order to address the aforementioned difficulties experienced on past programs. Although the GP7000 was not launched (due to shelving of the 747-500 and 747-600 program by Boeing), Day One Sourcing was.

Day One Sourcing is described so far as to illustrate the applicability of a manufacturing process capability feedback system. Figures E.3 through E.6 provide an overview of the Day One Sourcing process. Criteria and steps where manufacturing process capability is a key consideration have been emphasized in italic type.

#### **Initial Source Planning**

Day One Sourcing begins early in the preliminary design. The first part of the process is to develop a make/buy plan based on the criteria shown on Figure E.3. Parts are parsed into “Make”, “Buy” and “Partnership/Offset” categories. At this stage, manufacturing capabilities are not explicitly reviewed, however, new technologies are identified which may later drive sourcing decisions.



**Figure E.3: Day One Sourcing Process - Initial Source Planning**

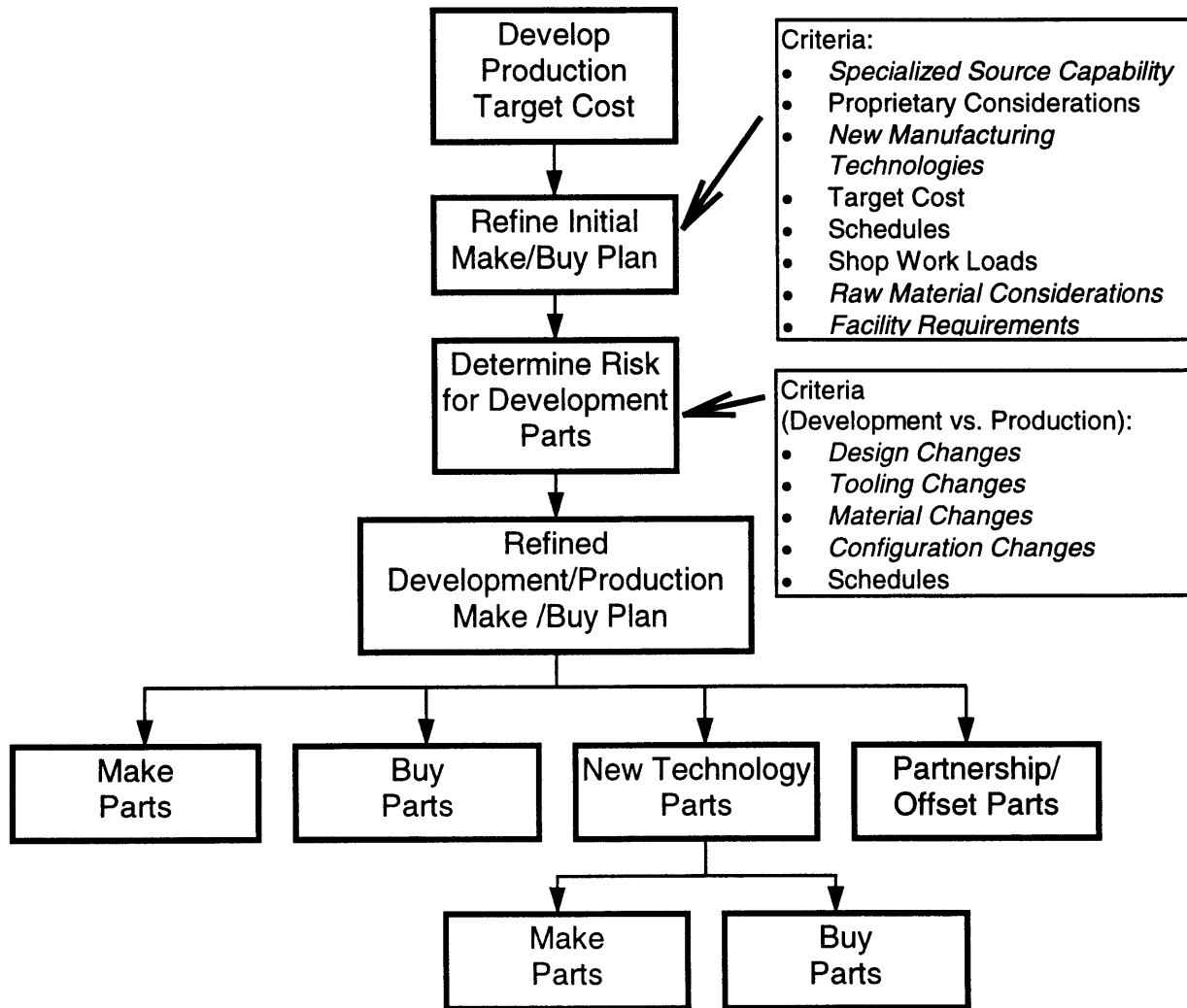
### Preliminary Design Phase

Once complete, the initial make/buy plan moves on for refinement after a review by cross-functional IPD management teams (IPMT's and CIPT's - see Appendix D). This refinement begins by defining a target manufacturing cost and the estimated manufacturing capabilities and technologies required (see Figure E.4). With these requirements in mind, the competency component of process capability described elsewhere in this document becomes useful to begin mapping parts to suppliers (internal and external).

The next step is to consider development hardware. Development hardware is sometimes intentionally different from production in terms of configuration material, or manufacturing method. The motive for this difference is generally cost and schedule. An example is the use of a welded fabrication for development where the production design calls for a casting with a higher characteristic relative fixed cost and longer lead time. Such changes have obvious impact on manufacturing and may cause development hardware to be sourced differently than



production. The result of this step is a refined source plan that addresses production and development hardware.



**Figure E.4: Day One Sourcing Process - Preliminary Design Phase**

### “Make” and “Buy” Parts

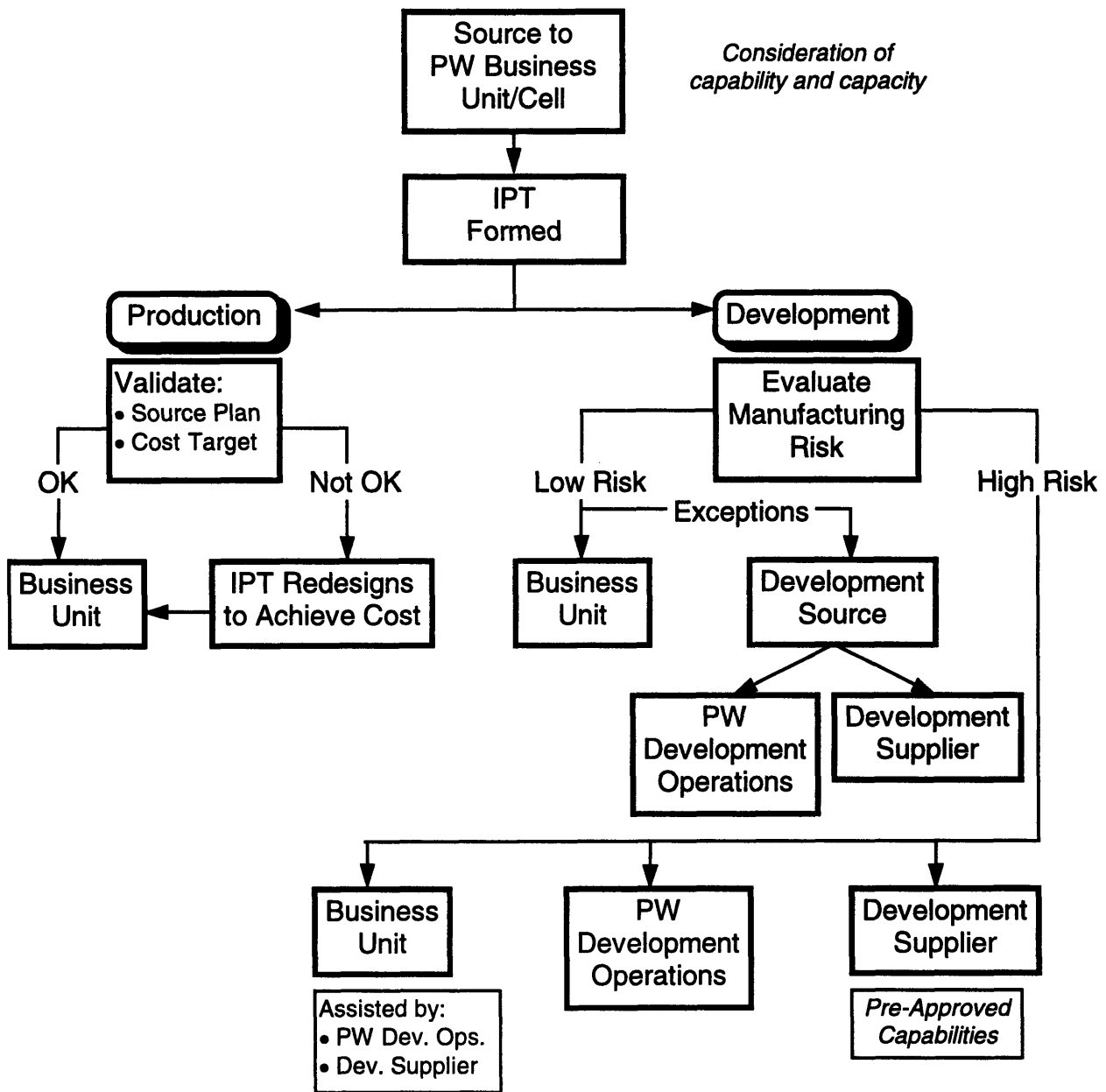
From this point the process looks at internally sourced parts and purchased parts separately (Figures E.5 and E.6 respectively). Internally sourced parts (“Make” parts) are assigned to a Pratt & Whitney Business Unit. This assignment is generally consistent with the organization of Business Units by part family<sup>7</sup>. Occasionally there may be capability overlap between Business

<sup>7</sup> Appendix A describes the product architecture and its relationship to the organization of Pratt & Whitney manufacturing facilities.

Units or capacity constraints such that a decision may have to be made as to which unit receives the part. In this case, the process capability competency information is again a key consideration in making the best assignment.

An important case is where the new part represents a departure from the past and thus new manufacturing capabilities may be required. By reviewing the competency information for the candidate Business Units, the source planning team, and those responsible for factory infrastructure can identify early on where additions or improvements to capital equipment may be needed. This case applies whether the part is sourced internally or to the supply base.

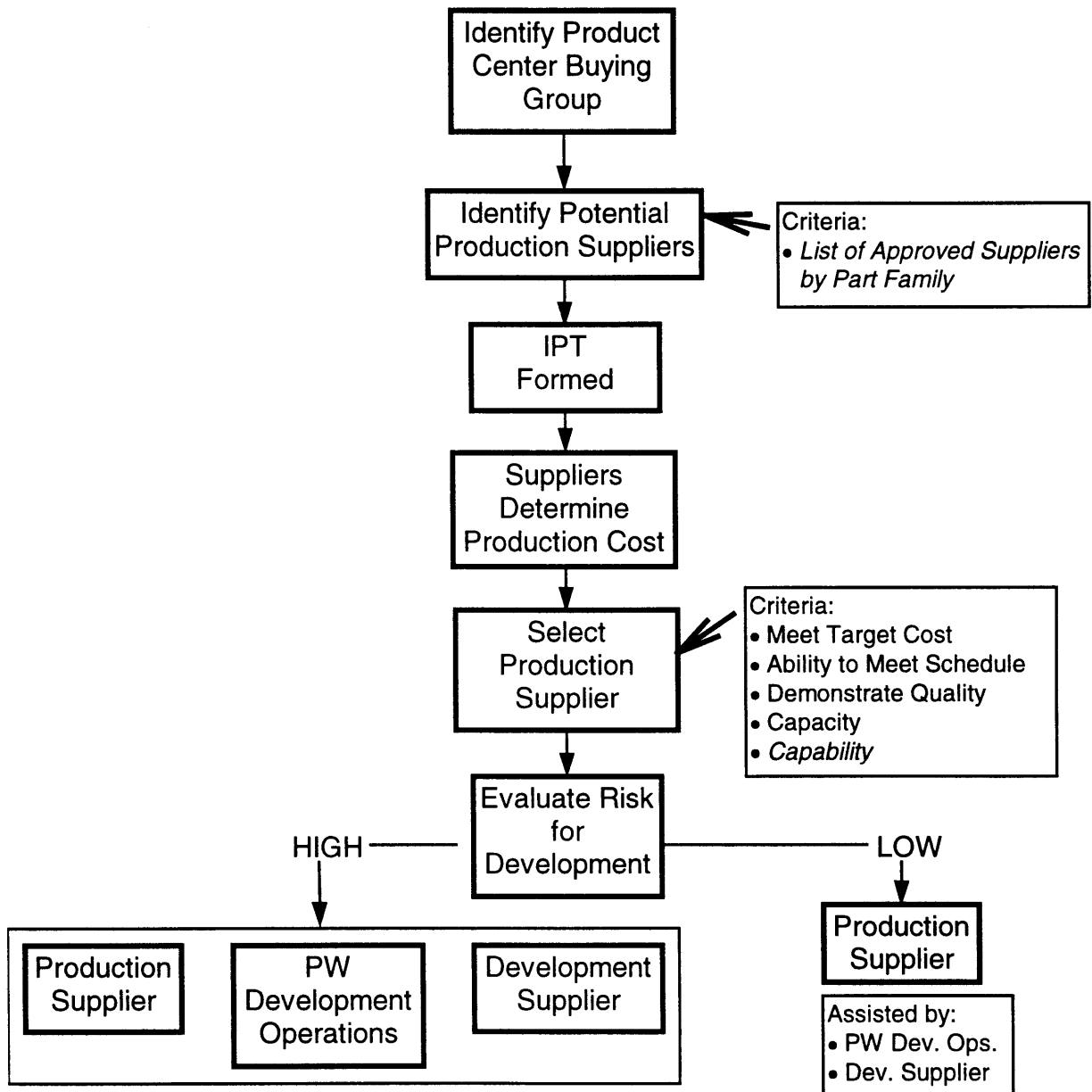
Another use of a process capability information system that stands out in the source selection process is a means to capture learning occurring during the manufacture of development hardware. As discussed previously, a significant problem with the past sourcing process is that the production source would miss out on lessons learned by the development source. Selecting the production source on “Day One” helps but does not necessarily prevent this loss. Having a process capability system in place at the development source provides an instrument to capture this learning for use in designing the production process.



**Figure E.5: Day One Sourcing Process - “Make” Parts**

“Buy” parts are assigned to specific suppliers depending on past performance and current capability. This is accomplished as shown in Figure E.6. This is perhaps where the most benefit from the application of a process capability information system to sourcing can be had. It is also the most difficult. The difficulty arises because of the need for the supplier to collect and provide what can be very proprietary information. Considerable effort and expense can also be

required to put the infrastructure in place to gather and maintain such information<sup>8</sup>. Whether Pratt & Whitney can persuade enough suppliers to undertake such an effort is unknown. The first step in addressing this issue appears to be in selecting a subset of key suppliers and establishing commitments that help reduce the risk that these suppliers may lose control of private information or fail to recoup their investment.



**Figure E.6: Day One Sourcing Process - “Buy” Parts**

<sup>8</sup> See Appendix D for a description of the infrastructure which Pratt & Whitney has or is planning to have to gather process capability data.

Defining such a list of preferred suppliers is an objective of Pratt & Whitney. As mentioned earlier, Pratt & Whitney currently has on the order of 600 suppliers. The intent is to reduce this number to approximately 200 to facilitate stronger relationships and reduce management oversight. The expectation is that these stronger relationships will also improve the willingness of suppliers to share process capability information with Pratt & Whitney.

### ***Summary***

The previous and existing Pratt & Whitney source planning processes have been described. The description of the Day One Sourcing process shows that manufacturing process capability information is an important criteria in supply chain design. This suggests that the opportunity exists for using a process capability information system to improve the quality of supply chain design decisions. The ongoing supply base rationalization is expected to tighten relationships and increase the likelihood that suppliers will become involved in such a system.



# Appendix F

## Process Improvement and Control Case Studies

### ***Introduction***

The process improvement and control case studies included in this appendix are discussed in terms of the Pratt & Whitney Process Certification initiative which is described in Appendix C. Case studies on the Pierce Press, Surface Grind and Counterbore processes are presented to illustrate both how Process Certification is applied to a variety of processes and how the process physics make a difference in approaching variation reduction.

A detailed review of the Process Certification case study conducted on the Pierce Press process is included to illustrate the depth to which the process is scrutinized during the Process Certification effort. The case studies for the other processes are less detailed, covering only the material required to illustrate the key differences in the application of Process Certification to these processes.

### ***Process Certification of the Pierce Press Process***

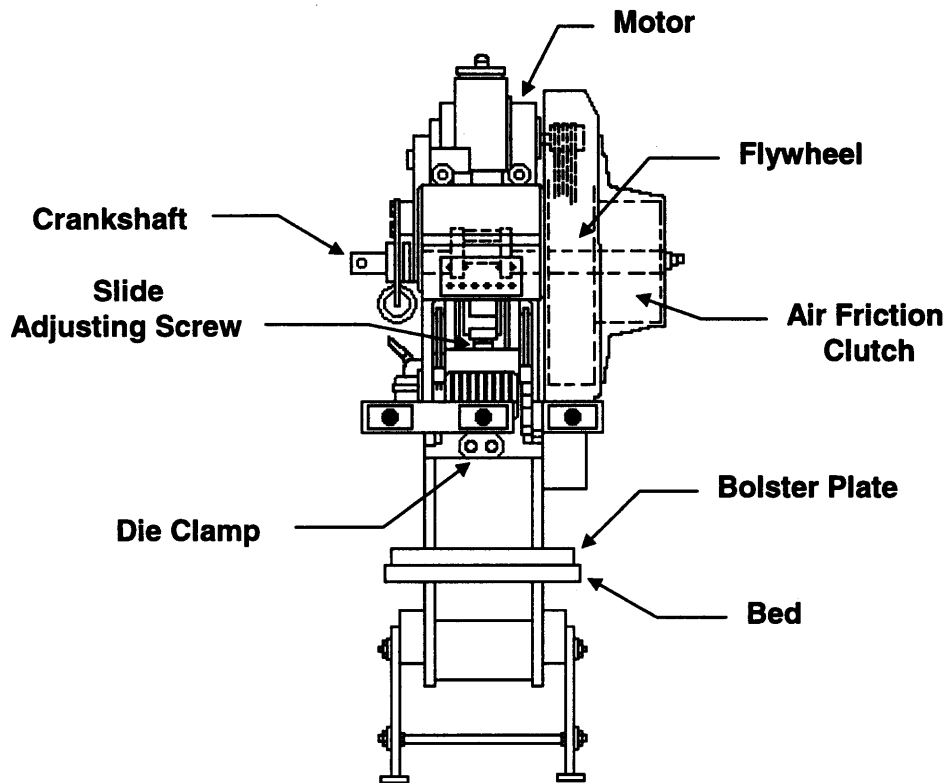
Table F.1, which is discussed in detail in Appendix C, is provided here as a convenient reference for the Pierce Press case study presented below.

**Table F.1: Process Certification Steps**

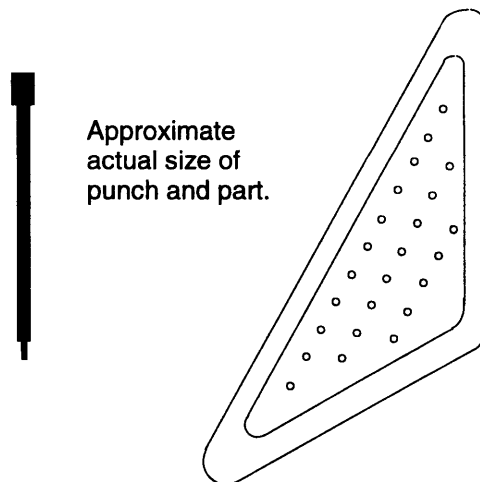
<b>Process Mapping</b>	1. Team Formation 2. Process Flow Charts 3. Process Baseline 4. Process Output Prioritizing
<b>Process Improvement</b>	5. Cause and Effect Diagram 6. Root Cause Analysis 7. Process Improvement Verification
<b>Process Control</b>	8. Control Plan 9. Documentation 10. Certification

## PIERCE PRESS PROCESS DESCRIPTION

The Pierce Press process is one of several processes performed on the mechanical press illustrated in Figure F.1 below. The small parts pierced on this press (see example in Figure F.2)



**Figure F.1: Mechanical Press Used for Pierced Parts**



**Figure F.2: Punch and Part View**



are loaded one at a time onto the appropriate die (one specially designed die exists for each part number). Not only are the dies designed to match the contour of the part, but they also incorporate special punches (see Figure F.2) in the required arrangement, one for each desired hole in the part. As the press forces the top and bottom die sections together, the punch tips “pierce” through the part, forcing out small pieces of the part (referred to as a slugs) to create the desired hole pattern. In an effort to promote better hole formation the parts are coated with a special lubricant before they are loaded onto the die. The parts produced on the Pierce Press are components of baffles which are installed inside blades and vanes to distribute “cool air” (relative to blade and vane surface temperatures) required to prevent surface overheating and catastrophic failure.

Before the parts are loaded and processed, the die for the part number to be pierced is loaded onto the bolster plate and both the top and bottom sections of the die are clamped in place. After the lot of parts has been processed, the die is unclamped and removed, clearing the way to load the die for the next part number.

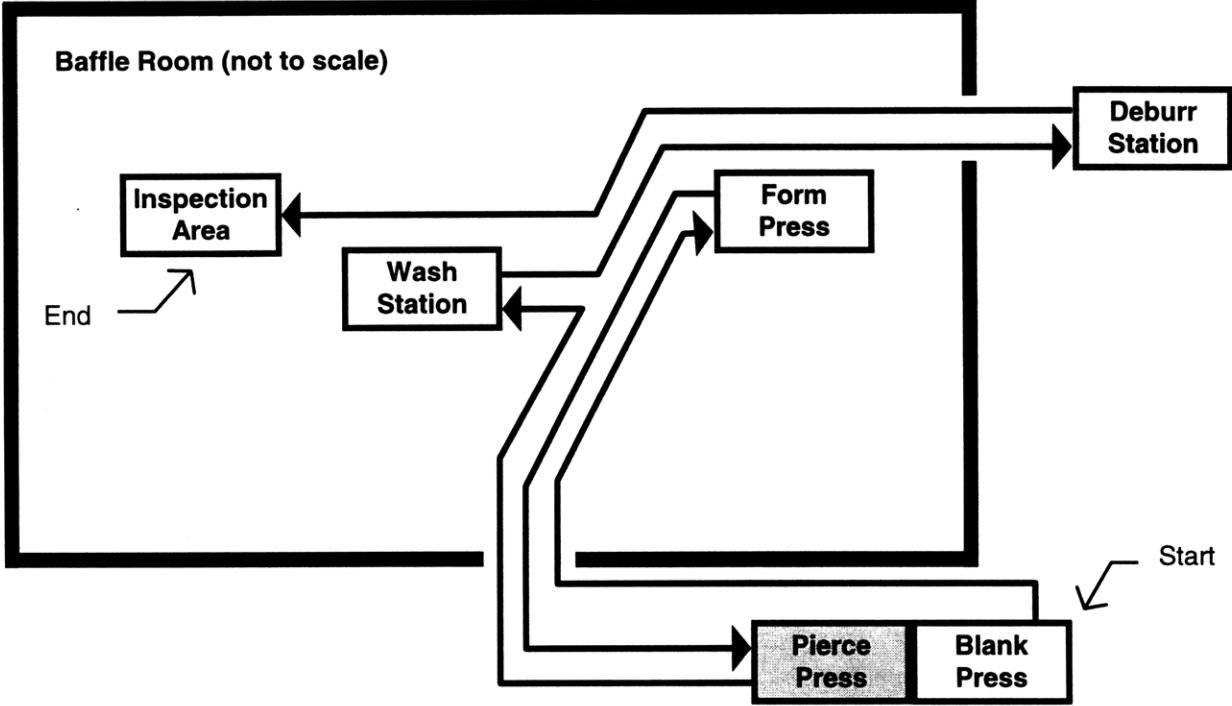
This overview of the Pierce Press process provides enough information to understand the topics covered in the following sections on the Process Certification steps followed toward certifying the Pierce Press process. It is important to note that this case study ended before the final improvements were completed to certify the Pierce Press process; however, this case still provides a solid illustration of Process Certification.

### **Process Mapping (Steps 1-4)**

Once the Process Certification team for Pierce Press process was established, including an Operator who ran the press, the first critical step was to develop a clear understanding of the overall process.

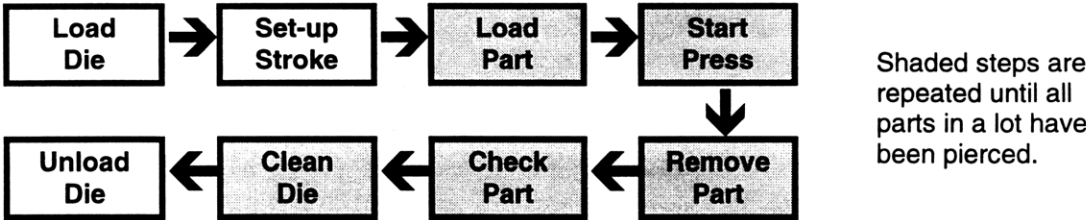
**Macro Process Flow.** As discussed in Appendix C, this understanding begins by developing of a macro process flow of the parts that go through the Pierce Press process. The macro process flow shown in Figure F.3 not only identifies all of the processes the parts go through in addition to the piercing press, but also illustrates how the part must travel some distance between operations. Part travel is one potential source of variation in the process, since parts can be damaged or contaminated as they travel from point to point. Although most of the machines for the Baffle Area are located in the Baffle Room, some of the machines had to be located outside of the Baffle Room walls, still within the Product Center facility, as a result of space limitations.

Also, the Blank Press and Pierce Press are actually the same mechanical press which performs both processes.



**Figure F.3: Macro Process Flow for Pierced Parts**

*Micro Process Flow.* The micro process flow for the piercing process shown in Figure F.4 indicates that the die is cleaned after each part is run. Cleaning in this instance refers to using pressurized air to blow slugs off of the die surface to prevent the introduction of toolmarks on the part surface. The combination of the lubricant (used to promote better hole formation holding the slugs in place, and the small size of the slugs (on the order of .02 inches in diameter), which makes them hard to see, makes cleaning the surface of the die both tedious and prone to error.

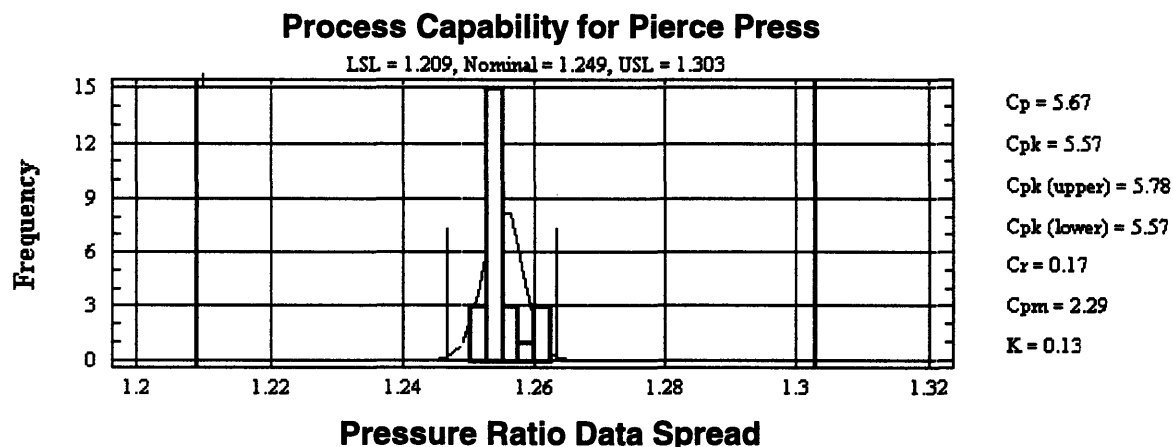


**Figure F.4: Micro Process Flow for Pierced Parts**

The lubricant used also plays a role in introducing slugs onto the surface of the die in the first place. After the punches penetrate the part and push the slugs into the bottom section of the die, the punches are pulled upward, out of the part as the die opens to allow the part to be removed and the next part to be loaded. As the punches are pulled up, the lubricant occasionally creates a small vacuum which causes a slug to be pulled up with the punch. When the punch clears the bottom section of the die, the slug clings to the die surface.

**Baseline Data Collection.** In parallel with the macro and micro process flow development effort, both attribute and dimensional data were collected on the process. The attribute data collected indicated that the process was performing at a DPM on the order of 2500. The defects which drove this high DPM were toolmarks (direct results of slugs and broken punch pieces remaining on the surface of the die) and missing holes (direct results of broken punches). Both of these issues will be discussed in detail in the root cause analysis portion of the next section.

The dimensional data was collected on an airflow bench used to measure the overall airflow passing through the pierced hole pattern in terms of a pressure differential. Therefore, looking at the graph in Figure F.5, as the pressure ratio reading moves to the right (increasing pressure differential) it corresponds to smaller holes in the part. Also by looking at the graph in Figure F.5 it is easy to see that these airflow readings have little variance and their distribution is nearly centered on nominal. This corresponds to the high  $C_{pk}$  of 5.57 shown to the right of the graph.



**Figure F.5: Process Capability Display<sup>1</sup>**

<sup>1</sup> Source: Statgraphics

Along with the attribute and dimensional data collection, the Gage R&R study was completed on the airflow bench. As shown in Figure F.6, the readings taken by the bench operators were consistent both in terms of repeatability and reproducibility and resulted in a Gage R&R of only 4.14%. The relatively low Gage R&R for the airflow bench was a result of three primary conditions:

- Controlled air flow, including an automated system check run before each lot sample
- Airflow pressure verification using a master part
- Controlled alignment and seating of each part on the measurement fixture

Gage No.	Serial No.	Tolerance	Trials	Parts	Operators	Date	
		0.094	5	2	2	7 / 18 / 97	
	<b>Operator A</b>		<b>Operator B</b>		<b>Operator C</b>		
	<b>Part 1</b>	<b>Part 2</b>	<b>Part 1</b>	<b>Part 2</b>	<b>Part 1</b>	<b>Part 2</b>	
<b>Gage Reading</b>	1	1.214	1.212	1.215	1.211		
	2	1.215	1.211	1.215	1.211		
	3	1.213	1.210	1.215	1.211		
	4	1.213	1.210	1.214	1.211		
	5	1.213	1.210	1.215	1.211		
<b>Repeatability (Gage Variation)</b>		0.00272		<b>Reproducibility (Operator Variation)</b>		0.00279	
<b>Pct. of Tolerance Consumed by Gage</b>		2.89%		<b>Pct. of Tolerance Consumed by Operators</b>		2.97%	
<b>Total Measurement System Variation</b>				0.00390			
<b>Pct. of Tolerance Consumed by Measurement Variability</b>				4.14%			

**Figure F.6: Gage R&R Calculation Display<sup>2</sup>**

### Process Improvement (Steps 5-7)

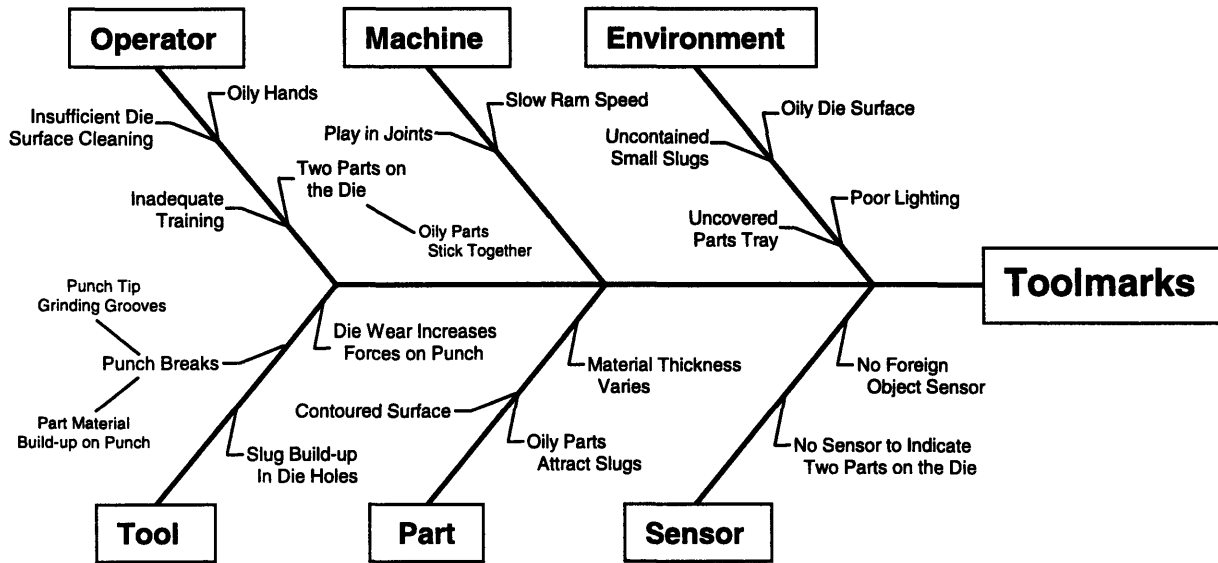
The data collected during the Process Mapping steps provided clear direction on where to focus process improvement efforts - work to eliminate the root cause(s) of toolmarks and missing holes. The search for the specific root cause(s) that had to be addressed started with the

<sup>2</sup> Source: Pratt & Whitney's Gage R&R software program.

development of a Cause and Effect diagram for each type of defect along with a detailed punch analysis and a review of the Pierce Press defect reduction history.

Cause and Effect Diagram

A simplified version of the diagram developed for toolmark defects is shown in Figure F.7.



**Figure F.7: Cause and Effect Diagram for Toolmarks**

On the whole, the items listed in the diagram relate in some way to slugs or broken punches getting onto the die surface and remaining there when the next part is processed. Additional information for some of the items listed in the diagram is included below to provide clarification on their meanings and roles in causing toolmarks.

**Operator:**

- oily hands promote foreign object attraction and subsequent transfer onto parts.
- accidentally placing two parts on the die at the same time causes punches to break under the pressure of higher stress.

**Machine**

- relatively slow ram speed places high forces on punch tips and promotes heat generation, plastic deformation of part material, and build-up of part material on punch tips (see Figure F.8).
- play in machine joints allows a non-uniform application of forces through the die.

Environment:

- poor lighting makes it difficult to see any foreign objects on the die surface.
- the uncovered parts tray allows foreign objects to fall onto parts awaiting processing.

Tool:

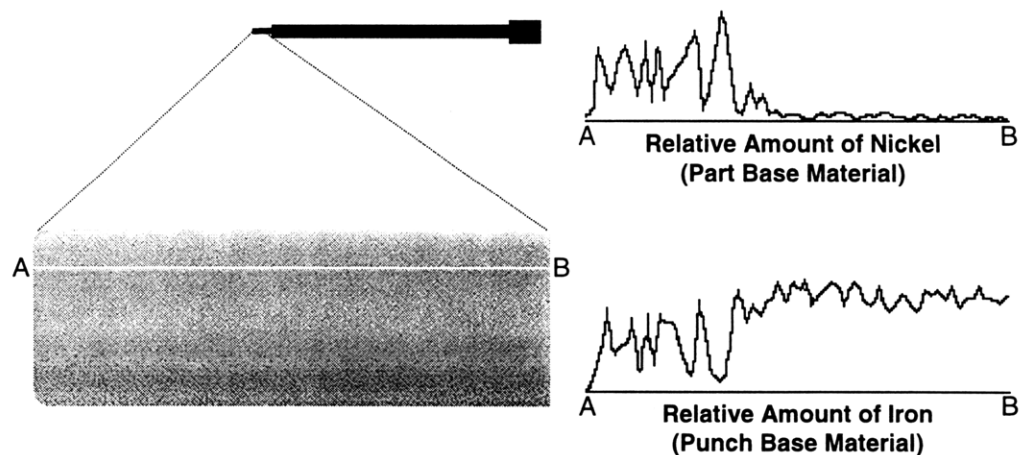
- grooves which create high stress concentrations in punch tips are formed during the in-house grinding process used to produce the required punch tip diameter on stock punch shaft material (see Figure F.9).
- slugs build-up and become wedged in the holes in the bottom section of the die (see Figure F.10) and cause punch tips to break when they impact the blockage.

Part:

- contoured surface geometry places side loads on the punch tips as they make initial contact with the part.
- material thickness variations toward the high side of the thickness tolerance induces higher forces which reach a critical level in the punch tips as the punch tip diameter to part material thickness ratio falls near or below 2.0.

#### Detailed Punch Analysis

One of the analyses performed on the punch was a Scanning Electron Microscope analysis of the material on the punch tip. The results of this analysis are shown in Figure F.8 below. From this



**Figure F.8: Punch Tip Scanning Electron Microscope (SEM) Analysis**

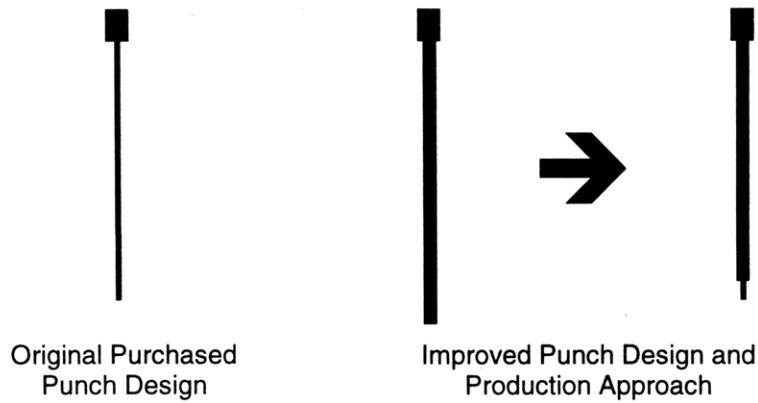
analysis it was clear that the interfacial shearing taking place at the part/punch interface as the punch pierced through the part was in effect causing the softer part material to weld to the surface of the punch. The relatively slow velocity at which the press drove the punches through the part generated heat at the interface which also contributed to this condition. This may seem counter-intuitive, however, there is actually less heat generated when high speed is used. Refer to the Improvement Approach discussion provided later in this section for more details on this concept.

In addition, analysis of punch fractures showed that the punch tips were actually failing in tension as the press was pulling the punches out of the part, rather than in compression as the punches impacted the part surface. Inspection of unused punches under a microscope confirmed the suspicions that the grinding wheel used to grind the punch tips to the required diameter created grooves around the circumference of the punch tips that were deep relative to those along most of the length of the punch tip. The stress concentrations at these grooves along with the part material build-up condition noted above were determined to be the primary contributors to recurring punch failure. Also during this inspection, it was easy to see the difference in surface quality between the smooth surface of the supplier ground stock material punch shaft and the heavily grooved in-house ground punch tip.

#### Defect Reduction History

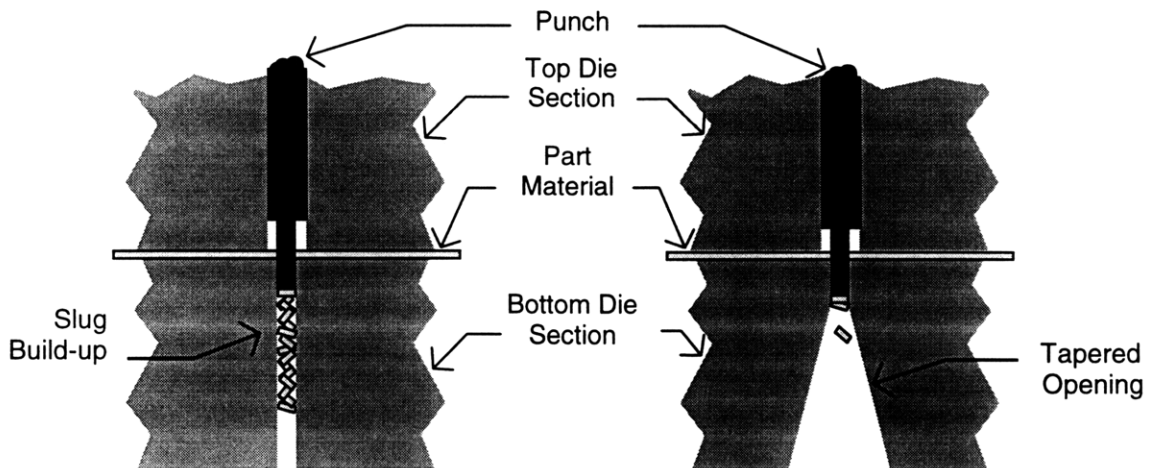
Prior to the Process Certification effort began on the Pierce Press, several changes aimed at reducing defects linked to punch breaks had been implemented. The first change dealt with the punch design. A short time after the Pierce Press began piercing parts it became clear that the small diameter punch failure rate was too high to allow the efficient operation of the mechanical press for piercing. To counter this problem, the Die Makers decided to discontinue ordering punches with diameters required to produce the correct hole diameter along the entire length of the punch shaft. Instead, they ordered punches with a larger diameter (which required a corresponding increase in the punch hole diameters in the top section of the die) and subsequently ground the punch tips down to the required diameter on an in-house grinder (see Figure F.9). The reduction in punch breaks was dramatic and the change was viewed as a big success. The additional costs associated with purchasing customized punches, over purchasing standard punches and grinding the tips in-house appeared to be cost prohibitive, so the in-house tip grinding practice continued.

The Die Makers also implemented a change to the bottom section of the die. As shown in Figure F.10, the initial die design was prone to the build-up of slugs in the exit holes in the bottom section of the die. This condition periodically resulted in punch breaks when the slugs



**Figure F.9: Punch Geometry Considerations**

became so firmly wedged in the upper end of the exit hole that a punch tip would break on impact before it reached the bottom of its travel. To alleviate this condition, the Die Makers tapered the exit holes so that the slugs would fall out much easier. A short portion at the upper end of the exit holes had to be left at their original diameter to withstand punching forcing and allow material for periodic die sharpening. This change also provided dramatic results, although slugs still occasionally became wedged and caused punches to break. The Operators when asked to periodically clear the holes with a pin: however, this was tedious, did not completely eliminate punch breaks, and countered one of the primary advantages of punching holes (versus using a laser drill or EDM) - fast processing time.



**Figure F.10: Die Design Revision**



### Root Causes

After considering the possible causes listed on Cause and Effect diagram, reviewing the results of the detailed punch analysis and discussing the changes previously implemented, two root causes came to the surface. First, the punch tip grinding process was introducing an unacceptable susceptibility of the punches to breakage and therefore a better process had to be pursued. And second, the process capability of the large mechanical press did not match what was required to pierce parts with such small holes. While it was true that the mechanical press could produce acceptable parts, it became clear that changes required to meet the certification criteria  $DPM \leq 63$  would not be economical, if even possible. The low ram speed drove the need to use lubrication on the parts which in turn lead to related problems such as slugs getting onto the die (due to oily Operator hands, parts and die surfaces attracting slugs, and the vacuum effect created as the punch was retracted from the bottom section of the die) and two parts getting loaded (due to oily parts sticking together). The combination of the slow ram speed and the lubrication also lead to the build-up of slugs in the exit holes which contributed to punch breaks.

### Improvement Approach

Two complementary actions were taken to address the two root causes noted above. To address the problem with the punch tip grinding process, the punch supplier was contacted for a quote on punches with the required overall lengths and specific tip diameters. The average price per punch quoted by the supplier turned out to be approximately 38% less than the cost of purchasing the stock punch shaft material and spending valuable Die Maker time to grind the tips in-house. Therefore, purchasing the required punches from the supplier would not only allow the use of higher quality punches, but also would result in a cost savings. This also would free up more time for the Die Makers to work on critical die design issues in the Business Unit.

Second, a high velocity press was ordered to be used specifically for piercing. This small (dimensions of only about two feet in each direction) and relatively low cost press offered many advantages such as removing the need for lubricants to aid punch penetration into the part and consistently ejecting slugs out of the exit holes. By using speed to punch through the parts instead of forcing the punch through the part with pressure, the punches actually last longer. An additional benefit is that the high speed punching action virtually eliminates burrs on the edges of the holes, which could potentially lead to removing the need for a downstream deburring process.

The press supplier offers the following information on the mechanics behind punching with a high velocity press:

“During typical punching operations materials undergo three phases: elastic, plastic and fracture. Because of high tool speeds, electromagnetic presses bypass most of the elastic and plastic phases. Essentially, the material doesn’t have time to react . . .”<sup>3</sup>

This fast action also reduces the amount of heat generated, since the material virtually goes straight to fracture.

**Process Control (Steps 8-10)**

With the new punches and high velocity press on order, a preliminary Control Plan was developed as shown in Figure F.11 below.

Workstation: <u>Pierce Press</u> Cell: _____ Approval: _____						
Audit Frequency: _____ Owner: _____ Date: _____						
What	KPP	Settings	Who	How	Where	When
<b>Machine</b>	Preventative Maintenance	As specified on Maintenance Sheets	Maintenance	Follow PM Documentation	Pierce Press	Quarterly
	Daily Walkarounds	As specified on Walkaround Sheets	Operators	Follow Daily Walkaround Sheets	Pierce Press	Daily
<b>Operator</b>	Communication between Shifts	Inform next shift of process variations	Operators	Review Rainbow chart and QCPC form	Pierce Press	Daily
	Communication with Inspection	Inform operators of process variations	Inspectors	In-line Inspection of first part in lot	Pierce Press	Every parts lot
	Machine Cleaning	As specified in 5S and TPM standards	Operators	Clean as needed to meet standards	Pierce Press	During weekly 5S shutdown
	Operator Training	Meet minimum skill requirements	Cell Leader	Use established procedures	Where arranged	As required
	Work Instructions	As specified in Work Instructions	Operators	Follow Work Instructions	Pierce Press	Every part
<b>Gage</b>	Airflow Bench Calibration	As specified in Gage Standard procedures	Gage Standard	Follow Gage Standard procedures	Airflow Bench	Calibration due date
	Airflow Bench Airflow Pressure	Maintain airflow Pressure	Inspectors	Perform pressure check with master	Airflow Bench	Before every parts lot sample
	Gage R&R	Maintain Gage R&R ≤ 10% of part tolerance	Operators	Take readings and calculate Gage R&R	Airflow Bench	Calibration due date
<b>Tooling</b>	Die Surface	Maintain die surface to Die Standards	Die Makers	Follow Die Standard procedures	Die Room	Check die surface after each parts lot
	Punch Life	Maintain punch use under set maximum parts pierced	Operators and Die Makers	Record punch use and replace before set maximum	Pierce Press, Die Room	Record punch use after each parts lot
<b>Part</b>	QCPC	As specified on QCPC forms	Operators	Fill out QCPC form and analyze results	Pierce Press	Daily
	C <sub>pk</sub>	Maintain C <sub>pk</sub> ≥ 1.33	Operators	Review airflow data	Airflow Bench	Every parts lot
	Yield	Maintain DPM ≤ 63	Operators	Fill out QCPC form and calculate DPM	Pierce Press	Daily

**Figure F.11: Pierce Press Preliminary Control Plan**

<sup>3</sup> Lourdes® Systems, Inc., product brochure.

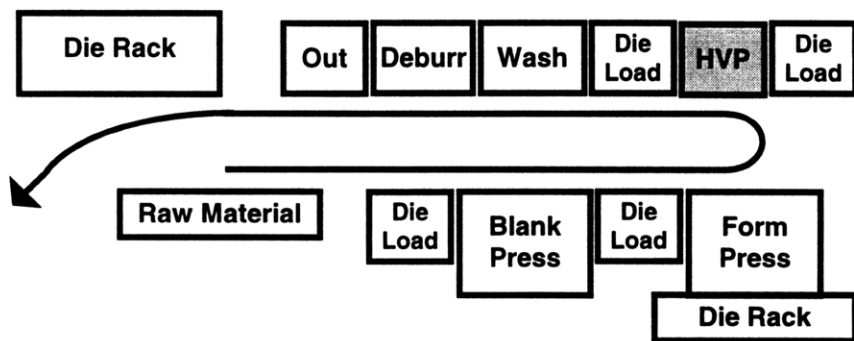
For the Control Plan to be successful there are several keys to control for the Pierce Press process:

- Punch quality and uniformity
- High velocity press utilization
- Scheduled punch replacement and die maintenance

The groundwork had already be laid for the first two keys to control, however, the issue of scheduled punch replacement and die maintenance had not been addressed. After the new punches and the high velocity press are received and ready for use, additional data must be gathered to determine the useful life of the punches and die surfaces. Once this information is available, it must be incorporated into the Control Plan (e.g., the punches might have to be changed out after every 2000 parts are run and the die surface might have to be sharpened after every 4000 parts are run). Only after the process improvements have been put in place and data confirming that the process meets all of the certification criteria can the process be certified.

**Additional Note**

Just as this case study ended, a Kaizen event was performed in the area and the layout of machines was modified from the original layout previously shown in Figure F.3 to the new layout shown below in Figure F.12. This layout provides a vastly improved process flow (e.g., reduced part travel and walking distance) and includes provisions for installing the new High Velocity Press (HVP) for piercing operations. Also note that die load tables have been included in the new layout to streamline changeover efforts and significantly reduce set-up times.



**Figure F.12: Post-Kaizen Macro Process Flow**

The Pierce Press process covered many of the details of Process Certification, now two other processes with different process physics will be reviewed to show how Process Certification is applied in other circumstances.

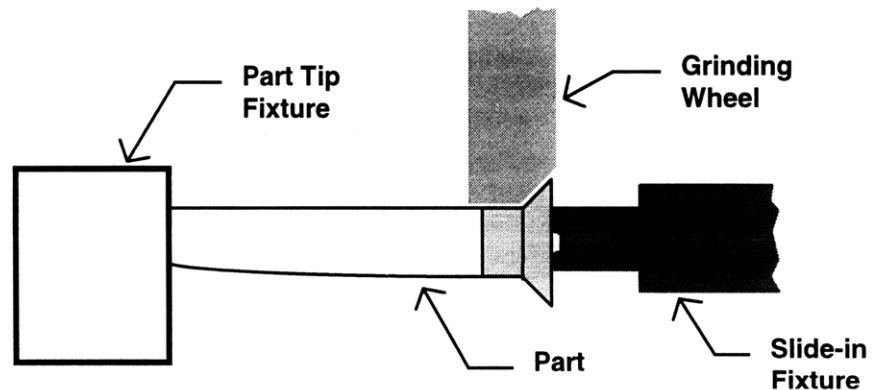
## ***Process Certification of the Surface Grind Process***

The Surface Grind process provides an example of how Process Certification can be applied to a process quite different from the piercing process. More specifically, the Surface Grind process illustrates how important it is to understand the function and use of the gages used to determine the quality of part features produced in a process.

### **SURFACE GRIND PROCESS DESCRIPTION**

The surface grind process discussed in this case study is performed on a grinding machine dedicated to work on a single part number. The parts ground in this process are impingement tubes, which will ultimately be installed in turbine blades to distribute cooling air on the interior surfaces of the blades. The overall length of the parts from a specified location on the angled surface is a key characteristic for ensuring proper alignment when they are installed in the blades.

In this process, the part tip is inserted into a fixture on one end (which is on a cam which rotates when the grinding machine is running) and held in place on the other end by locking fixture which slides into the two holes on the end of the part (see Figure F.13). The grinding wheel is specially shaped to grind the required angled surface.



**Figure F.13: Fixtured Part Configuration**

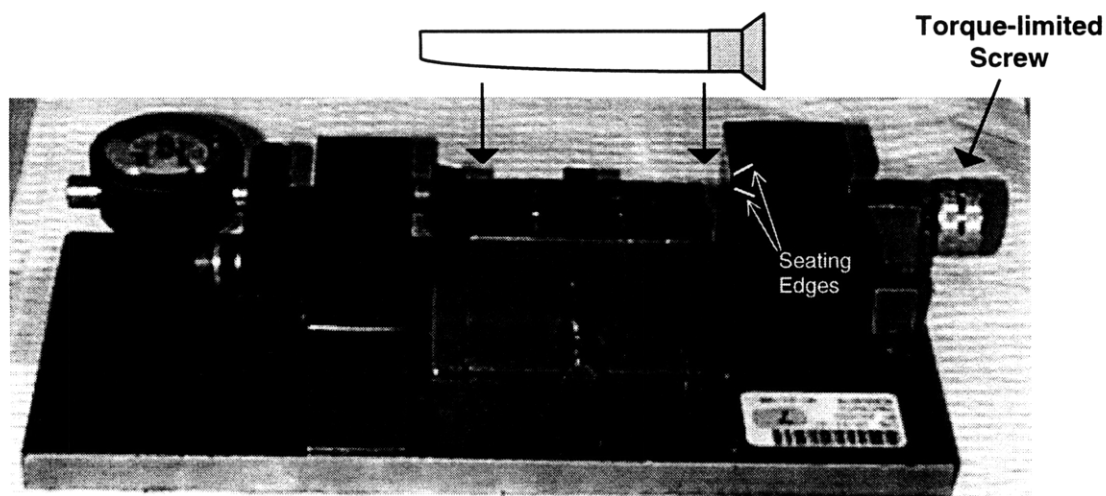
### **Process Mapping Key Issue**

During the initial stages of process data collection a Gage R&R of nearly 20% of part tolerance was calculated from data taken on the gage used to measure the overall length of the parts (see Figure F.14). Almost all of the calculated Gage R&R was due to part measurement variation between operators. Before accurate dimensional data could be collected on the part length, the high Gage R&R needed to be addressed.

## Gage Improvement

Determining the root cause of the significant variation in the gage readings taken between operators was relatively straightforward when the time was taken to actually observe the operators use the gage. After inserting the part into the gage as indicated in Figure F.14, the operators used a lever to seat the part in the length gage (by pushing the part to the left, such that the angled surfaces of the part wedged up against the gages seating surfaces, the top edges of which are indicated in Figure F.14). The force applied to the moment arm of the lever dramatically affected the gage reading. While each operator was able to get consistent readings by using essentially the same force when seating the part, the varying force used from operator to operator resulted in the noted measurement variations.

To reduce the variation of measurements between operators, a representative from the Gage Standard group and a Die Maker were called on to determine an acceptable and reliable alternative to seating the parts with a lever. The selected alternative was the installation of a torque-limited screw which is shown in Figure F.14.



**Figure F.14: Improved Ground Part Length Gage**

After the improvements were implemented and the gage was recalibrated, the new Gage R&R was calculated to be less than 3.5%. Subsequent dimensional and attribute data collection indicated the process was running at a  $C_{pk}$  of 1.9 and a DPM of 0. A Control Plan similar to the one for the Pierce Press was established, and the process was certified. A key to process control in this case is to ensure that the grinding wheel is changed every 5000 parts.

## Process Certification of a Counterbore Process

The Counterbore process provides another example of how Process Certification can be applied to processes with diverse process physics. This case study examines how utilizing data to analyze a process can clarify the reasons for inherent variation.

### COUNTERBORE PROCESS DESCRIPTION

The counterbore process discussed in this case study is performed on a five axis milling machine. More specifically, the key characteristic of this process is the depth of holes which are counterbored into a series of 24 nozzle bosses located around the circumference of a diffuser case (see Figure F.15). The machine begins work on an initial hole and proceeds around the part until all 24 holes are finished.

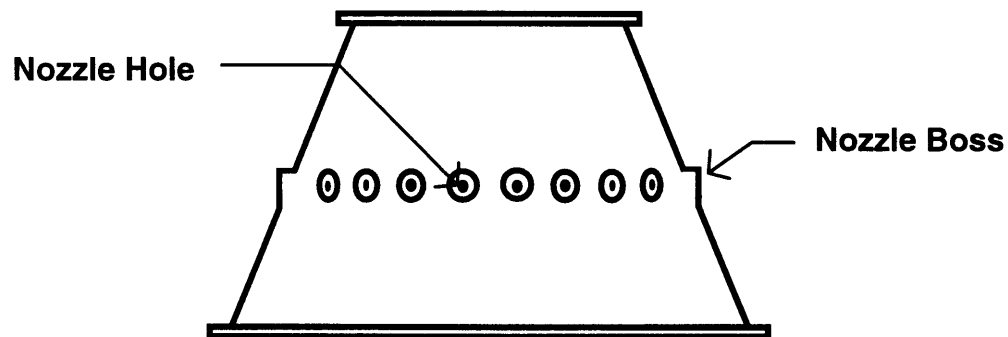


Figure F.15: Diffuser Case Nozzle Hole Arrangement

### Process Mapping

The initial effort of data collection provided a tool from which interesting insights were gained. As shown in Figure F.16 below, the process initially had a  $C_{pk}$  of 1.1, however, the

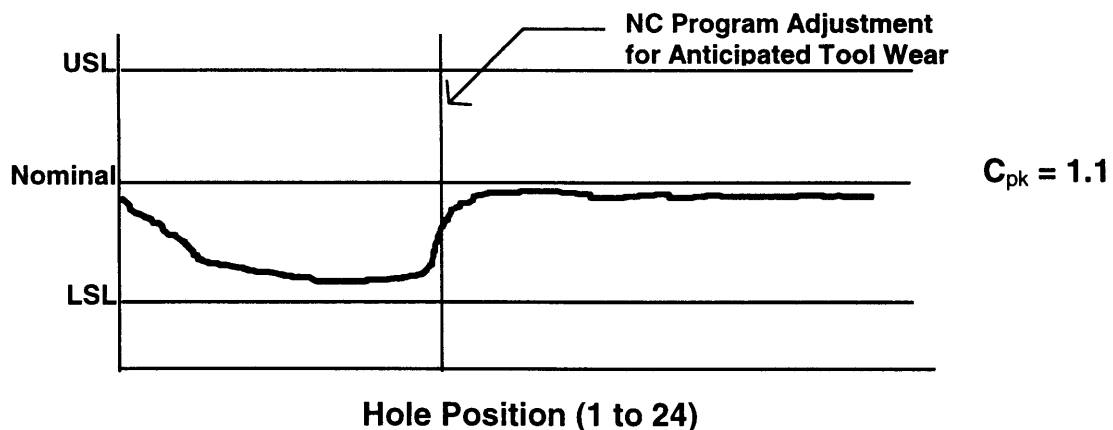


Figure F.16: Baseline Counterbore Depth Data

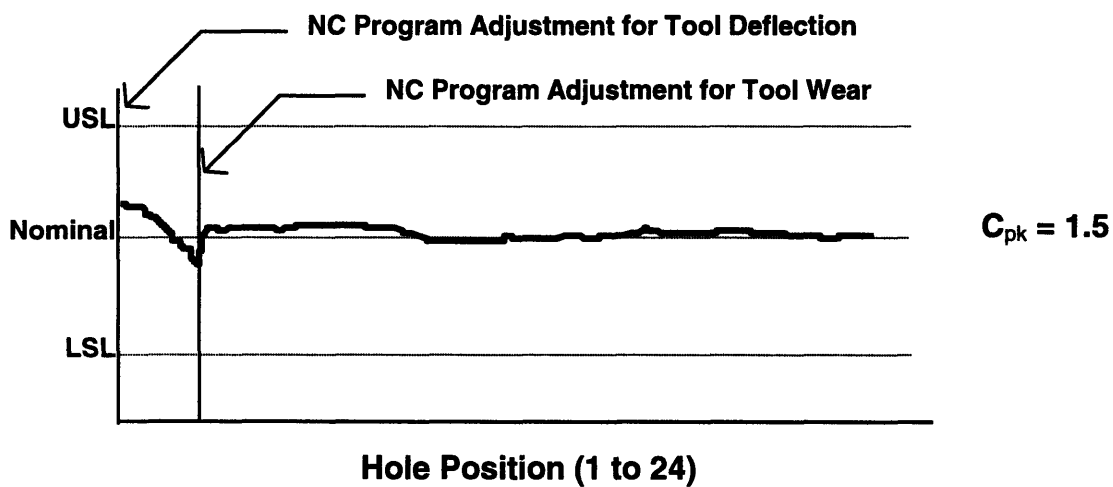
most significant information on the process came from the graphic display of the counterbore hole depths (a composite average from numerous diffuser cases) as the tool progressed from the first hole around the diffuser case to the last. As the graph illustrates, on average the hole depths didn't even start at nominal and all were biased to the lower specification limit. Also note that there was a programming adjustment after the 12<sup>th</sup> hole to account for anticipated tool wear.

**Process Improvement**

Root cause analysis of the problems exhibited in the data collected lead to the realization of the underlying causes of tool deflection and actual (in contrast to anticipated) tool wear. The root cause of the hole depths which started below nominal was determined to be tied to the process used to initialize the machine. On-machine probing was used to set the starting location for the cutting tool. Of course the force used to probe the part was minimal. However, when the tool began cutting the first hole, the force applied caused the tool to deflect. Therefore, the feedback loop to the machine indicated that the hole was the correct depth before the correct depth was actually reached.

The root cause of the problem associated with tool wear was that there was not a clear understanding of the actual pattern of tool wear. The program adjustment for anticipated tool wear was never evaluated for its correspondence to actual tool wear - and besides, before Process Certification, the process appeared to be performing well enough.

In this case the efforts for process improvement were actually minimal once an understanding of the process was reached. Figure F.17 below illustrates the programming changes implemented



**Figure F.17: Counterbore Depth Data After Improvement**

to take the process physics into consideration. First, an initial adjustment was incorporated to account for tool deflection. Then a second adjustment for the significant tool wear exhibited over the first three holes cut was incorporated to bring the counterbore depths back up to nominal. As the graph clearly shows, these adjustments resulted in substantial improvements in process capability, taking the  $C_{pk}$  up to 1.5.

### ***Summary***

A key message from these case studies is that with data the organizations were able to appreciate the physics of their processes and make the appropriate corrections. Before data was available and reviewed, the organizations did not have a quantified understanding of what their process capabilities really were, nor would they have known what actions would have been required to make significant improvements.

Another message is that by archiving the data collected for the purposes of process improvement and control, this data can also serve another purpose later - use in IPD. This data is now available for future part and process design studies. More information is also known about the data based on the analysis and documentation which occurred during the certification process, providing a richer context for the data.



# Appendix G

## Process Capability Feedback Case Study

### ***Introduction***

This appendix presents an example of the use of information technology to capture and present manufacturing process capability information. The information presented herein is taken from interviews at Pratt & Whitney and the personal experience of the authors who participated in portions of the construction of the Product Cell Capability Catalogue (PC<sup>3</sup>) at Pratt & Whitney's North Berwick Product Center. The findings from this study of the Pratt & Whitney PC<sup>3</sup> provide insight as to how to construct an IPD-focused process capability information system.

This appendix consists of four sections. First, the Pratt & Whitney North Berwick Product Center is described for background. The second and third sections are descriptions of the Information Kaizen methodology and the format of the PC<sup>3</sup> information system, respectively. The fourth section is a discussion of the key findings from this case. The fifth and final section is a brief summary.

### ***North Berwick Product Center***

Pratt & Whitney's North Berwick Product Center is a 880,000 square foot manufacturing facility located in southeast Maine. This plant employs a non-union workforce of approximately 1500 people. The plant produces engine compressor components, some turbine components and bearing supports. These products vary from single piece machined castings to assemblies of machined, stamped and composite details. The process technologies include metal-removal machining (milling, turning and grinding), roll forming, stamping and several surface preparation and heat treatment processes.

The plant is organized into manufacturing cells. In general, each cell is focused on one or more part families. This focus takes advantage of the geometric and process technology similarities within a part family. Cellular manufacturing strives to create an arrangement of all the necessary process machinery in the sequence that is needed to produce a particular product. However, few cells in North Berwick are currently able to operate in a true cellular flow fashion.

Many cells do not have all of the necessary process machinery within the cell (e.g., heat treatment furnaces are generally separate from the cell). Some cells have a product flow which requires some machines to process a part more than one time. Notwithstanding this complexity, the cellular arrangement provides a reasonable model of the North Berwick plant.

The arrangement of the North Berwick Product Center and the configuration of the products suggest certain structural requirements for a process capability information system. These requirements will be discussed in the section on the architecture of the PC<sup>3</sup>.

### ***Information Kaizen***

In the spring on 1997 members of Pratt & Whitney's Compression System Component Center (CSCC) in East Hartford, Connecticut conducted the first "Information Kaizen". The CSCC organization has design engineering responsibility for the fan and compressor modules in Pratt & Whitney engines. CSCC works closely with the Product Centers in Connecticut and Maine that manufacture fan and compressor parts. CSCC developed the idea of Information Kaizen as a means to improve the communication both within CSCC in East Hartford and between CSCC and the various Product Centers.

The Information Kaizen method is based on applying the *Lean Thinking* principles of Womack and Jones<sup>1</sup> to information flows using the focused process improvement technique of Kaizen (see Imai<sup>2</sup> and Imai<sup>3</sup>). Womack and Jones' principles are:

1. Identify the customer value stream.
2. Eliminate waste from the value stream.
3. Make the value stream flow.
4. Achieve customer "pull" in the value stream.
5. Pursue perfection of the value stream.

The Information Kaizen approach takes advantage of the existing support for lean principles and Kaizen in Pratt & Whitney. Pratt & Whitney is featured by Womack and Jones in *Lean Thinking* as an example of a large mass-producer beginning the transition to lean production. Also, the Kaizen method is in widespread use throughout the Pratt & Whitney manufacturing organization

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<sup>1</sup> James P. Womack and Daniel T. Jones, *Lean Thinking: Banish Waste and Create Wealth in Your Corporation*, (New York: Simon and Schuster, 1996)

<sup>2</sup> Masaaki Imai, *Kaizen: The Key to Japan's Competitive Success*, (New York: McGraw-Hill, 1986).

<sup>3</sup> Masaaki Imai, *Gemba Kaizen: A Commonsense, Low-Cost Approach to Management*, (New York: McGraw Hill, 1997).

and is credited with significant improvements to product quality, throughput and the productivity of the Business Units. With the Information Kaizen approach, CSCC sought to leverage this experience with lean principles and Kaizen to improve the critical flows of information.

The Information Kaizen technique was first applied to information flows between the Pratt & Whitney Product Center in North Berwick and the CSCC engineers in East Hartford. This Kaizen event identified about 70 items for improvement. These 70 items were prioritized by the potential for improvement and the ease of implementation. Those items which were high impact and easy to change (i.e., “low hanging fruit”) were addressed immediately. Items which were high impact but more difficult to implement were dubbed “acorns” and reserved for future Kaizen events.

One of the acorns concerned the development of a means to communicate the manufacturing capabilities of the plant to design engineers in East Hartford. This was considered a high impact item because CSCC had traditionally had difficulty in locating manufacturability information during the detail design process<sup>4</sup>. In addition, the Product Center had considerable experience with designs that required significant changes in order to bring the engineering requirements and manufacturing capabilities in line with one another. Moreover, the Product Center wished to standardize on certain configurations and process designs to reduce cost and improve quality.

The second Kaizen event was held in July, 1997 to address the flow of process capability data between two selected manufacturing cells (one in North Berwick and one in East Hartford) and the CSCC engineers in East Hartford. The result of this event was a web-accessible catalogue of process capability for the cells - the Product Cell Capability Catalogue (PC<sup>3</sup>). This catalogue was constructed through negotiations between the CSCC engineers and the cell manufacturing engineers and operators. During the Kaizen event, CSCC engineers, the eventual customers for the system, specified what sort of process capability information they needed in the design process. The manufacturing engineers and operators then set out to gather this information. Manufacturing engineers and operators also were responsible for specifying process limitations, standard process designs and for negotiating preferred and un-preferred design and process configurations with the design engineers.

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<sup>4</sup> Appendix D provides more information about the difficulty of locating manufacturability information.

The atmosphere of these discussions was described as a “healthy tension”. Design engineers generally negotiated for tighter allowable tolerances and greater flexibility in preferred configurations and materials. Manufacturing engineers sought to identify broad tolerances that would ensure high process capabilities and to limit future designs to standardized geometry and materials to allow process design standardization. By having both the design and manufacturing communities represented in the construction of this catalogue, the architects of the PC<sup>3</sup> hoped to ensure that statements about manufacturing capability would have joint buy-in and would serve as an effective means to simultaneously achieve Pratt & Whitney’s objectives for product performance, quality and cost.

Both North Berwick Product Center management and CSCC management were impressed by the results of the first and second Kaizen events. They asked the Kaizen team to expand the PC<sup>3</sup> to encompass the rest of the North Berwick plant. To begin this assignment, the Kaizen team constructed the following goal statement:

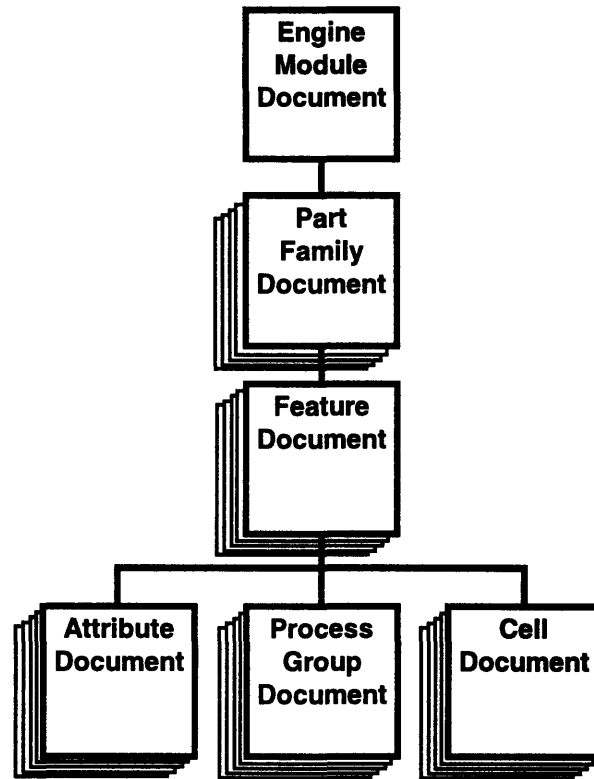
“Construct a high-quality document that contains critical information the design community must know about part manufacture in the N. Berwick Product Center to improve quality and reduce product cost.”

Some of the first tasks of this mission were for the Kaizen team to develop a standard PC<sup>3</sup> format and to design a process to populate the format with the necessary information. The standard PC<sup>3</sup> format is described in the following section. The process was dubbed “Mini-Kaizen” and entailed three-day events in which the design engineers, manufacturing engineers and certain operators representing a selected part family would be brought together for intensive training and to negotiate the content of the associated portion of PC<sup>3</sup>. The Kaizen team established an aggressive schedule to complete the Mini-Kaizen events over a three month period.

The key deliverable from each Mini-Kaizen event was a completed paper version of the catalogue for the part family. One or more individuals from the cell would then be selected and trained on how to enter the information from the paper catalogue into the database.

## ***The Architecture and Content of the PC<sup>3</sup>***

The architecture of the content of the PC<sup>3</sup> developed during the second Kaizen event served as a model for the plant-wide information system. The system is based on a Lotus Notes<sup>TM5</sup> document database that can be accessed and navigated via the Pratt & Whitney intranet using a web browser such as Netscape Navigator<sup>TM6</sup>.



**Figure G.1: PC<sup>3</sup> Hierarchy and Connectivity**

The architecture of the PC<sup>3</sup> is depicted in Figure G.1. This figure shows the hierarchy and connectivity between the various Lotus Notes<sup>TM</sup> documents in the database. The PC<sup>3</sup> is composed of six types of documents: Engine Module, Part Family, Feature, Attribute, Process Group, and Cell. The connectivity between the documents is established by HTML<sup>7</sup> links navigated via a web browser.

The content of each of these documents is guided by the templates developed by the July Kaizen team. These templates are shown in Figures G.2 through G.6. The templates shown in

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<sup>5</sup> Lotus Notes is a registered trademark of Lotus Development Corporation.

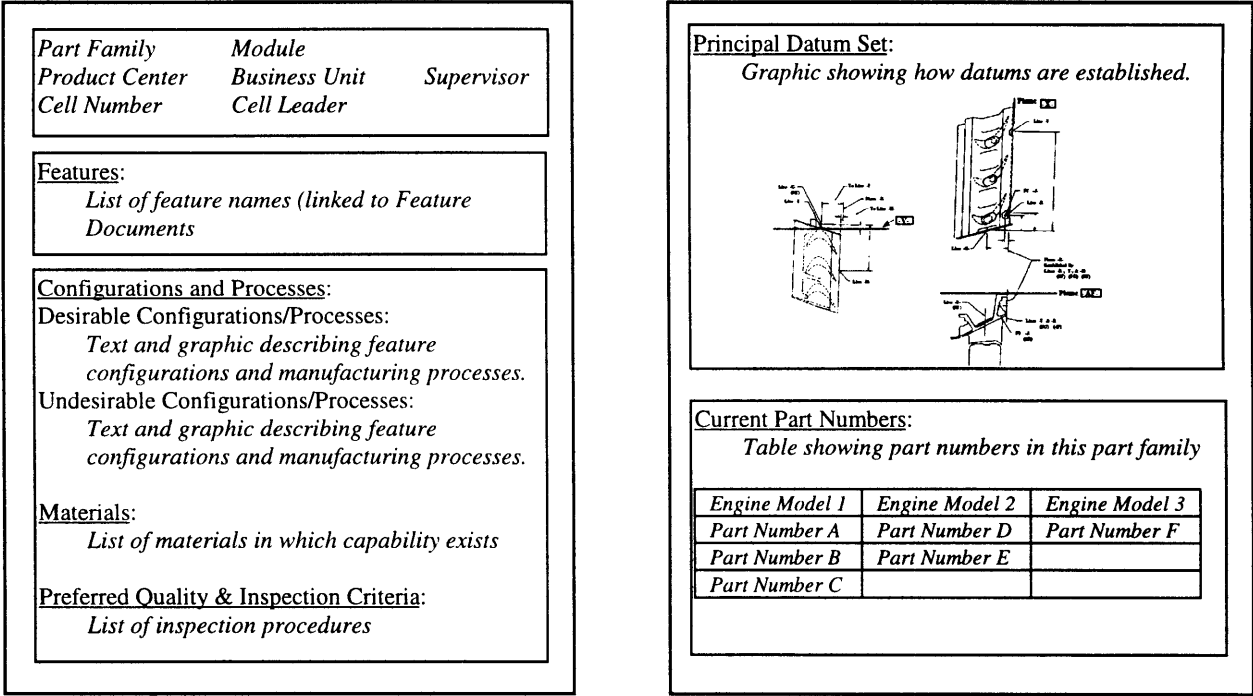
<sup>6</sup> Netscape Navigator is a registered trademark of Netscape Communications Corporation.

<sup>7</sup> Hypertext Markup Language.

these figures have been simplified for purposes of illustration. The Mini-Kaizen teams were asked to use these templates as a guide. However, the detailed content of the PC<sup>3</sup> was determined through negotiations between the appropriate design engineer and manufacturing engineer for the part family.

The Engine Module document is the top level of the PC<sup>3</sup>. This document is a simple list of Part Family documents by module (i.e., by fan, low pressure compressor, high pressure compressor, and so on<sup>8</sup>). Each of the part family names in this list is an HTML link to the associated Part Family document. The purpose of the Engine Module document is to facilitate navigation of the PC<sup>3</sup>.

The Part Family document is the top level document for each part family. As shown in Figure G.2, the Part Family document provides basic information about the part family and the manufacturing source. The header of the document indicates the Product Center, Business Unit and cell(s) where the part family is manufactured as well as names and phone numbers for selected engineering and manufacturing personnel. Much of the information in the header is carried through out the subordinate documents of the Part Family.



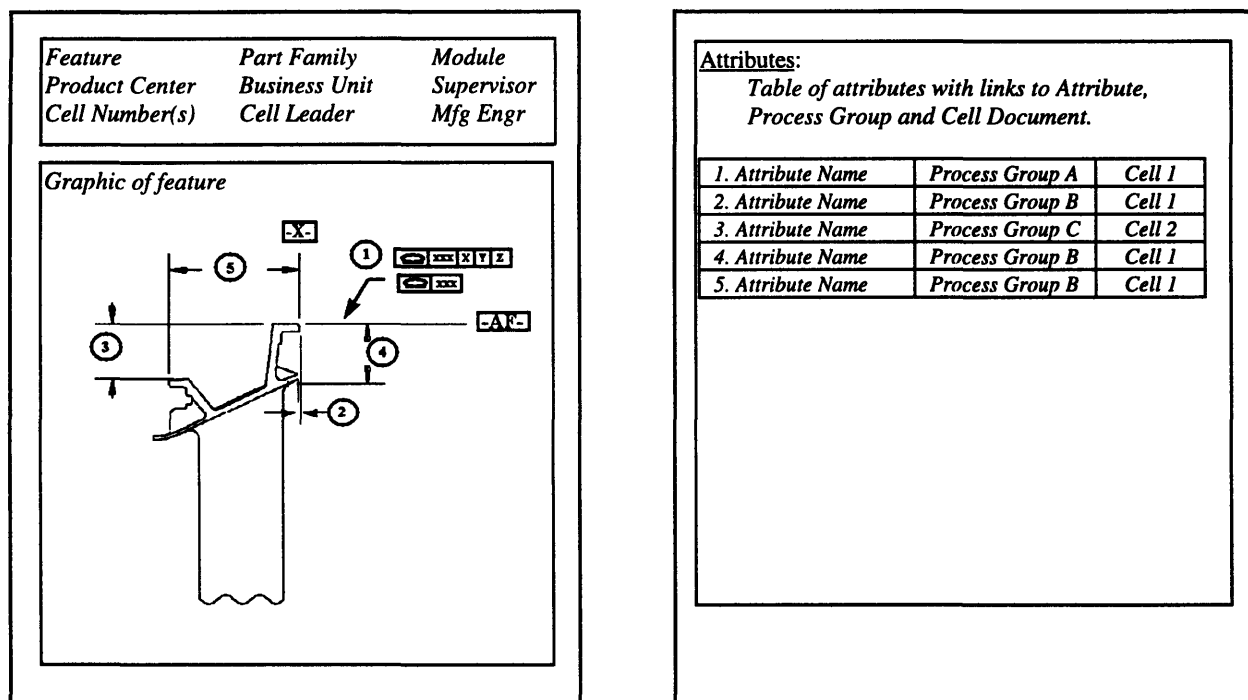
**Figure G.2: Part Family Document Layout**

<sup>8</sup> See Appendix A for further detail about engine modules.

The Part Family document lists the critical features. These are the features that the Mini-Kaizen team agreed are critical from the standpoint of manufacturability. Each feature name is in itself an HTML link to the underlying Feature document.

The majority of the information provided by the Part Family document is related to the preferences of the manufacturing source. This information is provided in the form of textual and graphical descriptions of preferred (and un-preferred) feature design configurations, manufacturing processes and inspection criteria. The Part Family document lists the materials for which the manufacturing source cell has capability. The document also indicates the datum sets used in processing the part.

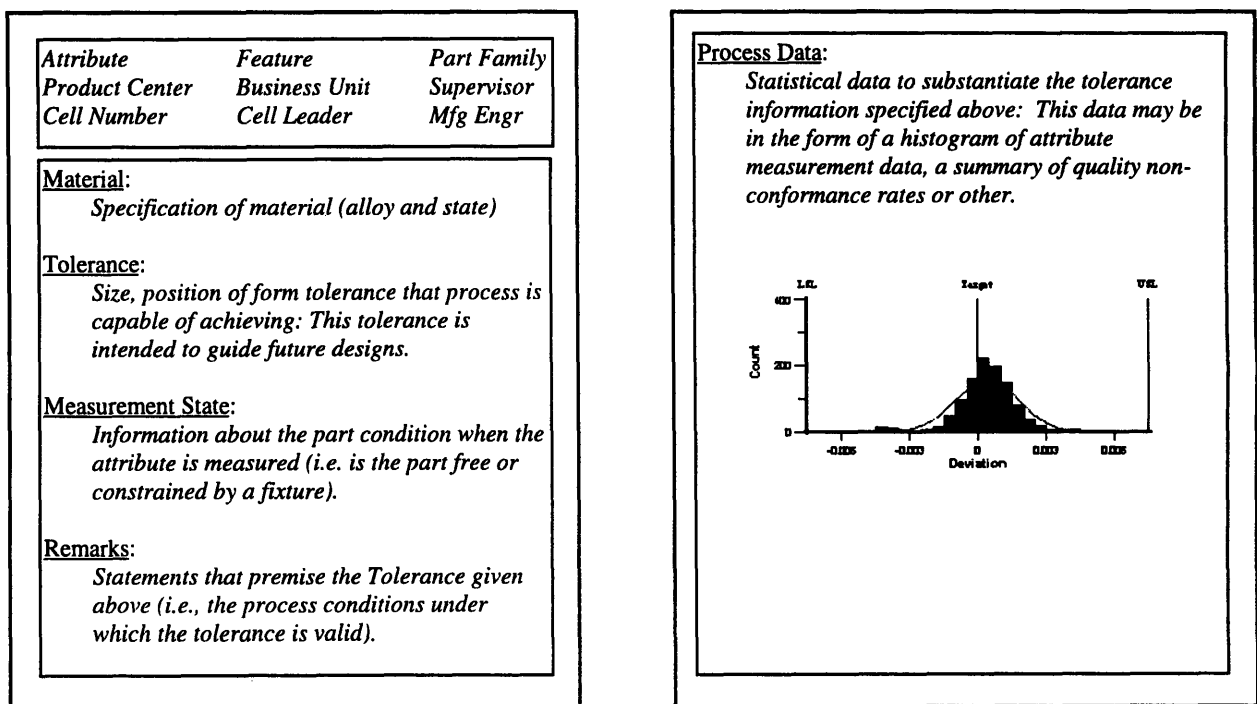
The Feature document defines the feature and the associated attribute set. An attribute<sup>9</sup> is a specific dimension or measurable aspect of a part feature. The Feature document usually includes a graphical depiction of the feature geometry and shows the location of the attributes (see Figure G.3). The Feature document also identifies the process group and cell associated with each attribute and provides links to the Attribute, Process Group and Cell documents.



**Figure G.3: Feature Document Layout**

<sup>9</sup> In this context the terms *attribute* and *characteristic* are interchangeable. The term *characteristic* is used elsewhere in this document.

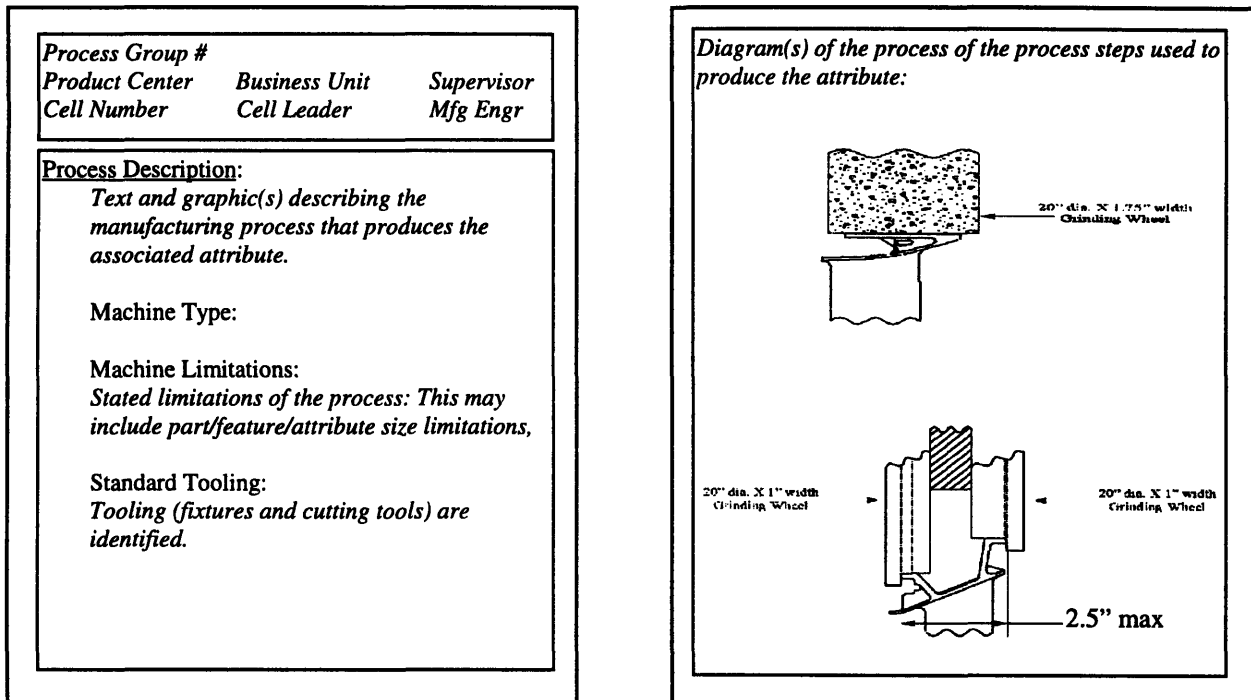
The Attribute document provides information about the capability of the manufacturing process to produce the attribute. As shown in Figure G.4, the statistical process capability for the attribute is given in the form of a *tolerance*. This tolerance is generally the result of the “healthy tension” negotiation between the design and manufacturing engineers and is intended to be the guideline for assigning tolerances on future designs. The tolerance may be substantiated by a histogram of process data, if available. The Attribute document also gives some of the important contextual information associated with the tolerance such as the material type and whether the part is constrained by a fixture during inspection. As with the Feature documents, the Mini-Kaizen participants determine which attributes are to be included and define names for each.



**Figure G.4: Attribute Document Layout**

The Process Group document defines the process under which the attribute is created. This document typically includes a textual and graphical description of the manufacturing process (see Figure G.5). The Process Group document is so named because of the recognition that *several* discrete machines or processes may be used to create a given attribute. In the simplest case, a single machine performing a single process is a Process Group if at least one attribute is created. Together the Process Group and Attribute documents define the context under which the stated tolerance capability of the process is believed to be valid.



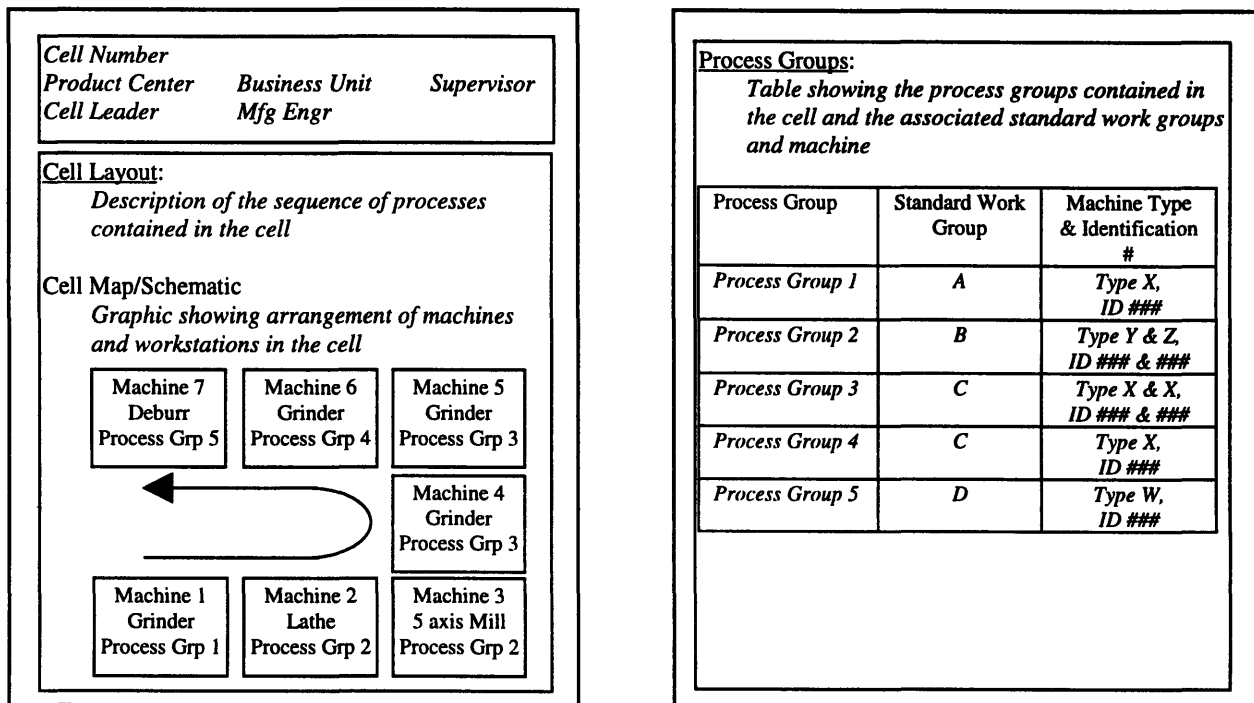


**Figure G.5: Process Group Document Layout**

Another important function of the Process Group document is to describe process limitations that may constrain future design. The second panel of Figure G.5 shows a grinding process with a 2.5 inch maximum feature size limitation. By documenting such limitations, IPD teams can easily identify areas where proposed designs may run afoul of current process capability and thereby plan deliberate action to alter the design or make improvements to manufacturing equipment.

Every Attribute document maps to a single Process Group document. This is an important aspect of the PC<sup>3</sup> because it ensures that the statistical statements of process capability are backed up by a description of the context of the process. Note that multiple Attribute documents may be associated with a given Process Group as it is possible that several attributes are created under the same process context (e.g., both the depth and width of a slot can be established during a single milling operation).

The Cell document, shown in Figure G.6, provides a high level description of the manufacturing cell. The Cell document describes the sequence of steps used to produce the part. A graphic is used to show the layout of the cell. The graphic shows the location of each process station or machine and to which process group each belongs. The document may also indicate standard work groups. A standard work group is the collection of process steps typically assigned to a single operator.



**Figure G.6: Cell Document Layout**

### **Key Findings**

The key findings from this case consist of certain structural and content requirements which are important for a process capability information system. This research also points to several considerations, or critical success factors, for implementing and maintaining such a system.

### **IMPORTANT STRUCTURAL REQUIRMENTS**

The structure of the North Berwick PC<sup>3</sup> reflects the architecture of the product and the arrangement of the manufacturing processes. As described in Appendix A, gas turbine engines tend to have a product architecture of the form engine/module/part-family/feature/characteristic. The PC<sup>3</sup> takes advantage of this architecture in the way that the Engine Module, Part Family, Feature and Attribute documents are organized and linked. The manufacturing environment at

Pratt & Whitney also has an arrangement of Product Center/Business Unit/cell/machine/process. The PC<sup>3</sup> takes advantage of this arrangement as well in the way the Process Group and Cell documents are linked. The product-based and process-based relationships are significant because they are intuitive to design engineers and manufacturing engineers, respectively, and thus enable easy navigation of the PC<sup>3</sup> by both communities.

Another important structural aspect is the linkage of product and process based relationships at the attribute and process group levels. Pratt & Whitney originally attempted to characterize the process group at a feature level. This proved to be unworkable since a feature may be composed of multiple attributes each produced by unique processes. The original linkage of the feature to process group remains in the way the Feature document is linked to the Process Group documents (see Figure G.1). However, the attribute to process group relationship is made by the table in the Feature document (see Figure G.3).

An important trade-off decision made during the construction of the PC<sup>3</sup> is the degree to which the information and the system architecture was customized to the local needs. The design and manufacturing engineers who negotiated the content of the PC<sup>3</sup> were focused on, an assigned to, the particular part family or cell. Thus, the content was being tailored to the needs of local users. This is an important benefit. However, such local tailoring does not necessarily facilitate the ability of engineers to share knowledge across part families or across cells. Some participants wondered whether an engineer from another part family, cell or Product Center would be able to benefit by searching the PC<sup>3</sup> for alternative design configurations or processes.

The architecture of the PC<sup>3</sup> also generated a tension between the Kaizen team and people outside the CSCC and North Berwick as to the appropriate architecture for a process capability system. The PC<sup>3</sup> is structured to meet the needs of the local users as opposed to global users. In this sense, a local user is a design engineer or manufacturing engineer assigned to the specific part family or cell described by the PC<sup>3</sup>. A global user is an engineer working on some other part family or in some other cell. Local users tend to navigate vertically within the PC<sup>3</sup> while global users tend to navigate horizontally. A local user may want to use the PC<sup>3</sup> to look up a specific fact about his/her part or cell. The PC<sup>3</sup> accommodates this well. However, a global user may want to look across several part families to compare how similar features are designed or manufactured. The PC<sup>3</sup> does not accommodate such searches. The existence of a similar feature, process, attribute, cell layout, machine, etc. can not easily be found. The information

system described in Appendix D is one possible approach to meeting this need. How the needs of local and global users are satisfied is an important consideration constructing a process capability information system.

### **IMPORTANT CONTENT REQUIREMENTS**

This study of the PC<sup>3</sup> suggests that a broad definition of process capability should be used when determining the content of the information system. As previously mentioned, the Attribute document provides the “tolerance” capability of the process. This characterization of process capability is referred to in this document as the *statistical* component of process capability. This is the mathematical representation of the capability of the manufacturing process to meet a tolerance. Together, the Attribute and Process Group documents provide what is termed herein as the *contextual* component which premises the statistical component. This contextual information is critical since the statistical component is of most value when the conditions (i.e., context) under which the data was gathered are known. The requirement inferred from this is that both statistical and contextual components are critical content for a process capability information system.

An apparent strength of the PC<sup>3</sup> is the degree to which process limitations and desirable/undesirable design configurations are addressed. The Part Family and Process Group documents are the prime conveyors of this information. Interviews with managers and engineers at Pratt & Whitney suggest that such information provides important guidance to the IPD teams. This type of information is referred to in the body of this document as the *competency* component of process capability. The inferred requirement is that the content of a process capability system should go beyond the statistical component and include the contextual and competency.

A weakness of the PC<sup>3</sup> is the lack of accurate statistical characterizations of process capability. At the time the catalogue was implemented, Pratt & Whitney had relatively few systems in place to analyze the process capability of each attribute. Some cells lacked an existing store of attribute measurement data from which to draw. In some cases, the inspection procedures were “go/no-go” and thus failed to capture actual measurements. As a result, the Mini-Kaizen teams often had to rely on the “gut feel” of the manufacturing engineer when it came time to specify a deliverable tolerance. Some teams simply used the existing engineering drawing tolerance as the tolerance for attributes. Notwithstanding this weakness, the Kaizen team asked the participants to make a best effort to determine a tolerance and to indicate the basis

for the determination. The Kaizen team intended to use this information to prioritize efforts to gather statistical process data. A key finding is the importance of systems for determining statistical characterizations of process capability.

One notable difficulty encountered by the Kaizen team was the lack of a dictionary for feature and attribute names. It was apparent from the beginning that identical features may have many different names. Sometimes the a feature or attribute occurs in multiple part families but has a unique name in each case. Sometimes, the manufacturing and engineering organizations refer to the same feature differently. Given the lack of a standard list, the Kaizen team elected to allow the Mini-Kaizen teams to create their own terms. The Kaizen team attempted to combine terms where possible. However, all involved realized that the feature/attribute dictionary was becoming unwieldy. The dictionary is important because of its use as a search criteria and must accommodate the languages of the manufacturing and engineering if the system is to serve both communities. A key finding is that the terms used in the system should be comprehensive, mutually exclusive and clear to all parties.

### **CRITICAL SUCCESS FACTORS**

This study of the North Berwick Product Center PC<sup>3</sup> demonstrated three critical success factors for the implementation and maintenance of a process capability information system: cross-functional participation, management commitment and information technology support. The first factor captures the importance of joint manufacturing and engineering participation in the construction of the system. Design engineers and manufacturing engineers will tend to be the principle users of such a system. Involving both groups in the construction of the system helps ensure that the information content meets the needs of both communities. Moreover, the participants in the development of the North Berwick PC<sup>3</sup> indicated that the so-called “healthy tension” negotiations between design and manufacturing engineers improved the accuracy and perceived credibility of the information. This credibility appears to be is a critical success factor to the acceptance of the system as a tool in IPD.

The second critical success factor is management commitment. Construction of the North Berwick PC<sup>3</sup> required a significant commitment of resources. The Mini-Kaizen process alone required over three months of intensive work. Each part family required several people from engineering and manufacturing to be dedicated for a minimum of three full days. In addition, a support staff of three to four was required for training and facilitation. Following each Mini-

Kaizen some support from the manufacturing Business Unit was required to enter the content of paper catalogue into the electronic database. The joint commitment of Product Center and CSCC management was critical to obtaining the resources needed for this effort.

Management commitment is also critical to ensure that the system, when complete, is used and maintained. The commitment to use the information seemed especially key to gaining the support of manufacturing. Pratt & Whitney had mixed success with a previous attempt to document manufacturability information. This attempt required significant efforts to assemble but never reached the desired level of use in IPD. The architects of the North Berwick PC<sup>3</sup> hoped to avoid this situation by securing and communicating the commitment of top management at the CSCC to make the use of the PC<sup>3</sup> information a mandatory requirement (i.e., by inclusion in the formal IPD stage/gate criteria). This commitment appeared to be critical for obtaining commitment from the Product Center to devote resources to construct and maintain the system.

The third success factor is the availability of information technology. Pratt & Whitney appeared to be successful in implementing the PC<sup>3</sup> quickly because of an existing information system infrastructure. Pratt & Whitney chose to use Lotus Notes™ as the document database. This system was already in use elsewhere in the organization for collaborative computing applications - most notably in the design community for capturing lessons learned. Pratt & Whitney also had the benefit of an existing intranet and a widespread PC/workstation web browser base. This existing infrastructure allowed the PC<sup>3</sup> to be deployed quickly at relatively low cost.

### ***Summary***

The PC<sup>3</sup> is an example of a process capability information system intended for use in IPD. The PC<sup>3</sup> has demonstrated several requirements of such a system and has highlighted some of the challenges surrounding implementation. In summary, the key findings are:

#### **IMPORTANT STRUCTURAL/CONTENT REQUIREMENTS**

- The structure of the process capability information system should be consistent with the product architecture and the arrangement of the manufacturing environment. This enables users to more easily navigate the system.

- The system should link manufacturing process capability to the product at the characteristic (or attribute) level. Manufacturing process capability is only meaningful in direct reference to a specific measurable aspect of the product produced by a specific process.
- The system should encompass all three components of process capability: statistical, contextual and competency.
- The system should make use of a well-constructed dictionary of feature and characteristics nouns.
- The architects of the system should consider how to balance the needs of local and global users. The system should accommodate both vertical and horizontal searches.

### **CRITICAL SUCCESS FACTORS**

- Cross-functional participation in the construction of the system is critical. Both engineering and manufacturing must jointly own the system and concur on the content.
- Management commitment is critical to successful implementation. Significant resources are required to construct such a system. The use and maintenance of such a system takes commitment from the leadership of the engineering and manufacturing communities.
- Information technology is critical to implementation. The development and deployment of the information system infrastructure must precede the implementation of the process capability information system. Firms should consider integration of the process capability system with those system already in use in the organization (especially by practitioners of IPD).

The key findings from this case study provide insight as to how to create an IPD-focused process capability information system. The main body of this document makes use of these findings as evidence to support the recommendations regarding such a system.





# Appendix H

## Some Approaches to Process Improvement and Control

### ***Introduction***

This section is intended to serve two functions. The first is to illustrate what is meant by the terminology “Process Improvement and Control Program”. The second is to identify a number of approaches designed to address process improvement and control and list the steps in each program to allow for a simple comparison. The methodology used to fulfill both of these functions is the presentation and review of several approaches - from some relatively well-known programs that have been used in industry for a number of years to some less well-known programs currently in use to a few new approaches discussed in recent literature.

The approaches reviewed in this section are:

- **Total Quality Management**
- **Six Sigma**
- **Redefining a Process in 14 Steps**
- **Software Failure Analysis**
- **Process Certification**

The presentation of the overall structure of these program is used as the primary avenue for conducting a comparison.

## **Total Quality Management**

Total Quality Management<sup>1</sup> (TQM) addresses many facets of quality management from a focus on customer to continuous improvement to total participation and even to societal networking<sup>2</sup>.

The focus here is on the continuous improvement facet of TQM. In TQM, three different elements of continuous improvement are discussed: proactive improvement, reactive improvement and process control. Proactive improvement relates to sensing and addressing problems before they develop into serious issues. Reactive improvement and process control are linked together for most problems addressed today. This link can be illustrated by looking at the 7 QC Steps listed below:

1. Select Theme
2. Collect and Analyze Data
3. Analyze Causes
4. Plan and Implement Solution
5. Evaluate Effects
6. Standardize Solution
7. Reflect on Process (and Next Problem)

Reactive improvement involves cycling through all seven steps to address identified problems, whereas process control involves cycling through only steps 4, 5 and 6 to ensure the process functions to the established standards. Along with these seven steps are the following 7 QC

Tools used to analyze and solve process problems:

1. Check Sheet
2. Graph
3. Pareto Diagram
4. Cause-and-Effect Diagram
5. Histogram
6. Scatter Diagram
7. Control Chart

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<sup>1</sup> Shoji Shiba, Alan Graham, and David Walden, *A New American TQM, Four Practical Revolutions in Management* (Portland, Oregon: Productivity Press, 1993).

<sup>2</sup> These are defined as the four revolutions of TQM.

## **Six Sigma**

Six Sigma programs are used at many companies today. From company to company there is some variation in the detailed steps followed, however, the steps noted below provide a good example of the steps in a Six Sigma program<sup>3</sup>:

1. Process Measurement
  - Define project objectives, metrics and resource requirements
  - Create detailed process maps
  - Identify and implement gage capability studies
  - Perform short-term capability study
2. Process Analysis
  - Complete Failure Modes and Effects Analysis (FMEA)
  - Review project and develop roadmap
3. Process Improvement
  - Perform Multi-Vari studies to identify key process input variables (KPIVs) and key process output variables (KPOVs)
  - Prioritize KPIVs for further study
  - Use Design of Experiments (DOE) to verify impact of KPIVs on KPOVs
  - Use DOE to establish operating window for KPIVs
4. Process Control
  - Develop detailed process control plan using FMEA
  - Demonstrate validity of operating window using long-term capability study
  - Perform an equipment utilization study
  - Program review and final report

This basic structure of Process Measurement, Process Analysis, Process Improvement and Process Control is very similar to the Process Mapping, Process Improvement and Process Control structure adopted by Pratt & Whitney for its Process Certification program (discussed at the end of this appendix, and in more detail in Appendix C).

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<sup>3</sup> AlliedSignal, *Six Sigma Program* (AlliedSignal internal program information).

## ***Redefining a Process in 14 Steps***

Another approach to process improvement and control is the 14 step program discussed by Brown and Lake<sup>4</sup>. The 14 steps discussed in their May 1997 article are presented below:

1. Process-Scope Description
2. Current Customer-Supplier Model
3. List of Performance Measures
4. Current Performance Data
5. Customer Feedback Data
6. Benchmarking Data
7. List of Performance Standards
8. List of Problems
9. Problem Analysis Report
10. List of Potential Solutions
11. Vision of the Future Process
12. Prioritized List of Initiatives Needed to Achieve Vision
13. Preliminary Cost-Benefit Analysis for Initiatives
14. Project Report

Here again, as in TQM and Six Sigma, this structure follows the basic pattern of documenting and analyzing the existing process and identifying areas for improvement, only in this case the actual implementation and institutionalization of improvements is carried out after management reviews the project report.

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<sup>4</sup> David L. Brown and Margaret S. Lake, "Redefining a Process in 14 Steps," *Quality Progress*, May 1997, pp 83 - 88.

## ***Software Failure Analysis***

Software Failure Analysis discussed by Grady<sup>5</sup> looks at process improvement from a different perspective - a perspective that is not focused directly on a physical product that can be held in one's hand. Grady's five steps noted below seek to shift software defect analysis from reactive efforts at the individual level to proactive efforts at the organizational level:

1. Extend defect data collection to include root-cause information. Start shifting from reactive responses to proactive responses.
2. Do failure analysis on representative organization-wide defect data.
3. Do root-cause analysis to help decide what changes must be made.
4. Apply what is learned to train people and to change development and maintenance processes.
5. Evolve failure analysis and root-cause analysis to an effective continuous process improvement process.

In addition, Grady's *Software Failure Analysis Maturity Model* illustrates the progression from *One-Shot Root Cause Analysis* to a more in depth *Post-Project Root Cause Analysis* and ultimately to a *Continuous Process Improvement Cycle*. This progression is intended to help the organization adapt from the reactive mode to the proactive mode.

Although this perspective is different from the process improvement and control programs already outlined, the essence of data analysis, change implementation and control through the elimination of root causes illustrates that it really is not so different.

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<sup>5</sup> Robert B. Grady, "Software Failure Analysis for High-Return Process Improvement Decisions," *Hewlett-Packard Journal*, August 1996, pp 15 - 24.

## ***Process Certification***

Process Certification<sup>6</sup> is one of seven initiatives within the Achieving Competitive Excellence (ACE) campaign at Pratt & Whitney. The ten Process Certification steps are listed below, however, refer to Appendix B for more information on ACE, Appendix C for a more detailed review of Process Certification and Appendix F for Process Certification case studies:

### **Process Mapping**

1. Team Formation
2. Process Flow Charts
3. Process Baseline
4. Process Output Prioritizing

### **Process Improvement**

5. Cause and Effect Diagram
6. Root Cause Analysis
7. Process Improvement Verification

### **Process Control**

8. Control Plan
9. Documentation
10. Certification

As mentioned earlier, the structure of the Six Sigma and Process Certification programs are very similar. Not only are these programs similar, but also, as discussed in the summary below, all of the programs outlined in this appendix generally follow a similar approach.

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<sup>6</sup> Pratt & Whitney, *Process Certification* (Pratt & Whitney internal document).

## ***Summary of Approaches***

The review of these approaches tends to illustrate that they are actually more similar than they are different. The general process improvement steps listed below summarize the overall intent of the approaches reviewed in this appendix:

1. Documentation of the Current Process Flow
2. Collection of Performance Data on the Current Process
3. Identification of Possible Sources of Variation in the Process
4. Root Cause Analysis of the Most Probable Sources of Process Performance Problems
5. Implementation of Process Improvements
6. Collection of Performance Data on the Improved Process
7. Institutionalization of the Improved Process

Within these steps there is typically some iteration between Steps 4, 5 and 6. Step 7 plays an important role in preventing the process from decaying back to its original state. A key element in eliminating variation and reaching a higher level of process performance (process capability) is establishing a better understanding of the process physics and operating practices.