Improving Producibility in Aerospace Engine Manufacturing: Process Automation vs. Process Reengineering

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

Master of Business Administration

AND

Master of Science in Materials Science and Engineering

In conjunction with the Leaders for Manufacturing Program at the

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ABSTRACT

In any aerospace manufacturing operation, including Pratt & Whitney's Compression Systems Module Center, producibility problems can be major drivers of cost. Much of the literature focuses on design for manufacturability as a solution to producibility problems. While this is a valuable approach, this study focuses on manufacturing process improvement as a solution to producibility issues. Two methods of process improvement are discussed, process automation and process reengineering.

This thesis first surveys some of the major producibility problems at Pratt & Whitney's Compression Systems Module Center, as well as some of the efforts underway to address them. One of the largest issues, operator data input errors, is described in detail as a case study. Wireless gauging with automatic offset adjustment is proposed as a focused technological solution to this issue. As part of this study, funding has been obtained to implement the solution and testing has been conducted. This is an example of process automation. However, a broader process reengineering effort is also proposed. The fundamental question of why producibility problems tend to persist is also examined.

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Note on Proprietary Information

In order to protect information proprietary to Pratt & Whitney, the data presented in this thesis has been hidden, disguised or shown in simply an illustrative manner. Any data shown does not represent actual values used by Pratt & Whitney.

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1. Manufacturing Producibility Background

Producibility does not appear to have one universally agreed upon definition. However, a common definition of both producibility and manufacturability is "the ease with which a product or part can be produced" (Bralla, 1999). This document will use the terms "producibility," "manufacturability" and "manufacturing producibility" interchangeably. As with the literature in general, within Pratt & Whitney there also does not seem to be one universally agreed upon definition of producibility. However, based on observation of how the term is used in practice, a definition might be the ability to produce without non-conformances. A non-conformance is an issue which causes a part not to pass inspection. For example, a dimension measured to be outside of tolerance or excessive surface damage (e.g., scratches) would be characterized as a non-conformance.

A broader definition of producibility might also be considered. Producibility could more generally be defined as the ability to produce products consistently as intended (as designed, with desired quality, at desired time and at desired cost). If one accepts this broader definition, then production non-conformances are only a subset of what must be considered to identify a comprehensive set of producibility issues. In addition to avoiding non-conformances, factors such as the manpower and machine capacity to produce parts should be considered. Overdue parts, late deliveries or average lead times could be measured to assess this new dimension of producibility. While this analysis would undoubtedly be informative, it is beyond the scope of this study. For the purposes of this study, producibility will be defined as the ability to produce without non-conformances.

Much of the producibility literature focuses on design for manufacturability (DFM), essentially simultaneous product and process design. Improvement focuses primarily on the design phase (Venkatachalam et al., 1993). However, this document will be focused on improving producibility for existing parts, those currently being produced. These parts are typically well-established, having been produced for many years. These parts also have very rigid requirements for tolerance and performance. In this environment, it is difficult (though not impossible) to redesign existing parts, and thus difficult to retroactively design these parts for manufacturability. Therefore, this document will focus primarily on impacting producibility by improving manufacturing processes.

2. Selected Producibility Issues in Pratt & Whitney's Compression Systems Module Center

Pratt & Whitney's Compression Systems Module Center (CSMC) produces parts and subassemblies for the high- and low-pressure compressor sections of multiple commercial and military aircraft engines. A large part of CSMC's business is the machining of parts critical to the performance of Pratt & Whitney engines.

As mentioned previously, one possible definition of producibility is the ability to produce without non-conformances. If one accepts this definition, then any non-conformance generated during the production process is an indication of a producibility problem. Non-conformances can be tracked, measured and analyzed, and, more importantly, so can their impacts. Non-conformances can lead to

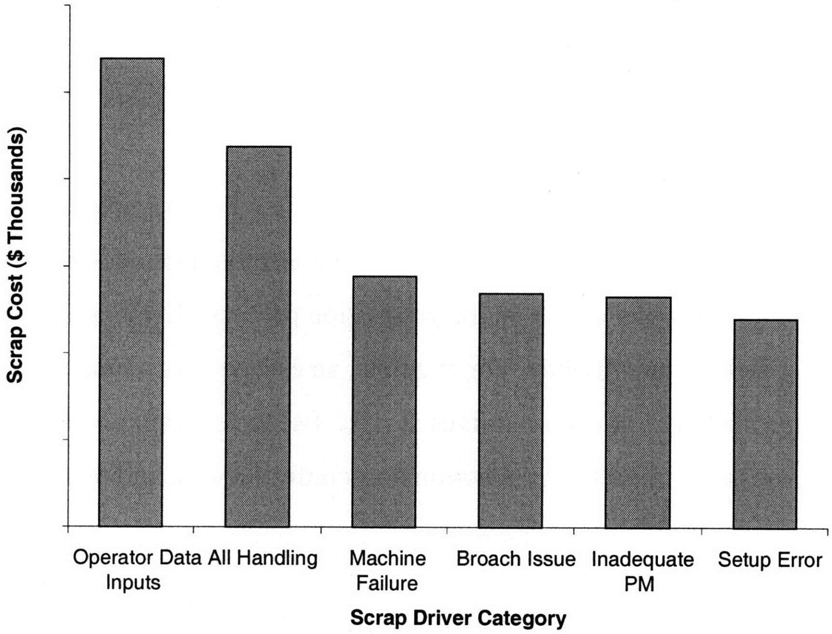
- **Escapes:** parts with errors passing inspection and being sent to a customer,
- **Scrap:** non-conforming parts which are no longer able to be fashioned into acceptable parts, and
- **Rework and repair:** the need to make non-conforming parts into conforming parts.

Escapes, scrap, rework and repair have corresponding costs. For example, the cost of scrap is often measured as the cost of the damaged material, but also the labor and overhead costs which have been allocated to that part earlier in the production process. Even escapes have costs, though these may be less quantifiable. For example, an escape may damage the company's reputation with the customer or even put lives at risk. Escapes, scrap, rework and repair can all be measured to assess the impact of production non-conformances, and therefore indirectly, the impact of producibility problems.

Every non-conformance found at CSMC is taken through a Root Cause and Corrective Action (RCCA) analysis and recorded with a quality notification (QN). The QN is essentially an electronic record of the non-conformance, containing a wealth of information for analysis. For example, each QN contains the part number, the manufacturing operation and the specific feature at which the non-conformance occurred. Additionally, each QN contains a qualitative description of the non-conformance's root cause and the action taken to correct the problem. These root causes essentially describe underlying producibility issues.

Because the root cause of each non-conformance is typically written by a different engineer, each root cause tends to be unique, making generalization difficult. However, grouping the root causes of non-conformances into meaningful categories gives insight into the producibility issues which are the major drivers of cost in CSMC. Figure 1 shows the scrap, rework and repair (SRR) costs associated with scrapped parts for the 12 months to October 1, 2007. The dollar values have been removed from the figure for confidentiality reasons, but Figure 1 shows which producibility issues are most costly when root causes are grouped into meaningful categories. The SRR cost attributable to each specific producibility issue shown below can be on the order of hundreds of thousands of dollars per year.

Figure 1: SRR Costs Associated with Scrapped Parts (12 months to Oct. 1, 2007)



A similar analysis could be done for the non-conformances which lead to rework and repair only (and not to scrap as shown in Figure 1). Analysis could also be done of the non-conformances which lead to escapes. However, SRR has traditionally been the focus of analysis, as it is a major driver of unnecessary cost across CSMC.

As mentioned previously, this study will focus primarily on improving producibility by improving the production process (as opposed to the design process). There are ongoing projects at CSMC to address specific producibility issues by improving the way parts are produced. For example,

- **Process Incidental Damage (PID) Reduction:** PID, also known as handling damage, is part damage that occurs repeatedly as a result of some facet of the manufacturing process. This damage often consists of nicks and scratches which require rework and repair efforts to correct. An effort to reduce this type of damage is underway, consisting primarily of observing the most heavily impacted processes, collecting detailed data on the damage incurred, and altering the processes in an effort to eliminate the damage.
- **Operator Data Input Error Reduction:** Operator data input errors, also known as offset errors, are a result of manual data input errors made by machine operators. This issue, and the efforts to eliminate it, will be discussed in detail in the next section.
- **Work Cell Mistake-Proofing:** Damage leading to SRR costs can be reduced in virtually any work cell by removing opportunities for mistakes. There are often efforts undertaken to mistake-proof work cells throughout CSMC.

Of course, within CSMC there are many additional producibility issues and many additional ongoing projects to address them. However, the purpose of this chapter is to give a broad overview of the impact of producibility issues at CSMC. The next chapter will discuss one of these issues in detail.

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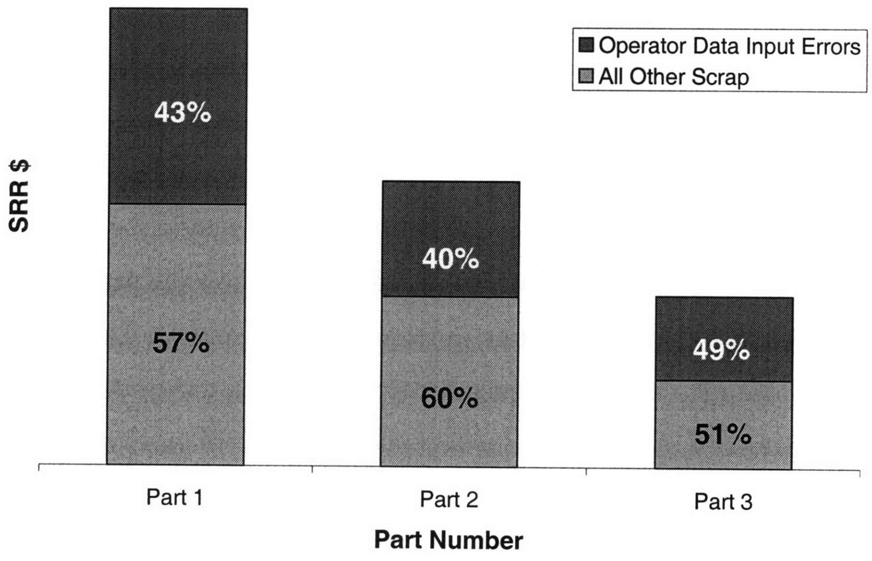
3. Operator Data Input Errors

As the largest driver of SRR costs for CSMC, the producibility issue of "operator data input errors" was examined in detail. This involved understanding the root causes of the issue, bringing the issue to the attention of the business unit, obtaining funding to address the issue, pilot testing a short-term solution and proposing a broader, longer-term solution.

The data suggests that operator data input errors can occur on a large number of parts and operations across CSMC. Operator data input errors can be tracked to specific parts, but also to specific operations, machines, dates and even specific operators. In order to make an initial examination practical, the three parts with the largest total SRR cost due to operator data input errors were selected for analysis. Figure 2 shows the proportion of all SRR costs attributable to operator data input errors for three parts.

Figure 2: SRR Costs by Part (Jan. 2006 to May 2007)

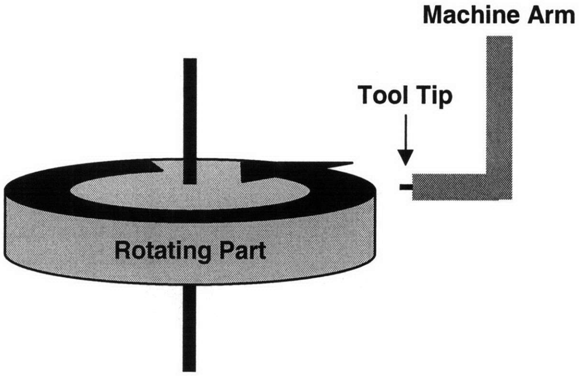


The dollar amounts have been removed from Figure 2 for confidentiality, but clearly operator data input errors are a major driver of unnecessary cost for these parts. For these three parts, the most costly type of machining process ("turning") was the area of focus. In this chapter, the drivers of operator data input errors will be described, and potential solutions will be examined.

3.1. Background on Machining Process

The generic cutting operation for which operator data input errors are most costly is referred to as "turning". During this operation, parts are mounted on a turning lathe, and can be oriented either vertically or horizontally. The part is rotated, and a mechanical arm with a tool tip cuts the part symmetrically around its diameter. Specific features cut on the outside of the rotating part are referred to as outside diameters (OD), and specific features cut on the inside of the part are referred to as inside diameters (ID). Figure 3 is an illustrative representation of a turning operation, with an OD being cut on a vertically mounted part.

Figure 3: Diagram of Turning Operation



A "part program" is a computer program which dictates exactly how the part will be cut, including dimensional measurements, cutting times and stopping points. Part programs are written to cut every feature to a specific dimensional value, referred to as the nominal value. However, a part's features will be designed with a tolerance band (e.g., 15 inches ± .003 inches*), to allow for variability in the cutting process. The tolerance bands are typically extremely small relative to the size of the feature. The part program is stored on, and executed from, a machine control, which is attached to the machine itself. Part programs can be

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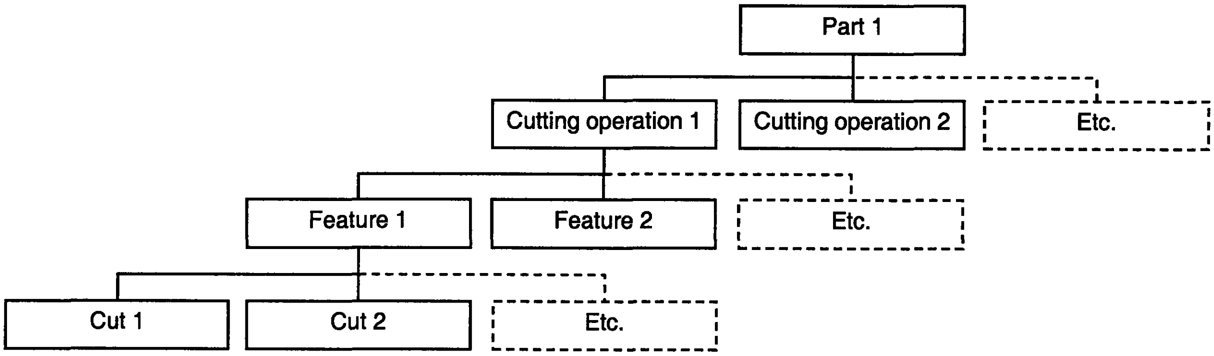
* Note: This dimension is completely fabricated. It is not intended to reflect a dimension for an actual part.

maintained and edited on standard PCs and then downloaded to specific machine controls at the time a part is to be cut.

There are many idiosyncrasies to each machine type and machine control. There can even be differences between the various machines of the same type. However, the preceding generic description serves as a first approximation of the turning process. Newer machines and machine controls with additional features exist, but the majority of CSMC's turning equipment is 20 to 30 years old.

For a sufficiently complex part, many individual cuts are required. One part can require many cutting operations, and even multiple turning operations. A single part cutting operation (which typically corresponds to a single part program) can involve the cutting of multiple features. The cutting of one feature can be made up of many of individual cuts. This proliferation of individual cuts is illustrated in Figure 4 below. A complex part could require dozens, or even hundreds, of individual cuts.

Figure 4: The Proliferation of Cuts Needed to Fashion a Complex Part



Part programs are typically written with pre-determined stopping points, usually at the end of each individual cut. At each stopping point, the operator measures the part with a gauge and then manually enters the numerical adjustment that he deems necessary (if any) to ensure that the next cut is made correctly. The operator's adjustment is referred to as an "offset adjustment." The arm with the tool tip, as shown in Figure 3, is physically "offset" (in the x, y or z dimension) by the amount that the operator enters. The operator then signals the machine control to continue to run the part program. For the large number of cuts made on an individual part, there are a correspondingly large number of manual offset adjustments which can be made.

3.2. Problem Description

When made incorrectly, offset adjustments are referred to as "offset errors" or "operator data input errors." These errors are typically noticed only when the error causes a feature to be cut outside of its designed tolerance. If tolerance bands are sufficiently large, then the variation in final dimension size due to offset errors will often be attributed to inherent variation in the machining process. If the tolerance band is exceeded, an investigation will sometimes discover that an operator data input error is the cause. These out-of-tolerance parts will typically require rework/repair or be scrapped.

3.2.1. Reasons for Manual Offset Adjustments

Discussion with, and observation of, operators has uncovered five main reasons why offset adjustments are made. It could be argued that some of these reasons truly justify an offset adjustment while others do not.

- **To correctly cut tight tolerance features:** Some features are designed with tolerances so tight (e.g. ± 0.001 inches from the feature dimension) that the current set of machine tools cannot consistently cut the feature within tolerance. In these cases, the operator will enter offset adjustments in an attempt to compensate. If the operator does not enter this adjustment, parts can be cut outside of tolerance.
- **To compensate for process problems:** In some instances, a part program will be written with a dimensional value that is not correct or not optimal. For example, for a relatively hard material, the machine may aim to remove 0.010 inches of material, but consistently remove only 0.008 inches. The reasons for this discrepancy are discussed in more detail in a later section (Section 3.2.2). In these cases, the operator will consistently enter the same offset adjustment to compensate for the process problem. If the operator does not enter this adjustment, the feature will consistently be cut incorrectly.

- **To interfere with statistical process control (SPC):** Certain final feature dimensions are measured and tracked in order to monitor the health of the processes used to cut them. If these measurements begin to exhibit a trend or exceed certain boundaries, the process is stopped and engineers become involved, even if the parts remain within design tolerance. In order to avoid engineer involvement, operators enter offset adjustments to keep final feature dimensions as close to their nominal values as possible. As with all offset adjustments, there is no record kept of the manual entries. Because the final feature measurement used in SPC is a combination of the automated cutting process and an unknown amount of operator intervention, the SPC process is not measuring the health of the machining process in any meaningful way. Theoretically, the automated portion of the process could be moving beyond some control limit while operator intervention hides this.
- **To make a part "better":** Because part programs are written with stops, the program typically halts after each cut. At these stopping points, the operator is required to check the sizes of the features being cut. Many operators feel that since the process is stopped and they are measuring a feature, they may as well enter an offset adjustment to cut the feature as close as possible to its nominal measurement, even if the part would otherwise be cut within tolerance. If the operator does not enter this adjustment, the feature would still be cut acceptably within tolerance.
- **To coordinate with subsequent operations:** Occasionally, subsequent operations are made easier if a part is cut over or under its prescribed size. In these cases, an operator will enter an offset adjustment, intentionally causing the part to be cut excessively small or large. If the operator does not enter this adjustment, the feature would be cut acceptably within tolerance, though subsequent operations might become more difficult or more unpredictable.

In practice, operators will often enter one combined offset adjustment for each cut, meant to address many of the above issues. In a later chapter, the general need for these adjustments will be evaluated, and potential alternatives to offset adjustments will be explored.

3.2.2. Material Properties Can Drive Need for Offset Adjustments

In the previous section, one reason for entering offset adjustments, to compensate for process problems, was mentioned. This problem often results from an engineer writing a part program without properly taking material properties into account. For example, if an engineer wishes to remove 0.010 inches of material from the OD of a part, he or she will often write the part program to position the cutting tool 0.010 inches inside the OD of the part. However, the material being cut provides a certain amount of resistance to the cutting tool, and a smaller amount of material than intended is typically removed.

For confidentiality reasons, the specific compositions of materials used in machining operations cannot be discussed. However, for the parts focused on in this study, the materials of interest are generally Ni-based superalloys and aerospace Ti alloys, being cut with carbide insert tool tips.

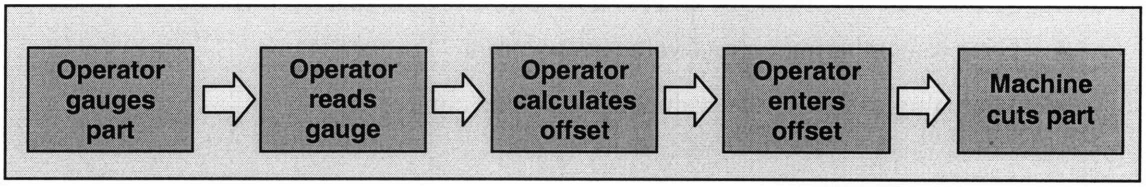
Operators typically account for the mismatch between the part program and actual practice by entering a manual offset adjustment. For example, if the intention is to remove 0.010 inches, but 0.008 inches is consistently removed, the operator will enter a manual offset adjustment of 0.002 or 0.003 inches. This adjustment would generally be consistent across multiple parts of the same type (the same part design, the same machining process and the same material). Therefore, the material hardness adjustment could easily be incorporated into the part program itself. This potential solution will be discussed in more detail in Section 3.4, when a solution broader than wireless gauging is explored for resolving operator data input errors.

Material hardness is not the only factor causing the amount of material removed to differ from the intended amount. Other factors, such as temperature expansion/contraction of the material and wear of the tool, are often issues as well.

3.2.3. Sources of Offset Errors

While there is no prescribed process for making an offset adjustment, there is a typical series of steps which an operator will follow. The major steps in this process are illustrated in Figure 5.

Figure 5: Typical Offset Adjustment Process



There are a number of smaller activities which must be performed during each of these major steps:

- **Operator gauges part:** The operator places a gauge on the feature being cut, physically adjusting the gauge until it is positioned correctly.
- **Operator reads gauge:** The operator looks at the gauge's indicator and notes the gauge reading (either mentally or on a piece of paper).
- **Operator calculates offset:** The basic offset adjustment is the difference between the previous cut's actual dimension and its nominal dimension. The theory is that the error in the previous cut will be repeated if an adjustment is not made. The operator will then factor in some or all of the other potential reasons for making an offset adjustment (listed in Section 3.2.1 above). Depending on the machine control being used, this value may need to be divided in half, as some machines take radial adjustments while others take diametric adjustments. The operator must also determine if this adjustment should be made in the x, y or z direction. These calculations can sometimes become complex. In practice, calculations are either done mentally or skipped entirely, with the result just estimated.
- **Operator enters offset:** the operator will access the proper screen for offset entry and type the offset adjustment value into the machine control manually.
- **Machine cuts part:** the operator will restart the automated cutting program and cutting resumes.

Some of the potential sources of error in the offset adjustment process are listed below:

- Improper positioning of gauge on part feature
- Improper reading of gauge measurement
- Miscalculation of difference between gauge reading and desired dimension
- Incorrect setting of offset direction
- Confusion between diameter and radius offsets
- Error remembering correct value at any point
- Mistyping of final offset value into machine control

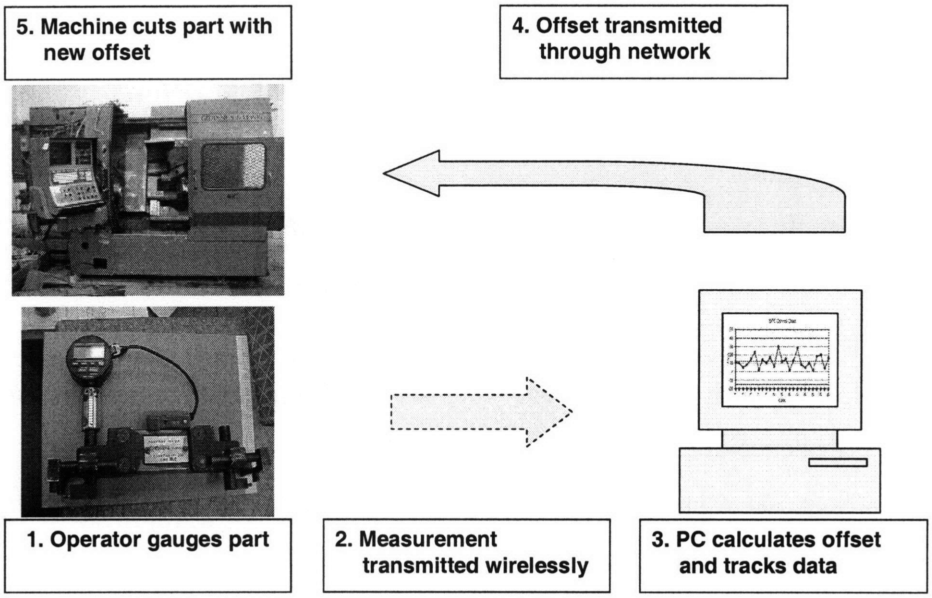
There are potentially other specific ways in which offset errors could be made, but the above list accounts for many of the most common. Unfortunately, data is not available to quantify what proportion of operator data input errors are attributable to each of the above error sources. However, observation suggests that all are significant. Obviously, when more offset adjustments are made, more opportunity for offset errors exists.

3.3. Potential Focused Solution: Process Automation

A highly focused solution meant to address the offset error issue is wireless gauging with automatic offset adjustment. In her article "Automate or Die", Perman describes Dell's automation work. Though Dell is an extreme example, Perman seems to suggest that automation is critical to the fast-paced business environment of the 21st Century (Perman, 2001). This wireless gauging system is largely an automation of the process which the operator currently follows manually. The goal of the system is to automate the process of entering offset adjustments to remove the manual sources of error mentioned previously (in Section 3.2.3).

The main components of the wireless gauging system are a gauge with wireless capability, a PC with wireless receiver, gauging and offset software for the PC, and updated machine control software. A diagram of the system is shown in Figure 6.

Figure 6: Wireless Gauging with Automatic Offset Adjustment



Wireless gauges can be created by retrofitting existing gauges with off-the-shelf wireless technology. Specifically, the original mechanical dial indicator can be replaced with a digital indicator, and a wireless end node can be attached to an output on the digital indicator. The wireless end node is capable of sending a transmission containing the numerical gauge reading (with the push of a button) to a wireless receiver, which is attached to a PC. Software on the PC captures the gauge reading, and software calculates the proper offset adjustment based on a preset routine created by the user. The offset adjustment values are then transferred to the machine control and read just as if entered manually.

The machine control and the part program are adjusted to allow for communication between the PC and the machine control. This adjustment is difficult and can require many rounds of testing, due to the age of the machine control technology (20 to 30 years old) relative to the age of the PC technology. Many newer machine controls are PC-based, and would allow for simpler communication. A simple web search yields numerous possibilities, for example, Okuma's THINC system (Okuma THINC).

3.3.1. Implementation of Solution

The effort to develop this focused solution and to prepare it for the production process consisted of four main steps.

1. **Identify Issues**
   - Initially, data analysis was conducted to identify the largest drivers of SRR cost in CSMC. The issue of operator data input errors was identified as one of these major drivers.
   - Specific parts and operations were selected for in-depth review, based on the prevalence of operator data input errors.
   - The selected parts and operations were studied to fully understand why offset adjustments are made and where errors can occur.
2. **Obtain Funding**
   - A potential solution (wireless gauging with automatic offset adjustment) was chosen and conceptually defined.
   - A business case for implementation was created, detailing all expected costs and savings. The business case was presented to CSMC managers and engine program managers, and funding for a pilot test was obtained.
3. **Design and Test Solution**
   - A team was assembled to implement the solution. This team included internal programmers, equipment/software vendors, machine operators, manufacturing engineers, management stakeholders, and others (approximately 30 individuals involved over initial six months of project)
   - Equipment was purchased and a prototype of the solution was created.
   - A demonstration was conducted for some senior executives.
4. **Conduct In-Process Pilot**
   - Iterative testing of the solution was conducted, with ongoing correction of errors.
   - A plan was created for hand-off to the implementation team.

A detailed plan was created for roll-out of wireless gauging with automatic offset adjustment across CSMC machining operations. The parts and operations with highest SRR cost due to operator data input errors were prioritized. The roll-out was to take place once the in-process pilot and iterative testing were complete.

3.3.2. Status and Next Steps

Currently, wireless gauging with automatic offset adjustment is able to be used on a production operation. However, a number of usability issues have kept this solution in the iterative testing phase. The main difficulty involves enabling the part program to repeatedly read data from the PC without operator intervention. Resolving this issue is difficult due to the age of the machine control technology relative to the age of the PC and data network technology. Currently, in order to be used in production, the wireless gauging solution would require a significant amount of operator intervention. However, if the operator must intervene excessively in this process, there would be a new opportunity for human error that might negate the benefits of eliminating operator data input errors. Attempts are underway to remove the need for operator intervention, but, as of the writing of this document, the issue has not been fully resolved.

Resolution of the operator intervention issue just described is one important next step. However, there are others. A number of other usability issues exist, which will not preclude the use of this solution, but should be resolved in order to use it optimally. For example, the placement of the wireless end node on the gauge is an important usability consideration, as the operator must be able to easily push the button to send the measurement while holding the gauge in place. This is one of many considerations. Once all basic usability issues are resolved, then the roll-out plan can be followed to implement this solution across a large number of parts and operations.

3.3.3. Expected Impact

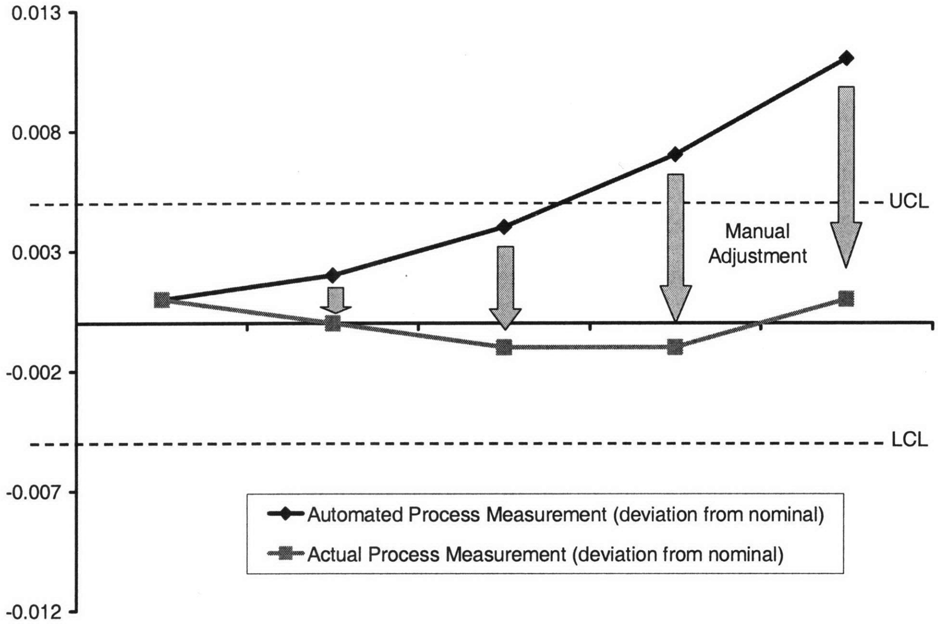
It is expected that wireless gauging with automatic offset adjustment will remove most sources of operator data input error from the current machining process. Of the potential sources of error mentioned previously (in Section 3.2.3), full implementation should reduce or remove all except "improper positioning of gauge on part feature." Even with this solution in place, the operator will still need to correctly position the gauge on the feature being measured.

The overall SRR cost to CSMC of operator data input errors is on the order of hundreds of thousands of dollars per year (exact figures cannot be stated for confidentiality reasons). As mentioned above, data is not available to quantify the proportion of operator data input errors attributable to each specific source. However, since observation suggests all of the sources mentioned are significant, wireless gauging should significantly reduce the overall problem.

There are other anticipated benefits to wireless gauging with automatic offset adjustment. For example, the system will create an entirely new source of data for analysis and SPC. SPC was the critical tool advocated by W Edwards Deming, one of the luminaries of the 20th Century quality movement. Random process variation could occur between an upper control limit (UCL) and a lower control limit (LCL). If measurements "fell between limits or did not trend" then the process was in control. (Garvin, 1990)

Pratt & Whitney currently conducts an SPC effort to track the health of machining processes. Currently, only the final dimensions of certain features are recorded and analyzed as part of this SPC effort. Because a measurement is taken after a part has finished being cut, the measurement reflects the process used to cut the part, but also an unknown amount of operator intervention. It is possible that the automated process itself could be trending in a worrisome direction or moving beyond the control limits for the process, with some unrecorded manual intervention making the final results acceptable. While it is important that parts be made acceptably, it is also critical to monitor the health of processes. The current system of manual interventions makes this monitoring impossible. This problem is illustrated in Figure 7.

Figure 7: How Manual Intervention Can Confuse SPC (Illustrative)



Wireless gauging will allow tracking of every measurement taken, including the final measurement. Meanwhile, the PC will record data on any offset adjustments automatically made. With this data available, it is trivial to calculate how the process would have performed without intervention.

Finally, it is hoped that this solution will provide a valuable new tool to operators. Operators will be able to track the offset adjustments being made over time, and be able to monitor their processes from the PC at their workstation. As the employees closest to part production, the operators are best suited to identify process problems as soon as they develop.

3.3.4. Potential Risks

While wireless gauging with automatic offset adjustment is expected to significantly reduce operator data input errors, there is the risk that new problems could be created, leading to new costs. These are risks that will exist even once the usability issues mentioned previously (in Section 3.3.2) are addressed. It is critical that these risks be understood prior to any wide-scale implementation of wireless gauging.

- **Increase in general operator neglect:** This is perhaps the largest potential risk of wireless gauging. Interviews with operators have suggested that automating the offset adjustment process will cause them to neglect the part cutting process in general. Operators may feel that their PCs are now responsible for ensuring that parts are cut correctly, and they are simply "button pushers." While wireless gauging largely automates the offset adjustment process, increased operator neglect would likely increase overall errors. One way to reduce this risk is to position the project attractively to operators. As mentioned previously, one of the main goals of the project is to provide operators with a new tool and to involve them in SPC. Involving operators and cell leaders in the development of the wireless gauging system, and proving them with proper training, should also reduce this risk.
- **Operator access to machine control:** The operators are extremely familiar with the machines used for part cutting and with the attached machine controls. It is possible at any point for an operator to access the machine control and undo or override the offset adjustment made by the wireless gauging system. Due to the age of the machine controls, no record of this adjustment would be kept. This risk could be reduced by properly training operators and including operators and cell leaders in the development of the wireless gauging system.
- **Temporary technology failure:** There are a number of technical problems which could arise once wireless gauging has been implemented. For example, the PC could fail or crash, the batteries in the wireless end node could die, or the electronic indicator or end node could get physically damaged. It is unlikely that these events could be completely avoided, so this risk can be minimized if operators have clear instructions for how to respond to these situations. Even though the process is largely automated, it is important that operators are constantly aware of what offset adjustments are being entered in case of a technical failure. In the event of major technical difficulties, the current manual offset adjustment process can be used so that production is not impacted.

Other risks will almost certainly be uncovered as the wireless gauging system is implemented.

One important method of mitigating the risks associated with automation is "pre-automation." Pre-automation refers to "the activities required to make the production process suitable for highly reliable automation.... To automate before might mean automating a process which was inherently inefficient or unreliable" (Pisano, 1992). Some pre-automation activities are: understanding process flows to streamline them and remove inventories, studying worker movements to increase efficiency, and specifying raw material quality and process tolerance levels (Pisano, 1992).

3.4. Potential Broad Solution: Process Reengineering

The focused solution described previously (wireless gauging with automatic offset adjustment) is a specific technological solution to the issue of operator data input errors. That solution essentially automates the manual offset adjustment process which an operator currently follows, without significantly altering that process. Mitigating the risks of automation with pre-automation work has been discussed. However, Michael Hammer suggests that automation is not a dramatic enough change to provide the improvements companies need. He suggests that "instead of embedding outdated processes in silicon and software, we should obliterate them and start over" (Hammer, 1990). This refers to process reengineering, radically redesigning processes to achieve dramatic improvements in performance. In this context, as an alternative to wireless gauging, it may be useful to reevaluate the general machining process, assessing if offset adjustments must be made at all.

The five major reasons that offset adjustments are made were discussed previously (in Section 3.2.1). For the purposes of process reengineering, offset adjustments can be grouped into three major categories.

- In some cases offset adjustments are not necessary and should be eliminated.
- In other cases, specific process changes are required before offset adjustments can be eliminated. However, the adjustments should be stopped.
- In some cases, offset adjustments will be required for a significant period of time, until broader, organizational changes can be made.

In some cases, operators make offset adjustments to bring the final measurements of their parts closer to the nominal dimension, even if the final measurement would otherwise be within the allowed tolerance. After each cut, the part program stops, and the process calls for the operator to gauge the part. At this point, it is relatively simple to enter an offset adjustment. The operators are making an effort to improve their parts, but in reality they are creating opportunities for manual errors. In these cases, operators should not be permitted to enter offset adjustments. Likewise, operators sometimes enter offset adjustments to make final measurements consistent for SPC, even if these final measurements would otherwise be within the allowed tolerance. While it is comforting to see final measurements be consistent, this creates opportunities for manual error and confuses the SPC process.

Manual offset adjustments are an ingrained portion of the machining process at Pratt &Whitney, so eliminating them will involve much more than simply instructing operators to stop. If parts can be produced within tolerance, then part programs should be re-written without stops between cuts. This would eliminate the opportunity for in-process gauging and in-process offset adjustments. The power to make offset adjustments could be restricted to manufacturing engineers, and only between successive parts. Of course, prior to eliminating offset adjustments, it will be critical to determine that the automated process is capable of cutting parts within tolerance.

In certain cases, manual offset adjustments can be eliminated with some basic redesign of the relevant part cutting operations. In some cases operators enter offset adjustments to compensate for process problems, such as the hardness of a part material consistently resulting in a different amount of material being removed than the nominal amount. In other cases, operators enter offset adjustments on one operation, purposely cutting the part differently from the nominal dimension, to make a subsequent operation on the same feature more accurate or easier to complete. In both of these cases, the part program could simply be edited such that the machine attempts to remove a bit more or less material than the nominal. Another option is to use different cutting tools, which can accurately cut the material in question. These changes should be consistent across parts. In fact, operators tend to enter a consistent offset adjustment from part to part in these situations.

Finally, there are cases in which the full process is simply not capable of consistently cutting features within tolerance. For these cases, in the short-term, offset adjustments are necessary. In fact, these may be cases in which wireless gauging is useful. However, in the longer-term, other solutions are possible. For example, new machines with greater capabilities could be purchased. Also, communications between design and manufacturing could be improved so that parts are designed with features that can be consistently produced. This is the incorporation of DFM concerns into the design process. These solutions have great potential value, but are beyond the scope of this study.

Even if some offset adjustments are still made, significantly fewer offset adjustments will lead to significantly fewer operator data input errors, which will in turn lead to reduced SRR costs. In the short-term, a rigorous assessment of every machining process can be conducted to determine where offset adjustments are needed and where they are not. Then, wireless gauging can be instituted in conjunction with process reengineering, removing offset adjustments from certain operations and redesigning others. In the long-term, capabilities can be upgraded and design for manufacturability can be addressed.

Realistically, as automation and process reengineering are pursued, there will be organizational and individual resistance to the proposed changes. Hence, in practice, producibility problems tend not to be resolved. Some of the reasons that producibility issues tend to persist at CSMC are discussed in the following chapter.

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4. Why Producibility Problems Tend to Persist in CSMC

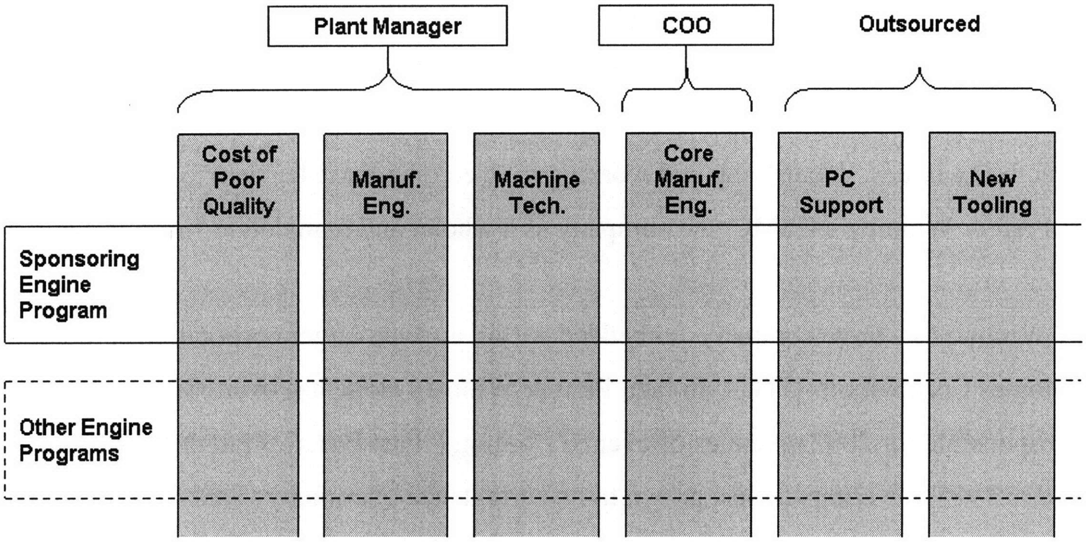
Producibility improvement is a specific instance of process improvement in general, and change is at the heart of these efforts. In organizations such as Pratt & Whitney, barriers to change exist, and huge organizational effort is often required to overcome them. The goal of this chapter is to highlight aspects of organizational design and organizational culture which impede the resolution of producibility issues. Identifying and working to overcome these barriers to change could benefit Pratt & Whitney's CSMC, the company as a whole, and many other firms as well.

Pratt & Whitney is a large company, embedded within an even larger corporation, United Technologies Corporation (UTC). In fact, Pratt & Whitney alone has over 38,000 employees and is responsible for 2007 revenues of over $12 billion ("Fast Facts", Pratt & Whitney website). Founded in 1925, the company has grown to its current size over many years. Pratt & Whitney's size and rich history are impressive. However, along with size and rich history has come bureaucracy: the required paperwork, processes and approvals which make even simple tasks lengthy and complex. Some of this bureaucracy exists for good reason. First, Pratt & Whitney works closely with military customers who demand a high level of traceability for parts made and processes used. Second, because flawed aerospace products can easily put many lives at risk, there is a focus on safety and manufacturing precision. Finally, many projects undertaken in an aerospace environment are large and expensive, meaning individuals are discouraged from making hasty decisions or being reckless.

There are less compelling reasons for bureaucracy as well. For example, because the industry tends to move slowly (i.e., with long product development cycles and life cycles), speed is not required on a day-to-day basis. Individuals tend to be overly conservative and hesitant to make major changes. Factors such as these have combined to create an environment in which many people must be involved in decision-making, projects require a huge number of approvals, and checkpoints are excessive. In this environment, changing production processes or organizational structures is a long and tedious process. Individuals sometimes give up, or have even changed jobs, before changes can be made and producibility improved in a significant way.

The structure of the organization itself makes change difficult to implement. To some degree, Pratt & Whitney is a matrix organization, as shown illustratively in Figure 8.

Figure 8: Matrix Structure of Organization (Illustrative)



Product lines are managed by engine programs, while functional groups provide expertise in specific areas. An effort to improve producibility (such as the wireless gauging solution described previously) will likely cut across a large number of these groups. This results in the involvement of many decision-makers with many competing priorities. Again, this makes producibility improvement a challenge.

There are other aspects of the organization which make producibility problems difficult to solve.

- **Focus on day-to-day production:** In CSMC, there is an intense focus on completing and shipping parts. At any moment in time, it is difficult to justify interrupting production for process improvement. In fact, significant process improvement aimed at improving producibility would likely interfere with production in the short-term, as it would take employee time and machine capacity. However, in the long-term, the improved processes would lead to improved production. Repenning and Sterman suggest that investment in improving capabilities (process improvement in this case) will often cause reduced output in the short term. However, eventually the improved capabilities will more than make up for this loss. This is referred to as the "worse-before-better" phenomenon (Repenning and Sterman, 2001).

- **Focus on accounting for time:** Many employees at CSMC are required to account for the hours they spend on various activities. This is a formalized process in which hours are allocated to charge codes, and project or department budgets are impacted. There is a tendency to ignore producibility improvement and process improvement in general, if it is not part of an established and budgeted program. There is an expectation among managers that improvements will be made as part of employees' routine work, but this is often not the case.
- **Lack of familiarity with processes for change:** Because process improvement is not regularly an area of focus, individuals are often not aware of the processes in place to make process changes. Most process change requires navigating through a complex system of forms and permissions, with unexpected roadblocks encountered regularly. This stems from the bureaucracy mentioned above, as well as the lack of frequent process improvement.
- **Negativity/cynicism:** Process changes, and especially cost reduction efforts, are viewed with cynicism among the hourly workforce, and to some degree among the salaried workforce. Internally, stories abound of operators being automated out of jobs and of management perfecting a process in order to gain leverage when outsourcing it. Issues of globalization and outsourcing are sensitive political topics very much in the national consciousness. There is an almost tangible sense of hopelessness about the future of jobs in the manufacturing operation. The actors on the shop floor, especially critical to producibility-related process improvement efforts, meet these efforts with extreme negativity.
- **Low production volumes:** Because CSMC produces low-volume parts, it can take a large amount of time for a process change to be sufficiently tested and approved. The high cost of these parts creates a fear of process change among employees. Any mistake can result in a large cost to the organization, and this is not something with which individuals wish to be associated.

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5. Summary and Conclusions

Producibility is a critical issue at Pratt & Whitney's CSMC, leading to significant costs. There is a wealth of data available for analysis of producibility issues, and a number of projects underway to address them. The largest driver of SRR costs in CSMC is the issue of operator data input errors. A focused, technical solution to this problem is wireless gauging with automatic offset adjustment. This solution has been proposed, funding has been obtained, and testing has been conducted. A fully tested and implemented solution is not possible at this point, but significant progress towards that solution has been made.

In addition to this focused solution, it is useful to consider whether manual offset adjustments must be made at all. In some cases they may be eliminated immediately, and should be. In other cases some process change must occur prior to eliminating these adjustments. In general, producibility problems are difficult to eliminate. Some reasons are: bureaucracy, the matrix structure of the organization, a focus on day-to-day production, a focus on accounting for time, the lack of familiarity with processes for change, negativity/cynicism and low production volumes.

An assessment of all producibility issues at CSMC with specific recommendations for solving them is beyond the scope of this study. However, some general changes might help to solve and even to prevent producibility problems in the future.

- **Further ingrain ACE:** Pratt &Whitney (in fact, all of UTC) has an operating system called ACE. This system contains powerful and well-structured tools for data analysis, decision-making and process improvement. The tools to solve many producibility problems exist here. However, ACE is often viewed as a set of initiatives or projects, not a part of each person's daily work. It is also perceived as something not appropriate for the hourly workforce. Professor Steven Spear of Harvard Business School spent many years studying Toyota, and, in an interview with Sarah Jane Johnston, attributes Toyota's success partially to the company's ability to "distribute a tremendous amount of responsibility to the people who actually do the work…." There is a "tremendous emphasis on teaching *everyone* how to be a skillful problem solver" (Johnston, 2001). For ACE to have its intended effect, and for producibility problems to be meaningfully solved, employees must "think ACE" in everything they do. This is especially true for the hourly workforce, who is closest to the product and to most producibility issues.

- **Take long-term view of producibility:** In the short-term, process improvement is often seen as non-essential. Projects intended to improve producibility cost money in the current quarter and interrupt production, and the benefits are often not seen for months or years. However, if producibility issues are to be solved, it is critical that management takes a long-term view, making the necessary investment today to eliminate current or prevent future problems. This is, again, a reference to the "worse-before-better" phenomenon (Repenning and Sterman, 2001).
- **Establish stronger connection between design and manufacturing:** Many producibility problems spring from the design of parts without sufficient consideration of the manufacturing process. Redesigning parts that have been produced for many years is difficult to justify, but can be done. More importantly, all new designs should be created with constant input from manufacturing engineers and operators. This problem will only be exacerbated as design work becomes geographically more distant from manufacturing.

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