IMPROVING PRODUCT MANUFACTURABILITY THROUGH THE INTEGRATED USE OF STATISTICS

by

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Submitted to the Sloan School of Management and the Department of Mechanical Engineering in partial fulfillment of the requirements for the degrees of

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Masters of Science in Mechanical Engineering

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ABSTRACT

Understanding the statistical nature of manufacturing error allows companies to increase the manufacturability of a product while achieving the required performance and quality. A technique known as Statistical Tolerancing may be used to match the capability of manufacturing processes to the performance requirements of a design. Balancing the design requirements with the manufacturing capabilities maximizes both the process yield and product performance. This thesis reviews a specific application of Statistical Tolerancing on the Carlyle 06N Geared Twin Screw compressor.

In addition to the mathematical model of the system, implementation is complicated by three major factors. 1. Different supplier's control different pieces of the same tolerance stackup. 2. "Goalposting" behavior with respect to tolerance limits. 3. The changing capabilities of the manufacturing processes. In order to implement a working system, these three factors were addressed through a combination of training and incentives related to delivery requirements. Continued success of the system is dependent upon the efficacy of these measures to affect long-term behavior.

Application of the technique and the required support system was successfully implemented on the Carlyle 06N Geared Twin Screw compressor. Increased manufacturability of the product resulted in a 70% decrease in the number of out of tolerance parts with no measurable decrease in product performance. Results also indicate that continued effort is required to systemically change behavior as desired.

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I would also like to acknowledge the resources, both physical and intellectual, made available to me at the Syracuse TR-3 plant at Carrier Corporation.

Finally, I am grateful for the support and encouragement of my wife Tiffany and my son Skyler who was born during the research period in Syracuse, NY. This thesis is dedicated to Skyler as we both embark on a new stage in life.

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SECTION 1: INTRODUCTION AND OVERVIEW

1.1 INDUSTRIAL REFRIGERATION AND THE NEED FOR HIGH PRECISION

Increasing global concern about the environment has resulted in a moratorium on HFCFC (ozone depleting) refrigerants as early as 2000 in Europe and by 2020 in the rest of the world.[1] A currently popular alternative refrigerant, HFC-134a, has no such environmental restrictions and is commonly used in the so-called "green" chillers. Despite its environmental advantages, HFC-134a is a less dense refrigerant than those commonly used in the past such as R22. As the refrigerant density decreases, adequate compression requires either a larger compressor for the same chiller size, or a compressor capable of compressing a higher volume of refrigerant. Screw compressor technology provides this higher displacement rate and, therefore, becomes more economical relative to reciprocating compressors as the world switches to less dense refrigerants for environmental reasons.

An additional economic consideration is the increasing costs of energy. As this is being written, a particularly relevant example of these rising costs is that of crude oil. From January 1999 to January 2000 the refiner's acquisition cost per barrel of crude oil rose from $10.47 to $25.44[2]. This is reflective of a temporary market condition, but the fact remains that demand for limited sources of energy continues to rise and energy costs are increasing. As energy costs increase, users of industrial refrigeration equipment are willing to spend more on the capital purchase of the equipment in exchange for higher efficiency and the accompanying lower lifetime cost.

Global restrictions on refrigerant use and increasing energy costs are primary industry drivers toward high efficiency compressors using environmentally safe refrigerants. Recently, screw compressors have been marketed as a higher efficiency and higher performance technology. Because of the direct relationship between the size of the internal clearances and the performance of the compressor there is a need to be able to consistently produce compressors with a very small clearance while maintaining the manufacturability of the product. This thesis will describe how statistical tolerancing was used to solve this paradox on one line of products and how the technique should be used in future designs.

1.2 PRODUCT DESIGN AND MANUFACTURABILITY

Classic engineering paradigms use an isolated team of engineers that serve as the brains to develop new products that use the latest technology. These designs are then passed along to production to work out the bugs and tweak the manufacturing processes until a working product is achieved. There may be several iterations of negotiation where manufacturing approaches the design engineers and asks for additional tolerance. In this scenario the engineers see their duty as defending the integrity of the design. Allowing more tolerance on a characteristic introduces risk into the design and may compromise performance or quality. Manufacturing knows that engineering is likely to be conservative and will often ask for more tolerance than the manufacturing processes require. Thus, the negotiations continue with eventual changes often coming as a result of manufacturing experiments or process excursions that are found empirically to have no negative effect on product performance.

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[1] Parsnow, J.R. "Five Reasons Why HFC-134a is the Refrigerant of Choice for Chillers", White Paper, Carrier Corporation, 10/3/1997

[2] "Energy Information Administration/Petroleum Marketing Monthly", March 2000, http://www.eia.doe.gov/pub/oil_gas/petroleum/data_publications/petroleum_marketing_monthly/current/pdf/pmmtab1.pdf

There are two primary problems with the classic paradigm: it is expensive, and it is slow. There is increasing global competition from fierce competitors who have found ways to make this development process much faster. Quality and cost competition are also causing manufacturers to re-examine the product development process.

In order to overcome the somewhat adversarial and slow-moving relationship between design and manufacturing, several techniques have been developed. Concurrent engineering involves the simultaneous design of product and process to improve the manufacturability and reduce the time required to successfully design a product and ramp up production. One of the most important aspects of this parallel process is involvement of product design, manufacturing, and marketing from the very early concept stages. Not only can technical difficulties be avoided early in the development process, but also relationships are developed that will help to overcome problems in the future.

Boothroyd and Dewhurst[3] propose a set of tools collectively called Design For Manufacturability (DFM) that directly addresses some manufacturability issues. By asking how many fasteners, how many types of fasteners, how many parts, etc. the designer assigns a manufacturability score and seeks ways to improve the manufacturability of the design. Additional tools known as Design For Assembly (DFA) and an integrated approach known as Design For Manufacturing and Assembly (DFMA) are also available to address this problem.

Despite these tools, the problem of transferring a design to manufacturing and bringing production up to full volume persists. The problem is a very difficult one, sometimes with its roots in the organizational structure or the traditional competencies of the company. The pressure to develop the next product makes it difficult for the design team to dedicate time to improving the manufacturability of a functioning product. Resources are being stretched as companies strive to do more with less both in manufacturing and design. Finally, the reward and incentive structures are often based on the classical paradigm and encourage adversarial behaviors despite other tools designed to defeat them.

At Carlyle Compressors some vestiges of the classical paradigm continue. The author observed negotiations between manufacturing and product design intended to establish the optimal balance of performance and manufacturability. Sometimes these decisions were made based on the balance of power and influence. In order to help make these decisions objectively, the author developed a method and a set of tools. This method will be presented and a case study of its application reviewed.

The rest of this thesis deals with the use of statistics in assigning tolerances to the 06N compressor at Carrier Corporation. Because this method requires an organizational change, the thesis first reviews the environment in which these changes were to be made. We then review the product itself and why precision tolerances are of vital importance. Next, we review how internal quality is currently measured and tracked. The proposed method is then introduced and its use analyzed. The analysis includes the barriers to its use and how these barriers were overcome. Finally, a case study of the method and the results are presented.

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[3] Boothroyd, G., 1988, Dewhurst, P., Product Design for Manufacture and Assembly, Vol 100, Iss. 4, p.42-46

2.1 COMPANY BACKGROUND AND POSITION

Carlyle Compressor Company is a division of Carrier Corporation, which is one of the companies of United Technologies Corporation. Carrier is the world leader in the manufacture and sale of heating, ventilating, air conditioning, HVAC systems, and products. Carlyle Compressor Company of Syracuse, NY manufactures and assembles compressors for use in industrial and commercial refrigeration and air conditioning systems. In addition to a state of the art TR-3[4] facility in Syracuse, NY, Carlyle has manufacturing facilities in Arkansas, Mexico, Scotland, France, India, China, Japan, and Korea. Internal manufacturing is comprised primarily of value added machining, inspection, and assembly. The TR-3 facility manufactures compressors with both reciprocating and screw technology operating on several different refrigerants. These compressors complement a larger product line offered by Carlyle to satisfy 40% of Carrier's compressor requirements. Carrier offers the broadest variety of vapor compressors in the industry. Figure 2.1 below[5] shows the variety of compressor types and their respective capacity ranges. Hermetic compressors are compressors in which the motor is sealed inside. In semi-hermetic compressors the motor is outside the sealed chamber and the power is transferred into the sealed chamber via a shaft. The 06N screw compressors that are the focus of this thesis are semi-hermetic compressors in the 40 to 70 ton range.

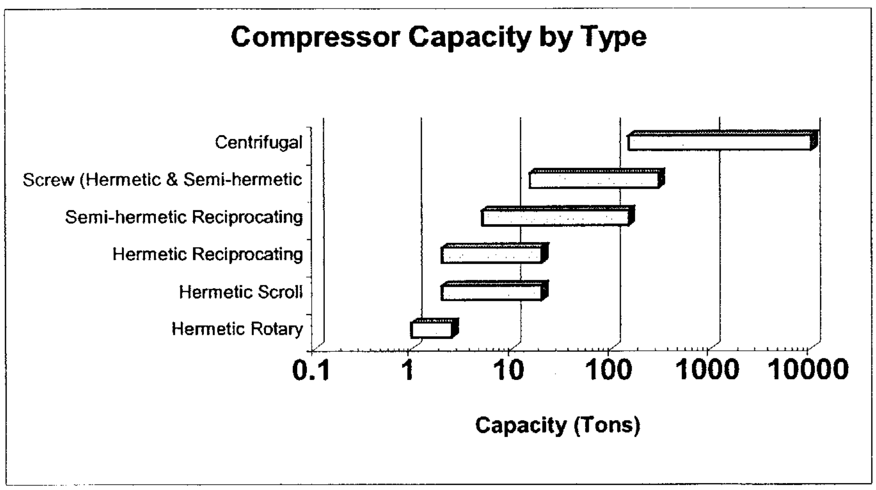

Figure 2.1. An overview of the types and capacity of compressor manufactured by the Carlyle Compressor division of Carrier Corporation. The TR-3 shop described in this thesis manufactures compressors from the following 3 categories: hermetic reciprocating, semi-hermetic reciprocating, and screw compressors. Typical applications for these compressors range from truck-trailer refrigeration units to mid-size industrial chiller systems.

2.2 MANUFACTURING STRATEGY

The TR-3 screw shop was set up with the intent of making all parts interchangeable. For this reason, many techniques of accommodating excessive variation are not acceptable. For example, maintaining alignment between two mating pieces is often achieved by mating the parts together and then machining the precision characteristics, e.g. dowel-pin holes and piston bores that these parts share. This technique requires that the

[4] TR-3 is the name of a building on the Carrier Syracuse Campus. TR stands for Thompson Road, which adjoins the facility. Buildings on the site are numbered 1 through 20.

[5] Adapted from an internal Carrier document, "Screw Compressors at Carlyle Compressor, Carrier Corporation"

two pieces that were machined together remain together through the service life of the product. Carlyle has chosen to allow any part on the compressor to be successfully mated to any other compressor. Achieving this goal requires close control of many characteristics within each component. The advantage of this approach is complete interchangeability and reduced complexity of manufacturing logistics. These benefits do not come without a price however; the disadvantage is the increased capability that is required of the machining centers, inspection equipment, and operators.

To date, the tight control of each of these characteristics has been maintained through meticulous 100% inspection of all characteristics on all parts. This results in high inspection cost, as well as procedures to evaluate and disposition parts that do not meet print specification. By applying the maximum allowable tolerance to the part while minimizing process variation, the probability of creating a deviant part will be greatly reduced. Carrier uses Statistical Process Control to measure and minimize the variation of each process. A capability score, P_{pk}, is assigned to each characteristic to quantify the probability of creating deviant parts. When the failure rate reaches 63 parts per million or below, Carrier will allow the parts to be produced and assembled without inspecting each part.

Before work on this project began, a significant number of the characteristics measured on the product did not meet the minimum process capability requirements. The objective of this work was to reduce the manufacturing cost of the 06N screw compressor by decreasing the number of characteristics that did not meet the minimum requirements. From the perspective of the product design team, statistics were used to increase the tolerance to manufacturing errors. From the perspective of the manufacturing organization, statistics were used to monitor and reduce product variation. Successful increase in process capability results in a lower cost through decreased scrap, reduced inspection time, and reduced administrative procedures.

2.3 PLANT ORGANIZATION & LABOR RELATIONS

In TR-3, the screw compressor products and the reciprocating compressor products are manufactured in separate sections of the factory. Although they eventually report to the same plant manager, the unit managers are separate and the production rules and even the labor contracts with the union differ. Separate engineering and production management staffs support the two operations. When Carlyle began manufacture of the screw compressors in 1994, the operation was purposely set up independent from the existing operations to allow experiments with production and labor management techniques. As the product matures and there are cost pressures on operations in the TR-3 facility, the isolated nature of the screw operations can be a source of friction within the plant. In addition, as company-wide labor reductions are enforced, the availability of labor for the screw operations is not at the discretion of the Carrier management team. Positions are given to those holding the most union seniority and experienced personnel can be "bumped" from their job when someone with higher seniority bids for it, even if this person is from another part of the plant. In addition to the normal equipment training that moving to a new position requires, operators new to the screw compressor operations must also be trained in the inspection techniques and production protocol, which differ from other production facilities on the site.

In order to meet the challenges of a rotating labor force and a technically demanding production system, Carlyle management provides extensive training to the operators. To be qualified as an operator on the finish machining centers for the screw compressors, for example, one must attend and pass certain training courses and progress through several operator levels of qualification. In addition, there is mandatory ongoing training that occurs to address specific issues or to improve the operators' understanding of the product being built. During the 6 months that the author was at the plant, the finish-machining operators were required to attend a Statistical Process Control class and a Screw Compressor Theory class.

The training measures described above are intended to offset the challenge of a constantly changing workforce. However, they do not address a more fundamental challenge of the environment. As operators are "bumped" from their positions they must find another place to work, possibly bumping somebody else along the way. The result is a workforce with a high percentage of changeovers with each labor adjustment. Possibly worse is a workforce with no certainty that they will be able to remain in the job they are currently performing. This uncertainty damages morale and contributes to the suspicious reaction of the operators when presented by a new technique by management or the engineering team.

The Sheetmetal Workers Union, which represents the operators, has a somewhat adversarial relationship with the Carrier management team and the situation has been worsened by recent business conditions. Carrier is growing at close to 10% annually. Much of this growth is through acquisition, and some of the old lines of business are shrinking or being outsourced. For example, the TR-1 plant is the oldest on the Carrier site. It houses the office and original ledger of Willis Carrier. In it is manufactured one of the staple products of the Carrier line, large centrifugal chillers that provide cooling for the largest industrial refrigeration and air conditioning systems. In 1999 the decision was made to move the manufacturing operations from TR-1 in Syracuse, New York to North Carolina, a non-union work environment. In the second half of 1999 the spare parts warehouse in TR-2 was rumored to be on the outsourcing block. Only after significant concessions by the union were these operations retained in house at the Syracuse site. Both of these conditions had the effect of churning the workforce and catalyzing the differences between the labor and management camps.

2.4 CORPORATE SOURCING INITIATIVES

In an effort to improve bottom line profit performance, United Technologies was engaged in a company-wide sourcing initiative. Carrier began its participation in the initiative in 1998 and continues to be involved as this thesis is being written. UTC had chosen to partner with FreeMarkets, Inc. to lower materials and subcomponent costs. FreeMarkets, Inc. "conducts online auctions for industrial parts, raw materials, commodities, and services. In these auctions, suppliers compete in real time for the purchase orders of large buying organizations by lowering their prices until the auction is closed."[6] A sample FreeMarkets event is shown in Figure 2.2. Price is shown on the vertical axis and time on the horizontal axis.

[6] FreeMarkets Company Website, "http://www.freemarkets.com/company/what-we-do.asp", March 8, 2000

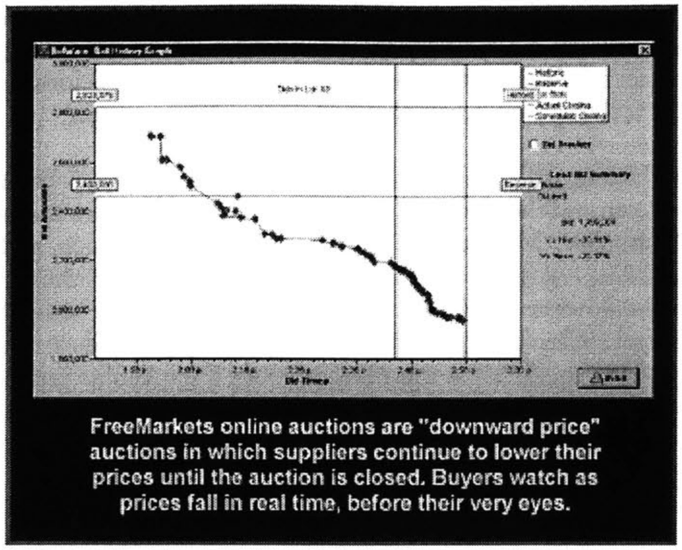

Figure 2.2. A sample FreeMarkets event.[7] *Price is on the vertical axis with time on the horizontal axis. In the case of engineered components, like those outsourced at Carlyle, suppliers are provided with engineering prints and a detailed description of how the part is used. The auction is used to narrow the field of potential suppliers; however, the final decision is only made after careful review of the process plan from each of the finalists.*

These events did yield significant cost savings to UTC as a whole, and to the Screw Compressor Operations within Carlyle. Another effect of the events was that there was an increase in the churning of the supplier base. Although FreeMarkets and the internal procurement team go to great lengths to ensure that the winners of such auctions are capable of reliably providing quality parts, there are costs associated with switching suppliers. Often engineering and other technical resources are required to ensure that the new supplier understands the requirements and to assist them in coming up the learning curve. One of the key components in the 06N compressor was the subject of a FreeMarkets event and as a result this part was transferred to a new supplier. The issues associated with this change and its effect on Carlyle's ability to use statistical tolerancing will be addressed as part of this thesis.

It is important to note that many parts being placed on this auction are not commodity parts. The process, therefore, requires continued support from the procurement and supplier quality organizations. Supplier decisions are not made based on price alone. The procurement and supplier quality organizations follow the auction with a plant visit and request a detailed process plan. The final sourcing decision is then made based on price, quality, and delivery. Although it is the intention of Carrier to maintain this emphasis on quality and the capability of the suppliers, the auction system provides tools and incentives for improving price alone. It is the opinion of the author that if these auctions are not supplemented with enhanced quality tools the incentives on price will shift the emphasis away from quality. If the focus shifts away from quality, the sourcing initiative with FreeMarkets may not deliver all of the savings indicated on paper. Additional time and resources will be required from the supplier quality organization to ensure the delivered product meets design requirements. It is imperative that quality be retained as a primary supplier selection criterion.

2.5 SUMMARY

In this section we saw the environment in which the change effort was to take place. Some aspects of this environment present challenges to the desired changes. For example, the labor conditions and a corporate-wide sourcing initiative add barriers to improving quality and manufacturability of the product. Section 6

[7] FreeMarkets Company Website, "http://www.freemarkets.com/company/what-we-do.asp", March 8, 2000

examines these barriers in more detail. The next section reviews the product itself and the processes used to monitor its quality.

With a better understanding of the environment in which this research was performed, we will examine the specific product and the technology behind its performance and manufacture. It is only recently that machining and inspection technologies have become adequate to consistently manufacture parts with the micron level precision required to make a viable screw compressor product. The 06N screw compressor discussed in this thesis began production in 1995. The compressor is roughly the size of a large block V8 engine and has individual characteristics that must be machined to within ±6μm. Successfully manufacturing this product requires advanced CNC machine centers, an elaborate environmental control system, highly accurate inspection equipment, and a skilled workforce.

This section will briefly describe how a screw compressor functions and why micron level precision is required. We will examine the use of Statistical Process Control and how it is designed to help achieve the necessary precision. The section concludes with a look at the product supply chain and the sourcing decisions relative to the 06N compressor. We will see that external suppliers manufacture some of the critical parts for the compressor. In order to take full advantage of the statistical techniques presented in this paper it is necessary for all suppliers to properly utilize SPC techniques.

3.1 SCREW COMPRESSOR TECHNOLOGY

Improvements in machining and manufacturing technology have made it possible to economically produce screw compressors with performance higher than equivalent reciprocating compressors. Screw compressors combine the robustness of rotating technology with the positive displacement. Positive displacement refers to the fact that with each cycle of the compressor a known amount of gas is compressed by a known compression ratio. The product of primary focus in this thesis is the Carlyle 06N 104mm Twin Screw Compressor. The product uses a two screw (or rotor) design with the male screw measuring 104 mm and driving the rotation of the female screw. A cutaway view of the product is shown below in Figure 3.1.

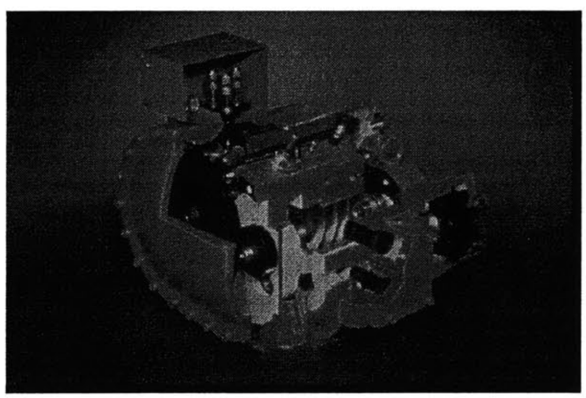

Figure 3.1. Cutaway view of 06N 104mm Twin Screw Compressor.[8] Note the configuration of the gears that drive the male rotor. By changing the gear ratio and the size of the motor, compressor capacity is changed without modifying the other parts in the compressor. A full product line is offered with capacity from 40 to 70 tons using a standard compressor platform.

The advantages of a screw compressor include:

- High envelope volume displacement rate (small size) compare to compressor capacity

[8] John McTiernan, "30gxcom.ppt" Internal Carrier Training Presentation, Carrier Corporation, 1996

- High reliability potential (rolling instead of sliding interfaces)
- Low vibration (achieved through dynamically balanced rotating mechanism)
- Low noise (low torque and pressure pulsation, no momentum reversing components - valves, vanes, pistons)
- Application tolerant (positive displacement, no surge like that associated with centrifugal compressors)

In a reciprocating compressor, just as in a reciprocating engine, there is a ring that sits in a groove on the piston and is held against the cylinder wall by spring force (see Figure 3.2). This prevents fluid in the high-pressure compression chamber from leaking to the low-pressure side of the piston. Fluid is allowed into the chamber by opening the inlet valve, and out of the chamber by opening the exhaust valve (see Figure 3.3).

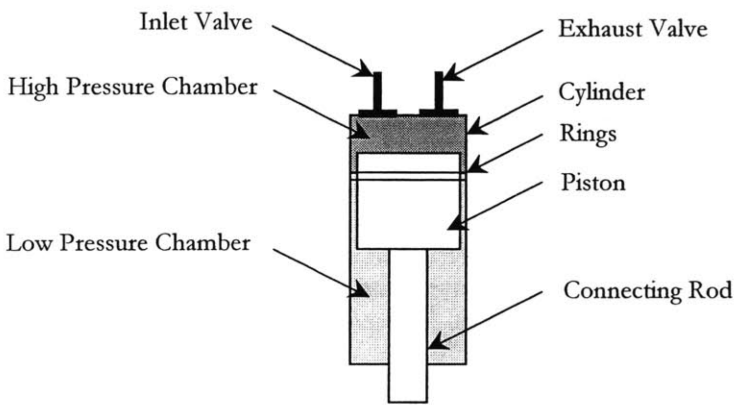

Figure 3.2. The Compression chamber of a reciprocating compressor. The rings slide directly against the walls of the cylinder, creating a seal that prevents the escape of gas from the high-pressure chamber to the low-pressure chamber.

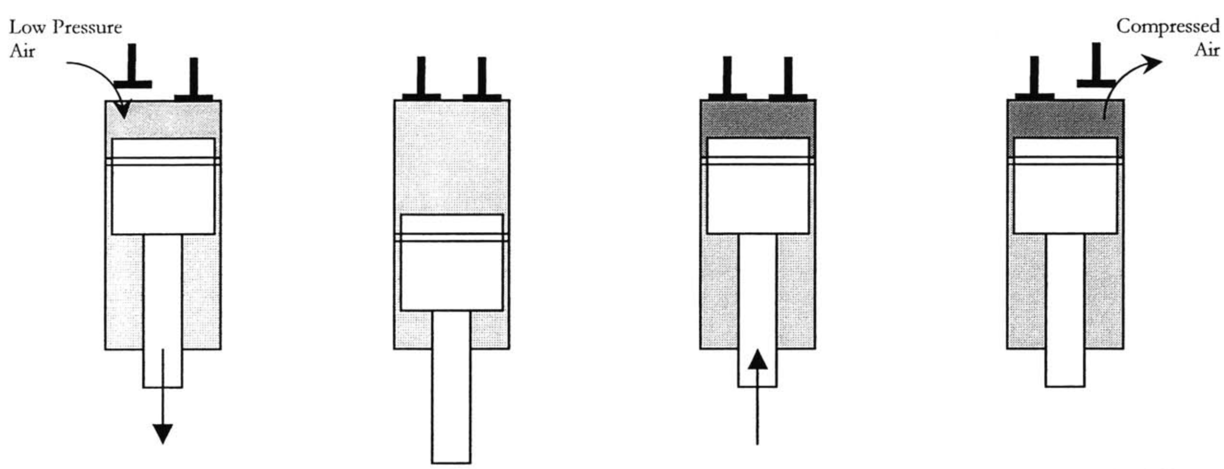

Figure 3.3. The Compression process in a reciprocating compressor. The inlet valve is opened while the piston is retracted. When the compression chamber has filled, both valves are closed and the piston advances, compressing the gas in the compression chamber. Finally, the outlet valve is opened and the compressed gas escapes.

One of the weaknesses of a reciprocating compressor is the susceptibility to getting liquid (an incompressible fluid) in the compression chamber. This condition results in a broken rod or other compressor failure. The inherent robustness of a screw compressor allows for some liquid in the compression chamber and the compressor will even operate for a short time with the compression chamber full of liquid. This robustness allows for a much simpler oil management system in the refrigerant circuit. There is no safety mechanism required at the shutdown of the compressor to prevent oil accumulation.

In a screw compressor, the compression chamber is formed between the lobes of the mating screw rotors and the walls of the cylinder bores in the rotor case. There is no physical seal like the ring in a reciprocating compressor. The only thing preventing fluid from flowing out of the high-pressure chamber to the low-pressure chamber is a thin film of oil between the lobes of the screw rotors and the walls of the cylinder bore. After compression, oil is separated from the compressed refrigerant and recycled back to the inlet side of the compressor providing lubrication for the gears, bearing, and rotors. In practice, the running clearances are maintained on the order of 50 to 100 microns. The smaller the clearance, the less refrigerant escapes and has to be re-compressed, and the higher the efficiency of the compressor.

Rather than valves that open and close to control the flow of gas in and out of the compression chamber, ports allow the gas to enter and escape from the compression chamber. The process is described in conjunction with Figure 3.4 below. Each of the frames represents the same set of rotors in a sequence of time steps. The male rotor is turned by the motor and transfers power to the female rotor. In frame 1 the gas enters the compression chamber behind the rotors. As the rotors turn to the position denoted by the shaded helix, gas is allowed to fill the entire helix on each rotor. In frame 2, the rotors continue to turn and the helixes are twisted together, decreasing the size of the compression chamber and compressing the fluid inside it. In frame 3 the compression chamber has reached its smallest size and the mating surface at the end of the rotors is exposed to an opening, the outlet port. The compressed gas escapes from the outlet port and the cycle begins again at the other end of the rotors. This process repeats itself 4 times per rotation at the rate of 12,000 rotations per minute.

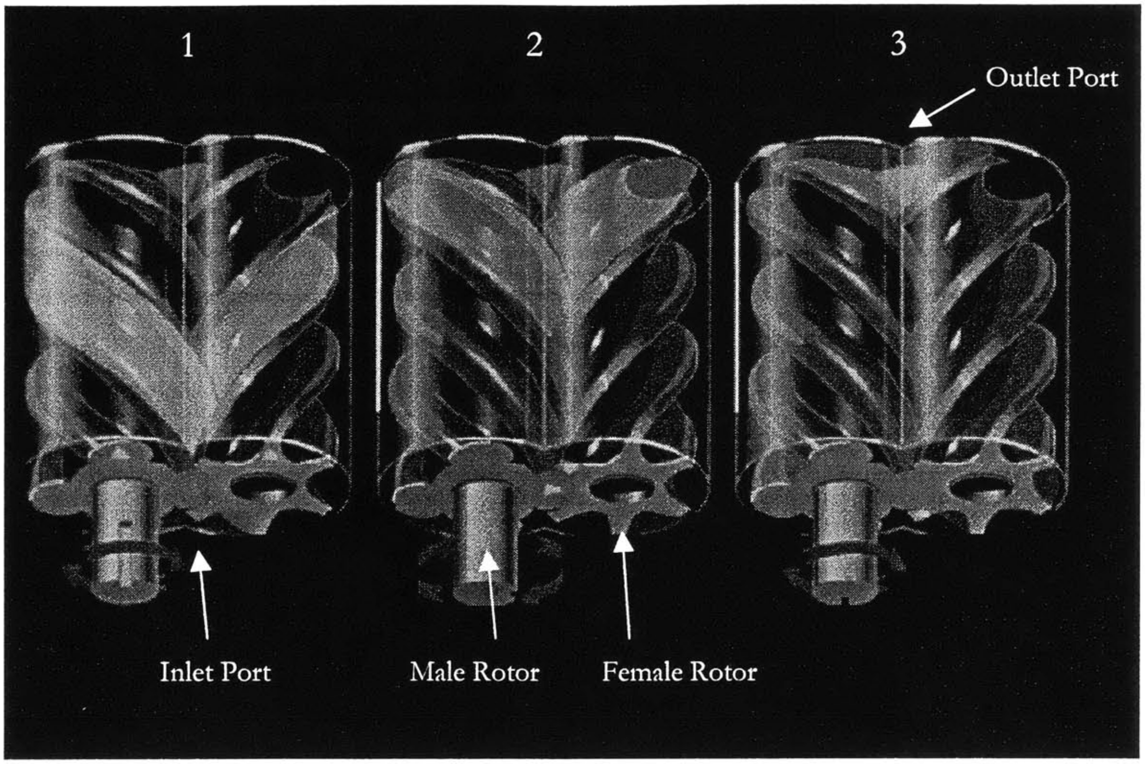

Figure 3.4. Compression in a screw compressor. Note that the inlet to the compression chamber takes place on the opposite side of the compressor. The chamber as shown in frame 1 of the figure has already been rotated 180° from the inlet position.

UNLOADING THE COMPRESSOR

There are times when the cooling requirements of the system are less than its capacity. Having the ability to "unload" the compressor, or operate it at less than full capacity, allows the system to conserve energy. In the 104mm 06N compressor this unloading is achieved by effectively shortening the length of the compression chamber. Rather than having the compression begin at the end of the rotor as shown in Figure 3.4, compression begins a third of the way up the rotor. Because the uncompressed volume of the chamber is smaller, the compression ratio is decreased.

This change in compression chamber volume is accomplished through the use of an unloader piston that short-circuits the uncompressed gas to the low-pressure side when the piston is disengaged. Figure 3.5 shows a schematic of the unloader pistons and the screw rotors. When the piston is engaged, it is designed to sit flush with the surface of the rotor bore, completing the seal with the lobes on the screw rotor. A piston is located at different locations of both the male and female rotors. Because the two unloader pistons are placed at different locations, or stages, along the length of the rotor (see Figure 3.6), it is possible to load the compressor in stages to achieve 40%, 70%, or 100% of capacity. The unloader piston and its interface with the rotor bore are the primary focus of the case study at the end of this thesis.

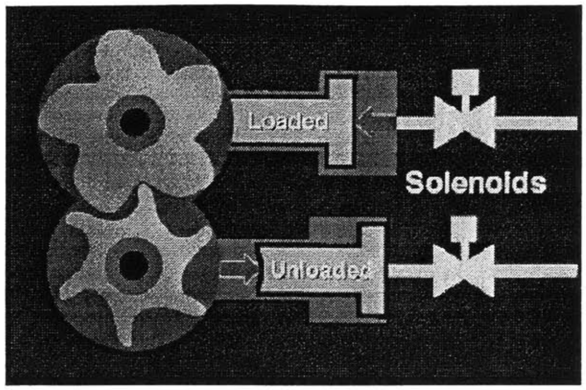

Figure 3.5. Unloader piston schematic. In this figure the male unloader piston is in the loaded position and the female unloader piston is in the unloaded position. The unloaded piston provides a short circuit to the low-pressure refrigerant and effectively decreases the uncompressed volume of the compression chamber. As shown the compressor operates at 70% of full capacity to conserve energy.

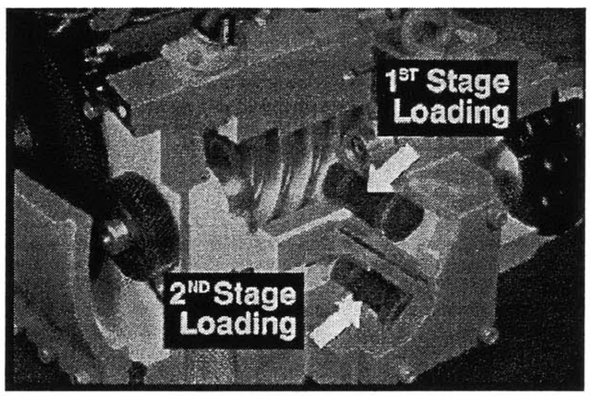

Figure 3.6. Staging of the unloader pistons at different locations along the screw allows the compression chamber to be shortened to conserve energy. Engaging both pistons provides 100% of capacity, unloading 1 piston provides 70% of capacity, and unloading both pistons provides 40% of full capacity.

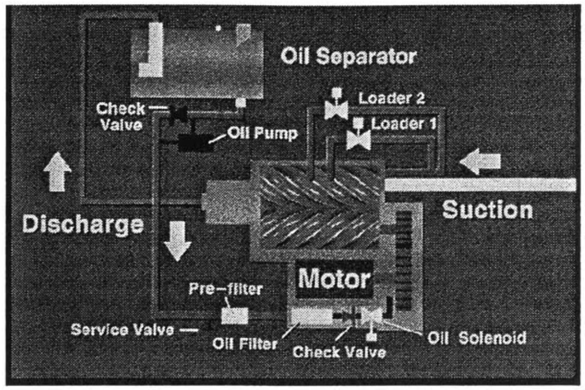

Figure 3.7. Schematic of the compression unloading circuit and the oil circuit. This view orthogonal to the length of the rotor shows the unloading of the compression chamber at different locations along the length of the rotor. When the piston is in the "unloaded position" away from the rotor, the compression chamber is opened to the low-pressure side until the lobe passes the piston bore.

3.2 USE OF STATISTICS IN PRODUCTION

Within Carrier Corporation an internally standardized method called Statistical Process Control (SPC) is used. Each characteristic that is generated in production is measured against criteria important to the function of that characteristic. Using SPC it is possible to measure only a sample of the product generated and state probabilistically the fraction of the entire population that meets the design requirements. Furthermore, SPC provides operators with simple rules to identify when a machine or a process requires an adjustment. These rules cut inspection time and reduce variability.

SPC is based on the assumption that a process that is "in control"[9] will produce parts that vary according to the normal distribution. As an example, let us consider a characteristic whose nominal dimension is 100mm and the tolerances for acceptance are ±10mm. In this case the operator will accept parts that measure between 90mm and 110mm. Why not just make every piece 100mm? Because it is impossible. There is variation in every process, materials used, temperature, targeting errors, tool wear, etc. In order to compensate for this variation, the operator should attempt to make every part as close to the nominal dimension as possible. This will result in the majority of the parts being close to target, with fewer and fewer parts measuring at values deviating further from the target.

The random component of variation (also known as common cause variation) will result in a normal distribution of error. Another type of variation, assignable cause variation, is due to "special" causes such as tool wear, a change in coolant temperature, a different operator, or a different lot of material. A "special" cause is a source of variation that can be traced directly to a cause. In a short time frame, assignable causes yield measurements that would not be expected under a normal distribution. These causes are detected under SPC rules. Over a longer time frame, assignable causes have the effect of increasing the observed variation of the population, but the distribution typically remains a normal distribution. The power of SPC lies in statistically detecting when a special cause of variation is affecting the distribution of measurements from a process. Once detected, these special causes can be identified and eliminated.

Figure 3.8 below shows a histogram of the actual measurements of the male rotor bore diameter. These data were collected over a 6-month period and include all sources of error. As shown here, errors collected over a

[9] Being in control means that the variation observed is due to a stable system of chance causes, the special causes of variation having been eliminated. Grant, Eugene L.& Leavenworth, Richard S., "Statistical Quality Control", McGraw-Hill, New York, 1996, p. 13

long period of time relative to the frequency of the special cause variation aggregate to produce a normal distribution.

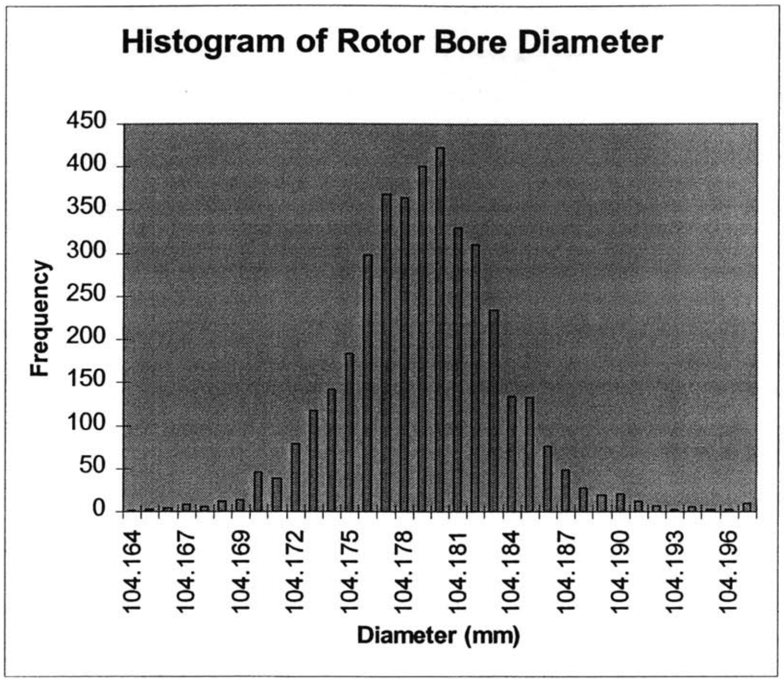

Figure 3.8. Sample shop data. Nearly 4000 data points were collected from 3 different machines, from more than 10 operators, and during a period of six months. Note that the aggregation of these data allows the computation of the long-term process capability, which includes all sources of error. Without any further improvement efforts, the process is expected to be able to perform at this level on a long-term basis.

Once we characterize the process with a measure of its mean (Equation 3.1) and standard deviation (Equation 3.2), we can compare this to the allowable variation to create a process capability score. This capability score P_{pk} is a measure of the probability that the process will produce a defect. P_{pk} quantifies the distance between the mean of the process distribution and the nearest specification limit in terms of its standard deviation. The formula for P_{pk} of a two-sided distribution is found in Equation 3.3 below.

Equation 3.1 $$\overline{X} = \frac{\sum_{i=1}^{n} x_i}{n}$$ *Sample mean*

Equation 3.2 $$\sigma_X = \sqrt{\frac{\sum_{i=1}^{n} \left(x_i - \overline{X}\right)^2}{n-1}}$$ *Sample standard deviation*

Equation 3.3 $$P_{pk} = \min\left(\frac{\left(USL_X - \overline{X}\right)}{3\sigma_X}, \frac{\left(\overline{X} - LSL_X\right)}{3\sigma_X}\right)$$ *Process capability*[10]

Where:

USL	=	Upper Specification Limit
LSL	=	Lower Specification Limit
target	=	Nominal Specification
X-bar	=	Sample Mean
σ_X	=	Sample Standard Deviation

The best way to understand what the capability of a process represents is to see it graphically. Process capability for a given amount of variation is highest when the mean of the process coincides with the nominal dimension. Process capability is also improved when the variation of the process, measured by the standard deviation, is low. Figure 3.9 shows several examples of processes with various process capabilities. As seen in the figures, one cannot hope to achieve a high process capability without the process being targeted on the nominal dimension. This point is very important and is a requirement of implementing statistical tolerancing, which uses centered distributions as an assumption when allocating tolerances.

[10] Those familiar with SPC will note the similarity between P_{pk} and C_{pk}. In fact, the only difference is the number used to characterize the standard deviation of the process. To calculate Ppk, one takes a large sample of the population that includes all sources of variation and calculates the standard deviation according to Equation 3.2. To calculate C_{pk} one uses an estimate of the standard deviation based on the Range of small subgroup measurements. When the process is in a state of statistical control the estimates of standard deviation will be the same. When special causes of variation remain, the estimate based on subgroup ranges will be much smaller than the standard deviation. Therefore, C_{pk} may overestimate the long-term capability of the process.

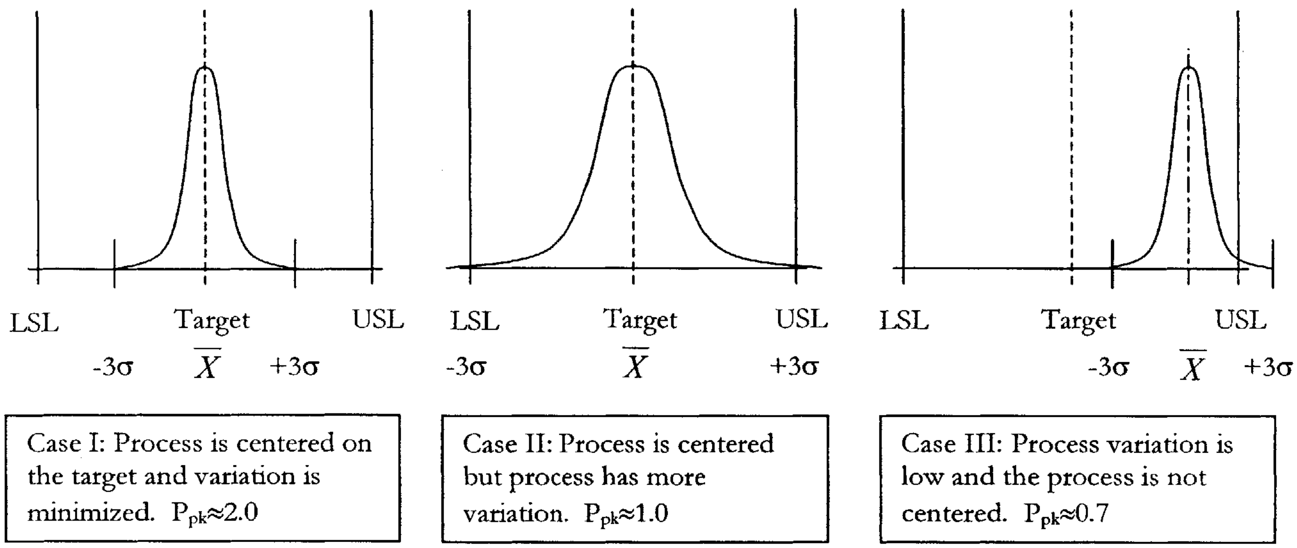

Figure 3.9. Example distributions with various process capabilities. Note that Case III has the smallest process capability despite having low variability. As seen in the figure, some of the parts within three sigma of the mean will exceed the USL resulting in a P_{pk} of less than 1.0.

In addition to quantifying the capability of the processes, SPC is used to improve and maintain the capability. This thesis does not attempt to fully explain the theory of statistical process control. For this purpose, the reader is referred to a text on the subject such as *Statistical Quality Control* by Grant and Leavenworth. However, because SPC is one of the tools used in the implementation of statistical tolerancing, the subject is worthy of a brief introduction here.

SPC uses the statistical nature of a process that is in control to identify the occurrence of special cause variation in the process. Subgroups of data are collected and plotted on an X-bar chart and an R chart. The size and the frequency of the subgroup are chosen based on the process. The X-bar chart is a representation of the process mean, while the R chart is a representation of the process variation. The subgroup mean, X-bar, is calculated from Equation 3.1 above, while the range R of the subgroup is given by Equation 3.4.

Equation 3.4
$$R = Subgroup_{\max} - Subgroup_{\min}$$

Three lines of interest are plotted on the X-bar chart. The first is the target for the characteristic. Operators must strive to keep the characteristics as close as possible to the target. The other two lines are the Upper Control Limit (UCL_X) and the Lower Control Limit (LCL_X). The UCL_X and LCL_X represent statistical limits for the subgroup mean and depend on the size of the subgroup. In the example shown, the subgroup size is 3. The range chart also has a UCL, a mean, and an LCL. In Figure 3.10 below, the LCL is not shown on the range chart because the subgroup size is so small that measuring the same value for each part, or a range of zero, is a statistically feasible event. The SPC rules used in production refer to the location of subgroup plots relative to these control limits.

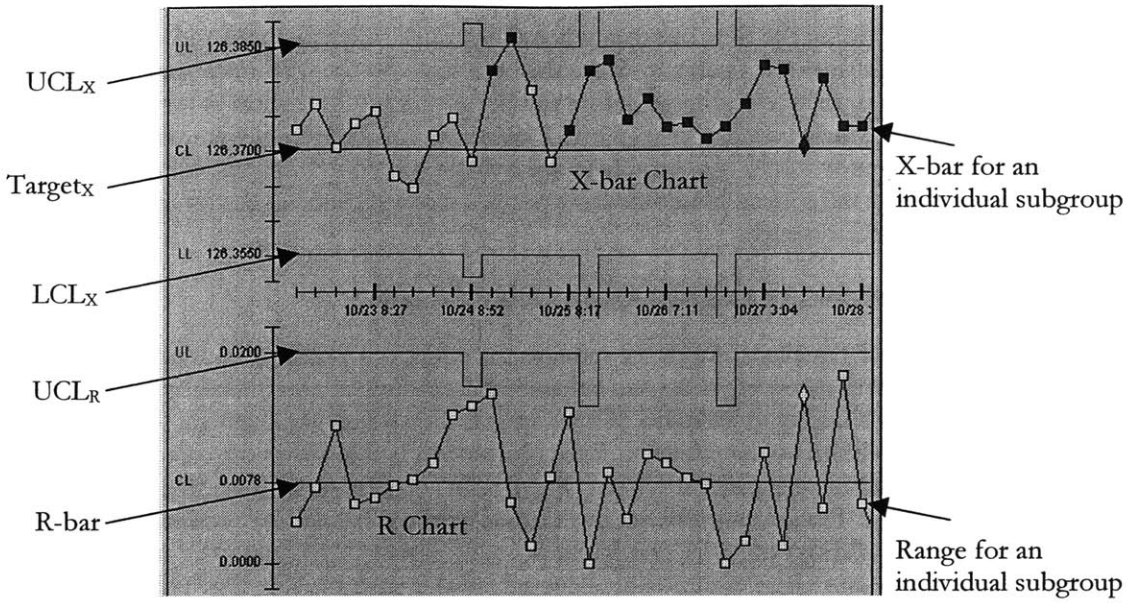

Figure 3.10. A sample control chart. Each mark records the results of analyzing one subgroup using Equation 3.1 and Equation 3.4. Note that on the X-bar chart, nearly all of the values are above the target value indicating that the process is not centered on the target value and must be adjusted. The software recognizes the out of control condition and indicates it by shading the violating subgroup points. The gaps in the USL and LSL lines indicate incomplete subgroups.

Because the control limits are based on statistical calculations, the SPC rules indicate when a statistically significant change in the process has occurred. For example, a single subgroup that exceeds a control limit is a statistically significant event. Immediate investigation and corrective action is required. A series of seven subgroup means on the same side of the target indicates a shift in the process mean. A single subgroup range that exceeds the UCL_R indicates that something has introduced more variability into the process. A process that violates any of these conditions is said to be "out of control."

An important attribute of SPC is the normalizing of subgroup data. No matter what form the frequency distribution of the population takes, x-bar values will tend to assume a normal distribution. This allows the use of SPC techniques even in cases where the process is non-normal.[11] SPC rules specify that operators should not make adjustments to the process based on the results of individual measurements, but should wait for the results of an entire subgroup. Waiting for a subgroup reading helps to avoid excessive adjustments and indicates a need to adjust only in response to true process shifts.

In the TR-3 Screw Operations, X-bar and R charts were recorded for each Critical Characteristic on the finish machining operation. These data are collected automatically for most characteristics and are stored in a database by a software package known as *Quantum SPC*. The data were then available for process control on the shop floor and for further analysis by process engineers and the quality assurance organization.

Although the data were being collected, a poll of the operators in July of 1999 revealed that only approximately 50% of the operators knew how to access and use this information effectively. Information for many of the characteristics was available only after the Coordinate Measuring Machine (CMM) had measured the part. Furthermore, measurement on this sensitive equipment required the part to be thoroughly cleaned at an elevated temperature and the temperature stabilized. This process introduced an

[11] Shewhart, W.A. "Economic Control of Quality of Manufactured Product" Van Nostrand Reinhold Co., Litton Educational Publishing, 1931, pp. 181-182

average of a 7-hour delay in the time between when the part was manufactured and when the measurement information was available to the operator. Since the cycle time for the 06N rotor case is approximately 1 hour, 6 to 9 rotor cases are manufactured before the operator has information as to whether the process is in control. Furthermore, the operators worked on 12 hour shifts and the cases were tracked in subgroups of 3, meaning that the operator would only be able to see a single subgroup from his shift before leaving the plant. The information delay introduced by the cleaning process was a substantial barrier to the complete implementation of SPC methods.

3.3 PRODUCT SOURCING STRATEGY AND SUPPLY CHAIN

Successful assembly of a quality compressor requires materials, components, and subsystems provided by outside suppliers, as well as components and subassemblies manufactured internally. Final assembly is performed in the TR-3 facility in Syracuse, NY where it is then tested and painted. TR-3 builds to target inventory levels established by the planners. From Syracuse it is shipped to the customer site where it is integrated into a chiller or refrigeration system. Finally, these chiller systems are installed at the customer site by trained technicians. Technicians who receive Carrier training also perform maintenance on the systems. Because of the high reliability of screw compressors, many parts of the compressor are not designed to be field-serviceable. To date, these compressors have achieved industry-leading low failure rates and reliability engineers immediately scoop up the rare field failures for analysis. A schematic of this supply chain is shown below in Figure 3.11.

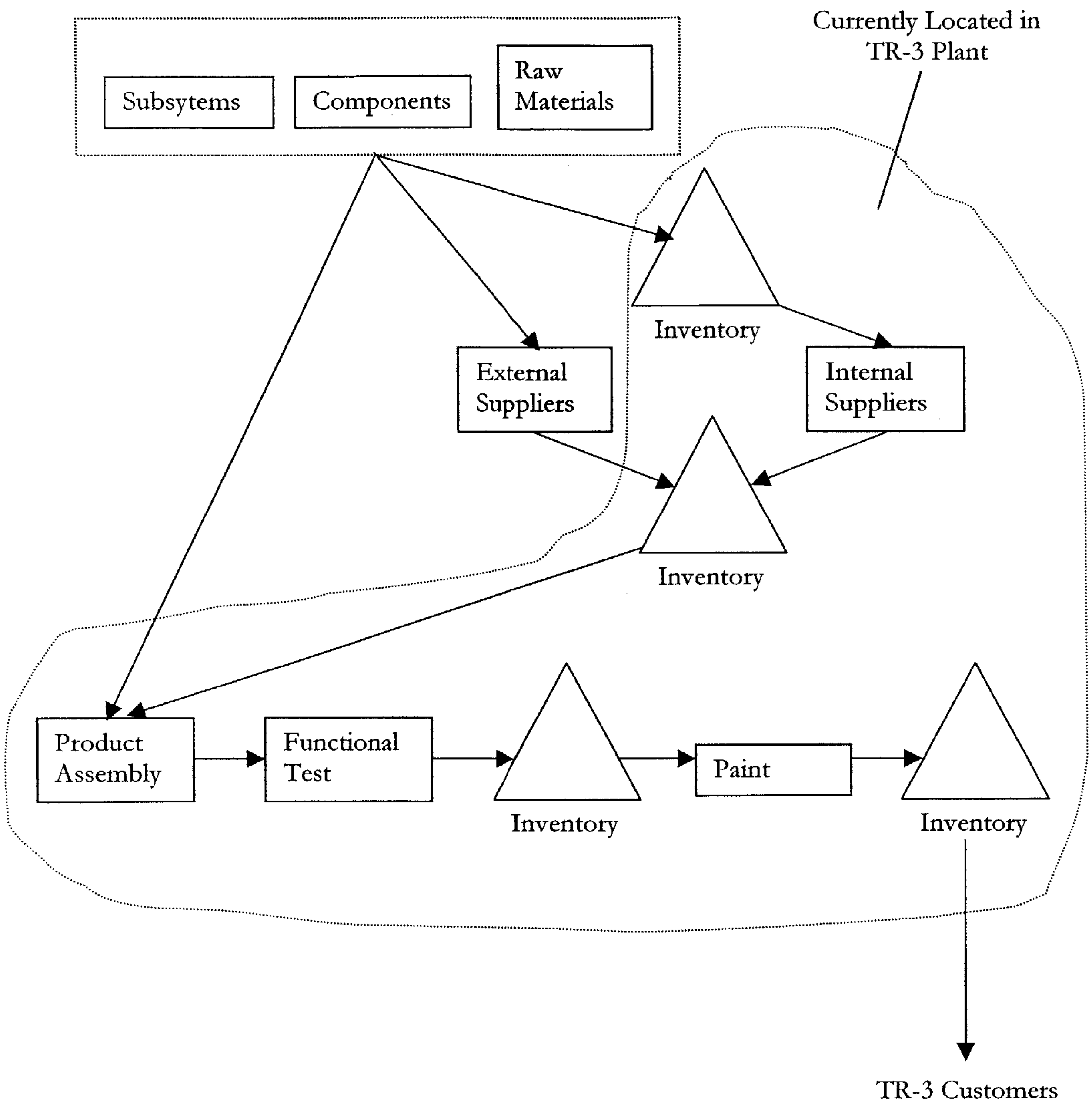

Figure 3.11. Supply chain schematic.

This supply chain becomes important for the successful assembly of the product because external suppliers provide precision-engineered components directly to the point of assembly. The suppliers are, therefore, stakeholders in the system through which statistical tolerancing is implemented. In addition, because one of the benefits of statistical tolerancing is reduced inspection, Carrier relies upon the suppliers' quality systems to provide statistical measures of their quality. Both Carrier and the suppliers can benefit from the use of the statistical tolerancing and quality system described in this thesis. As manufacturers, both benefit from having a product that is more manufacturable. As a customer, Carrier benefits by eliminating internal inspection on parts manufactured and quality certified by suppliers. Selecting suppliers who are capable of providing this level of quality control is not possible through automated tools such as the FreeMarkets auction system described above. Supplier quality engineers and the procurement organization thus play crucial roles in ensuring a successful supplier relationship.

The design of the compressor was done entirely by Carlyle's design engineering department. These engineers continue to own the design of each component whether it is sourced internally or externally. Any change that is requested to improve the manufacturability or performance of the part requires the signature of a design engineer. There is also much manufacturing expertise internal to Carlyle that is available to assist suppliers having quality problems and to provide Design for Manufacturing (DFM) feedback to the design engineering department.

The application of statistical tolerancing is complicated by the fact that multiple suppliers of critical parts use different quality systems. Because there is not a uniform quality system, no assumptions can be made regarding the suppliers' ability to provide parts that meet the statistical requirements discussed in the following subsection. There are some suppliers that are very advanced in the use of statistical quality techniques, while others limp along with classic 100% inspection with go-no go gauges. A successful relationship with the suppliers should provide incentives for the supplier to provide statistical quality data. The proposed dual-tolerancing system described in Section 7.3 provides such an incentive.

3.4 SUMMARY

In this section we examined how a screw compressor works and why a larger clearance in the compressor decreases the performance of the compressor. Small running clearances require small tolerances on each of the parts that contribute to the size of this clearance. One of the tools used to control variation is Statistical Process Control. Although SPC has been used in TR-3 Screw Operations since 1995, labor churn and the long cycle time of the product have prevented the shop from realizing the full benefits. In addition, we saw that some of the critical parts of the compressor are manufactured by external suppliers. Some of these suppliers do not understand nor use SPC. To successfully use the statistical tolerancing techniques in this thesis, the suppliers must learn and apply SPC.

In the following section we will see how TR-3 measures the quality of its processes and how these processes were doing in June of 1999. In the case that the quality objectives are not being met, we will quantify the cost of non-compliance. Quantifying process capability and quantifying the cost of incapable processes shows the potential financial benefit of this project.

4.1 EXISTING PROCESS CAPABILITY

The Screw Compressor Operations were set up in 1995 with automated data collection capabilities. One of the tenets of this new operation was the use of Statistical Process Control and the necessary tools were installed along with the production equipment. Data for each of the processes of interest are available dating back several years. Using the rotor case as an example, there are hundreds of characteristics specified on a 16 page engineering drawing. Some features of the design have multiple characteristics such as diameter, parallelism, and depth. Of these many characteristics, 44 have been designated as Critical Characteristics and are tracked and controlled via SPC

The existing processes have been continuously improved since 1995. Tooling has been modified, machine speeds adjusted, and the number of cuts on a feature optimized to obtain the highest process capability in the minimum time. Despite these efforts, in June of 1999 many characteristics did not meet Carrier's internal requirement of $P_{pk}=1.33$. Table 3.1 below summarizes TR-3's process capability for the 06N rotor case in June of 1999.

Total Number of Measured Characteristics	Number of Characteristics with P_{pk} of greater than 1.33	Number of Characteristics with P_{pk} of less than 1.33
89	23	66

Table 3.1. The state of process capabilities as of June 1999. The number of characteristics measured exceeds the 44 deemed Critical Characteristics because many Critical Characteristics require multiple measurements for machine control. For example, knowing that a hole does not meet its true-position requirement does not tell the operator which way to adjust the machine, therefore, such characteristics are measured in both X and Y.

It should be noted from Table 3.1 that although many of the characteristics did not meet the requirements for sample inspection, defective products did not proceed to the assembly process. 100% of the parts were inspected and measured against specifications, a very expensive and time consuming process. Parts that measure beyond the specification limits are recorded and tracked via a process known as In Plant Off-Spec Authorization. This process and its associated costs will be discussed at length in the following subsection.

In some cases the process capability requirements were not met because the machines were not capable of accuracy and repeatability at the required level. In this case the part to part variability is large, causing the subgroup range to be large. More often, however, it was due to long term sources of variability that are not evident during the relatively short process qualification. For example, seasonal environmental fluctuations would not be detected during process qualification. Nor would variation due to a slight temperature increase in the coolant as the particle filter becomes saturated and the pump must work harder. Capabilities between operators may also be difficult to predict. These long-term factors combine and increase the variation of the process over a long time horizon. To avoid overestimating the capability of a process, we use the long-term process capability, P_{pk}, in evaluating and assigning tolerances.

4.2 DISPOSITION OF NON-COMPLIANT PARTS - IPOSAS

Parts that do not meet print specifications are handled via a process known as IPOSA – In Plant Off Spec Authorization. Internal parts are manufactured on precision computer numerical control (CNC) machines. Some process verifications occur directly following the process step. However, most of the process verification takes place after the part has been cleaned and its temperature allowed to stabilize. Precision measurement takes place on a Coordinate Measuring Machine (CMM) that is capable of measuring large parts with accuracy and repeatability in the sub-micron level. All 89 characteristics mentioned in the preceding subsection are measured and verified at the CMM. Some characteristics must be held within ±6.5μm, and most critical characteristics have a total tolerance width of less than 40μm. A part that does not meet the print requirements for one or more of these characteristics is set aside and documented. The violated characteristics are noted along with the allowed and actual variation. A copy of the documentation is kept in the production logs, and a copy is circulated among the responsible process engineer, the product engineer, the machining superintendent, the quality assurance manager, and others for disposition.

There are two things that can happen with a deviant part: the part may be evaluated and deemed to be acceptable, or the part may be scrapped. In most cases, rework is not possible because the measurement occurs after the part has been removed from the machining fixture. When a part is placed in the machine, all of the critical characteristics are machined to their finish dimensions. The small tolerances make it impossible to re-locate the part accurately enough to rework a single characteristic. Scrapping or accepting the part on deviation requires a signature or processing from six individuals. Acceptance of a deviant part requires the approval of all signatories, while a single individual may reject a part. The documents are circulated and tracked manually by moving papers from the inbox of the first individual through to each signatory. The reviewer evaluates the acceptability of the deviation based on history, mathematical tolerance analysis, empirical results (actually testing the functionality of the deviant characteristic), or other means. When the evaluator has made a decision, the IPOSA is sent to the next person on the list until the evaluation is complete. Because this process requires the use of historical information, study of the prints, or accessing a database of measurement information, it is most efficient to process IPOSAs in batches at the beginning of the day. It is common for a part to wait for several days, sometimes weeks, until its evaluators determine its fate.

The IPOSA process disrupts the flow of material through the shop and adds cost to the product in several ways. First, when a planner releases material to the shop floor it is difficult to predict when all of the parts will be completed. This uncertainty requires the planner to add a buffer to the run of required compressors in order to ensure that the required amount will be available. The result is increased work in process (WIP) and finished goods inventory. The author observed more than $50,000 of inventory in the IPOSA hold area for a single part, the O6N rotor case.

Another cost to the Company is the time itself required to determine whether the parts are acceptable. Interviews with the people involved in the IPOSA process revealed the productivity cost of IPOSAs as outlined in Table 3.2.

IPOSA Processing Costs			
Average minutes of evaluation & signature/person		5	
Number of signatures required		6	
Minutes of evaluation/IPOSA		30	
Minutes to write IPOSA		10	
Minutes to write hold tag & move material to IPOSA hold		10	
Move material back from IPOSA hold		10	
Minutes of material handling		30	
Total minutes/IPOSA			60
IPOSAs/year		900	
Average labor cost/hour	$	50.00	
Estimated Annual Cost of IPOSAs in TR-3 Screw Ops			$ 45,000.00

Table 3.2. Estimated cost of processing IPOSAs. Salary level professionals perform the evaluation, while hourly employees perform material handling and documentation activities. The labor cost used is an average of rates for both salary and hourly workers.

One of the objectives of this thesis is to reduce the cost incurred by Carlyle due to incapable processes. The cost reduction will be accomplished through the improved use of statistical techniques in product design and manufacturing. Although SPC is being used in the shop, sample inspection, one of the major benefits of SPC, may not be used until all of the critical characteristics are capable.

4.3 INSPECTION REQUIREMENTS

In order to make accurate measurements of characteristics with tolerances less than 10 μm, the inspection equipment must be extremely sensitive. In TR-3 this inspection equipment includes Coordinate Measuring Machines, air gauges, and dial indicators. How does one know if the measurement equipment is adequate to meet the inspection requirements? It is generally recommended that inspection equipment be capable of measuring with a total error of less than 20% of the tolerance width. In order to ensure this capability, the quality department performs a gage R&R study on each piece of inspection equipment.[12] Gage R&R stands for gage repeatability and reproducibility. Gage error is considered the statistical sum of error in the gage itself plus error introduced by different inspectors or different gauges. Gage repeatability derives from the characteristics of the gage itself averaged over several users. Reproducibility derives from differences among users of the gauge or system. The total error can be represented as follows:

Equation 3.5

$$\sigma^2_{error.of.measurement} = \sigma^2_{repeatability} + \sigma^2_{reproducibility}$$

In order to perform the R&R study, an operator measures a part just as would be done in the production environment. This measurement is repeated and collected into a subgroup. Data are collected the same way as for SPC subgroups in production, recording Xbar and R for each subgroup. This process is repeated for multiple pieces. Several operators repeat the entire procedure to obtain the following values:

$\overline{\overline{X}}_i$	grand average for each operator. Equals the sum of xbars divided by the number of subgroups
$\overline{R}_i$	average range for each operator. Equals the sum of ranges for each subgroup divided by the number of subgroups.
d_2	SPC multiplier, depends on the number of samples in each subgroup

Table 3.3. Values required for the calculation of a gage R&R

Now the error derived from repeatability and the error derived from reproducibility may be calculated according to the following equations:

12 Grant, Eugene L.& Leavenworth, Richard S., "Statistical Quality Control", McGraw-Hill, New York, 1996, pp 304-306

Equation 3.6 $$\sigma_{repeat} = 1/\left(d_2 \sum_{i=1}^{n} \overline{R_i} \right)$$

Equation 3.7 $$\sigma_{reproduce} = 1/\left(d_2 \left(\overline{\overline{X}}_{\max} - \overline{\overline{X}}_{\min}\right)\right)$$

Because the total error is the sum of the squares of repeatability and reproducibility, if either of these components is large, it will dominate the total error. In order to accurately determine whether the process requires an adjustment, the measurement from the gage is considered to be a true measurement. When gage error is less than 20% the true measurement assumption is a good one, particularly when averaged over a subgroup. However, if the error exceeds 20% it is not known whether the variability is in the process or in the measurement. This is a very important concept, and one that not all suppliers of parts to the TR-3 facility practiced. In fact, one supplier controlled the production process with a gage that had measurement error equal to the tolerance. When measuring a part, a third component of error is introduced: part error. Measuring a part with a gage that has large measurement error does not give the operator enough information to know whether the observed variation is due to the part being measured or due to the gage.

A further requirement of an inspection system for statistical process control is understanding when it is acceptable to measure a sample of the parts as a representation of the entire population of parts being produced. As mentioned above, Carrier has as its internal standard a P_{pk} of 1.33 or greater. This ensures that the mean of the sample measured is at least 4 standard deviations from the nearest specification limit. In this case the probability of producing a part that is not measured that exceeds a specification limit is approximately 63 parts per million. Such a simulated distribution is shown in Figure 3.12 below.

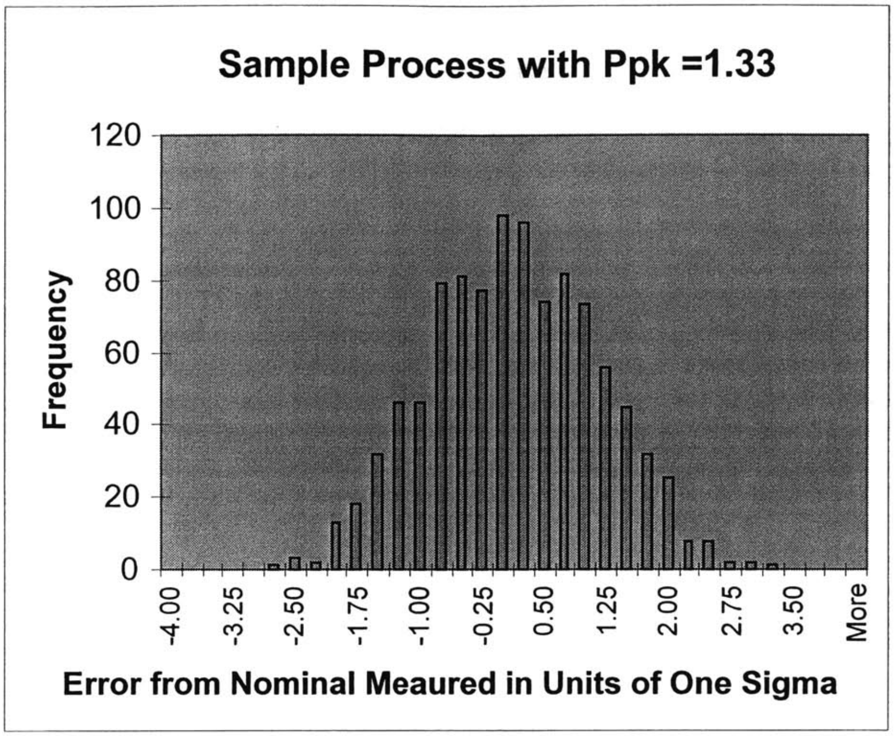

Figure 3.12. Sample distribution of 1000 parts from a normally distributed process with a mean value of 0 and a standard deviation of 1. Note that from the 1000 parts, none measure at the extremes of $\pm 4\sigma$.

With a process that demonstrates P_{pk} of 1.33 or greater we are confident that the probability of producing a defective part without detecting it is so low that it is not worth measuring. At this point we are measuring to verify that the process has not changed. This is a loftier goal, to measure the process rather than the part. Using SPC techniques a shift in the process can be detected and corrected long before the process risks creating a defect.

If all the 42 critical characteristics on the rotor case had $P_{pk} \geq 1.33$, then only a sample of rotor cases would need CMM inspection. The sample of measurements would verify that the processes continue to be in control. If any characteristic had Ppk $\leq$ 1.33, 100% CMM inspection is required for that characteristic. In fact, once the case is on the CMM all 42 characteristics can be measured without much additional time or effort. Therefore, the resource saving arises only if all geometric rotor case characteristics have $P_{pk} \geq 1.33$.

In addition to the logistical and statistical requirements of the inspection system, any sampling scheme to be implemented would need to meet the requirements of providing timely feedback to the operators. Therefore, the sampling frequency and the subgroup size should be chosen to balance statistical requirements and timeliness. The takt time of 1 hour for this product makes a large subgroup size impractical. For example, a typical subgroup size of 3 pieces would mean that an operator would rarely receive feedback from more than one subgroup before leaving his shift. The challenge of implementing SPC for low volume processes is that by the time data about the process is collected, one cannot tell if the process has changed in the meantime. These issues present much more of a problem to successful implementation than the calculations required and are addressed further in Sections 6 and 7.

4.4 SUMMARY

In this section we have seen that in June of 1999, 23 of the 89 critical characteristics met Carrier's internal capability requirement of $P_{pk} >= 1.33$. We saw that processing of non-compliant parts costs the shop $45,000 per year. Some of these non-compliant parts are thrown away at a cost of $80,000 per year. Increasing the capability of these processes would nearly eliminate these costs. An additional benefit of increasing process capability is sample inspection. With the 06N rotor case, however, the benefits of sample inspection cannot be realized unless all of the geometric critical characteristics are capable.

We are now poised to ask two critical questions. Does the design achieve the proper balance of performance and manufacturability? Are the tolerances allocated to individual characteristics in such a way that matches the capability of the manufacturing processes? We may find that of the 22 characteristics that exceed P_{pk} of 1.33 some exceed it by a great amount. In this case, it may be possible to re-allocate some of the tolerance to characteristics that have a lower capability. Not all of the characteristics are likely to have worst-case error on the same assembly. By using statistical theory we are able to allow more error to the individual characteristics while maintaining a low probability that the sum of the errors will exceed the limit. The following section provides a methodology for balancing the design through statistical tolerancing.

SECTION 5: STATISTICAL TOLERANCING

Tolerances assigned to the product will, to a large extent, determine the cost of manufacturing it. In many cases, production equipment is capable of easily producing the part with acceptable error. In some cases, however, parts of the design must be very closely controlled to ensure the function and performance of the product. The objective of statistical tolerancing is to optimally assign tolerances to these critical characteristics in order to ensure performance and minimize the cost of procurement, production, and inspection.

In order to function properly, there are many parts of a design that must be carefully controlled, these are known as Critical Characteristics. When the characteristic of interest is a result of combining other characteristics, the laws of probability can be used to predict frequency of failure. In our nomenclature, a characteristic comprised of multiple characteristics is known as a Super Critical Characteristic. An example of a SuperCritical Characteristic on an automobile is the gap between the front edge of the driver's door and the front quarter-panel. The size and location of the door and the quarter-panel determine the size of this gap. Variation in any of these components changes the size of the gap.

The chance that all characteristics will experience maximum error in the same direction, called worst case error, is very small. Statistical tolerancing uses this fact to assign tolerances that are larger than those derived through a worst case stackup. The relationships between characteristics and error inherent in the production process are used to allocate the tolerances optimally. It should be noted that one of the fundamental assumptions of the method described here is the statistical independence of the characteristics in a stackup. In other words, knowing the measurement of one characteristic does not tell you anything about what measurement should be expected from another characteristic.

Statistical tolerancing requires extensive product and process knowledge. Successful implementation requires input from product engineering, manufacturing engineers, and supplier quality engineers. Because this procedure requires extensive analysis and cross-functional collaboration, it is only used on characteristics critical to the design. Other characteristics are assigned tolerances easily within the capability of current production processes. The first subsection explicitly defines terms used to describe statistical tolerancing in this document.

5.1 NOMENCLATURE

STATISTICAL TOLERANCE – A requirement for a characteristic that is based on statistical interaction of characteristics.

CRITICAL CHARACTERISTIC (X) – A measurable attribute that has a significant, measurable impact on the performance, safety or manufacturability of the product.

SUPER CRITICAL CHARACTERISTIC (Y) - A Critical Characteristic that is a result of two or more other Critical Characteristics. An example of a Super Critical Characteristic is the clearance between the rotor and the rotor bore, which depends on the location of the bearing bores, rotor bore, rotor size, etc.

SENSITIVITY (S) – The mathematical relationship between a characteristic of interest (Y) and one of its contributors (X). A change of amount D in X results in a change of amount SD in Y.

LONG TERM PROCESS CAPABILITY (P_{pk}) – A measure of the number of standard deviations from the mean of a statistical distribution to the nearest specification limit. Measured in multiples of 3 standard deviations, e.g. a P_{pk} of 1.0 indicates that the mean is 3 standard deviations from the nearest specification limit. The index is distinguished from the Process Capability Index (C_{pk}) by the scope of variation considered. For P_{pk}, the sample used to calculate the standard deviation has a sufficiently long time horizon to include all sources of variation: seasonal, operator to operator, material, etc.

UPPER SPECIFICATION LIMIT (USL) – The maximum acceptable value of a characteristic. The limit is determined by the function of the design and is unrelated to the capability of the manufacturing process. The number is expressed relative to the nominal dimension, e.g. a specification of 100mm ± 1mm has a USL of 1mm.

LOWER SPECIFICATION LIMIT (LSL) – The minimum acceptable value of a characteristic. The limit is determined by the function of the design and is unrelated to the capability of the manufacturing process. The number is expressed relative to the nominal dimension, e.g. a specification of 100mm ± 1mm has an LSL of 1mm.

5.2 STATISTICAL METHODOLOGY

The probability calculations in this technique use the normal distribution. As multiple characteristics are combined, the Central Limit Theorem states that the resulting distribution will be approximately normal.[13] From the normal distribution, the number of standard deviations from the mean determines the probability of exceeding a specification limit. Normal tables are compiled according to the normalized parameter z and list the percentage of the population expected to exceed z.

Equation 5.1

$$z_{upper} = \frac{USL - mean}{\sigma}$$

Equation 5.2

$$z_{lower} = \frac{mean - LSL}{\sigma}$$

The abbreviated table below shows the number of defects that would be expected at various multiples of the standard deviation.

z_{upper}, z_{lower}	Failures (ppm)
2	45,600
3	2,600
4	63
5	0.6

Table 5.1. Abbreviated table of expected defects from a normal distribution whose mean is centered on nominal and is z standard deviations from the specification limit. The table assumes a two sided distribution where USL - mean = mean - LSL.

The benefits of the improving quality levels are weighed against the costs of achieving this quality. In Carrier Corporation the corporate standard for moving to a sample inspection scheme is a P_{pk} of 1.33 or greater, which equates to 4 standard deviations from the mean.

[13] Ott, R. Lyman, "An Introduction to Statistical Methods and Data Analysis", 1993, Duxbury Press, Belmont, CA., 1993, p. 178

The power of statistical tolerancing lies in the nonlinear increase of error as characteristics are combined. It can be shown that as independent variables are combined, the standard deviation of the resulting distribution increases with the square root of the number variables. This is due to the relationship shown in Equation 5.3. A brief example is instructive.[14]

Equation 5.3. $$\sigma_{clearance} = \sqrt{\sigma^2_{bearing} + \sigma^2_{shaft}}$$

5.3 AN EXAMPLE OF STATISTICAL TOLERANCING

Consider an assembly consisting of a bearing and a shaft. The designer requires a shaft with a nominal diameter of 25mm and a clearance from 20μm to 100μm. Using traditional methods, the designer may specify that the range of acceptable diameters for the shaft is 24.980mm to 25.020mm. The range of acceptable inside diameters of the bearing is 25.040mm to 25.080mm. The smallest shaft mated to the largest bearing yields a clearance of 25.080mm - 24.980mm = 0.100mm. The largest shaft mated to the smallest bearing yields a clearance of 25.040mm - 25.020mm = 0.020mm. The designer has met his requirements, however, if the two parts are independent and come from a normal distribution of parts that are randomly paired, this specification may cause inspection to discard acceptable parts.

Let us suppose that after measuring the diameters of 100 shafts we find that the distribution of diameters has a mean of 25.000mm and a standard deviation of 0.010mm. To determine the number of failures that are to be expected we must calculate z. From Equation 5.1 and Equation 5.2 we find that $z_{upper} = z_{lower} = 2$. Consulting a normal table we find that with the USL and LSL 2 standard deviations from the mean, only 95.4% of the shafts are expected to meet the design requirements of 25.000mm ± 0.020mm. Furthermore, after measuring the bearings we find that the mean and standard deviation are 25.060mm and 0.010mm respectively. Again this means that 95.4% of the parts will be accepted and 4.6% must be thrown away!

Returning to the original objective of maintaining a clearance from 20μm to 80μm, we may look at the clearance as a statistical stackup of part distributions. The mean value of the clearance is simply the mean value of the bearing minus the mean value of the shaft, or 25.060mm - 25.000mm = 0.060mm. Because the parts are independent, the standard deviation of the clearance is given by Equation 5.3 and is equal to 0.0142mm. We know that all assemblies with clearances from 0.020mm to 0.100mm should be accepted. Returning to Equation 5.1 we find that $z_{upper} = (USL - mean)/\sigma = (0.100 - 0.060)/0.0142 = 2.82$. Consulting the normal table reveals that only 0.5% of the assemblies are expected to have a clearance outside of the acceptable limits.

Over 4% of the parts are being thrown away despite the fact that when considered as part of an assembly they perform acceptably. As the number of parts going into the stackup, or Super Critical Characteristic, increases, the benefit of using statistical tolerancing also increases. The table below shows the difference between a worst case end to end stackup and a statistical combination of the distributions as the number of components in an assembly increases.

[14] This example is adapted from Cangello, Carl, "Statistical Methods and Process Control", Corporate Quality Department, United Technologies Carrier, Syracuse, NY, 1991

Number of Characteristics	Worst Case Error Stackup	Statistical Error Stackup
1	10	10.0
2	20	14.1
3	30	17.3
4	40	20.0
5	50	22.4

Table 5.2. Comparison of calculated error stackup by worst case and statistical methods. Note that when each element contributes the same amount of error to the total, the statistical error stackup is equal to the traditional error stackup divided by the square root of the number of elements.

5.4 STATISTICAL TOLERANCING PROCESS

The matching of process capability to design requirements can start from the design requirements or the manufacturing capabilities. One can assume certain process capabilities and design to allow for the expected variation. Alternatively, one can create a design that requires a certain level of variability in order to function and design the manufacturing system to be able to achieve it. It is the opinion of the author that the maximum benefit of this technique is realized when neither data set is assumed at the outset and the problem is considered as a system. This holistic approach requires significant investment in analysis up front and must only be done for design attributes that are truly critical to the performance of the product.

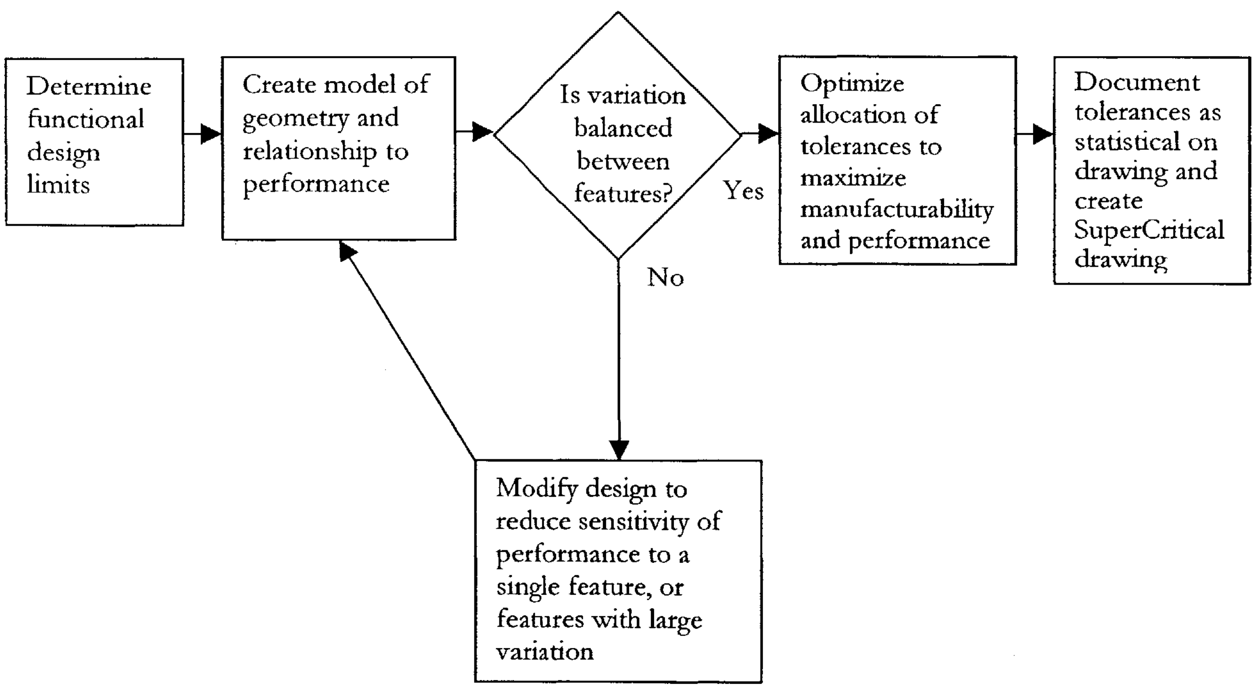

Figure 5.1. Statistical tolerancing process flow chart.

The process shown in Figure 5.1 is applicable to the holistic technique described above. In many cases, if the optimization is done after product release, the manufacturing system is in place and must be considered a hard constraint for the system. A step by step summary of the process and the mathematical formulae used for this thesis is given in Table 5.3. Table 5.3 applies the general process flow to the specific work of this thesis, improving the manufacturability of the 06N compressor. Aside from the notes on software specific tools used and specific relationships to performance, the steps listed may be generalized.

#	Key Tasks and Substeps	Quantitative Evaluation Criteria	Results	Analytical tools used, References & Comments
1	Define the Super Critical Characteristic and its design limits		Fully specified Super Critical Characteristic.	
1.1	Determine the relationship between the Super Critical Characteristic and product performance	Efficiency, capacity, other quantified performance measure	Specification limit. For clearances, this is most often the USL	May require designed experiments, engineering models, etc.
1.2	Determine the failure condition.	Mechanical interference, excessive stress, etc.	Specification limit. For clearances, this is most often the LSL	
2	Determine mathematical relationship between the Super Critical Characteristic and its component Critical Characteristics	$Y = f(X_1, X_2, X_3, \ldots, X_m)$	Relationship between the Super Critical Characteristic and each of its component Critical Characteristics.	
2.1	Determine component Critical Characteristics	Depends on datum structure and characteristic location on drawing	List of contributing characteristics	Mechanical Advantage software tool
2.2	Calculate sensitivity of Super Critical Characteristic to each of its contributing characteristics.	$S_i = \frac{\partial Y}{\partial X_i}$	Sensitivity of the Super Critical to each of its component Critical Characteristics.	Mechanical Advantage software tool, geometric analysis
2.3	If required, modify design to minimize sensitivity to a single characteristic, or to characteristics with large expected variation.			May require different design solution, or adjusting datum structure. This process is not addressed here, but is a crucial part of the robust design process.
3	Quantify the statistical distribution for each Critical Characteristic		Expected statistical distribution for each Critical Characteristic	For the purposes of this analysis, distributions are assumed to be normal

#	Key Tasks and Substeps	Quantitative Evaluation Criteria	Results	Analytical tools used, References & Comments
3.1	Obtain statistical summary data for each characteristic.	$\overline{X}_i = \sum_{j=1}^{n} \frac{x_j}{n}$, $\sigma_{Xi} = \sqrt{\frac{\sum_{j=1}^{n}(x_j - \overline{X}_i)^2}{n-1}}$	Mean and standard deviation for each Critical Characteristic. n = the number of measurements being used. x_j = an individual measurement from the population n.	Data from the actual production process should be used when possible. When it is not available, the mean may be estimated as the nominal dimension and the standard deviation may be estimated from a similar characteristic in a similar production environment. ** Accuracy of this information determines the quality of the model **
4	Statistically allocate tolerances to maximize manufacturability			
4.1	Statistically combine contributing Critical Characteristics to get the expected mean and standard deviation values of the Super Critical Characteristic	$\overline{Y} = \sum_{i=1}^{m}(S_i \cdot \overline{X}_i)$, $\sigma_Y = \sqrt{\sum_{i=1}^{m}(S_i \sigma_{Xi})^2}$	Fully specified statistical distribution of the Super Critical Characteristic	Excel, statistical analysis software
4.2	Evaluate the expected capability of the Super Critical Characteristic	$P_{pkY} = \frac{(USL_Y - abs(\overline{Y} - target))}{3\sigma_Y}$		USL_Y is determined from the performance requirements in step 1.1.

#	Key Tasks and Substeps	Quantitative Evaluation Criteria	Results	Analytical tools used, References & Comments
4.3	Assign preliminary upper specification limits (USL) to each of the Critical Characteristics and calculate the standard deviation required to achieve a P_{pkXi} of 1.33	$\sigma_{X_i*} = \frac{USL_{X_i} - abs(\overline{X}_i - target)}{4}$ $\sigma_{Y*} = \sqrt{\sum_{i=1}^{m}(S_i\sigma_{X_i*})^2}$	Starting assumptions for iterative optimization process. These calculated values are distinguished from the measured values by the *.	
4.4	Estimate the P_{pk} of each Critical Characteristic using the USL_X above	$P_{pkY*} = \frac{(USL_Y - abs(\overline{Y} - target))}{3\sigma_{Y*}}$ $P_{pkX_i} = \frac{(USL_{X_i} - abs(\overline{X}_i - target))}{3\sigma_{X_i}}$		The derived standard deviation is used to evaluate Y as a baseline. The empirical standard deviation is used to evaluate X's to allow allocation of tolerance according to capability
4.5	Using the Specification Limits on the Super Critical Characteristic from step 1 as a constraint, iteratively adjust the USL_X for each Critical characteristic to maximize the individual P_{pk}s without exceeding a constraint condition.	Adjust each USL_x from 4.4 above to maximize P_{pkXi} while maintaining P_{pkY*} above 1.33. P_{pkY} will be greater than 1.33 as long as the following relation is true: $\sigma_{Y*} <= \frac{USL_Y - \overline{Y}}{4}$	An optimized result yields the largest possible tolerances on the individual characteristics while ensuring performance of the design. If the design constraint is related to the LSL, symmetry may be used to obtain USL.	This step can (and should) be automated through the use of an optimizing routine like "Excel Solver" or tolerance optimization software package like "CE Tol."

Table 5.3. Step by step instructions for the evaluation and allocation of tolerances.

There are several areas in which the process described deviates from existing models. In most cases these differences are simplifications to make implementation of statistical tolerances practical with existing tools like Microsoft Excel. The formulae given in Step 4.2 and Step 4.4 are used because they work with two-sided and all one-sided distributions encountered in this project. P_{pk} simply measures the number of 3 standard distribution multiples from the USL to the mean. The value is penalized by the targeting error of the distribution, quantified as the difference between the mean and the nominal dimension.

In order to perform a tolerance allocation, it is necessary to assume a distribution mean. For two-sided distributions, this was assumed to be the nominal dimension. In practice, nearly all two-sided distributions measured within 1 or 2 microns of the nominal, validating this assumption. Assuming a nominal mean is not possible for geometric features because GD&T tolerancing reports only absolute error. Feature specifications like true position, perpendicularity, and parallelism all report only absolute error and result in a one-sided distribution. For example, if the nominal specification for perpendicularity is zero, many of the measurements will be close to zero, but very few will actually measure exactly zero.

A one-sided distribution was found empirically to have its mean approximately 1 standard deviation from the physical limit. For example, with parallelism the nominal dimension and the lowest possible measurement with GD&T is 0. If the standard deviation of such a distribution is 5μm, for tolerance allocation purposes the mean of the distribution was assumed to be 5μm. The frequency distribution for measurements that exceeded the mean was assumed to follow a normal distribution. Generally, optimization was performed on only the top 4 or 5 contributors to a Super Critical Characteristic. See Appendix A for a more detailed discussion of optimization using Microsoft Excel.

One further note regarding GD&T tolerancing practices. GD&T does a very good job of ensuring that two parts will assemble together. However, there is no effort to ensure performance of the assembly, or to measure how well they assemble. Furthermore, because of the loss of information, tolerances measured by GD&T standards do not provide usable process feedback. GD&T reports only how far the process is from the desired measurement, not which direction. Advocates of Vectorial Tolerancing address this problem by reporting all errors with the direction information. If Carrier had been using Vectorial Tolerancing the issue of one-sided distributions would be eliminated.

5.5 ROLE OF DESIGN

Successful implementation of statistical tolerancing requires the designers to isolate those characteristics that are truly critical to the performance of the product. Furthermore, the relationship between the critical characteristics and performance should be quantified. A partnership with internal or external suppliers who will be manufacturing the product is also a key requirement. Once this set of information is available, it is possible to optimize the design for lowest system cost, using process capability as a proxy for manufacturing cost.

Performance relationships are very difficult to quantify before a prototype has been built. It is here that a designer's role truly adds value. The designer relates the performance of the product directly from design characteristics. In the example of the screw compressor, any dimension that is potentially a leakage path is up for consideration as a critical characteristic. This narrows the field from hundreds to tens of characteristics. All of these characteristics will be controlled more carefully than those that simply provide relative location or a threaded hole to attach an electrical box, for example. However, it is important to understand which of these characteristics truly are critical to the performance of the design. It is incumbent upon the designers to progress as far as possible through analytical models, functional prototypes or leveraging of past designs to quantify these relationships.

Just as product performance is difficult to quantify before it is tested, it is challenging to know the capabilities of the production system before the parts are being manufactured at full volume. This knowledge is not only needed before production has ramped up, but good estimates are required in the very early phases of the design. For this reason the inclusion of manufacturing experts on the design team is imperative. The manufacturing processes should be designed simultaneously with the product to achieve a balanced design. The manufacturing expert may be asked to recommend appropriate processes, provide input on design for manufacturability and design for assembly. One of the critical pieces of information needed early in the design procedure is an estimate of the standard deviation of the manufacturing processes. By choosing the technology and equipment type that will perform the operations, it is possible to make an educated guess regarding the expected variation.

Table 5.4 compares various characteristics of a feature type with its relative cost and approximate standard deviation. A manufacturing expert can provide this type of data, as well as an understanding of the manufacturing environment necessary to achieve the requirements. For example, Table 5.4 could be misleading if it was used for a supplier who did not have climate control to within ±1°C or a CMM capable of submicron gage capability. By understanding these requirements the designer can better make decide the appropriate tradeoff between product performance and manufacturing cost.

Type of Feature	Example	Feature Size (mm)	Tool L/D Ratio	# of Cuts	Finish Tool Type	Relative Cost	Typical Sigma (mm)
Diameter	Male Dowel	0 - 25	5	3	reamer	$$$	0.0022
Diameter	Female Bearing	25 - 60	< 2	3	single point	$$$	0.0046
Diameter	Male Piston	25 - 60	6	4	reamer	$$$$$	0.0031
Diameter	Male Bearing	60 - 100	< 2	3	single point	$$$	0.0044
Diameter	Male Rotor *	100 - 200	3	3	single point	$$$	0.0043
Diameter	Stator Bore	200 +	< 1	2	single point	$$	0.009

* Interrupted cut

Type of Feature	Example	Feature Distance (mm)	Thermal Error (mm)/ deg C	Typical Sigma (mm)
Position	Bearing Bore Spread (77)	100	0.0011	0.0025
Position	Dowel Pin Spread (235)	200	0.0021	0.0045
Position		500	0.0053	

Table 5.4. Process capability data collected from features of the 06N compressor over 6 months of actual production. These data may be used for capability estimates of similar features on future designs. One caveat is that the conditions under which these capabilities were achieved must be well understood and met or exceeded in order for the estimates to be valid.

5.6 ROLE OF PRODUCTION

The earliest involvement of the production team has already been described in the subsection above. An experienced member of the production team should be involved from the early phases of the design process. This holds true whether the product will be manufactured in house or sent to an external supplier.

Once production has assisted the design team in achieving a balanced design, it is their responsibility to monitor and improve the processes using SPC methodology. Statistical tolerancing assigns tolerances based on the assumption that the characteristics will have distributions centered about the nominal value. Consistent deviations from this assumption can dramatically increase the expected number of product failures.

One of the greatest fears of the product design organization is tolerance slippery slope. That is, when greater statistical tolerances are allowed in production, less care will be taken and the variability of the process will increase. In order for statistical tolerancing to be successful, it is imperative that the production organization focuses on delivering the maximum capability of the process. An increase in process variation will be met with knowing looks from a wary design team. This distrust leads to the situation described in the following section where the design team allows less than the design could tolerate and the production team asks for more than they need. This classic negotiation tactic is inefficient and will not be as successful as a fully cooperative sharing of information.

SPC is a powerful tool in combating the deterioration of process capability. Process performance is measured against known capability to statistically determine whether the parts are coming from the same distribution. If there has been a change in the process, including less care from the operators, it will be identified on the control charts and corrective action is required. Machine maintenance is another item that must be watched very carefully. With the larger statistical tolerances it may be tempting to increase the interval of machine maintenance. This is done at the peril of process capability and will start the process down the slippery slope of process capability deterioration. These dynamics are shown graphically in the causal loop diagram of Figure 5.2.

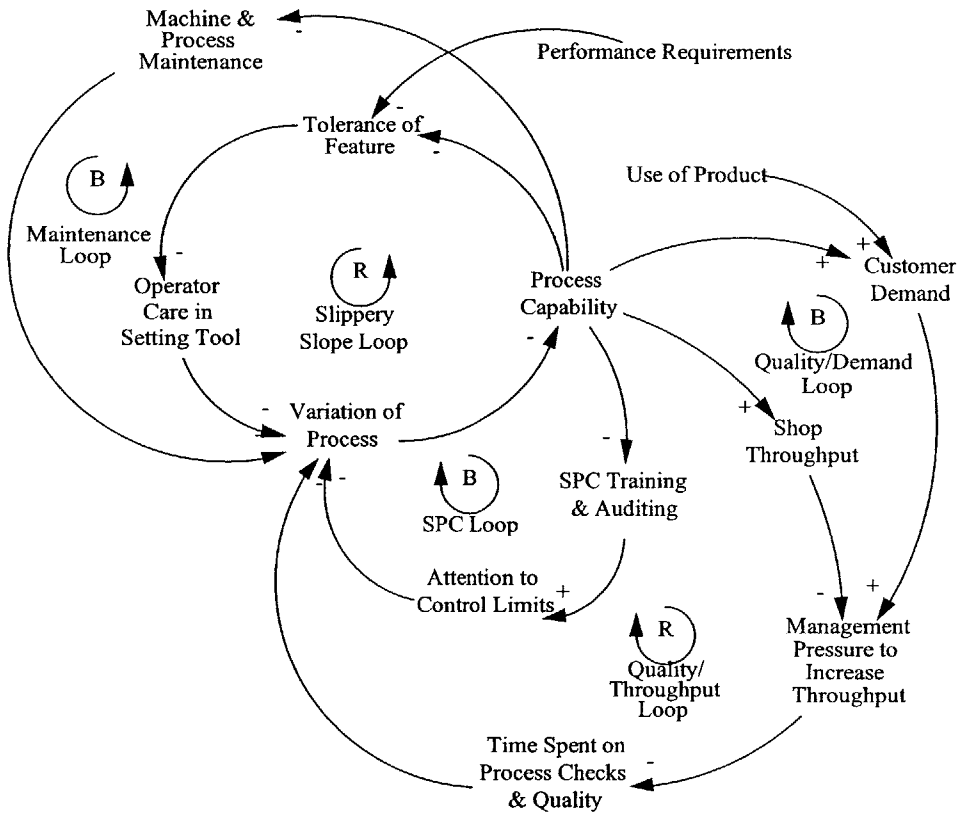

Figure 5.2. Causal loop diagram of elements effecting process capability. With statistical tolerancing, it is the role of production to use SPC and machine maintenance to sustain and improve process capability.

5.7 ROLE OF INSPECTION AND QUALITY CONTROL

The biggest change for an inspection organization can be one of going from a mindset of verifying the parts individually to qualifying populations of parts. There are situations in a statistical quality program where parts would be accepted because of the low probability of failure that would have been rejected in a worst-case tolerancing scenerio. Similarly, there are situations in a statistical quality program where a group of parts is easily within the "worst-case" tolerances, yet the parts should be rejected. A thorough understanding of how populations of parts affect product performance and reliability is necessary in order for the quality organization to make the right decisions. A simple example will illustrate the point.

Suppose that we have two parts that are stacked end to end as shown in Figure 5.3 below. The end location of the second element should measure 200 ± 20 units. In this example the objective of the shop is to maintain a P_{pk} of greater than 1.0. Under worst case tolerancing, the elements are allowed ± 10 units of error each. Under statistical tolerancing, the elements are allowed ± 14 units of error each. Suppose that the process is producing parts that vary according to the normal distribution with a standard deviation of 3.33. Most of the time the parts will measure within the worst case tolerance error. Now suppose that a part is produced that measures 111 units in length. Under worst case tolerancing, this part would be rejected. Under statistical tolerancing the part would be accepted. Now consider 20 of part 1 in a row that measure 109 units in length. Under worst case tolerancing anything between 90 and 110 is acceptable so the parts are accepted without question. With statistical tolerancing, however, these parts indicate a shift in the process and will need to be considered carefully before accepting. The reason for this is that the error cancellation that allows greater tolerances is not present. By quantifying the expected error on the assembly the reasoning becomes clearer.

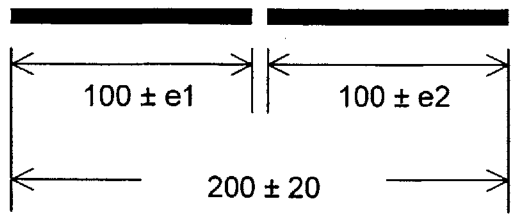

Figure 5.3. Schematic of a simple 2 part assembly. The tolerance that we will accept on parts 1 and 2 depends on whether we are employing statistical or worst case tolerance methodology.

In case 1 the mean and standard deviation of both populations of parts is 100 and 4 respectively. The mean and standard deviation of the assembly can be found by following step 4.1 of Table 5.3. Since these parts are stacked end to end, $S_1=S_2=1$. Therefore the mean = $X_1 + X_2$ = 100 + 100 = 200. The variance is the sum of the variances = 16 + 16 = 32. Finally the standard deviation of the assembly is the square root of the variance = 5.67. To calculate the probability of failure we use Equation 5.1 and Equation 5.2 to find z_{upper} = (220 – 200)/5.67 = 3.54 and z_{lower} = 3.54. From symmetry, the probability of failure = 2 * the probability of exceeding z_{upper} = 0.0004. This is a low probability of failure and the inspectors were justified in accepting the part that measured 111 units.

In case 2 we will only consider the 20 parts that measured 109 for the population of part1. The population of part2 again has a mean of 100 and a standard deviation of 4. Following the procedure described above we find that the mean value of the assembly is 209 and the standard deviation is 4. Z_{upper} = 2.75 and z_{lower} = 7.25. The probability of getting a part below 180 is negligible, so the probability of failure is obtained from z_{upper} alone and is equal to 0.006. All of the parts met the worst case tolerance requirements, but the probability of failure increased by a factor of almost 15!

5.8 SUMMARY

In this section we have seen the statistical method of tolerance analysis and allocation proposed by the author. This integrated approach requires the cooperation of design, production, and inspection functions. The role of each of these organizations was reviewed.

The use of statistical tolerances requires change from each of the organizations involved. Tradition, organizational structure, and even some of the tools used to improve manufacturing yields can act as barriers to change. In the following section we investigate these barriers to change.

Academic literature on the subject of statistical tolerancing abounds. Carrier's Corporate SPC manual[15] contains a section on statistical tolerancing. Professor Ken Chase describes the method of automated statistical tolerance analysis in the Dimensioning and Tolerancing Handbook.[16] In fact, nearly every textbook on tolerancing at least addresses the topic formally. Despite the abundance of knowledge regarding statistical tolerancing, many who previously attempted its use at Carrier were uncertain how to ensure the assumptions were met.

Proper implementation of statistical tolerancing goes far beyond making rudimentary assumptions about process distributions and assigning larger tolerances than otherwise possible. Simply using the statistics to assign larger tolerances is bound to create a higher than predicted failure rate. The reason for this is that without training, production personnel are likely to be less careful when new drawings arrive with larger tolerances. Statistical tolerancing must be accompanied with proper use of SPC. SPC serves to decouple the process variability from the print tolerance.

An informal survey of manufacturing companies inside and outside of United Technologies indicated that the understanding of statistical tolerancing has not made it into everyday production. A well-known automobile manufacturer uses computer software to assign statistical tolerances, but has no formal feedback mechanism to assure that the assumptions in the model are being met. Not coincidentally, this manufacturer's product is consistently rated among the lowest quality of its competitors.

This section identifies barriers that were experienced within the Carlyle TR-3 plant during the implementation of statistical tolerancing. It is likely that these conditions exist within other manufacturing organizations as well. To be successful, these barriers must be recognized and addressed early in the implementation process.

6.1 PHYSICAL AND LOGISTICAL BARRIERS

One of the difficulties for the production team is the long delay time between the production of the part and the measurement information. This complex product requires an hour to complete each step of the machining process. As many as 6 parts have already been produced by the time an operator receives feedback from the CMM. When waiting to complete a subgroup, the queue between the operator and the feedback of information may be as much as 9 hours. With a single production shift lasting 12 hours, the operator would typically receive information on just one subgroup that was produced during his shift. For example, if an operator arrived at the beginning of the shift and saw from the control charts that the process had been out of control for the last 5 subgroups, his adjustment could not be verified by a single subgroup until the end of his shift. If another adjustment were necessary, the operator on the following shift would need to make the correction.

Under ideal conditions this would not be a problem, because information would be handed off seamlessly to the subsequent shift and the operation would proceed without interruption. In reality, however, many operators had different techniques from others and used different criteria to determine when a process adjustment was required. One operator, seeing the need for a process adjustment, may move the target of the machine by the difference of the last subgroup and the process nominal. Another operator, more wary of

[15] Cangello, Carl, "Statistical Methods and Process Control", Corporate Quality Department, United Technologies Carrier, Syracuse, NY, 1991, Section 13

[16] Drake, Paul Jr., editor, "Dimensioning and Tolerancing Handbook", McGraw-Hill, 1999, Chase, K. W., "Chapter 13- Multi-Dimensional Tolerance Analysis."

moving the machine the wrong direction[17], may only make a very slight adjustment to get the next subgroup just within the control limits.

Another barrier to the complete implementation of statistical tolerancing was the use of so-called target (or true-position) charts. Rather than use the automated data collection provided by the CMM and the Quantum SPC software, many operators preferred using target charts. In target charts the location of a characteristic is measured and recorded in both X and Y coordinates. A point at the center of the chart represents the perfect characteristic. By recording these data and the order in which they are received, trends can be detected. They are also useful to show at a glance the magnitude and direction of adjustment needed. There were 3 main problems with using these charts: they provided no rules or guidelines for when adjustments are necessary, they discouraged the seemingly redundant use of SPC charts, and they encouraged response to single data points instead of subgroups of data.

Figure 6.1 below shows a sample process in which position error varies from 8 to -5 in the Y direction and 9 to -8 in the X direction. Assuming that the specification limits are ±10μ in both X and Y, the chart shows that no parts exceed the specification limits. However, in order to achieve a P_{pk} of 1.33 the Upper and Lower Control Limits would have been +4.3μ and -4.3μ respectively[18]. The first subgroup (denoted by the bold markers) of Y-direction error results in an x-bar of (5+8+7)/3 = 7.33. The first subgroup demonstrates that the process is not centered and requires adjustment.

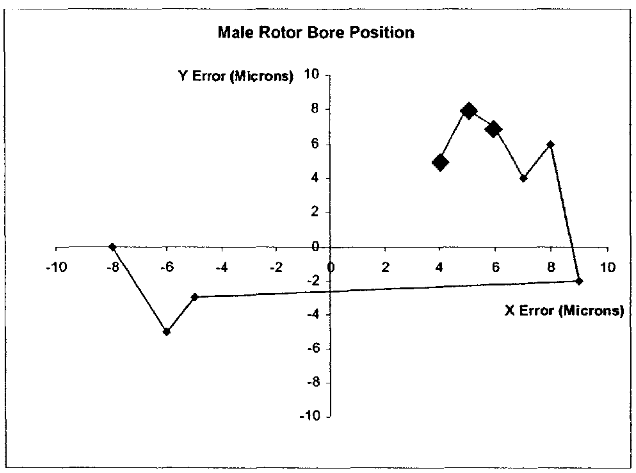

Figure 6.1 Sample target chart. Note that although there is a lot of historical information communicated at a glance, there are no criteria to inform the operator when an adjustment is necessary. The arbitrary nature of the decision process resulted in many processes being allowed to continue production despite being out of control because they met specifications.

6.2 TRADITIONAL GOALPOSTING BEHAVIOR

Traditional manufacturing measured each part against the print requirements. A part that measured within the specification limits was accepted and a part that measured outside of these limits was rejected. This

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[17] The machine coordinate system was often different from the coordinate system created by the datum structure of the part. The inspection equipment reported error in terms of the part datum structure, but machine moves had to be made in the machine coordinate system. This was problematic and was the source of occasional operator errors.

[18] The UCL can be obtained by setting Ppk = 1.33, USL = 10, subgroup size (n) = 3, process nominal = mean = 0. Since the mean = process nominal, σ = USL/4 = 2.5. UCL = mean + $3\sigma/n$ = 0 + 3*2.5/√3 = 4.33. From symmetry LCL = -UCL = -4.33.

behavior is often referred to as goalposting because the specification limits can be considered goalposts and anything that measures between them is considered a good part. Statistical measures are an effort to move away from this go/no-go mentality toward the goal of making each part as close to the nominal specifications as possible.

One particular area in which this behavior is visible is with tool changes. Operators who are goalposting will set the tool near the upper specification limit and allow it to wear until it reaches the lower control limit. Goalposting results in a run chart like that shown in Figure 6.2. Note that this series of points was collected over approximately 5 shifts. The histogram from this set of points is shown in Figure 6.3.

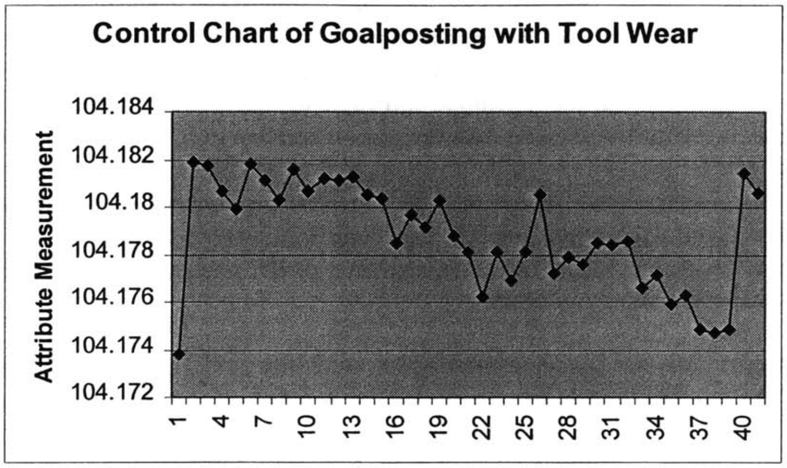


Figure 6.2. Control chart demonstrating effects of tool wear.

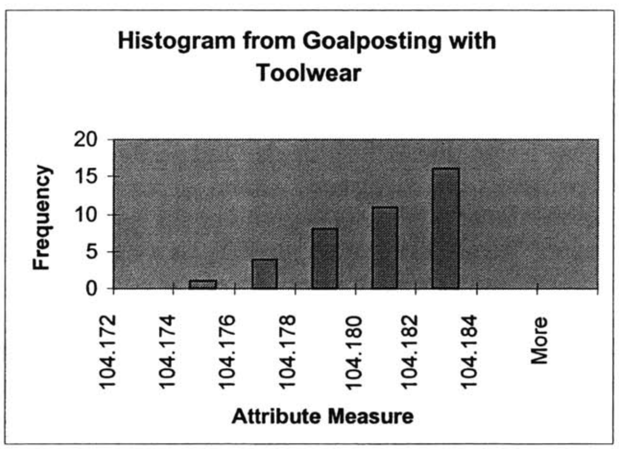


Figure 6.3. Histogram of data set displayed in Figure 6.2.

In the TR-3 Screw operations, the importance of striving for the nominal dimension on each part in general was not equally well understood by all of the operators. Behavior such as that shown in Figure 6.2 was not uncommon in June of 1999. Some operators had been with the Screw Compressor Operations since its inception in 1995 and had received extensive SPC training. Others had recently transferred to the facility from other production areas that were far less sensitive to process adjustments and did not utilize SPC techniques. This was an area of opportunity for improvement within TR-3.

6.3 CONFLICTING GOALS OF MANUFACTURING TOOLS

SPC has been explained in some detail in this thesis and is the focus of much attention at the TR-3 plant. The benefits of SPC include providing operators with straightforward rules to minimize variation and to recognize when an input to the process has changed. Another tool that has been used extensively in the Screw Compressor Operation at TR-3 is Geometric Dimensioning and Tolerancing (GD&T). GD&T is the subject of entire textbooks and will not be discussed at length here. For a detailed description of GD&T the reader is referred to the ANSI standard: ANSI Y14.5 1992.

Worthy of discussion here are the benefits of GD&T, and some of the ways in which it conflicts with SPC. GD&T directly communicates the reference surfaces and characteristics by which the part should be manufactured and inspected. A drawing properly dimensioned with GD&T reduces ambiguity regarding the acceptability of a part. In addition, the technique considers function of the characteristics to some degree. For example, if a hole is meant to coincide with the pin on another part, both the size and location of the hole are important. The larger the hole is, the more error is allowable in the location of the hole and still mate with the pin. Such a condition is denoted with a material condition bonus modifier. In the example the position of the hole is given a tolerance that is valid at maximum material condition, or the smallest allowable hole diameter. The difference between the actual diameter of the hole and smallest allowable diameter is then added to the positional tolerance as a bonus.

There are two problems with this bonus scheme when used with SPC. First, bonus tolerancing requires knowledge of the hole size before one can determine the amount of bonus to be allocated to the position. Bonus can only be applied if both characteristics on every part are measured. Measuring every part defeats some of the benefits of SPC. Through statistical tools, SPC allows production to continue by measuring only a sample of the parts being produced. In order to get the benefit of the bonus tolerance the benefit of statistical sampling must be sacrificed. It is interesting to note that although bonuses are disallowed in statistical tolerancing, statistical tolerance width typically exceeds the total GD&T tolerance width with bonus. Therefore, it is usually beneficial to use the statistical tolerances, even on a part by part basis.

The second conflict is perhaps more subtle and more important. Bonus tolerancing often leads operators to target characteristics at values other than the nominal dimension. The following scenario describes a condition under which this may occur. From the hole size and position example above, the capability of the process to create a hole of the correct size may greatly exceed its positioning capability. In this case the operator may choose to machine the hole near the high end of the size tolerance in order to apply the maximum bonus to the position. Recall that process capability is a measure of how closely the mean coincides with the nominal dimension, as well as a measure of the variability of the process. Therefore, as the operator moves the mean of the capable, hence narrow distribution toward the specification limit, the process capability of the hole size decreases. Additionally, because different operators have different ideas about the ideal amount to deviate from nominal, they target different values. This is similar to tampering as described by Deming and always increases process variability when considering the work of several operators. The process capability is further deteriorated. Thus, in an effort to take advantage of the bonus tolerance for hole position the process capability of hole size is sacrificed. The graphical analog of this scenario is shown in Figure 6.4 below.

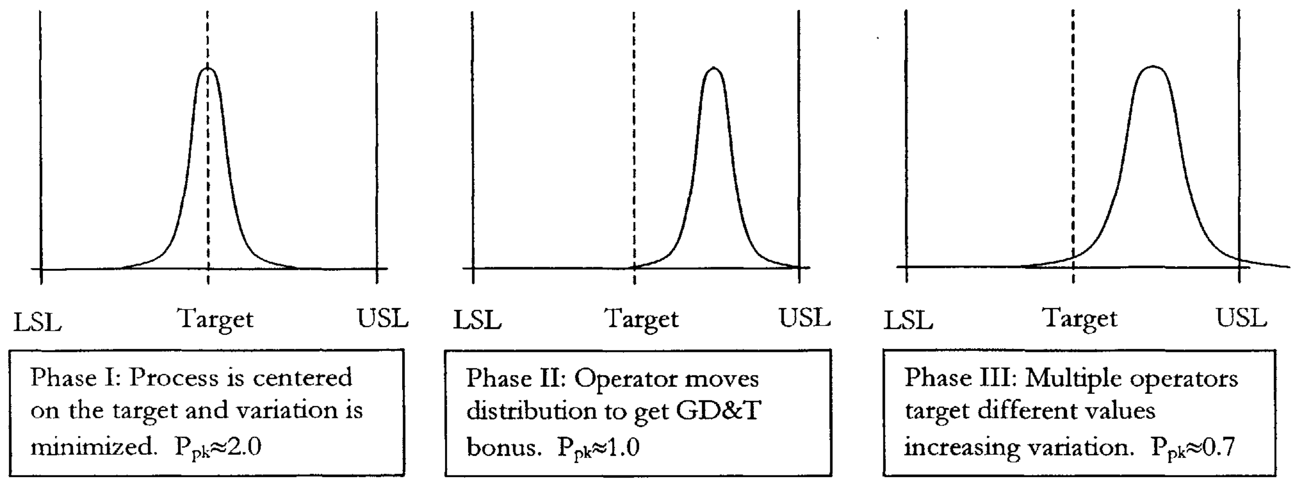


Figure 6.4. Diagram of process capability deterioration due to the conflicting goals of GD&T and SPC.

Correcting this problem is very frustrating for the operators, many of whom have spent a lot of time learning about GD&T and how to get the maximum amount of functional tolerance from a given drawing. If the part is dimensioned statistically from the outset, there is no benefit in arbitrarily moving the mean of one process to get bonus on another. In fact, in statistical tolerancing, there is no GD&T bonus at all. The low probability of having a small hole and a large location error is already taken into account and allocated to the characteristics as a larger tolerance. Furthermore, the balance of tolerance between the characteristics will be appropriate because the tolerances were allocated according to the inherent capabilities of each process.

6.4 LABOR RELATIONS

As described in the background portion of this document, labor relations were strained at the time the improvement efforts were taking place. The movement of personnel, often against their wishes, created resentment within the workforce. Often the displacement of workers, or "bumping", was due to union rules and against the wishes of management. Nevertheless, the workers resented the changes that were occurring and ascribed much of it to the decision to move the assembly operation of large centrifugal chillers away from the Syracuse campus to North Carolina.

Another item of contention with many of the operators was the new "continuous operations" schedule. This schedule required the operators to work 4 12-hour shifts one week, followed by 3 12-hour shifts the next. By running two shifts on days and two shifts on nights, the plant achieved continuous operation 24 hours a day, 7 days a week. This production schedule had the effect of jumbling the workforce. Prior to this arrangement there was a day shift and a night shift. The operator on the day shift knew who would be coming to operate his machine at night and developed a relationship with him. The operators felt that they could communicate more easily under the prior schedule, and be more confident in running the machines without checking every setting and adjustment before proceeding.

Under continuous operations the plant had the benefit of manufacturing more product without further capital expenditure. However, the sequence of operators on a particular machine was changed much more often, deteriorating the communication between operators. With the labor displacements many of the operators were new to their positions and did not have a thorough understanding of SPC or the care required to successfully manufacture parts with micron level tolerances. With the feelings of resentment and frustration created by recent labor movement and layoffs, some operators chose to operate the machine their own way and were not receptive to new programs proposed by management.

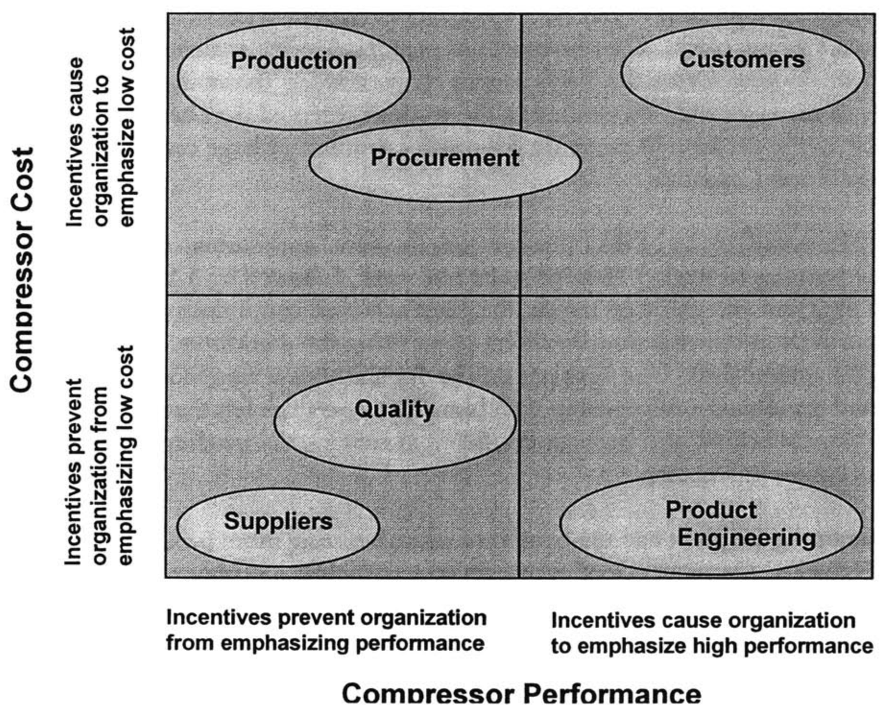
Professional or "exempt" employees were also affected by recent downsizing efforts. United Technologies, the parent company of Carrier, had declared that there was to be a 10% reduction in the size of the workforce. Some long time employees were either laid off or given early retirement incentives in late 1999.

Some employees were asked to move to new positions against their preferences and others were asked to do work that was left by those who moved or were transferred. Many salaried personnel were also feeling frustrated and overwhelmed by these events. Without the continuous support of the TR-3 upper management the implementation of statistical tolerancing would not have been possible under these conditions.

6.5 MISALIGNED INCENTIVES BETWEEN STAKEHOLDERS

The issue of incentives is probably the most subtle of the barriers to implementation and the most difficult to overcome. Because the incentives differ between the stakeholders and are sometimes at odds with what is best for the Company, they are difficult to identify as the reason for stopped progress.

The stakeholders identified include the following five groups: customers, production, design engineering, quality, and procurement. An elementary analysis of the behavior drivers of the stakeholders leads one to see immediate differences. The two dimensions along which we will examine preferences and incentives are product performance and product cost. Figure 6.5 shows the stakeholder groups' relative positions along these dimensions. Incentives for high product performance indicate that this stakeholder group will receive rewards for improving or protecting the performance of the compressor. Incentives for low product cost indicate that the stakeholder group will receive rewards for decreasing the cost of producing the compressor. Let us examine each of these stakeholder groups independently to see where conflicts may arise from these subtle preferences. The rewards referred to here are those given by management or organizational structure of the particular stakeholder group. For example, at Carrier production had a variable pay plan that paid employees directly for increased volume of compressors that met print specifications. This incentive plan



was intended to minimize the labor cost content of the compressor.

Figure 6.5. Stakeholder preferences along two dimensions: product performance and product cost. Emphasis on high product performance indicates that the stakeholder is rewarded for improving and protecting the performance of the compressor. Emphasis

on low product cost indicates that the stakeholder is rewarded for lowering the product cost, or for increasing volume at the same cost.

The first group is the customer. The customer is very easy to figure out and the preferences are not subtle. The customer wants the highest performing compressor for the lowest cost. When given the opportunity, the customer will push Carlyle to deliver improvements along both of these dimensions. At the opposite end of the spectrum are the suppliers. Suppliers will strive to provide parts at the highest possible cost, while negotiating for additional tolerances and lower quality requirements. Increased tolerances may decrease the performance of the final product, but as long as the parts leaving the suppliers' factory are accepted and paid for, they are not sensitive to product performance.

Having defined the obvious external players, we can examine the internal stakeholders to illuminate why some decisions are made and some actions are taken or not taken. Product engineering is the organization responsible for designing the product as a part of the chiller system. Along with the chiller designers, product engineering establishes a target product capacity and efficiency. If product performance can be improved, the system can either deliver cooling capacity at a lower energy cost, or the system may be designed with a smaller chiller. Both of these alternatives are very attractive to the marketing teams at Carrier. As mentioned in the introduction to this paper, lower energy costs are a powerful selling point. Likewise, if the system cost can be reduced through a more efficient compressor, chillers can be sold for more profit. In order to increase performance in screw compressors, the clearances must be reduced. This leaves less room for error and requires smaller tolerances. The smaller tolerances make the compressor more difficult and time consuming to produce and inspect, increasing the cost of the compressor. When faced with the decision of whether to relax tolerance, the default position of product engineering was that this would compromise the performance of the compressor.

Production lies directly opposite product engineering. Production receives rewards based on how many compressors are manufactured in a given time period, and how many of these compressors meet the print requirements. Since allowing more tolerance would allow some processes to be done more quickly, and increase the percentage of compressors accepted, increasing tolerances is an objective of the production organization. Although not many people in the production organization understand the geometric relationships and performance sensitivity of the components, they have vast amounts of data from compressors that have been produced. If a compressor was successfully assembled with known amounts of error in the past, production's default position is that same amount of error should be accepted and allowed on all subsequent assemblies. This position does not consider the performance or reliability risks that may be introduced.

The procurement organization is rewarded primarily on cost and delivery performance of their suppliers. As a result of these incentives, the buyers were squeezing suppliers very heavily on cost with activities like the FreeMarkets events described above. Buyers' goals were directly related to how much new contracts saved over existing contracts. Because larger tolerances may result in lower cost quotes in some cases, the procurement organization was generally favorable to increasing tolerances. This places them on the low side of the compressor performance spectrum. Although not considered in this simple model, there is another item that dampens the enthusiasm of the procurement organization for statistical tolerancing. Not many suppliers understood the statistical requirements for maintaining a process per SPC. This could significantly restrict the base of suppliers from which to draw quotes.

Last but not least, the quality organization curiously ends up sharing the same quadrant with the suppliers, but for a very different reason. Quality has its performance measured primarily by how well it identifies and contains manufacturing problems. In addition, reliability of the compressors after they leave the plant and are installed at the customer site is of concern to the quality department. By trading performance for greater clearances, tolerances in the compressor may be increased without increasing the risk of compressor failure. Because increasing tolerances will decrease the number of problems experienced in production, there will be fewer problems for quality to address. Clearly they would favor this situation and have a lower priority on the performance of the compressor. On the other hand, quality is responsible for making sure that no defects are sent on to the customer. Therefore, they support multiple inspections, additional process steps, and other measures to ensure that the product exceeds the specified requirements. These measures increase the cost of the product and place quality on the high end of the cost spectrum.

Although the majority of this thesis describes the technical issues of implementing statistical tolerancing, overcoming the barriers, particularly the misaligned incentives, was the most difficult part of the implementation process. It is much easier to collect the data and create a model of the error propagation than it is to convince various players to accept something they perceive is contrary to their incentives. The incentive map shown is an artifact of the organizational structure within Carrier and the industry structure in which they operate. It is the opinion of the author that a similar mapping with different companies in different industries would yield similar results.

6.6 SUMMARY

In this section we examined some of the barriers that made wholesale acceptance of statistical tolerancing difficult for various stakeholders. The product itself is a large, complex product that requires over an hour for each production step. There is a long delay between the manufacture of the product and the feedback of measurement data to the operator. The long processing and feedback times complicate some of the common SPC procedures. Complete SPC implementation is further complicated by goalposting behavior and, at the other extreme, operators attempting to game the GD&T bonus system. Finally, organizational structure and incentive systems sometimes place stakeholders at odds with respect to finding the appropriate balance of compressor cost and performance.

Some of the barriers introduced are attributes of the product and manufacturing system, which were investments that had already been made. Changing the organizational structure and incentive systems were beyond the scope of this project. The solutions to the barriers presented in the following section represent creative ways of working within the organizational structure and manufacturing systems that were not changeable in the short term.

Various incentives and interests placed the different stakeholders in diverse locations on the Cost/Performance preference map of Figure 6.5. In this section we will examine the suite of tools and methods used to overcome the barriers and achieve alignment with the customer expectations. The different stakeholder groups had different needs, so multiple tools were used.

Production needed improved alignment between labor and management. In addition, the assumptions of statistical tolerancing demanded the proper use of SPC. Product design required assurance that the increased tolerances would not result in a decrease in product performance, and that the system would be monitored to ensure process maintenance. Suppliers required an incentive to upgrade their quality systems to a state of statistical control. Figure 7.1 shows the tools used to align stakeholder interests with the customer.

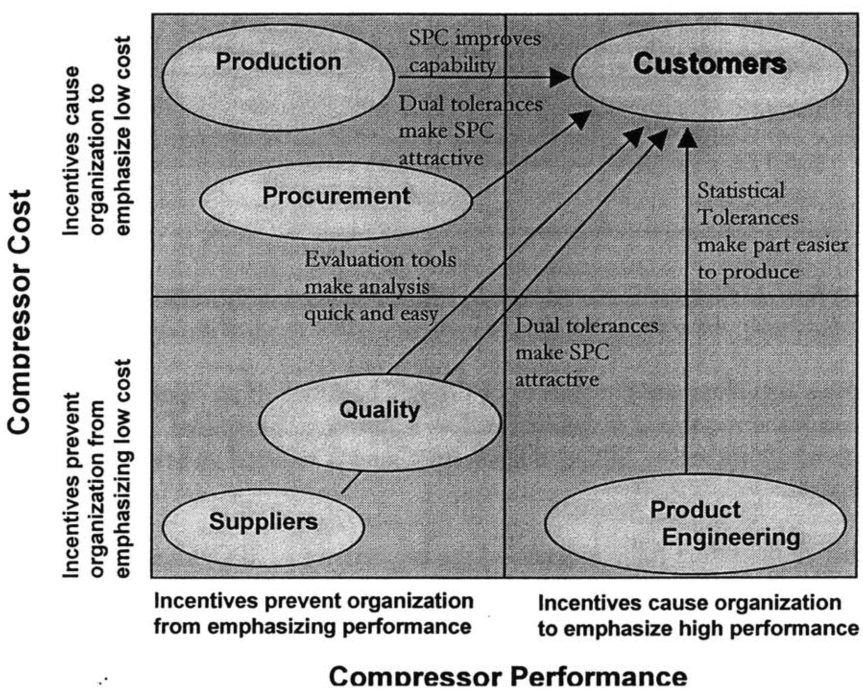


Figure 7.1. Aligning stakeholder preferences with the customer.

7.1 SPC TRAINING AND REINFORCEMENT

Although not a panacea for production problems, simply reinforcing the importance of SPC and training the operators helped the production organization to minimize and maintain process variation. SPC provides a framework with a very simple set of rules that have powerful consequences on process improvement. The statistical tolerancing team in TR-3 decided to focus the message on 2 key SPC "out of control" conditions:

1. Any subgroup outside the control limits

2. Five subgroups in a row on the same side of the mean.

The associated SPC rule is that either of these conditions indicates that the process is out of control. Corrective action must be taken and documented. If both of these rules are being adhered to, the process will remain centered and variation should not increase. A centered process with predictable variation is the fundamental assumption in the statistical tolerancing model. Goalposting behavior is eliminated because it will result in a violation of one of the two rules. In Figure 6.2 the process would have required an adjustment after the first 5 points. Knowing this, the operator will not set the tool so close to the upper limit in the first place. Figure 7.2 below shows the improvement from Figure 6.2 that is achieved with appropriate adjustments for tool wear.

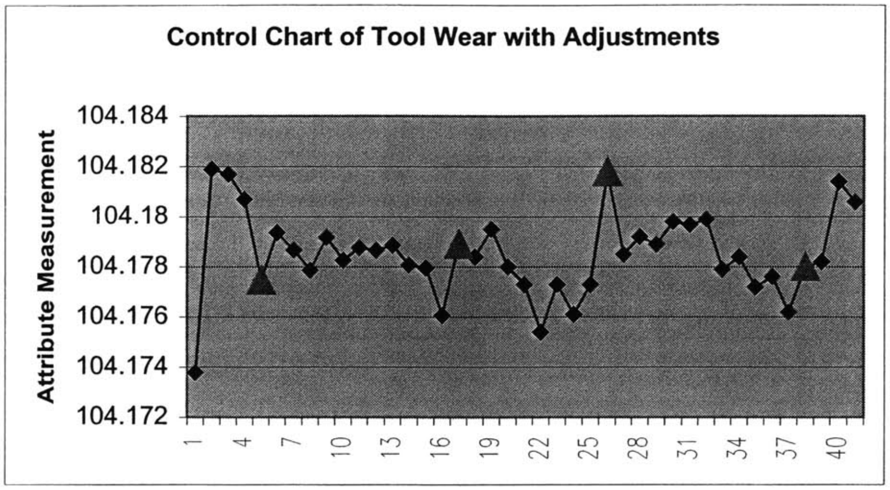


Figure 7.2. Control chart from the Goalposting example with hypothetical adjustments for toolwear. Triangles denote the subgroup directly following a tool adjustment. All of the random variation remains, yet the standard deviation has been reduced by 25%.

The two basis SPC rules also eliminate the gaming of GD&T bonuses. If an operator targets any value other than nominal, SPC condition number 2 is violated and an adjustment is required. If the process is centered and variation of the machine increases, SPC condition number 1 is violated and the operator must alert the maintenance organization.

In order to ensure that all operators fully understood the importance of SPC, interactive SPC training was provided. The author and a TR-3 quality expert devised a 6 hour course that was attended by all of the finish-machining operators. The course described the two types of error, random cause and special cause, and the tools used to identify and eliminate special cause error. SPC rules and a specific characteristic of the rotor case were carefully tracked. The close attention to SPC on a specific characteristic allowed a weekly communication regarding the performance to SPC requirements, and also showed graphically how the process was improving. The machining superintendent and the shift supervisors performed supplemental SPC training right on the production floor.

These actions had multiple benefits. The operators increased their skills and understanding of SPC, and the increased interaction helped to break down some of the cultural barriers described in Section 6. Many of the operators expressed enthusiasm about learning SPC and using the computer terminals at their workstations more effectively. One operator in particular agreed to test the theory to the letter. By following the rules exactly for a two-week period the capability of his machine more than doubled. Having an early success with this operator provided an example and credibility to the approach. For his efforts the operator was financially rewarded, helping to reinforce the importance of SPC to the organization.

7.2 DUAL TOLERANCING SYSTEM

Suppliers who were not already using SPC required an incentive to manage their processes statistically. A very attractive incentive is the large tolerances allowed by statistical tolerancing. However, the product design organization and the supplier quality organization were not willing to give the larger tolerances without some way of ensuring that the required SPC techniques were being followed. The solution is a two tiered tolerance system. This system assigns two tolerances to each Critical Characteristic. If the supplier is using SPC techniques and is providing the required data, parts are accepted according to the statistical tolerances. If the supplier is not using SPC techniques, 100% inspection to the standard tolerances is required.

This acceptance structure allows the use of statistical tolerances for internal suppliers even when external suppliers are not capable. Because a supplier not using SPC must supply parts with narrower tolerances, the supercritical error stackup will remain at an acceptable level. If all suppliers revert to worst case tolerances the design will be accepted according to the same criteria that were used prior to the implementation of statistical tolerancing. Figure 7.3 below demonstrates how a characteristic is toleranced with both worst case and statistical tolerances.

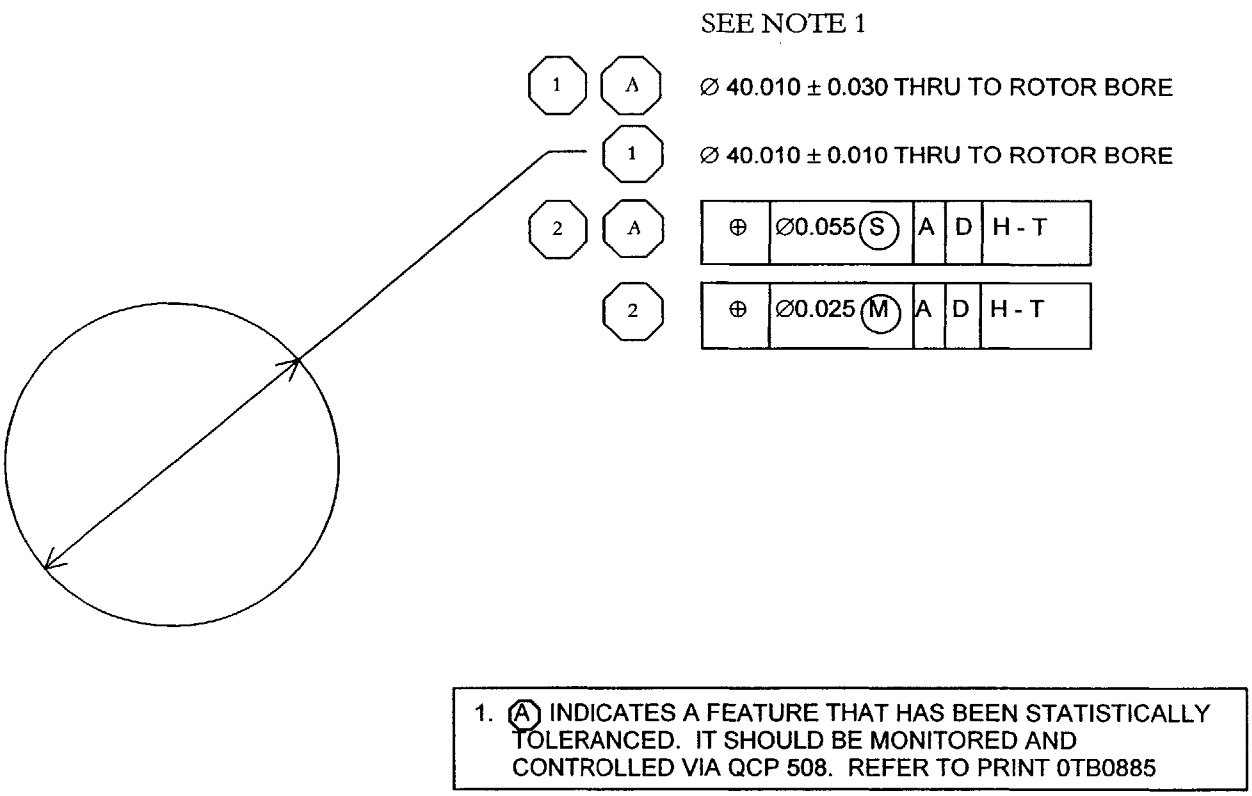


Figure 7.3. Sample characteristic that has been dual-toleranced. The drawing reflects both statistical tolerances, which apply regardless of feature size, and worst case tolerances, with which a material modifier may be used. QCP 508 is the TR-3 *quality control plan with respect to statistical tolerancing. Print 0TB0885 refers to a drawing of the Super Critical Characteristic to which this characteristic contributes error. By referring to the Super Critical Drawing, one can see all of the contributors and the sensitivity of the Super Critical Characteristic to each contributor.*

This system provides a set of tolerances that is known from 5 years of production to work, while allowing suppliers an opportunity to use SPC and decrease their costs through sample inspection. Suppliers who agree to use SPC are supported in part by Carrier Quality manuals that explain SPC very clearly. The supplier quality organization also provides some support to suppliers making the transition. In fact, increasing the use of statistics is one of the objectives of the supplier quality organization.

One risk of dual tolerances is that users may be confused and not know which of the tolerances applies. This risk exists partially because there is no ISO or ANSI standard for statistical tolerancing and the team had to come up with a solution that all stakeholders agreed to. The dual tolerancing solution was embraced willingly by the product design and quality organization. 22 characteristics were set to be toleranced using this method at the end of the research period for this thesis. However, because the system was not in full use at the end of the research period, it is unknown as to whether the aforementioned confusion became a problem.

7.3 EVALUATION TOOLS

One of the barriers for both the product design and the quality organizations was the concern that a failure condition could theoretically occur with parts that meet specification. In worst case tolerancing, as long as the part was within the specified limits, performance of the assembly is guaranteed. With statistical tolerancing, successful assembly depends upon the measurements of all contributors. Another concern was the need to replicate the statistical analysis if, for example, a supplier had a batch of deviant parts.

The solution is a set of straightforward analysis tools that have the geometric and statistical relationships built in. Because the tool was created in Microsoft Excel, it is accessible and easy to use for every appropriate stakeholder. This is in stark contrast to many of the traditional statistical tolerancing tools, which use engineering workstations in conjunction with sophisticated CAD software to perform the analysis. This tool was designed to be as simple as possible and provide the information necessary to make acceptance decisions on individual parts, or with populations of parts. Table 7.1 below shows the default condition of the evaluation tool. These numbers represent the mean and standard deviation of these characteristics as measured over a 6-month period.

Male Unloader Piston Clearance

Characteristic Name	Known Value	Sensitivity	Estimated Mean	Estimated Stdev
Unloader Bore Depth		1	126.37	0.009
Piston Length		-1	74.184	0.015
Unloader Piston Perpendicularity		0.5	0.02	0.004
Rotor Bore Diameter		-0.5	104.179	0.004
Unloader Bore True Position (Along H-T)		-0.13	0	0.008
Clearance Values			0.1065	0.0177

Decision Criteria	
Most Likely Value of Clearance	0.1065
Probability of Piston Protruding into Bore	9.8e-10
SuperCritical P_{pk}	1.62

Table 7.1. Sample output from the Excel statistical evaluation tool. Current values reflect the populations as measured over a 6-month period. The estimated mean and standard deviation may be adjusted to reflect more recent data, or a batch of deviant parts.

The tool may be used to validate the continued use of the statistical tolerances. As long as the SuperCritical P_{pk} remains above 1.33, the probability of experiencing a failure is so remote that the larger statistical tolerances of the contributors are acceptable. To model statistical change in a particular process, one inputs the values into the Estimated Mean and Estimated Standard Deviation columns. The evaluation tool calculates the mean of the supercritical distribution, the probability of failure, and the SuperCritical P_{pk}.

The tool may also be used to evaluate the probability of failure due to a single, errant part. When evaluating a single part, the known value of a single characteristic is entered into the known value column. Because the value of the characteristic is known, it does not contribute to the standard deviation of the supercritical characteristic. The standard deviation is calculated using the statistical data from the remaining characteristics. When evaluating a single part, the relevant output from the tool is the expected value of the clearance and the probability of failure. Using these numbers, quality assurance personnel can make an objective decision regarding the acceptability of a deviant part. Table 7.2 gives an example of evaluation of a rotor case that with an unloader piston depth characteristic that was machined too deep. Note that the SuperCritical P_{pk} value is not recalculated in this case because the single value in the known value column is a single point and not a representation of a statistical distribution. The values that are calculated when evaluating a single part are The Most Likely Value of the Clearance, and the Probability of Protruding into the Bore. The part from Table 7.2 would be scrapped because the part has almost a 1% probability of failure.

Male Unloader Piston Clearance

Characteristic Name	Known Value	Sensitivity	Estimated Mean	Estimated Stdev
Unloader Bore Depth	126.3	1	126.37	0.009
Piston Length		-1	74.184	0.015
Unloader Piston Perpendicularity		0.5	0.02	0.004
Rotor Bore Diameter		-0.5	104.179	0.004
Unloader Bore True Position (Along H-T)		-0.13	0	0.008
Clearance Values			0.1065	0.0177

Decision Criteria	
Most Likely Value of Clearance	0.0365
Probability of Piston Protruding into Bore	0.008515
SuperCritical P_{pk}	1.62

Table 7.2. Example of using the tool to evaluate the acceptability of a part that is out of specification. When a number appears in the "known value" column, the value is assumed to be known. There is no variation associated with this characteristic. In this case a single part is being evaluated and the SuperCritical P_{pk} has no meaning.

7.4 MANAGEMENT SUPPORT

In addition to the specific tools used to overcome barriers, management support was instrumental in the continuing progress of the project. Hearing the message from supervisors, the shop superintendent, the quality manager, and the unit manager helped operators to internalize the importance of SPC. Management support was also instrumental in developing the links between the design and manufacturing organizations. Implementation of a complex program requiring a unified effort of so many different stakeholders requires this consistent message from management.

Figure 7.4 shows the organizational relationship of the internal stakeholders to each other.

Carlyle Compressor Organization Chart

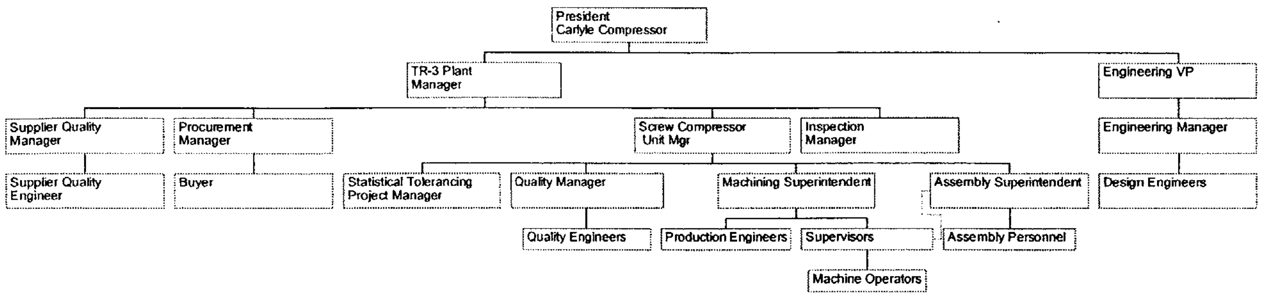


Figure 7.4. Carlyle Compressor Organization Chart at the time of project implementation.

A specific example of management support that helped to spread the understanding and embracing of statistical tolerancing is the kickoff event. Representatives from every stakeholder organization were invited to hear a discussion on statistical tolerancing and why it would benefit the company. Many people were familiar with the effort because of a previous attempt. Many of the same people had valid concerns about moving forward. By arranging to have all of the stakeholders present at the kickoff, management was able to communicate the importance of statistical tolerancing and the potential benefit to the company. Furthermore, the implementation team was made aware of the concerns that would have to be addressed in order to be successful.

It would be difficult for management to convincingly support a new process without a thorough understanding of its principles. The management team at Carrier, specifically the TR-3 Plant Manager and the Screw Compressor Operations Unit Manager, were well versed in the issues. When a machining supervisor or an operator had a concern regarding one of the assumptions, the management team was able to intelligently recognize and discuss the concern. Recognizing the barriers and communicating a credible plan to overcome them helped to break down some of the walls erected by the unfortunate labor realignment.

7.5 SUMMARY

In this section we saw how specific tools were developed to address the concerns of the various stakeholder groups. Re-emphasizing SPC basics in production help keep processes centered and avoid an increase in variation. A dual tolerancing system provides incentives for suppliers to use SPC. Dual tolerances also provide a fallback position if suppliers are unable to maintain centered processes. An evaluation tool, developed using Microsoft Excel, allows quick evaluation of the SuperCritical Characteristic when processes shift.

It would be possible to more closely align the incentives of the stakeholder groups shown by organizing in a different way. One possibility would be to assign a product team comprised of members from each stakeholder group. Any incentive system would then reward the team based on comprehensive results. Although such a change was beyond the scope of this project, appropriate organizational design is a powerful way to overcome many of the barriers encountered.

Once the tools to overcome the barriers were developed and put in place, Carrier was prepared to experiment with the use of statistical tolerancing on the 06N compressor. The next section of this thesis is a case study of the first practical use of statistical tolerancing in the Carrier TR-3 facility.

The first Super Critical Characteristic optimized was the end surface of the unloader piston relative to the cylindrical surface of the rotor bore. If the piston protrudes into the rotor bore there will be mechanical interference and the compressor will fail. If the piston is recessed from the rotor bore surface there will be an escape path from a high-pressure chamber to the following helical chamber at a lower pressure. This leakage path compromises compressor efficiency. This relationship was chosen as the first formal application of statistical tolerancing at Carlyle for the following reasons:

1. The relationship is defined by a manageable set of 5 characteristics.

2. Piston location has a direct, measurable impact on compressor performance.

3. Some of the characteristics included were on parts provided by an external supplier. In order to be successful with this technique in the long term, it is essential that Carlyle learn how to include external suppliers in the application of statistical tolerancing.

Because the surface being considered is in 3 dimensions, we must decide how to map this to the 2 dimensional error model. One approach is to calculate the average perpendicular distance from the cylindrical surface of the rotor bore to the surface of the unloader piston. This approach gives a very accurate representation of the effect on performance. However, calculating the risk of interference is not possible from an average position. Instead, it is necessary to analyze the point on the end surface of the piston that protrudes furthest into the bore. A star denotes the 2 possible locations of the Risk Point in Figure 8.1. Using the Risk Point as a proxy for the x-direction location of the surface ensures that there will never be a collision with the rotor. Figure 8.1 shows the end surface of the piston, created from the intersection of two cylinders, along with the eccentric diameter of the piston.

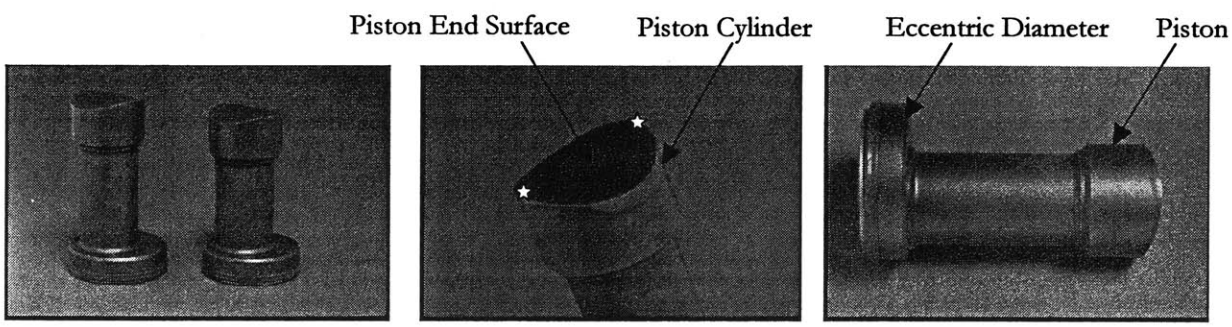
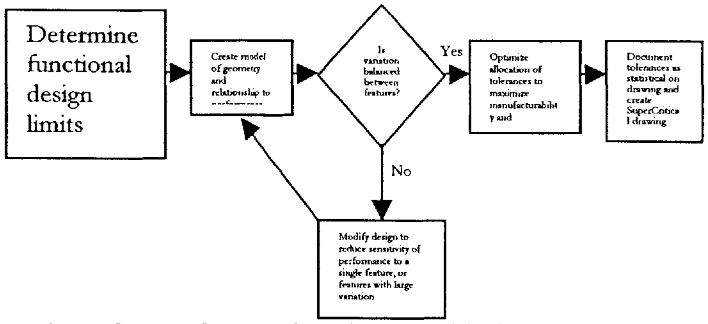


Figure 8.1. The unloader piston. The first frame shows a male and female piston side by side. A close-up of the end surface of the piston is shown in the second frame. Also shown in the second frame are the "Risk Points" of the piston. The third frame shows a side view of a female piston. Because the male piston is shorter, the L/D ratio of the piston is smaller, making it the more restrictive constraint. All analysis and calculations were performed using the dimensions and capabilities from the male piston and extrapolated for use on the female characteristics.

The case study will follow the process flow shown in Figure 5.1.

8.1 DESIGN REQUIREMENTS



The function of the piston is to alternately complete the seal with the rotor bore in the rotor case and to create a short circuit for the refrigerant, effectively shortening the compression chamber. This process was described in further detail in Section 3.1 above. In order to fulfill this requirement the end surface of the piston must align as closely as possible with the surface of the rotor bore. As the surface of the piston recedes away from the surface of the cylinder bore, performance of the compressor degrades.

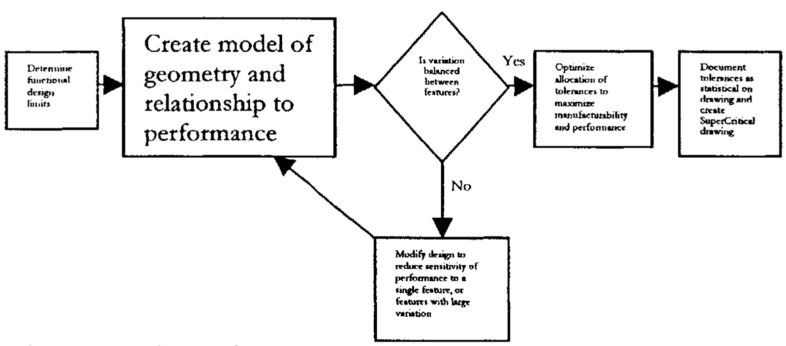
The functional design limits for the piston are the following:

1. The piston must fit as closely as possible into the rotor case without interference.

2. The end surface of the piston must align as closely as possible with the surface of the rotor bore without protruding into it.

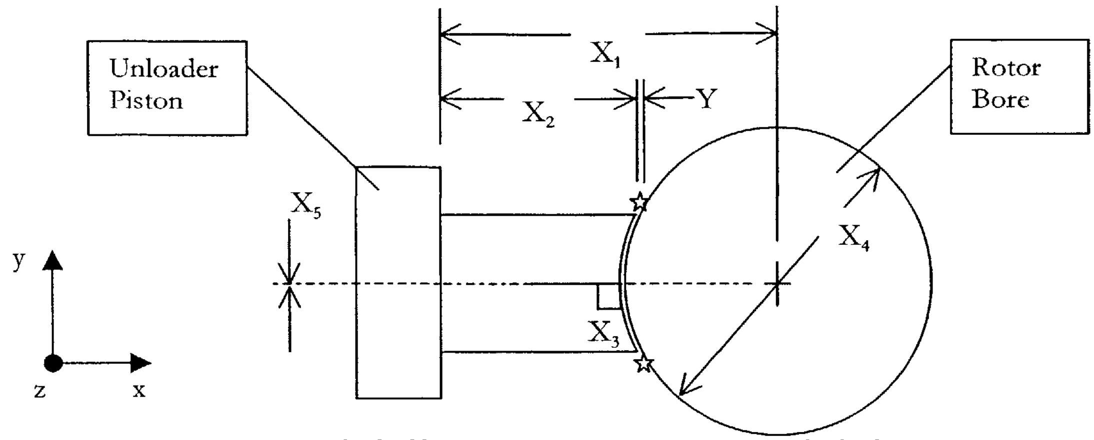
Both of these requirements are important to the compressor performance, but condition 2 is the subject of this case study.

8.2 GEOMETRIC ANALYSIS AND RELATIONSHIP TO PERFORMANCE



The surface of the piston must be as close as possible to the rotor bore to maximize performance. The performance requirement can only be checked by summing the individual characteristics to calculate the location of the surface. This case study will focus on assigning tolerances to individual characteristics on the rotor case and the unloader piston to ensure functionality and performance.

Figure 8.2 below contains a schematic with the characteristics that contribute the most error to the position of the piston surface.



Characteristic Name	**Label**
Unloader Bore Depth	X_1
Piston Length	X_2
Unloader Piston Perpendicularity	X_3
Rotor Bore Diameter	X_4
Unloader Bore True Position (in y direction)	X_5
Super Critical Unloader Piston Clearance	Y

Figure 8.2 Piston layout schematic. The area shaded in bold is the unloader clearance, the super critical characteristic of interest. Although true position is defined as a diameter, in this case it is only error in the x and y directions that effect the performance and reliability of the compressor. The unloader bore true position is measured relative to the location of the rotor bore.

Piston clearance is a function of the other characteristics as shown in Equation 8.1. See Appendix C for a detailed geometric analysis.

Equation 8.1

$$Y = X_1 - X_2 - \frac{X_3}{2} - \frac{X_4}{2} - \frac{X_5}{8}$$

Before moving on to the performance relationship of the Super Critical Characteristic, let us re-examine the supply chain introduced in section 3.2.

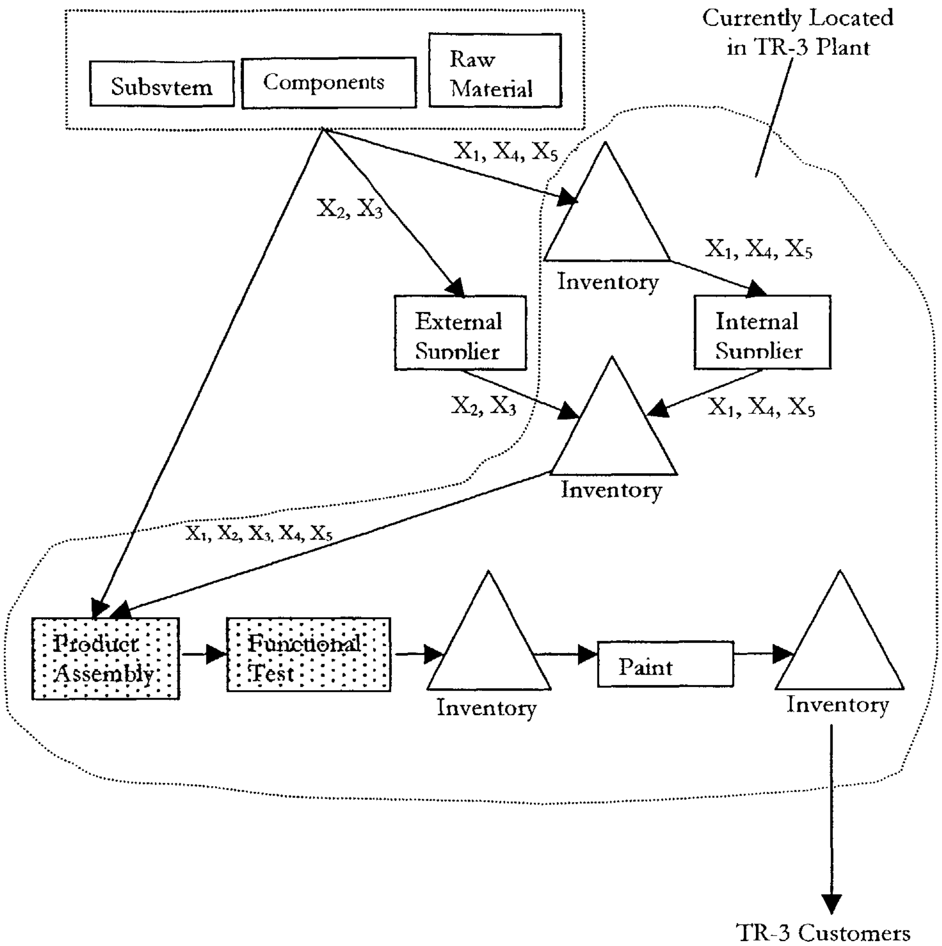


Figure 8.3. Supply chain of critical characteristics. In the case study, Carrier controlled 4 of the Critical Characteristics, while an outside supplier controlled 1 Critical Characteristic. Boxes with the patterned background indicate process steps where a failure in the Super Critical Characteristics can be identified.

Gross failures of the Super Critical Characteristic are identified at assembly by pistons that visibly do not align with the surface of the rotor bore. Further defects are identified at functional test by physical interference with the rotor.

Experience has shown that pistons that do not fail here will function adequately for the life of the compressor. However, if the gap between the piston and the rotor is large, the compressor will function at a lower level of efficiency. Before one can optimize performance vs. manufacturability, it is important to quantify the relationship between gap size and compressor efficiency. To this end, an experiment was designed and performed. The location of the piston was varied with a micro-threaded screw and verified with a dial indicator. The compressor performance was then measured under standardized conditions on the test calorimeter. The relevant results are shown in
Figure 8.4 below.

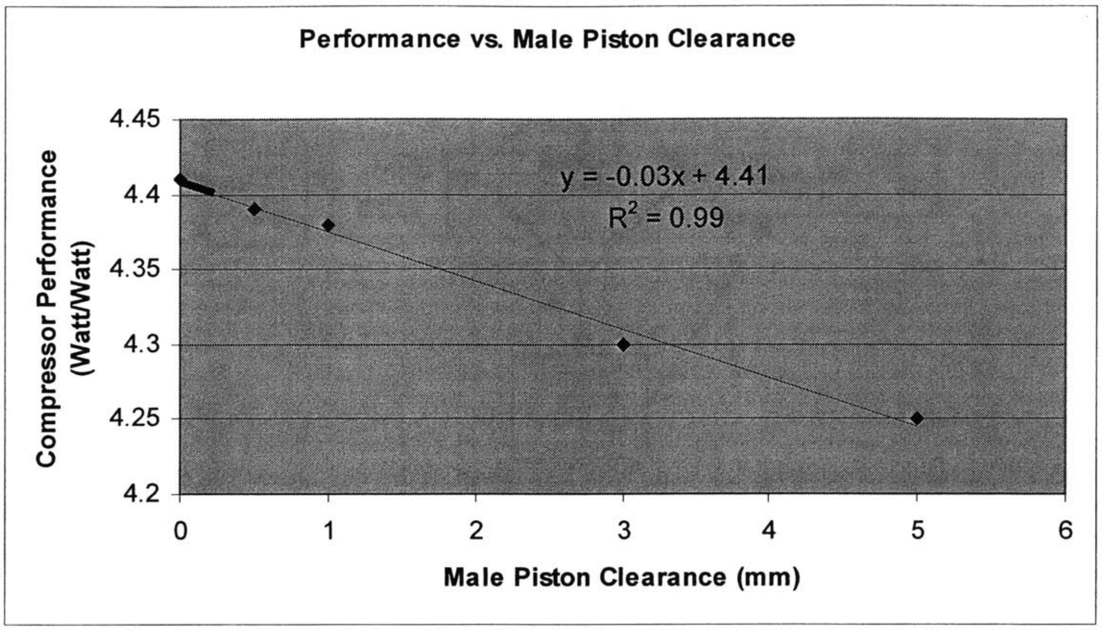


Figure 8.4. Experimental results of compressor performance vs. piston position. Results were collected for a variety of compressor load conditions and the relationship in every case was linear. The region of interest must be interpolated between the fully loaded position (0mm) and the point at 0.5mm. The bold portion of the best-fit line denotes the region of interest.

Compressor performance is found to vary with the male piston clearance according to the following equation:

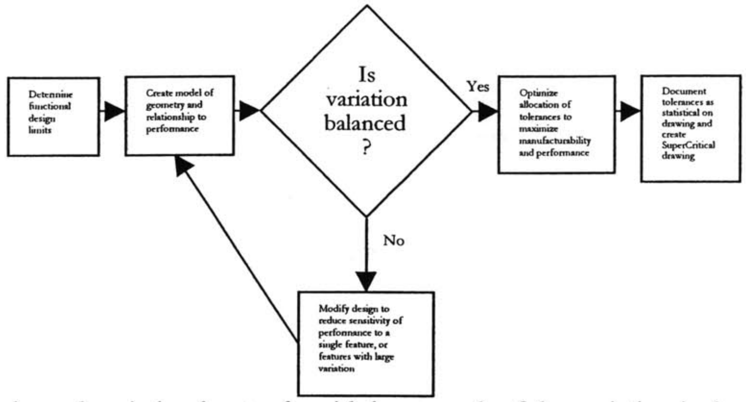
Equation 8.2 $$y = 4.41 - 0.03x$$ *where y = performance (Watt/Watt), x = clearance (mm)*

It is possible to accommodate a lower compressor performance with additional coils in the heat exchanger of the chiller. This, of course, costs money. Previous economic analyses of the chiller system indicated that for every unit loss of performance, the added cost to the system was $68/ton of cooling capacity. This relationship is expressed with the following equation:

Equation 8.3 $$Cost = \$68 \cdot \Delta Performance \cdot T$$ *where T = tonnage of compressor*

For a practical example, consider an increase of 30 microns in the nominal value of the clearance. From Equation 8.2 the change in performance = 0.03 * 0.01mm = 0.0009 Watt/Watt. The system cost would be $68/EER/ton * 0.0009EER * 80 tons = $4.90. In fact, this change in performance is undetectably small and does not affect the performance rating of the compressor in any way.

8.3 DESIGN BALANCE AND MANUFACTURING CAPABILITY



The question of balanced variation has to do with how much of the variation is due to a particular characteristic. This step requires making assumptions about the process capability and modifying the design based on the tolerance analysis. Because our example deals with a released product, a product redesign is beyond the scope of this project. The optimization presented achieves the best balance of tolerance allocation with the existing design and the existing production processes.

The expected variation in the piston clearance can be obtained by combining Equation 8.1 and the expected distributions for each of the contributors. Six months of historical data was used to estimate the mean and standard deviation of each contributor. The historical mean and standard deviation of each component is shown in Table 8.1 below.

Male Unloader Piston Clearance

Characteristic Name	Sensitivity	Nominal	Estimated Stdev	USL	LSL	Ppk
A Unloader Bore Depth	1	126.34	0.009	0.020	-0.020	0.74
B Piston Length	-1	74.184	0.015	0.030	-0.030	0.67
C Unloader Piston Perpendicularity	0.5	0	0.004	0.025	0.000	1.56
D Rotor Bore Diameter	-0.5	104.179	0.004	0.011	-0.011	0.92
E Unloader Bore True Position (Along H-T)	-0.13	0	0.008	0.020	-0.020	0.83
Clearance Values		0.0665	0.0177	0.193	0.000	1.25

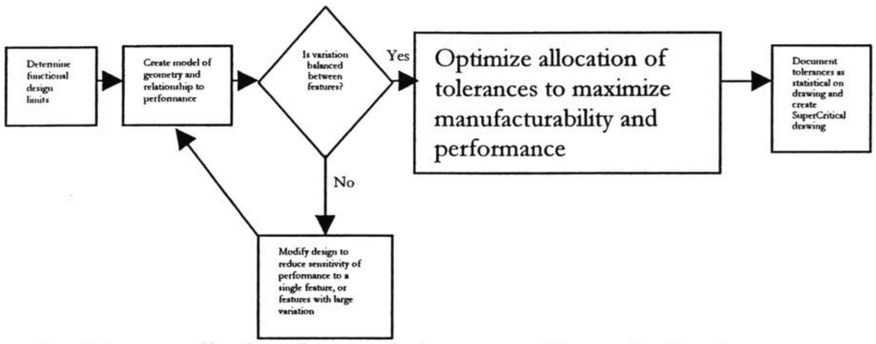
Table 8.1. Pre-optimization values for all contributors to the male unloader piston clearance. Sensitivity values come directly from Equation 8.1.

At Carrier a capable process is defined as one with a P_{pk} of 1.33 or greater. Table 8.1 shows that many of the characteristics that defined the unloader piston clearance were not capable. The capabilities listed are those assigned from the original product design using the worst-case tolerancing method. Note that the Super Critical Characteristic (Clearance) has P_{pk} of 1.25, which is much higher than most of its component characteristics. Worst case tolerancing caused the capability of the Critical Characteristics to be unnecessarily low.

Another concern was that the largest contributor (71%) to the expected clearance variation was from a part manufactured by an external supplier. This meant that no matter how much Carrier managed to reduce variation on the parts they produced, they would not be able to decrease the variation of the piston clearance by more than 29%. However, if the design could tolerate slightly more variation, the benefits averaged over the 3 Carrier components would have a tremendous impact on the manufacturability of the product. Based on the results of the performance analysis, this was exactly the course taken.

We saw from the previous section that recessing the piston an additional 30 microns from the rotor bore has a negligible effect on performance, a decrease of only 0.0009 Watts/Watt or 0.02%. In the following subsection we will see the benefits of allowing the additional clearance.

8.4 SYSTEM OPTIMIZATION



Tolerances for each of the contributing characteristics were reallocated using the process outlined in Section 5. The results are shown with the original clearance value in Table 8.2 and with the additional 30 microns of clearance in Table 8.3.

Male Unloader Piston Clearance – Optimized Case I

Characteristic Name	Sensitivity	Nominal	Estimated Stdev	USL	LSL	Ppk
A Unloader Bore Depth	1	126.34	0.009	0.034	-0.034	1.25
B Piston Length	-1	74.184	0.015	0.056	-0.056	1.25
C Unloader Piston Perpendicularity	0.5	0	0.004	0.020	0.000	1.25
D Rotor Bore Diameter	-0.5	104.179	0.004	0.015	-0.015	1.25
E Unloader Bore True Position (Along H-T)	-0.13	0	0.008	0.030	-0.030	1.25
Clearance Values		0.0665	0.0177	0.133	0.000	

Table 8.2 New tolerances for the contributors to the male unloader piston clearance. The tolerance limits are labeled USL and LSL. Note that each process now has a capability of 1.25

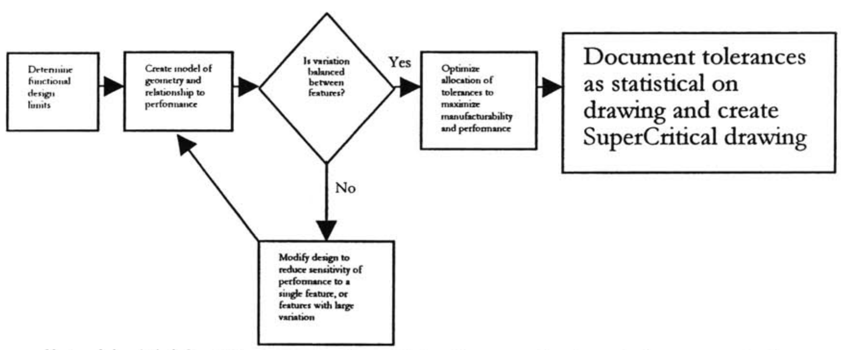
The optimizer adjusts the tolerances until all process capabilities are equal and the clearance mean – 4 * clearance standard deviation = 0.000. Moving the piston by 30 microns increases the nominal Unloader Bore Depth to 126.370. Re-running the optimization yields the results shown in Table 8.3.

Male Unloader Piston Clearance –
Optimized Case II

Characteristic Name	Sensitivity	Nominal	Estimated Stdev	USL	LSL	Ppk
A Unloader Bore Depth	1	126.37	0.009	0.049	-0.049	1.81
B Piston Length	-1	74.184	0.015	0.081	-0.081	1.81
C Unloader Piston Perpendicularity	0.5	0	0.004	0.029	0.000	1.81
D Rotor Bore Diameter	-0.5	104.179	0.004	0.022	-0.022	1.81
E Unloader Bore True Position (Along H-T)	-0.13	0	0.008	0.043	-0.043	1.81
Clearance Values		0.0965	0.0177	0.193	0.000	

Table 8.3. New tolerances for the contributors to the male unloader piston clearance. The optimization was run after increasing the nominal dimension of characteristic A to 126.370.

8.5 DOCUMENTATION AND TRAINING



The new tolerances listed in Table 8.3 were assigned to the product and documented according to the dual-tolerancing process outlined in Section 7.3. The Super Critical drawing documented the relationship between the unloader piston clearance and each of its contributors so that this information was readily available for future reference. Evaluation tools were provided to the product design, production, and quality organizations to allow for easy evaluation of the current state of assembly capability. This also provided the tools necessary to evaluate failure probability due to a single deviant piece, or a group of deviant parts. When process excursions occurred, the evaluation was straightforward and objective. Decisions could be made based on failure probabilities rather than an obscure knowledge that a part with similar error had been accepted in the past.

Training for the use of these tools was very straightforward. The data that goes into the acceptability model was already being collected. Because the characteristics now had such a high capability, all that was required was a quarterly audit of unloader clearance capability performed by the quality assurance organization. The model performed the audit and required only the most recent mean and standard deviation values for each of the contributors. If the unloader clearance was below 1.33 corrective action was required. An internal quality control plan was developed[19] that specifies at what point corrective action is necessary.

[19] VonBorstel, Steve & Terry, Andrew, "Stastistical Tolerancing", Screw Compressor Operations Quality Plan, QCP 508

8.6 RESULTS

All of the steps above were also performed for the female unloader piston. With both male and female pistons recessed from the rotor bore by an additional 30 microns, the expected decrease in performance was 0.06%. For the first month after the nominal location of the unloader piston was changed, the performance audit of the compressor was watched carefully. As expected, there was no perceptible change in the performance of the compressor, yet the benefits to the manufacturing organization were plentiful.

Taking advantage of statistical tolerancing brought the capability of all processes to $P_{pk} = 1.25$. Increasing the piston clearance allowed us to further increase the capability of all processes to $P_{pk} = 1.81$. To understand the benefit of this increase, let us compare the expected failure rate for Characteristic A at the original process capability of 0.74 and the improved capability of 1.25. Assuming a distribution centered on nominal, the failure rate at $P_{pk} = 0.74$ is 26,400 parts per million. At a P_{pk} of 1.25 the expected failure rate is 177 parts per million. This is a decrease of 150 times! When considered at the final P_{pk} value of 1.81, the failure rate is 0.06 parts per million. This reduction was achieved with no measurable decrease in performance.

Statistical tolerances were implemented on 8 internal characteristics for a period of 3 months before the research for this thesis was completed. During this time there were no parts that were scrapped due to the statistically toleranced characteristics. A severe machine excursion caused 2 parts that were out of tolerance, however, the analysis tools quickly verified that the probability of failure was extremely low and the parts were sent on to the assembly process.

The statistical tolerancing method described here was eventually applied to a total of 22 characteristics. The benefits of the increased tolerances were not measured directly because most were changed at the end of the project. However, by making some assumptions about the performance of the manufacturing processes, we can estimate some of the financial benefits.

Assuming that the process variability does not increase more than 10%, IPOSAs for these 22 characteristics will be virtually eliminated. Because the characteristics that were optimized had historically been the source of 70% of the IPOSAs, the total number of IPOSAs processed will be reduced by approximately 70%, saving $30,000 per year in opportunity cost. The scrap of rotor cases due to these characteristics will also be eliminated, saving an additional $40,000 per year.

8.7 SUMMARY

In this section we reviewed the practical application of the statistical tolerancing method presented in Section 5. The clearance between the end of the unloader piston and the surface of the rotor bore was determined to be both important to the performance of the compressor and an area of low manufacturing capability. The functional design requirement was to have the end surface of the piston as closely aligned with the surface of the rotor bore as possible without protruding into the rotor bore. Engineering performed a designed experiment to quantify the relationship between the piston position and compressor performance. Production provided data that showed many of the contributing characteristics of the clearance were not capable. The result of the incapability was a lot of additional cost to the production process.

Allocating balanced tolerances to the contributing characteristics resulted in each characteristic attaining a P_{pk} of 1.25. By moving the nominal location of the piston 30 μm away from the rotor bore increased the capability of each characteristic to Ppk = 1.81. The performance decrease due to this change was immeasurably small.

The statistical tolerancing procedure was repeated on a total of 22 characteristics of the 06N rotor case design. Statistical tolerancing is expected to produce annual savings of over $70,000 through reduced scrap and reduced IPOSA processing. Further benefits that have not been quantified include a faster average throughput time, lower WIP inventory, and simplified material flow.

In the final section of this thesis, we will examine the recommended conditions under which statistical tolerancing is applied. If statistical tolerancing as presented in this thesis is used on a product design, one should understand the risks and benefits of using statistical tolerancing. A discussion of the risks and benefits is included.

SECTION 9: FUTURE USE OF STATISTICAL TOLERANCING

This thesis presented a framework for the implementation of statistical tolerancing. We reviewed the barriers to the use of statistical tolerances at Carlyle TR-3, and the methods used to overcome them. In addition, a case study was presented in which statistical tolerances were assigned to a product that was already designed and in production. Ideally, this technique would be applied during the initial product and process design phase. Done at this early stage, true tradeoffs between product performance and manufacturability may be made. Additionally, design attributes that are sensitive to a particular feature may be reworked to become more robust to variation.

In the initial implementation of statistical tolerancing at Carrier Corporation, assumptions were made in order to keep the approach to statistical tolerancing simple. Even in its simplified state, statistical tolerancing requires disciplined application of SPC and monitoring of the Super Critical Characteristics. Statistical tolerancing should be used along with SPC and statistical inspection methodology to minimize the cost of manufacturing a product while ensuring its performance.

9.1 INTEGRATION WITH EARLY DESIGN PROCESS

In the future, the use of statistical tolerancing techniques described in this thesis should be used as early as possible in the design of a new compressor. By identifying the SuperCritical Characteristics early and working with a manufacturing expert, it will be possible to create a design that is much more balanced than the case study seen in the previous section. Detailed analysis of the variation contributors may also lead to fundamental design changes. It is at the early stages of design that it is often possible to make creative changes that allow both increased performance and increased manufacturability.

Another tool for ensuring that manufacturability concerns are addressed is standard work. Through engineering standard work proven methods are followed in the design process. It is one way that learning is passed from one development project to the next, or from an experienced design engineer to less experienced colleagues. The author provided Carrier with an engineering standard work document for the application of statistical tolerancing.[20] The document provided outlines the process as it is presented in Section 5 of this thesis. Following this procedure will ensure that production capability is taken into account early in the design process.

Applying the statistical tolerancing techniques before the manufacturing processes have been developed requires making some estimations of process capability. By coordinating with a manufacturing expert, reasonable estimates can be obtained. Although the information is not perfect, such coordination will result in a design that is much more balanced than arbitrary assignment of tolerances.

9.2 RISKS OF STATISTICAL TOLERANCING

Once statistical tolerances have been applied to the design, it is required that the characteristics have distributions that are centered on nominal. The system of dual tolerancing presented in this thesis is a double edged sword. The dual tolerancing system was developed because it provides suppliers with an incentive to make use of SPC and be able to reduce the cost of inspection. However, there is a risk that a supplier will agree to the use of SPC yet not implement it properly. This makes the continuing evaluation of critical characteristics by the supplier quality organization essential. The system of having some parts delivered with the centered distributions, and some parts being delivered under worst-case tolerancing has not been tested in all of its permutations.

[20] Terry, Andrew, "Statistical Tolerance Analysis and Allocation", Carrier Internal Document, SWPSC-#48, 11/23/99

In order to ensure continued capability of the SuperCritical Characteristics of a design, an internal document specifies the required frequency of reviewing capability. Critical Characteristic capability is reviewed on a monthly basis. If the capability falls below 1.33 a corrective action request is issued and a team is put together to address the problem. In such a case the Supercritical Characteristic is reviewed monthly. If all Critical Characteristics maintain capability above 1.33 the capability of the SuperCritical Characteristic is ensured. In this case, the capability of the SuperCritical Characteristic is reviewed on a quarterly basis. The internal quality assurance organization performs these reviews with information provided by production and the supplier quality organization.

The process of maintaining capability of the Critical Characteristics and SuperCritical Characteristic is unique to the approach developed for this thesis. The process is not in use at other manufacturing organizations within Carrier. For this reason there is a risk that with the change of personnel some of the knowledge will be lost. New quality engineers may not realize the importance of maintaining the capability of the Critical Characteristics and may not perform the required reviews. Incorporating the review procedure into the TR-3 quality manual mitigates this risk; nevertheless, new personnel will not be as familiar with the issues.

The potential savings from reduced scrap and reduced IPOSAs was based on the assumption that the variation of the processes would not increase from the measured values. SPC seeks to decouple the relationship between process variation and process specifications. Human nature, however, is to decrease effort when one is clearly exceeding the design requirements. For example, if a process tolerance requires a hole diameter to machined within 10μm, an operator will naturally take more care than for a tolerance of 30μm. Changing the scale of comparison from process specifications to process capability will be an ongoing challenge for users of statistical tolerancing.

There is some technical risk with the analytical approach taken in the optimization process. The technique assumes that the mean of single-sided distributions is one standard deviation from the physical limit. This was observed empirically from 5 different characteristics of the 06N rotor case. There is, however, no theoretical reason why this should always be the case. If the actual mean of a single sided distribution is significantly greater than 1 standard deviation from the limit, the model underpredicts the probability of failure.

9.3 RECOMMENDATIONS & CONCLUSIONS

Statistical tolerancing should be used as part of a suite of statistical tools through the design, production, and inspection process. Together, these tools allow manufacturers to protect the performance of the compressor while reducing the amount of money spent on manufacturing and inspecting the product to overly restrictive tolerances. We have shown that statistical tolerances enabled annual savings of $70,000 dollars on the O6N rotor case. Using statistical tools to achieve capability on 100% of the geometric tolerances of the 06N rotor case would reduce labor requirements by the equivalent of 2 inspectors, saving an additional $200,000 per year.

Time that was spent evaluating deviant parts and processing IPOSAs may now be spent improving the processes, or supporting additional volume without increasing headcount. Parts that used to sit around for days or weeks waiting for approval now flow directly through the plant and on to the assembly process. This reduces the yield variation experienced by the production planners and allows them to more accurately match production volume with demand requirements, reducing inventory.

Converting to the use of statistical tolerancing will yield benefits many times its cost. Production and engineering will consider each other's concerns more carefully. Inspection and supplier quality are required to consider the output of manufacturing as a set of statistical data rather than parts that are either good or not good. Shifting to the statistical mindset opens the door to a variety of cost and quality improvement tools.

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2. Drake, Paul Jr., editor, "Dimensioning and Tolerancing Handbook," 1999, McGraw –Hill, Chase, K. W., "Chapter 13- Multi-Dimensional Tolerance Analysis," "Chapter 14- Minimum-Cost Tolerance Allocation." This work describes the formation of matrix equations describing the relationship of contributing characteristics to the characteristic of interest. An automated, closed-loop solution is presented for both worst case and RSS tolerance methods.

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5. Shiba, Shoji, et. al., "A New American TQM: Four Practical Revolutions in Management", 1993, Productivity Press, Cambridge, MA. Introduces the philosophy and tools used in TQM. Change management and continuous improvement are discussed.

6. Thornton, Anna C., "A Mathematical Framework for the Key Characteristic Process," Working Paper, Mechanical Engineering Department, Massachusetts Institute of Technology. This paper first develops a mathematical definition of a KC based on a variation propagation model. Second, this paper develops a quantitative effectiveness measure used to prioritize where verification, variation reduction, and on-going monitoring should be implemented. The effectiveness measure incorporates the cost of control, the benefit of control, as well as the expected change in process capability.

7. Vining, G. G., "Statistical Methods for Engineers" 1998, Duxbury Press, Pacific Grove. An introductory text on statistics, this book provides necessary background information on random variables and probability distributions. Most of the Critical Characteristics exhibit behavior that can be reasonably modeled by the normal distribution.

The optimization process employed for the work in this thesis was performed exclusively in Microsoft Excel with the built-in Solver. All of the variables were transformed into squared space so that the variances could be added directly. This transformation enabled a linear program, which ensures that the optimal solution is achieved. One can easily check whether the optimization worked by calculating P_{pkX} for each of the critical characteristics P_{pkY^*} for the Super Critical Characteristic. An optimized result should have a P_{pkY^*} of 1.33 and all of the P_{pkX} should be equal.

The Solver optimization was set up with the following parameters:

Decision Variables	Square of the relative USL for each Critical Characteristic Minimum squared Ppk value, MPK2
Constraints	Clearance variance must be less than $\left(\frac{\bar{Y}-LSL}{4}\right)^2$. This constraint ensures that the clearance will not be less than zero at a P_{pk} of 1.33. For all i: MPK2 – $P_{pki}^2 \leq 0$ (This constraint ensures that the final P_{pk} values will be equal, essentially maximizing the minimum P_{pk})
Objective Function	Maximize the minimum P_{pk}.

Table A.1 Excel Solver optimization parameters.

A sample optimization spreadsheet is attached below.

	K	L	M	N	O	P	Q	R
13				Decision Variables				MPK2
14								1.56
15		Sens.^{2}	Mult.	USL^2	Var Contrib		Ppk^2	
16	Unloader Bore Depth	1	0.0625	0.001135	7.09E-05		1.56	0.00
17	Piston Radius Profile	1	0.0625	0.003153	0.000197		1.56	0.00
18	Unloader Piston Perpendicularity	0.25	0.04	0.000399	3.99E-06		1.56	0.00
19	Rotor Bore Diameter	0.25	0.0625	0.000224	3.5E-06		1.56	0.00
20	Unloader Bore True Position (Along H-T)	0.015625	0.0625	0.000897	8.76E-07		1.56	0.00
21								
22					0.000276			
23								
24	**Constraints**							
25	Clearance Variance		<=	0.000276				
26	MPK2 - Ppki^2		<=	0				

Table A.2 Sample optimization spreadsheet. All of the variables are shown in the squared domain. Once the solution is obtained, the USL and P_{pk} values are obtained by taking the square root of the numbers shown here.

The clearance variance is simply the sum of the variance contribution from each of the Critical Characteristics. The sensitivity and multiplier determine the contribution of each Characteristic. Each Characteristic is assumed to be a normal distribution centered on the nominal dimension or a one-sided distribution with the mean 1 standard deviation from the nominal dimension as shown in Figure A.1. Using these assumptions, and a P_{pk} of 1.33 as a baseline, the variance is then assumed to be (USL – nominal)/4 for two-sided distributions, and (USL – nominal)/5 for one-sided distributions. In squared space, the multipliers are then $1/4^2$ and $1/5^2$, respectively.

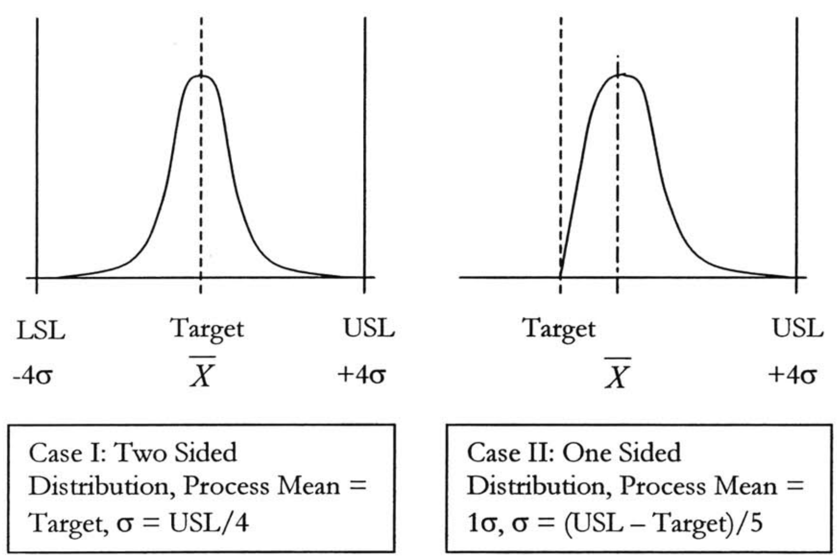


Figure A.1 Graphical representation of assumptions for two-sided and one-sided distributions in the optimization spreadsheet.

The problem is now to iteratively adjust the USL of each characteristic to satisfy the constraints and objective function given in Table A.1. The spreadsheet shown in Table A.2 is solved using Microsoft Excel Solver with the following parameters.

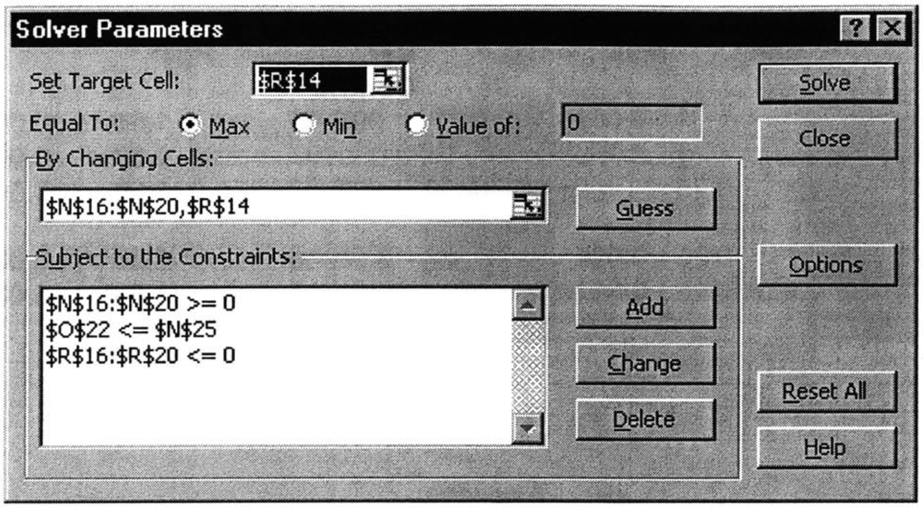


Figure A.2 Actual Solver parameters used to solve the spreadsheet example shown in Table A.2.

Because of the transformation to squared space, the optimization problem is linear. Therefore, as long as the parameters allow a feasible solution, the solution given will be optimal.

The author recognizes that the simplifications used to represent one-sided distributions in the optimization are approximations. Using a more advanced optimization tool it would be possible to perform the optimization as described in Section 5 of this thesis. An even better scenario is to measure all Characteristics using Vectorial Tolerancing and to avoid the one-sided distributions artificially created by GD&T.

APPENDIX B: USEFULNESS OF TOLERANCE ANALYSIS SOFTWARE

APPENDEX B.1 COGNITION'S MECHANICAL ADVANTAGE

Mechanical Advantage was the software tool used to perform the geometric and variation analyses for this thesis. The software is designed primarily as a design tool, and therefore did not provide an easy interface for evaluating actual production results. Tolerances could be assigned to each of the characteristics, then an option specified the number of standard deviations this tolerance represented. It was not possible to have the print tolerances and the actual production variation represented simultaneously. This quickly led the author to replicating the model in Microsoft Excel where there was additional flexibility.

The greatest value of Mechanical Advantage was developing the transfer function terms of Equation 5.2.2. Once these terms were obtained, analysis and further calculations were performed in Excel. Obtaining the transfer function terms required reproducing the datum structure as specified in the part drawings. Because the software is designed only to function in 2D, some simplifying assumptions were required.

The software was not user friendly and required significant training for the creation of a single model. Because the software is not integrated with the CAD tool used at Carrier, all of the work must be recreated. A design technician at Carrier required 2 months of half-time work to create a functioning model of the rotor to rotor clearance in the 06N compressor.

The author does not recommend the long-term use of this software because of the shortcomings outlined above. Although the software does help one to understand the issues of error propagation and statistical summing, the interface is neither integrated with existing tools nor easy to learn.

APPENDEX B.2 CE TOL

The last day of this project a representative from CE Tol came to Carrier to provide a demonstration of this product. CE Tol integrates directly into Pro-Engineer and establishes the datum structure within the existing Pro-E model. This software also appears to provide additional what-if capabilities and other tools that are very useful in the early phases of the design project. The software performs its analysis in 3 dimensions and more accurately models the modes of variation experienced in manufacturing.

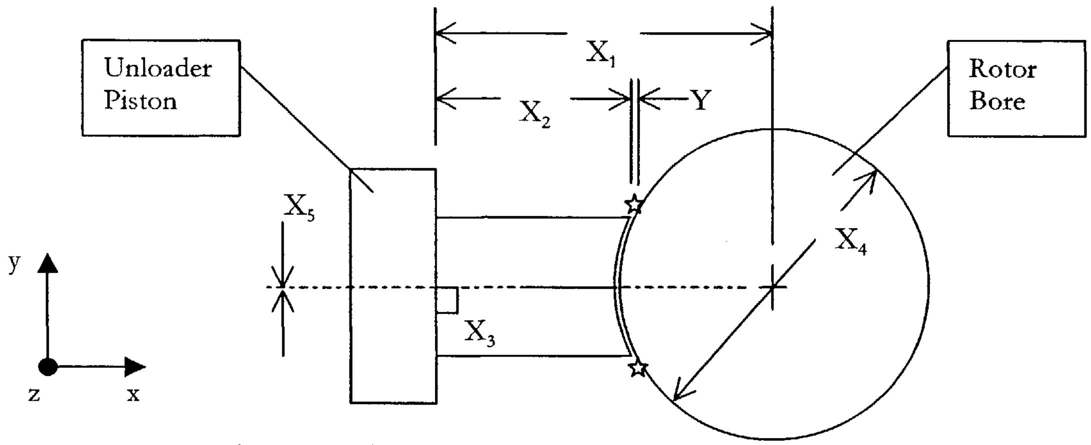
Like Mechanical Advantage, CE Tol does not provide an integrated approach to variation analysis. The software concentrates solely on the design phase and does not provide tools to re-evaluate the design using actual production data.

Because the author's exposure to this package was solely through a demonstration, there was no way to make an evaluation of the learning curve required. It was clear that this is a complex piece of software and would not be immediately intuitive to use.

APPENDEX B.3 GENERAL ISSUES

The mathematical algorithms in these variation analysis packages require the specification of a single kinematic state. Different combinations of characteristic variation may result in multiple possible kinematic states. Therefore, the results of a single analysis may predict results that are much more restrictive than those that are experienced in assembly. The author is not aware of any commercially available variation analysis capable of modeling multiple kinematic states.

This appendix reviews the geometry introduced in Section 8. We investigate how a unit change of each of the contributing characteristics affects the Unloader Piston Clearance. Recall the following figure and equation from Section 8.



Characteristic Name	Label
Unloader Bore Depth	X_1
Piston Length	X_2
Unloader Piston Perpendicularity	X_3
Rotor Bore Diameter	X_4
Unloader Bore True Position (in y direction)	X_5
Super Critical Unloader Piston Clearance	Y

Figure 8.2. Geometric relationship of characteristics. X_1 through X_5 represent the Critical Characteristics that comprise the SuperCritical Characteristic Y. Y is the minimum distance between the risk point of the piston and the surface of the rotor bore.

Equation 8.1

$$Y = X_1 - X_2 - \frac{X_3}{2} - \frac{X_4}{2} - \frac{X_5}{8}$$

To obtain the transfer function terms, S_i on each characteristic, we will examine each characteristic individually. In general, from Section 5, $S_i = \frac{\partial Y}{\partial X_i}$. First, we evaluate the Unloader Bore Depth. In this case we hold every other term constant and vary the Unloader Bore Depth (X_1). The observed change in the clearance (Y) allows us to solve for S.

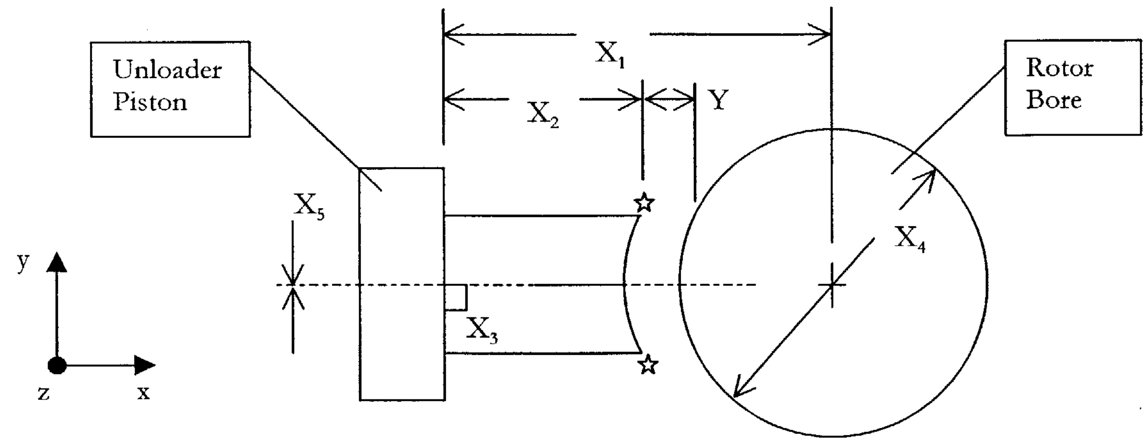


Figure C.1. A 1 unit positive change in X_1 results in a 1 unit positive change in Y.

It can be seen from Figure C.1 that a 1 unit increase in A results in a 1 unit increase in Y. Therefore, $S_1 = 1/1 = 1$.

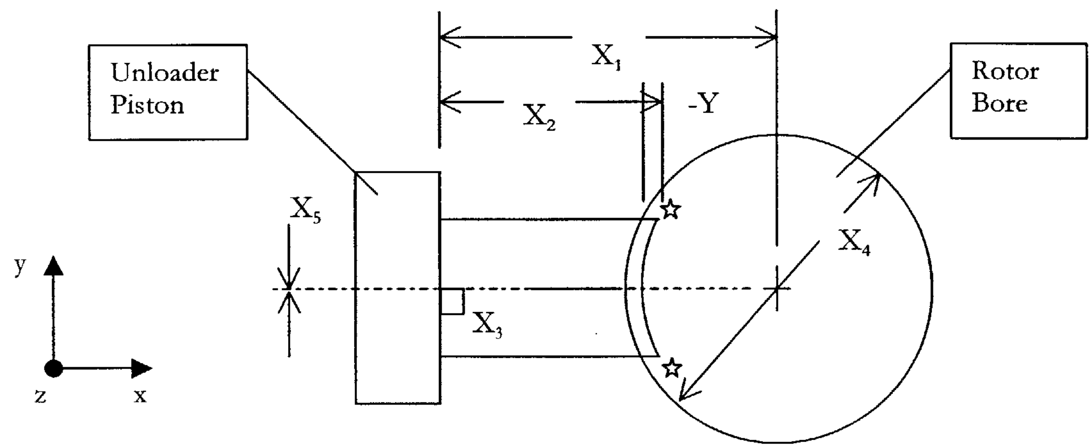


Figure C.2. A 1 unit positive change in X_2 results in a 1 unit negative change in Y.

In Figure C.2, as X_2 increases, Y decreases by an equivalent amount. Therefore, $S_2 = -1/1 = -1$. We now turn our attention to X_3 the analysis is not a function of feature size, but accuracy. Specifically, X_3 measures the perpendicularity of the piston relative to its base.

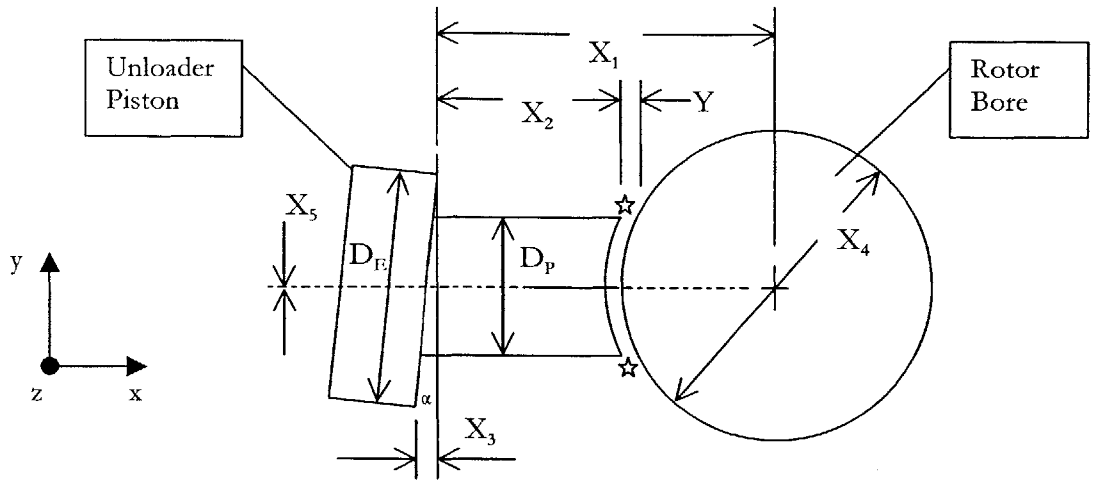


Figure C.3. Schematic drawing of piston perpendicularity error. The piston bore in the rotor case confines the orientation of the piston as shown in the figure. The schematic shows that as X_3 increases, Y increases. This relationship holds true no matter the direction of the perpendicularity error.

In GD&T, perpendicularity (X_3) is measured in units of length, being the maximum displacement of the feature from its nominal position. α is the angular difference from $\pi/2$, or perfect perpendicularity. For small angles $X_3 = D_E * \alpha$. To convert X_3 to a change in Y, we observe that the piston will move the same amount as the center of the eccentric diameter. Therefore $S_3 = (D_E/2)*\alpha/(D_E*\alpha) = 1/2$. On a perfect piston α measures zero. Because perpendicularity can never be less than zero, X_3 is a single sided distribution.

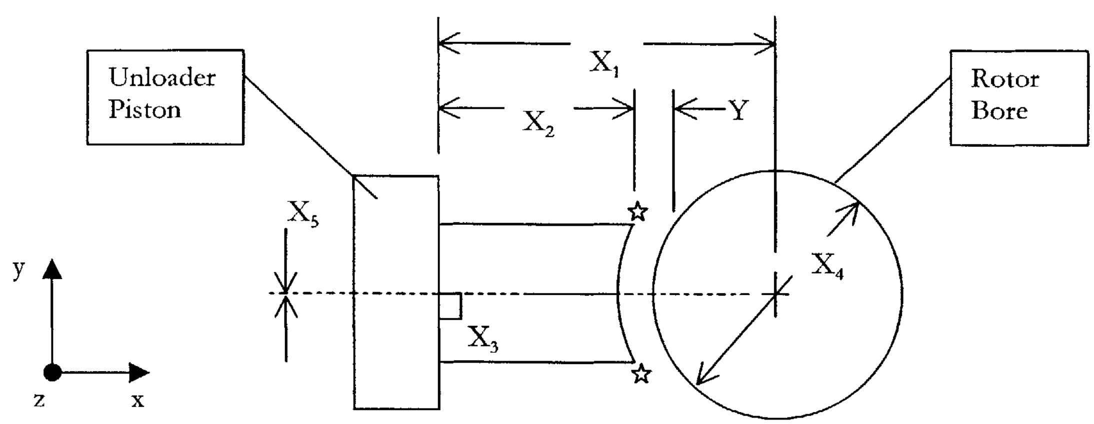


Figure C.4. Schematic demonstrating the effects of error in the Rotor Bore Diameter, X_4.

Figure C.4. shows the effects of decreasing the Rotor Bore Diameter, X_4. Because the Unloader Piston Clearance is measured from the surface of the rotor bore it varies approximately with the radius of the rotor bore. Therefore a unit decrease in X_4 results in a ½ unit increase in Y. $S = ½*X_4/(-X_4) = -1/2$. X_4 is a 2 sided distribution that varies symmetrically about its ideal value.

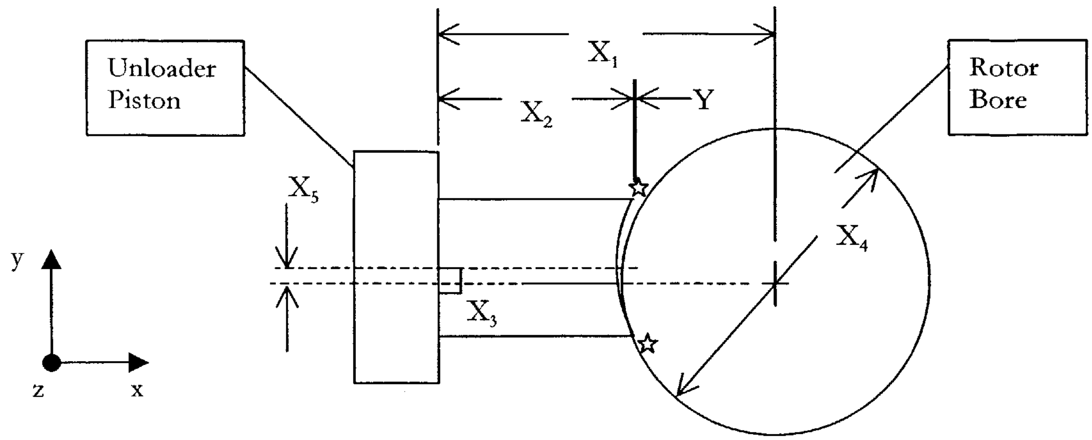


Figure C.5. Schematic demonstrating the relationship between piston location in the y direction (X_5) and the Unloader Piston Clearance (Y).

The final dimension to be analyzed is the Unloader Bore True Position in the y direction, X_5. Note that although the bore position also varies in the z direction, variation in z does not affect the Unloader Piston Clearance. A first order approximation of the change in clearance is obtained by estimating the "slope" of the rotor bore near the risk points. The linear approximation can be seen in Figure C.6. below.

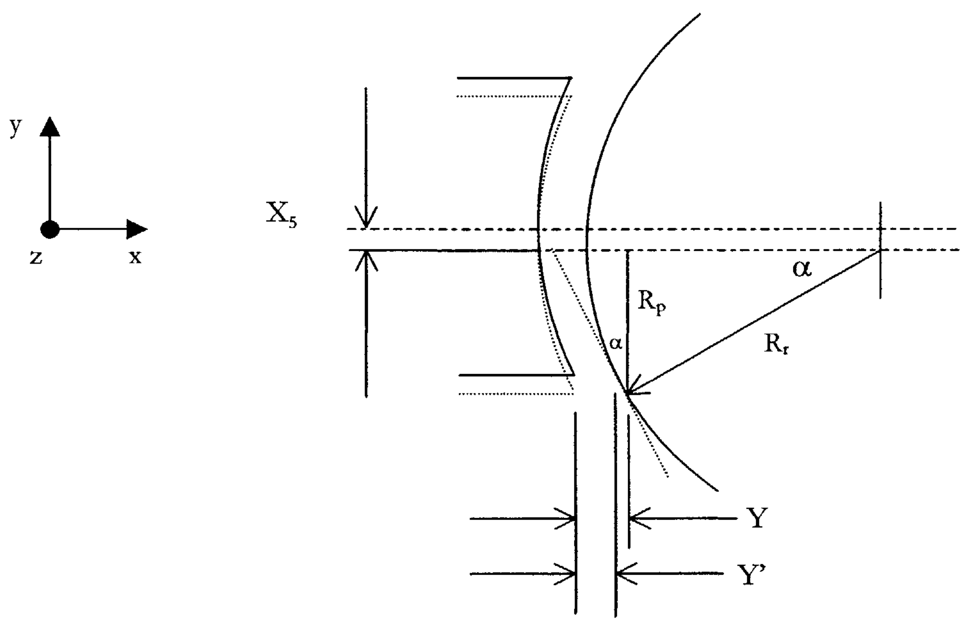


Figure C.6. Diagram of the first order approximation of S_5. The system is modeled as a change relative to the dotted line tangent to the rotor bore at the risk point.

Change in the Unloader Piston Clearance is represented as Y'–Y. From the geometry of the figure, it can be seen that $Y'-Y = -X_5 * \sin(\alpha)$. S_5 is therefore $-X_5 * \sin(\alpha)/X_5 = -\sin(\alpha) = -R_p/R_r = -20/52 = -0.38$. The astute reader will note that this is significantly larger than the sensitivity number used in Equation 8.1. The simple model shown here holds as long as the diameter of the piston end surface is equal to or less than the diameter of the rotor bore. In reality it is slightly larger. Because the piston end surface diameter is larger, in the nominal location the point closest to the rotor bore is actually the center of the piston. As the piston translates in the y direction, the point of the piston closest to the rotor bore moves as well. With large displacements, the "risk point" at the edge of the piston is closest. The movement of the risk point is highly non-linear. The number used in the calculations was taken from the software model of the problem, which accounts for the complex geometry.