Getting Started: Six-Sigma Control of Chemical Operations

The success of Six Sigma vs. classic quality metrics lies in its ability to more usefully measure defects.

Many world-class companies are hopping on the Six Sigma bandwagon. Early leaders such as Motorola and General Electric showed the way, claiming huge benefits from their programs. Numerous publications describe their results (1, 2, 3). Experts state that U.S. industry, on average, operates somewhere between $3\sigma$ and $4\sigma$. The cost of poor quality falls somewhere between 25% and 40% of sales at $3\sigma$, and between 15% and 25% of sales at $4\sigma$, according to Harry and Schroeder (1). Thus, the opportunity for cost reduction is staggering.

As companies adopt Six Sigma quality programs, they are insisting that their suppliers develop Six Sigma capability as well. A company's quality level will be limited to that of incoming materials. Since the entire supply-chain quality is only as good as its weakest link, Six Sigma is expected to become the minimum quality level acceptable across industry.

In addition to providing a rallying cry and motivator, Six Sigma produces tangible benefits. Such a program enables identification of process entitlement, which is defined as the level of quality or cycle time that a product/process design should achieve if the process is in control. Six Sigma provides unambiguous measures of process performance, unlike traditional quality metrics. A Six Sigma program involves every employee, supplier, and customer in a simple, well-focused improvement program, resulting in reduced operating cost, rework, inventory and cycle time.

**Six Sigma vs. classic quality metrics**

Why is Six Sigma succeeding where numerous other quality programs have fallen short? Management commitment and broad participation across the company in Six Sigma are key factors, but the reason most often cited (1) is the following — Six Sigma measures defects more usefully than do "classical" quality programs (Table 1).

The following terms will help illustrate the difference between Six Sigma and other quality programs: • Critical to quality characteristic (CTQ) — an

<table>
<thead>
<tr>
<th>Table 1. Differences between traditional quality metrics and Six Sigma.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>First-time Yield (traditional)</strong></td>
</tr>
<tr>
<td>• Based on number of units</td>
</tr>
<tr>
<td>• Unit sensitive</td>
</tr>
<tr>
<td>• Insensitive to product/process complexity</td>
</tr>
<tr>
<td>• Measures production capability</td>
</tr>
<tr>
<td>• Little correlation to cost, cycle time and inventory</td>
</tr>
</tbody>
</table>
attribute of either the product or process that affects customer acceptance
- Defect — nonconformance to a CTQ; this can be applied to either a product or process
- Defects per unit (DPU)
- Defects per million opportunities (DPMO)
- Opportunity — any action in material supply, process operation or customer usage that has the potential to create a defect
- Sigma level — a statistical measure of DPMO used to describe the overall performance of a process or product.

The following equations define Six Sigma metrics:

\[ TY_i = \text{Conforming CTQs/Total CTQs} \]  \hspace{1cm} (5)

where \( TY_i \) is the throughput yield.

\[ \prod_{i=1}^{N} TY_i \]  \hspace{1cm} (6)

Equations for classic quality metrics include:

First-time yield = Conforming product/Total product \hspace{1cm} (7)

Final yield = Conforming product/Total product after rework \hspace{1cm} (8)

Note that \( TY_i \) does not depend on how the defects are distributed within a unit of measure and that no rework is allowed prior to the measure being taken. In Six Sigma, we identify all of the CTQs, count the conforming CTQs and divide by the total number of CTQs. Thus, Six Sigma is sensitive to “defects” rather than to number of units produced.

To illustrate the difference between the two approaches, let’s examine a simple coating operation. Consider two cases, in which two rolls of product are produced. According to Table 2, the classic metric, first-time yield, is the same for both cases. However, the Six Sigma metric, DPU, shows that there are four times as many defects occurring in Case II than in Case I, an important indication of a difference in the operation. Such information would alert operators to investigate and determine the cause.

Another advantage of Six Sigma metrics is less ambiguity in yield data. A single simple metric to describe the defects occurring. Consider the results

What is the meaning of Six-Sigma?

The term Six Sigma has two meanings:
- In operational terms, it means 3.4 defects per million opportunities or a process capability index, \( CP \), equal to 2.0.
- In managerial terms, it means having a disciplined improvement program that involves all aspects of the business, and exposing every important product and process defect. It also means focusing improvement programs on the process root causes, rather than the product yield.

Figure 1 shows a process attribute of normal distribution, operating within 1.5\( \sigma \) of its mean, \( \mu \). Six Sigma implies that the occurrence of any attribute value falls beyond the lower specification limit (LSL) and the upper specification limit (USL) no more than 3.4 times per million opportunities.

For a process operating at \( \mu \), \( CP \) is defined as:

\[ CP = \frac{USL - LSL}{6\sigma} \]  \hspace{1cm} (1)

Thus, for a Six Sigma process, \( CP = 2 \).

For an uncentered process:

\[ \text{Lower } CP = CP_{\text{L}} = \frac{\mu - LSL}{3\sigma} \]  \hspace{1cm} (2)

\[ \text{Upper } CP = CP_{\text{U}} = \frac{USL - \mu}{3\sigma} \]  \hspace{1cm} (3)

\[ \text{Average } CP = CP_k = \text{Min} \left[ CP_{\text{L}}, CP_{\text{U}} \right] \]  \hspace{1cm} (4)

The Six Sigma methodology assumes that processes always operate within \( \pm 1.5\sigma \) of their mean. Assuming this deviation is a worst case, then \( CP_k = (6\sigma - 1.5\sigma)/3\sigma = 1.5 \). The \( CP_k \) measure is preferred over \( CP \) in practical manufacturing, since processes are generally not operating at their mean. \( CP_k = 1.5 \) is the generally accepted Six Sigma requirement.
for Case III in Table 2. Here, 100 rolls are produced with a total of 5 defects. Depending on how the defects are distributed, the first-time yield can be anywhere between 95% (1 defect in each of 5 rolls) and 99% (all defects in one roll). The Six Sigma metric DPU (5 defects/100 rolls), on the other hand, has only one value — 0.05. Assuming that there are 20 CTQs per roll, the DPO becomes 0.0025 and the DPMO 2,500. From Table 3, we can now estimate the Sigma level of this operation to be about 4.3. Table 3 is the basis for estimating the Sigma level for various processes and, therefore, is often used for benchmarking.

The Six Sigma metric RFY, as defined in Eq. 6, provides a metric that reflects both the CTQ yield of each process step and the number of steps that must be performed serially to manufacture the product. The first-pass yield is obtained by running the process without rework, manual tweaking or other interfaces to adjust the process or product. After identifying the CTQs, the number of opportunities to create a defect either product or process is estimated. The exact number is not critical provided one maintains a consistent basis for future comparisons. Table 4 shows the RFY at various Sigma levels as a function of number of opportunities. This table is useful to estimate the Sigma level of an operation consisting of several cascaded steps, such as a coating machine or chemical manufacturing plant.

The decision process

In brief, the decision process (Figure 2) depends on identifying the “critical few” process verifiers that have the greatest impact upon CTQs. Once identified through modeling, design of experiments or experience, these verifiers must be “control-charted” to determine whether there are any special causes of variability. If such causes are found, then the process is considered to be “not in control” and the special causes must be eliminated. Once this is achieved, the common-cause variability can be determined.

If the common-cause variability exceeds the acceptable level for the overall process performance (e.g., the goal for the year may be to reach 4σ and the common-cause variability is limiting the process to 3σ), the process or product must be redesigned to reduce complexity. This is often the quickest route to reducing common-cause variability (4).

The nature of variability in a process defines its predictability. Considering the impact of unpredictability on cost and schedule, it is clear that the number one priority in process improvement should be to eliminate special causes of variability. Generally, the most direct approach is to identify and eliminate their root causes. Effective tools to help identify the root cause include:

- control charts
- Pareto charts
- fishbone diagrams (cause and effect)
- functional analysis systems technique (FAST) diagrams.

Figure 3 shows a decision process for determining the root cause aided by the use of control charts. The Memory Jogger II (5) is a handy pocket reference on the use of the first three tools, plus many others. FAST diagrams were developed as a systematic approach for designing military systems (6). They are a particularly helpful tool for displaying the functional relationships in nested processes.

Figure 4 is a FAST diagram to identify the hierarchy of variables in a web-
■ Figure 2. The Six Sigma decision process helps to identify any special causes of variability. Once this is determined and fixed, the process then identifies the common-cause variability. * Near-term target level (7).

■ Figure 3. Control charts, such as the one shown here, are used to identify the root cause of a problem.
coating process. By establishing the functional relationship of each process step, one can identify the key dependent variables, also called the "voice of the process." These are the vital signs of the process that are needed to continuously measure and control-chart the process.

A complete FAST diagram for a large coating machine might require 6 to 10 levels of functional dependence. Experience has shown that getting input from all the key stakeholders will result in a more effective FAST diagram. It is particularly important to involve the manufacturing operators and technicians, since they have the practical knowledge of how the machine actually functions. Whereas its main purpose is to identify critical dependent variables, a well-constructed FAST diagram will serve many other purposes: reference document, training tool, troubleshooting guide, design improvement aid, etc. In the author's personal experience, the investment of putting this valuable tool together will pay off many times over. Furthermore, displaying the FAST diagram on the shop floor along with control charts greatly facilitates communications and problem solving.

**Application to a continuous process**

Six Sigma defect rates are based on the number of CTQs in a unit of product. The question that often arises is, "How can Six Sigma methodology be applied to continuous processes, such as those found in unit operations of a chemical plant in which the products are not discrete parts?"

For any type of manufacturing operation, the Six Sigma principles apply. In the case of continuous input and output, we analyze the process to define the CTQs of both process and product, define a characteristic unit quantity, collect data on the critical CTQs, and describe the defect rate in terms of DPU and DPMO. The operational Sigma level is then estimated from Table 3.
Defect rate = (24,000/50)(250/50)(600/50) = 4,800 kg defective/mo
Unit rate = (20 kg/mo)(43,200 min/mo) = 864,000 kg/mo
DPU = (4,800 kg defective/mo)/864,000 kg/mo = 0.00552
Step 4: Calculate the DPMO
DPMO = 0.00552(1,000,000) = 5,520 defects/million opportunities
Step 5: Look up the Sigma level from Table 3.
Sigma level = 4.1 (approximately)

Note that the first-time yield of product meeting specification will fall between 99.4% and 100%, depending on the capability to detect and remove defective product. The quality level of this operation is more usefully reflected by the Sigma level based on process measures rather than by product yield. As the Sigma level is increased, the product yield will certainly improve, but process-improvement actions needed are better focused by using a process CTQ. In fact, product yield provides no useful information on where to make the improvements.

In the next issue of CEP, an article by Sasol North America will highlight a successful Six Sigma application on an ethylene unit.

Summary
Six Sigma programs can drive a company’s improvement in the bottom line. Most companies have an opportunity to reduce cost by 20%–40% by committing to a Six Sigma program. Except for the use of new metrics such as DPU and DPMO, the tools required to accomplish Six Sigma are well-established and have been practiced in industry for years. The difference in a Six Sigma program is the corporate commitment to employ statistical thinking throughout the business. If the right questions are asked by the right people often enough, decisions will become data-driven and statistically based. Six Sigma “blackbelt” programs are used by a number of larger companies to formalize the corporate commitment to train personnel at all levels in the both the basic understanding of Six Sigma principles, as well as to develop “practitioners” who devote full time to applying Six Sigma improvement programs to current processes.

Literature Cited