

Boost Competitiveness via Six Sigma

Quality programs based on six sigma can substantially reduce defects, leading to enhanced customer satisfaction, higher market share, and improved bottom-line performance.

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“Six sigma” denotes a specific measure of how well a process is performing. A six sigma process produces extremely few defects — 3.45 per million opportunities (99.9997% defect-free). A defect is something that results in customer dissatisfaction. Customer satisfaction is the goal of six sigma; better bottom-line performance results as a byproduct. Six sigma applies equally well to all enterprises, large and small, manufacturing and transactional (nonmanufacturing).

The current standard based on statistical process control (SPC) is three sigma, which translates to approximately 66,800 defects per million opportunities (6.68% defective), or 93.32% good. The impact of improvement from three sigma to six sigma can be enormous.

Six sigma concepts (see sidebar) were pioneered at Motorola during the early 1980s, and contributed to its receiving the Malcolm Baldrige National Quality Award from President Reagan in 1988. In recent years, success with six sigma quality programs has been so dramatic that such programs are spreading like wildfire across corporate America, prompting popular periodicals such as *The New York Times* (1), *Fortune* (2), *Wall St. Journal* (3), *USA Today* (4), and *Chicago Tribune* (5) to carry full-length articles on the subject. Perhaps much of the credit for the widespread interest in six sigma quality across corporate America should go to John F. Welch, Jr., Chairman of General Electric. In 1995,

GE embarked on an ambitious corporate-wide six sigma initiative in all its businesses, both manufacturing and nonmanufacturing — including GE Capital, NBC, Aircraft Engines, Plastics, and Medical Systems. The benefits from six sigma quality programs at GE exceeded \$1 billion at the end of 1998 (more than 10% of total earnings), and are expected to surpass \$2 billion at the end of 1999.

The standard road map to achieving six sigma quality utilizes linear principles. Real-world processes, both manufacturing and nonmanufacturing, are often nonlinear. Articles have shown how certain concepts from artificial intelligence could be exploited to accommodate these nonlinearities and lead to superior performance.

Why six sigma?

On the domestic front, competitive pressures have been steadily rising. Highest quality products and services must be offered at the lowest possible costs, thus maximizing customer satisfaction. Yet, downsizing has made the task of staying competitive more challenging. So, stress levels in corporate America arguably are at an all time high. Under these circumstances, six sigma initiatives assume great significance because they focus on how to work smarter, not harder.

Meanwhile, globalization has intensified competition worldwide. Developing countries in Asia, with a population base of over two billion, are in the pro-

Six Sigma — an Overview

The Greek letter σ commonly represents standard deviation. The phrase six sigma, on the other hand, denotes a specific performance level — namely, 3.45 defects per million opportunities. Six sigma concepts are inspired by three fundamental ideas:

1. All that we do has cause and effect. Furthermore, the effect from one cause is, in turn, the cause for another effect (India, 1,500 B.C.) This idea applies to all endeavors, manufacturing and transactional. The endless chain of cause and effect is known as karma. Whereas the goal in karma yoga is to break down the endless chain of cause and effect through meditation for personal enlightenment, the goal in six sigma quality is to build cause-and-effect relationships for defect reduction in the material world.

2. It has been found through many years of experience that a large variety of continuous physical observations follow the normal (or, equivalently, standard normal) probability distribution (Gauss, 19th Century A.D.). On the other hand, discrete random variables follow binomial, Poisson, or hypergeometric distributions. These ideas also apply to all endeavors, manufacturing and transactional.

3. Common-cause variability is inherent in all systems. Additional variability occurs due to assignable causes that must be investigated and eliminated (Shewhart, Deming, Juran, Taguchi, 20th Century A.D.)

The basis of six sigma can be best illustrated with the standard normal distribution. The standard normal variable z is related to the normal random variable x by the relationship:

$$z = (x - \mu) / \sigma \quad (1)$$

The standard normal distribution has the probability density function:

$$f(z) = \frac{1}{\sqrt{2\pi}} e^{-\frac{1}{2}z^2} \quad -\infty < z < \infty \quad (2)$$

The standard normal distribution has zero mean and a unit variance.

The normalization allows performance comparison of a wide variety of processes and operations with widely varying units and dimensions. Equation 2 leads to the familiar bell-shaped curve.

The probability that the standard normal variable assumes a value between $-\infty$ and Z is given by:

$$F(Z) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^Z e^{-\frac{1}{2}z^2} dz \quad (3)$$

Therefore, the probability that the same standard normal variable exceeds Z is given by $1 - F(Z)$. Table 2 lists illustrative values of $F(Z)$ for selected values of Z , and shows that the unilateral tail area rapidly decreases as Z increases — meaning that a significant drop in defects in parts per million occurs even for a modest reduction in standard deviation σ . Now, suppose, a product or transaction has a one-sided specification, say, an upper limit. If Z denotes that upper specification, then, as Table 2 indicates, for $Z = +6$, roughly 0.001 parts per million will not perform per specifications. In contrast, conformance to $Z = +3$ implies that 1,350 parts per million will not meet specification. Thus, the shift from three sigma to six sigma represents a giant leap in performance. Note that the standard deviation σ and the performance level sigma are inversely related. The quest to improve the sigma level of a process or endeavor must necessarily involve efforts to reduce the standard deviation σ .

Experience in discrete parts manufacturing has led practitioners to conclude that long-term performance degrades by about 1.5σ due to such factors as machine wear and operator fatigue. Thus, a process or transaction producing 0.001 defects per million (corresponding to $Z = 6$) in the short term will produce no more than 3.45 defects per million in the long run (corresponding to $Z = 4.5$). Such a product characteristic and the process or transaction that produced it are said to be six sigma.

cess of opening up their economies to international competition, creating tremendous opportunities and challenges. Six sigma companies are the ones that will capture significant market share in the intensely competitive global markets.

Because customer satisfaction is important to all businesses, regardless of products or services, there is no enterprise that will not substantially benefit from six sigma. Indeed, we could cite an extensive, varied, and rapidly growing list of successful programs. The experience of companies that have deployed six sigma suggests that the positive margin impact on the bottom-line is on the order of 10% of revenues per year.

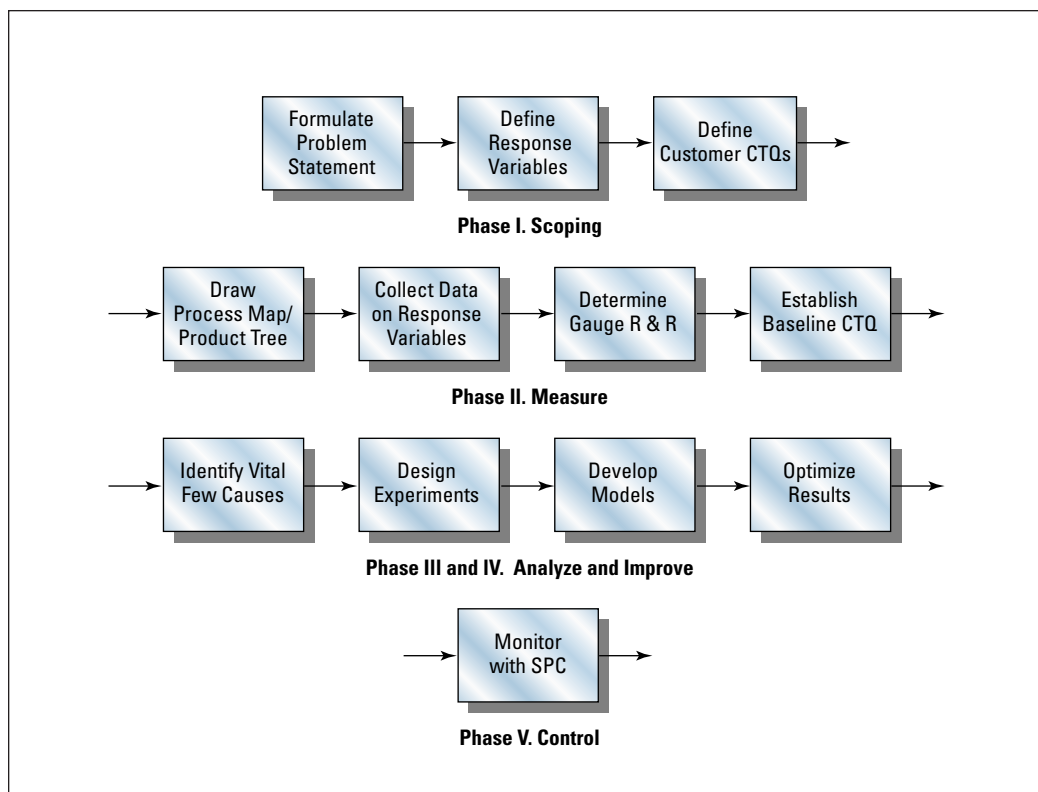
The road map

The goals of defect reduction, yield enhancement, improved customer satisfaction, lower costs, and, thus, higher net income are attained by an effective use of statistical, artificial-intelligence, and optimization tools to analyze data and to drive business decisions based on facts, not gut feel. GE's Welch aptly states, "Six sigma represents a paradigm shift from fixing products so that they are perfect to fixing processes so that they produce nothing but perfection, or close to it." In the context of control engineering, this implies an emphasis on inputs (causes) and outputs (effects). The root causes of problems are fixed

and solutions optimized. Controls are put in place, so that the problems once fixed stay fixed.

Six sigma solutions heavily rely on data; therefore, their implementation can be facilitated by enterprise resource planning (ERP) software. These packages offer integrated solutions to materials handling, production scheduling, sales and distribution, and finance and costing. ERP programs provide instantaneous access to data and show the impact of a change in any of the functions throughout the entire chain. Using such software, however, is not a prerequisite to implementing six sigma quality programs.

■ **Figure 1.**
The five phases of
a six sigma
quality program.



There are five phases of six sigma:

1. scope;
2. measure;
3. analyze;
4. improve; and
5. control.

In control engineering, the “improve” phase is labeled as the “control” phase and the “control” phase is termed the “monitor” phase. These five phases lead to a step-wise procedure for implementing a six sigma program of quality improvement, as depicted in Figure 1.

Scope

Formulate problem statement. Example — 15% of shipments are received late by customers, leading to customer dissatisfaction and loss of business to competition.

Define response variable(s). Example — number of days from order to receipt.

Specify customer critical to quality characteristics (CTQs). Specifications on the response variables are the CTQs. Example — order-to-receipt

time must be two days or less. The tools to identify customer CTQs are customer surveys, brainstorming sessions, market analysis, and the like. Defects are out-of-tolerance CTQs.

Measure

Draw product tree (for manufacturing processes) or process map (for transactional processes). A product tree details all the subsystems in a product. A process map shows all the linkages among the causes and the effects (response variables). A process map highlights complexity and problem areas and aids in problem solving by pinpointing bottlenecks, redundancies, and waste.

Collect data. Focus on gathering data on the response variables.

Determine the gauge repeatability and reproducibility. Response variables must be measured accurately for results and conclusions to be meaningful. Good gauge repeatability and reproducibility (Gauge R&R) is essential for progress toward six sigma quality. Statistical methods for

determining Gauge R&R are available. Table 1 lists hypothesis-testing tools for this purpose.

Establish base line CTQ. This provides a quantitative measure of how well the process or transaction is performing prior to six sigma implementation and, thus, a means for later assessing the extent of improvement. For this purpose, data on the response variables are collected, and defect levels in percent or in parts per million are established. Proper sample size is an important consideration for obtaining reliable estimates of defects. Statistical methods are available for establishing proper sample size for different confidence levels.

Analyze

Collect data and identify the vital few causes. On the basis of the data gathered, determine the causes having the largest impact on the response variables using tools such as those in Table 1. Some causes may predominantly contribute to the mean, while others mainly to the

Table 1. Six sigma tools.

Standard Statistical Tools	
Tool	Use
Mean	Measure of position
Variance and standard deviation	Measures of dispersion in the data
Frequency distribution	Quantitative classification of data
Histogram, Pareto chart	Graphical presentation of frequency distribution
Poisson (discrete) distribution	Aids in per-step yield calculations
Normal (continuous) distribution	Aids in sigma calculations, establishes common-cause variability
Standard normal distribution	Allows treatment of response variables of varying units
Statistical sampling	Correct amount of data required for analysis
Normality check	Checks for presence of assignable causes
Point estimation	Estimation of population statistics (mean and standard deviation)
Interval estimation	Estimates margin of error (between population and sample statistics) due to sample size
Hypothesis testing	Comparison of means and standard deviations
Statistical process monitoring	Detects the presence of assignable causes
Design of experiments	To find vital few causes; also used to develop models
Multiple linear regression	Modeling of linear static processes
Nonlinear regression	Parametric modeling of nonlinear static processes
Goodness of fit	Model validation
Additional Tools for the Chemical Process Industries	
Principal component analysis/ partial least squares	Handles large-dimensioned linear systems; collinearity
Time series analysis	Transfer functions of static and dynamic multivariable systems; identification of noise structures
Dynamic matrix identification	Step response modeling of dynamic multivariable systems
Logistic regression	Data-driven modeling of multivariable nonlinear systems; handles categorical variables
Artificial neural network	Models static and dynamic nonlinear processes
Minimum variance control	Limit of perfection; tradeoff between system stability and dynamic performance
Linear programming	Constrained optimization of linear multivariable processes
Linear constrained model	Combines feedforward compensation, dead-time compensation,
predictive control (CMPC)	interaction compensation, constraints handling, and optimization all in one software package
Nonlinear CMPC	Extends CMPC to multivariable nonlinear static and dynamic systems
Optimal control theory	Unconstrained CMPC; good for certain dynamic multivariable systems for some types of loads
SPC in the context of engineering process control	Extends SPC concepts to continuous systems
Experts system	Fault monitoring; model validation

variance. Identifying these vital few causes allows focusing efforts on minimizing their contributions to the defects. This will have the beneficial effect of shifting the process mean of the response variables in a favorable direction and reducing their variance. Tests can determine if the improvements made really are statistically significant.

Improve

The first two steps of the Improve Phase contain elements that are com-

mon to the Analyze Phase, as well. This commonality arises from the fact that data once analyzed lead to improvements that, in turn, warrant confirmation.

Design of experiments. Carry out design of experiments (DOE) and collect data on the causes and the response variables. The nature of DOE will vary depending upon whether the process is static or dynamic, linear or nonlinear.

Model development. Relate the response variables to the causes (inde-

pendent variables). With the recent advances in systems identification, highly complex, nonlinear dynamic models can be developed. Note that in problems of practical interest, both manufacturing and transactional, the models invariably will turn out to be multivariable in nature. Tools from statistics, system identification, and artificial intelligence are available for modeling purposes (see Table 2).

Find optimal solution. Solve for the values of the causes that give the best possible results. Linear and non-

linear optimization algorithms provide a means for solving such optimization problems.

Control

Implement SPC. Monitor all pertinent variables with statistical process control.

Proven in practice

Let's now look at three real-life examples that show the value of applying six sigma. Confidentiality agreements prevent the disclosure of certain details.

1. Omni Medical, located in Louisville, KY, provides home health-care supplies. Orders are placed by phone or facsimile by nursing organizations. Shipments are made from two warehouses, one in California and the other in Louisville. Customer dissatisfaction was becoming an increasing issue. It centered on four types of complaints: (1) a shipment sometimes did not come on time; (2) when a portion of an order was shipped from one warehouse and the remainder from the other, the two did not reach the patient on the same day; (3) a shipment was incomplete because some items were on back-order; and (4) a shipment sometimes contained generic substitutes, some of which were not permitted in the order.

In this case, the CTQ was defined as "full and correct orders received within two working days." A process map was prepared showing all

the potential causes contributing to customer dissatisfaction. Data on the causes were compiled from in-house sources. Customer surveys indicated a base line defect rate at the start of the project of 34% (sigma level = 1.93). Analysis of the data led to the identification of the major causes of customer dissatisfaction. One turned out to be that some fax orders were delayed because they went to the Louisville office after its closing hours; they could have been handled that day by the still-open California office. Once the causes were attended to, a second set of surveys was compiled. The defect rate declined to 11% (sigma level = 2.73), an improvement of 68%. In this instance, only the top few vital causes were considered. Efforts aimed additional defect reduction are underway.

2. A manufacturer of a common appliance was receiving consumer complaints centered around unacceptable noise levels.

Preliminary investigations indicated that the suspension system of the machine was responsible for excessive noise during operation. Here, the response variable was "noise level from the suspension system in decibels." The CTQ was "noise in excess of a certain level," as determined through customer focus groups. A product tree showing all the sub-assemblies of the entire suspension system and all the components in each respective subassembly was de-

veloped. Its objective was to narrow the source of noise. Two vital causes contributing to the problem were: (1) variance in the diameter of a certain component; and (2) mean width of another component.

In this case, the component diameter became the primary focus of efforts. The part in question is made in an injection molding machine. So, a project was undertaken to identify the vital few causes responsible for introducing excessive variance in diameter.

A fish-bone diagram was developed for the injection molding process, and identified fill pressure, pack pressure, and mold temperature as independent variables in the process that controlled the component diameter. A set of full factorial experiments were conducted to model their effects on component diameter. These experiments pinpointed how to optimize the three independent variables to center the mean value of component diameter within its tolerance. The six sigma program resulted in reducing the defect level in component diameter to under 1,000 ppm from 90,000 ppm. As a consequence, customer complaints subsided.

3. In a petrochemical plant, inefficiencies in off-gas removal were causing variations in feed composition, leading to suboptimal operation. In the plant, raw materials enter a reactor and undergo an exothermic reaction to form a product. Reactor temperature is regulated by a coolant flowing through the jacket. Off gases in the product stream must be removed to prevent accumulation. Off-gas removal takes place in a unit downstream.

In this example, the CTQ was "the standard deviation of the off-gas composition in the stream entering the off-gas-removal system must be less than 0.9." Out-of-tolerance CTQ constituted a defect. The response variable was "off-gas composition in the product stream." On-line analyzers were the gauges.

To establish Gauge R&R, on-line

Table 2. Areas under the standard normal distribution.

Z	Cumulative Area	Tail Area	Defects per Million
0	5.00000 E-01	5.000 E-01	500,000
1	8.41300 E-01	1.587 E-01	158,700
1.5	9.3320 E-01	6.680 E-02	66,800
2	9.77250 E-01	2.275 E-02	22,750
3	9.98650 E-01	1.350 E-03	1,350
4.5	9.999965 E-01	3.451 E-06	3.451
6	9.99999987 E-01	1.248 E-09	0.001248

Literature Cited

1. **Deutsch, C. H.**, "Six Sigma Enlightenment," *N. Y. Times*, p. C1 (Dec. 7, 1998).
2. **Bylinsky, G.**, "How to Bring Out Better Products Faster," *Fortune*, p. 238B (Nov. 23, 1998).
3. **Carley, W. M.**, "Charging Ahead," *Wall St. Journal*, p. A1 (Jan. 13, 1997).
4. **Jones, D.**, "Firms Aim for Six Sigma Efficiency," *USA Today*, p. B1 (July 21, 1998).
5. **Franklin, S.**, "In Pursuit of Perfection," *Chicago Tribune*, p. 5-1 (Apr. 4, 1999).

Further Reading

- Deming, W. E.**, "Quality, Productivity, and Competitiveness Position," M.I.T. Ctr. for Adv. Eng. Study, Cambridge, MA (1982).
- Deshpande, P. B.**, "Globalization, Economic Development, and Competitiveness: Opportunities and Challenges," presented at Univ. of Arkansas, Fayetteville (Apr. 23, 1998).
- Deshpande, P. B.**, "Emerging Technologies and Six Sigma," *Hydroc. Proc.*, p. 55 (April 1998).
- Deshpande, P. B.**, "Science, Spirituality, and Six Sigma," *Reflections*, p. 1 (May 1999).
- Deshpande, P. B., and S. S. Yerrapragada**, "Predict Difficult to Measure Properties with Neural Analyzers," *Control Eng.*, p. 35 (July 1997).
- Deshpande, P. B., S. Ramasamy, and S. S. Yerrapragada**, "Neural Nets Improve Batch Quality," *Control Eng.*, p. 53 (Apr. 1996).
- Deshpande, P. B., J. A. Caldwell, S. S. Yerrapragada, and M. A. Bhalodia**, "Should You Use Constrained Model Predictive Control?," *Chem. Eng. Progress*, **91** (3), p. 65 (Mar. 1995).
- Deshpande, P. B., R. E. Hannula, M. A. Bhalodia, and C. W. Hansen**, "Achieve Total Quality Control of Continuous Processes," *Chem. Eng. Progress*, **89** (7), p. 59 (July 1993).
- Fielier, P. E., and N. Lorerro**, "Defects Tail Off with Six Sigma Manufacturing," *Circuits and Devices*, p. 18 (Sept. 1991).
- Harry, M. J., and J. R. Lawson**, "Six Sigma Productivity Analysis and Process Characterization," Addison-Wesley, Reading, MA (1992).

analyzers were calibrated to insure satisfactory performance prior to data taking. Analysis of normal operating data showed that the standard deviation of the off-gas composition in the stream entering the off-gas-removal system was 1.5, and that the data were non-normal, which is indicative of the presence of assignable causes.

So, experiments were designed to determine the causes of variation. Based on the data collected, two vital causes were identified: (1) reactor inlet-temperature variations; and (2) efficiency of the off-gas-removal system.

Investigations pointed to a faulty feed pre-heater as the source of the reactor inlet-temperature variations. Fixing this problem led to a modest decrease in the variability of the response variable.

A major cause of variation turned out to be the efficiency of the off-gas-removal system. The off gases generated in the reaction must be removed consistently or else feed-composition variations occur. A constrained model predictive controller (CMPC) was installed to improve performance. The controller was designed to regulate the off-gas concentration in the stream leaving the off-gas-removal system by manipulating the flow of a heating medium and a solvent. A month's results following the successful implementation of CMPC have confirmed the following benefits: (1) 20% reduction in the cost of the heating medium; (2) 10% cut in the cost of solvent; and (3) decrease in the standard deviation of off-gas composition to 0.8. As a result, the raw material usage has come down by 15%.

Embrace six sigma

In this article, we have presented an overview of six sigma concepts and provided examples of their use. Six sigma is neither new nor is it rocket science. It is, however, an elegant collection of tools for problem-solving that, when properly exploited,

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will lead to handsome returns and globally competitive positions. Based on our combined sixty-plus years of experience in quality related areas in manufacturing and nonmanufacturing operations, we firmly believe that potential opportunities for six sigma quality programs in all enterprises worldwide are endless.

CEP

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