START
Selected Topics in Assurance Related Technologies
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Six-Sigma Programs

Introduction

In 1988, Motorola Corp. became one of the first companies to receive the now well-known Baldrige National Quality Award. The intent of this award is to recognize firms that are deemed worthy role models for other businesses. The specific Motorola innovation that attracted the most attention was its six-sigma program. The emphasis was that modern technology was so complex that the old ideas about acceptable quality levels were no longer acceptable.

Background

Six-sigma is basically thought of as a process quality goal. However, it must always be remembered that quality processes are just one of the key elements of product reliability. Designing for reliability encompasses a great deal more than this. If the individual parts themselves do not start with an adequate level of quality and reliable design is not adequately addressed during the development, final product reliability at the six-sigma level is simply not possible.

While building on SPC as its foundation, an effective six-sigma program actually represents a paradigm shift. It goes far beyond just measuring, identifying and segregating defective items; it entails an entirely new management approach. It requires trusting all of the members of the workforce and educating and training of them (including top management). The intent is a participative-management process that emphasizes employee involvement at all levels. The program goal is teamwork.

The primary objective of this new approach is to assure total customer satisfaction. Understanding the customer, his needs and desires should be the focus of the effort. An essential corollary to this principle is the fact that there are actually a variety of customers. These customers include, for example, the next department in the assembly sequence and the product distributor as well as the ultimate consumer. Each customer must be recognized and his or her individual needs and/or desires must be addressed in their proper context.

As a normal result of the manufacturing process, all manufactured items are subject to item-to-item variation. This variation is the enemy of quality. Sigma (σ) is the standardized statistical measure of the variability or the dispersion within a given population of items. Specifically it is the distance between the standard deviation and the mean of the population. The formula for σ is:

$$\sigma = \sqrt{\frac{\sum (x - \mu)^2}{n}}$$

where:

σ = standard deviation
x = individual measures of some parameter of interest
μ = mean of the process
n = number of items in the population

These facts have long been recognized and the science of statistical process control (SPC) was designed specifically to measure and to control product variation within acceptable limits. These techniques helped to assure that the vast majority of items produced were acceptable. Inspection procedures were then relied upon to identify and to subsequently remove nonconforming items before delivery of the product to the customer.

The Six-Sigma Concept

Historically, controlling a manufacturing process to a nominal + or — three-sigma variation was considered adequate for most manufacturing processes. This resulted in 99.73% of the items being within specification or conversely, 0.27% were out-of-spec. The out-of-spec. items were then (hopefully) removed following inspection. This level of defects, however, is nowhere near acceptable with today's highly complex equipment in our worldwide, highly competitive and quality-conscience marketplace.

The six-sigma concept, while based upon SPC, carries the concept a great deal farther. A manufacturing process actually controlled to + or — six-sigma (a total spread of 12σ) would assure that 99.9999998% of the items were within specification, or only 0.0000002% (or 2 parts per billion) out-of-spec. Assuming a normal or Gaussian distribution (which is realistic for the typical parameters of interest), this represents seven orders of magnitude improvement, as shown in Figure 1.

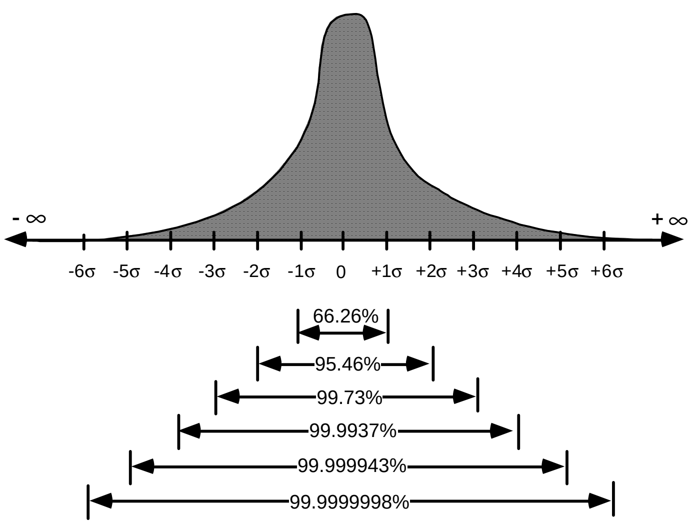

Figure 1. Normal Distribution

Essential SPC Metrics

Two essential SPC metrics associated with six-sigma programs are Process Capability and Process Performance. It is vital that the reader has a clear understanding of what these metrics are and the difference between them.

Process capability (C_p) is a measure of the ability of a process to produce acceptable products. C_p can be considered to be a short term metric. It is measured by comparing the variation in the product to the upper and lower specification limits, assuming that the product mean value is centered between the upper and lower specification limits. A high C_p (e.g., $C_p = 2$) indicates that the process is under control and capable of reproducing the desired characteristic. It makes no statement about whether the process is centered on the desired mean. The formula is:

$$C_p = \frac{|USL - LSL|}{6\sigma}$$

where:

USL = Upper Specification Limit
LSL = Lower Specification Limit

Process performance (C_{pk}) combines both variance and off-target process means. C_{pk} can be considered to be a long term metric, i.e., it also accounts for process drift. A high C_{pk} indicates that the process is actually reproducing the desired characteristic within the desired limits. It makes no statement about the inherent process capability, other than its minimum value. The formula is:

$$C_{pk} = \text{Minimum\_of\_}\left[\frac{\text{Target} - LSL}{3\sigma};\frac{USL - \text{Target}}{3\sigma}\right]$$

From this equation, we can see that when C_{pk} and C_p are identical the process mean is on target.

In most of the literature, however, it is assumed that the actual process performance is somewhat degraded from the optimum, i.e., that the actual mean of the manufacturing process has been displaced somewhat from the process nominal specification target.

Typically a 1.5-sigma shift, as shown in Figure 2, is assumed. Thus, when the process mean is 1.5σ off target, the shortest distance from the process mean to either specification limit is 4.5σ. This is reflected in C_{pk} by reduction from 2.0 to 1.5. Thus while a theoretical six-sigma program would appear to require a C_{pk} = 2.0, in practice a C_{pk} = 1.5 is more frequently used.

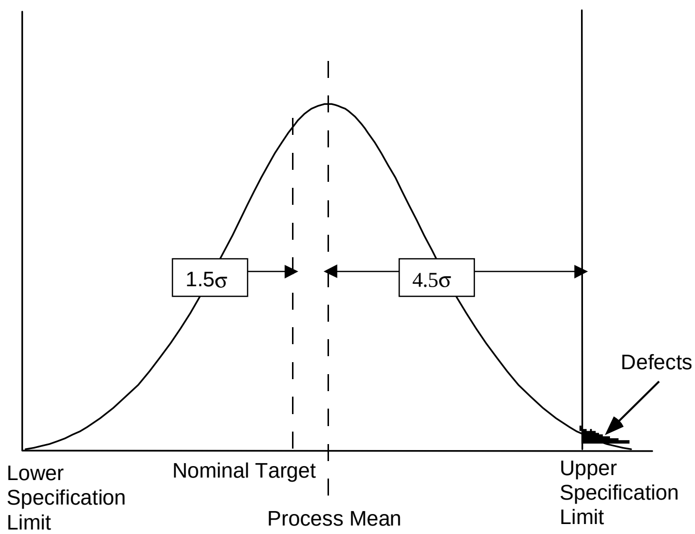

Figure 2. Process Performance

In spite of the degradation of process performance resulting from this 1.5σ shift of the process mean, the process is still capable of producing items with an equivalent defect rate of only 3.4 parts per million (e.g., + or—4.5σ).

While these techniques were developed in a manufacturing environment, it is also important to understand that the application of a six-sigma program is not just limited to the manufacturing arena. It can also be applied to virtually any process-oriented business; even those not described by a normal distribution. For example, questions to the IRS are answered either correctly or not. This is actually a binomial process. Still, such cases can be related to the others through their error rate. For a relative feel for how six-sigma results might compare with other measures of quality in the real world, see Figure 3.

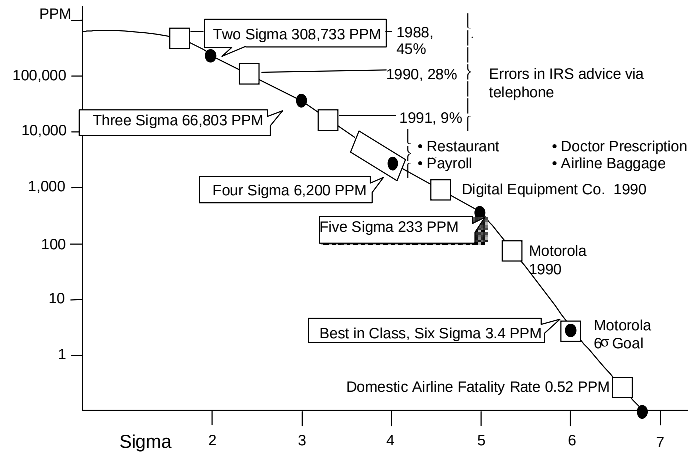

Figure 3. Typical Quality Estimates

Implementing a Six-Sigma Program

Implementation of six-sigma program requires close cooperation between the product design effort and the design of the manufacturing process. One of the goals of product design is to increase the allowable tolerance to the maximum that will still permit successful functioning of the product. On the other hand, process design has the goal of minimizing the variation of the process that reproduces the characteristic required for successful functioning of the product, and the centering the process on target (nominal) value of the desired characteristic.

Typically, there are three primary sources of product variation: a) insufficient design margin, b) use of less than optimal parts or materials and c) inadequate process control. All of these sources of variation need to be addressed if optimum process capability is to be reached.

Design Margin. The first step is to identify the critical parameters for the item, and to address the specification limits for them. Many times the specification limits have been set rather subjectively without sufficient study. A Design of Experiments (DOE) approach, Taguchi Methodology or Robust Design approach should help to assure that the specification limits are optimally selected.

Other import design reliability tools that should also be considered at this point in the design effort due to their potential impact upon design margins would include Failure Mode and Effects Analysis (FMEA), Fault Tree Analysis (FTA), Worst Case Circuit Analysis (WCCA) and Accelerated Testing.

The basic premise is that it is much easier, and more cost effective, to eliminate bias from the design target characteristics than it is to reduce the variation itself. What we want is a robust design, one that is very insensitive to all subsequent variations in the manufacturing process, variability in the environmental operating conditions and possible future deterioration with age.

The achievement of a robust design allows the specification limits on parts dimensions, materials composition, and the myriad of other parameters that appear on drawings and specification to be less stringent without a commensurate loss of reliability.

Incoming Components and Materials. One goal of a six-sigma program is to completely eliminate incoming inspection, whenever possible. Suppliers should be expected to incorporate the necessary process controls to detect and correct manufacturing defects well before the completion of their finished product. The total cost to acquire materials from a supplier and the cycle time required to produce these materials is influenced by the suppliers' manufacturing yield and any non-productive steps added to the manufacturing process in an attempt to "inspect in" quality of the supplied materials.

Key contributors to process variation comes from the differences in the incoming material quality, particularly if there are multiple suppliers. In some instances it may be best to reduce the number of suppliers and to concentrate instead on improving a few preferred suppliers. To meet six-sigma requirements, control of these suppliers must go far beyond just incoming inspection; an actual partnership with the vendor may need to be established to assure compliance.

Inadequate Process Control. Total process characterization is the key to adequate process control. This involves establishing specific values of C_p and C_{pk} for each of the critical parameters and then optimizing the manufacturing process. An intimate knowledge of the manufacturing process and its physical basis is thus required to identify and eliminate these causes of variability.

A closed-loop Failure Reporting, Analysis and Corrective Action System (FRACAS) might also be an effective tool at this point to help identify and correct these problems.

The tools of SPC must be mastered in order to identify the sources of long-term variation in the presence of background noise, to measure any reduction in variability, and to gain early warning of disturbing influences. Success requires first bringing each process into control, making the process stable so that over the short term there is a well-defined σ. Then the systematic causes of long-term variation must also be reduced or eliminated.

Motorola's approach to implementing its six-sigma program is documented in its well known "Six Steps to Six-Sigma" shown in Table 1. Obviously each of these steps, in turn, can then be expanded further.

Table 1. Motorola Six Steps to Six-Sigma

1. Identify the product you create or the service that you provide.
2. Identify the Customer(s) for your product or service, and determine what **they** consider important.
3. Identify your needs (to provide product/service so that it satisfies the Customer).
4. Define the process for doing the work.
5. Mistake-proof the process for doing the process and eliminate wasted effort.
6. Ensure continuous improvement by measuring, analyzing, and controlling the improved process.

Many companies, other than Motorola, even in such diverse industries as banking and hospitals have successfully implemented a six-sigma program within their corporate structure. One of the most prominent of these is GE. GE launched a major corporate wide six-sigma initiative in 1995 and claims 150% savings of its original investment during just the first two years of operation. Since then GE has effectively employed six-sigma programs in a number of their diverse operating divisions including Medical Systems, Power Systems, Electrical Distribution & Control and Plastics.

For Further Study:

1. Web Sites: Additional information on six-sigma and related topics can be obtained from the following web sites:

   a. www.mpcps.com
   b. www.qualityamerica.com
   c. www.6-sigma.com
   d. www.sixsigmaqualtec.com
   e. www.gelearningsolutions.com

2. Publications:

   a. Paul E. Fieler, "Understanding Motorola's Six-Sigma Program", Tutorial Notes 1990 International Reliability Physics Symposium.
   b. Mario Perez-Wilson, "Six-Sigma, Understanding the Concept, Implications and Challenges", Advanced Systems Consultants, P.O. Box 1176, Scottsdale AZ 85252.
   c. Thomas Pyzdek, "The Complete Guide to Six-Sigma" (602) 423-0081.
   d. E. E. Lewis, "Introduction to Reliability Engineering", especially Chap. 4, "Quality and its Measures", John Wiley & Sons, Inc.
   e. Anthony Coppola, "Tutorial: Measuring Process Variation or, Why does 6σ = 3.4 ppm?", RAC Journal, Volume 5, No. 3.
   f. GE Six-Sigma Quality Coach, 1-888-722-0990.
   g. Rod Bothwell et al, "Reliability Evaluation: A Field Experience form Motorola's Cellular Base Transceiver Systems", 1995 Proceedings Annual Reliability and Maintainability Symposium.
   h. Anthony Coppola, "Practical Tools for the Reliability Engineer", RAC publication STAT.

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Future Issues:

RAC's Selected Topics in Assurance Related Technologies (START) are intended to get you started in knowledge of a particular subject of immediate interest in reliability, maintainability and quality. Some of the upcoming topics being considered are:

- Mechanical Reliability
- Software Reliability

Please let us know if there are subjects you would like covered in future issues of START.

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About the Author:

Norman B. Fuqua is a Senior Engineer with IIT Research Institute (IITRI). He has 40 years of varied experience in the field of dependability, reliability and maintainability and has applied these principles to a variety of military, space and commercial programs. At IITRI he has been responsible for reliability and maintainability training and for the planning and implementation of various dependability, reliability and maintainability study programs.

Mr. Fuqua developed unique distance learning Web-based and Windows™-based computer-aided reliability training courses. He is the developer and lead instructor for the Reliability Analysis Center's (RAC) popular Design Reliability Training Course. This three-day course has been presented almost 200 times to some 6000+ students in the US, England, Denmark, Norway, Sweden, Finland, Germany, Israel, Canada, Australia, Brazil, and India. Audiences have included space, military, industrial and commercial clients.

He is also the lead developer and instructor for a two-day Dependability Training Course for an Automotive Supplier and a three-day Robust Circuit Design Training Course. These courses enable mechanical and electronic design engineers and reliability engineers to utilize advanced software-based tools in producing designs that exhibit minimum sensitivity to both internal and external variations.

Mr. Fuqua holds a Bachelor of Science degree in Electrical Engineering from the University of Illinois, Urbana Illinois, is a Registered Professional Engineer (Quality Engineer) in California, and a Senior Member of the IEEE and the IEEE Group on Reliability.

He is a former Member of the Editorial Board, "Electrical and Electronics Series", for Marcel Dekker Inc., and the Education and Training Editor for the "SAE Communications in Reliability, Maintainability and Supportability Journal". He is also a former Member of the EOS/ESD Association, and Chairman of three different EOS/ESD Association Standards Committees.

He is the author of a number of technical papers, eight RAC publications and a reliability college textbook published by Marcel Dekker Inc.

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