PDCA (PLAN-DO-CHECK-ACT)

The PDCA cycle, which Deming refers to as the PDSA cycle (Deming, 1993, p. 134), is a flow chart for learning and process improvement. The basic idea began with Shewhart's attempt to understand the nature of knowledge. Shewhart believed that knowledge begins and ends in experimental data but that it does not end in the data in which it begins. He felt there were three important components of knowledge (Shewhart, 1939, 1986): a) the data of experience in which the process of knowing *begins*, b) the prediction in terms of data that one would expect to get if one were to perform certain experiments in the *future,* and c) the degree of belief in the prediction based on the original data or some summary thereof as evidence. Shewhart arranged these three components schematically as shown in Figure 7.5.

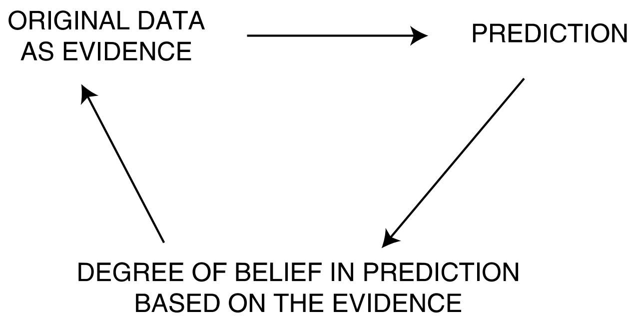


Figure 7.5. The three components of knowledge.

Since knowledge begins with the original data and ends in new data, these future data constitute the operationally verifiable meaning of the original data. However, since inferences or predictions based upon experimental data can never be certain, the knowledge based upon the original data can inhere in these data only to the extent of some degree of rational belief. In other words, according to Shewhart, knowledge can only be *probable.* Also, the data are not "facts" in and of themselves, they are merely measurements that allow us to draw inferences about something. In other words, *we can not have facts without some theory.*

Shewhart applied these principles in many practical ways. For example, he identified the three steps of quality control in manufacturing as specification, production, and judgment of quality (inspection). He noted that, in practice, specifications could not be set without first having some information from

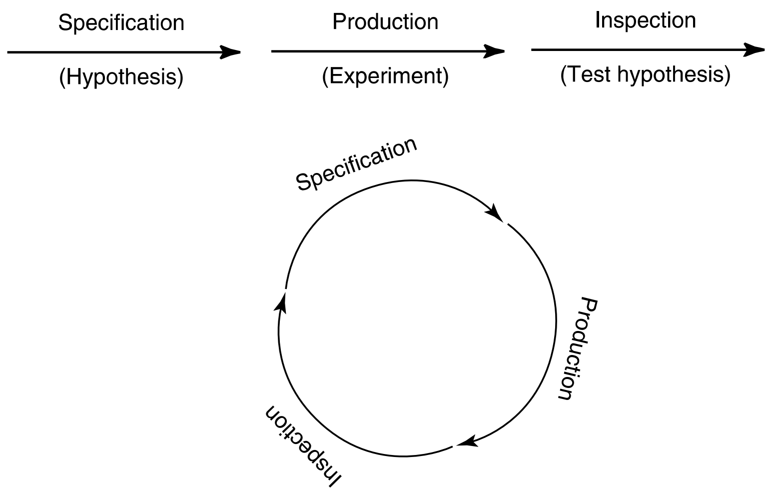


Figure 7.6. Scientific process of acquiring knowledge.

inspection to help establish process capability, and that this information could not be obtained until some units had been produced. In short, Shewhart modified the sequence of specification-production-inspection as shown in Figure 7.6. He also observed that the specification-production-inspection sequence corresponded respectively to making a hypothesis, carrying out an experiment, and testing the hypothesis. Together the three steps constitute a dynamic scientific process of acquiring knowledge.

Note that Shewhart's model of knowledge forms a circle. Shewhart followed the teachings of philosopher C.I. Lewis, who believed that all good logics are circular. The essence of this view is to see knowledge as dynamic. It changes as new evidence comes in. As Shewhart put it (Shewhart, 1939, 1986, p. 104):

> Knowing in this sense is somewhat a continuing process, or method, and differs fundamentally in this respect from what it would be if it were possible to attain certainty in the making of predictions.

Shewhart and Deming revised the above model for application to the improvement of products and processes. The new model was first called the PDCA cycle, later revised by Deming to the Plan-Do-Study-Act, or PDSA cycle (Deming, 1993, p. 134). The Shewhart-Deming PDSA cycle is shown in Figure 7.7.

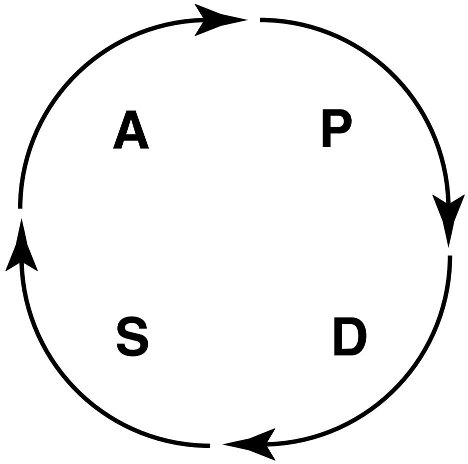


Figure 7.7. The Shewhart-Deming PDSA cycle for learning and improvement.

Plan a change or a test, aimed at improvement. This is the foundation for the entire PDCA-PDSA cycle. The term "plan" need not be limited to large-scale planning on an organization-wide scale, it may simply refer to a small process change one is interested in exploring.

Do. Carry out the change or the test (preferably on a small scale). It is important that the DO step carefully follow the plan, otherwise learning will not be possible.

Study the results. What did we learn? What went wrong?

Act. Adopt the change, or abandon it, or run through the cycle again.

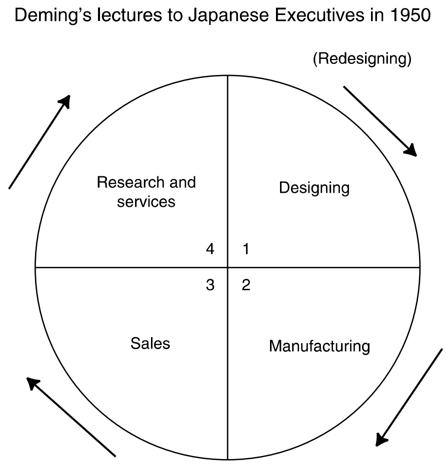
The PDCA approach is essentially a management-oriented version of the original Shewhart cycle, which focused on engineering and production. A number of other variations have been developed, two of Deming's variations are shown in Figure 7.8.

Juran depicts quality as a "spiral," as shown in Figure 7.9.

Because of their historical origins and logical appeal, circular diagrams are ubiquitous in the quality field. In quality management, the circle represents continuous improvement of quality by continuous acquisition of knowledge.

DYNAMIC MODELS OF LEARNING AND ADAPTATION

The PDSA cycle describes planning and learning in an environment at or near a stable equilibrium. The PDSA loop indicates that plans are con-



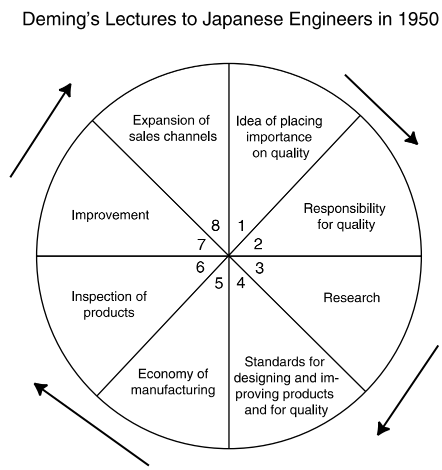


Figure 7.8. Some variations of the PDCA-PDSA cycle.

tinuously improved by studying the results obtained when the plans are implemented, and then modifying the plans. However, the PDSA model fails to account for the activities of other agents, which is a characteristic of complex adaptive systems, such as a market economy. For this situation I propose a new model, the Select-Experiment-Adapt (SEA) model depicted in Figure 7.10.

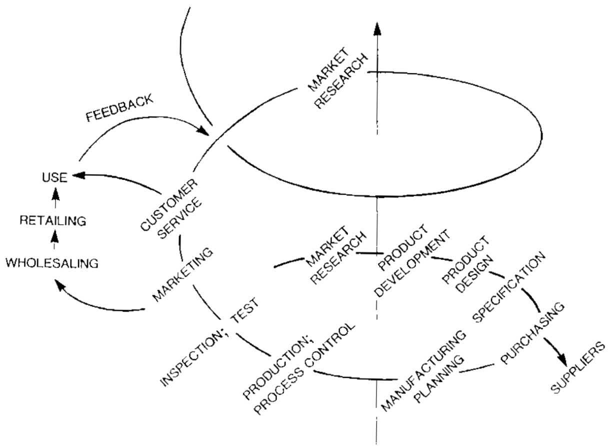


Figure 7.9. Juran's spiral of progress in quality.

In real life, experimentation goes on constantly. Experimenting involves executing a performance rule activated by a message received from the environment. We observe something, or induce something based on thinking about past observations, and decide which course of action would be most beneficial. The action taken in response to the environmental messages is called a *performance rule*. Adaptation occurs by adjusting the strength of the performance rule based on the payoff we actually received from it. Repeated iterations of the SEA cycle mimics what computer scientist John Holland calls the *bucket brigade algorithm* (Holland, 1996) which strengthens rules that belong to chains of action terminating in rewards. The process amounts to a progressive confirmation of hypotheses concerned with stage setting and subgoals.

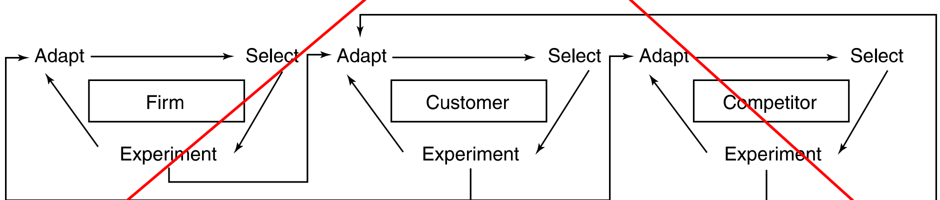


Figure 7.10. The Select-Experiment-Adapt (SEA) model for non-linear systems.

and due dates necessary to produce the deliverable should be carefully listed. If the process changes are extensive, the control subproject may require another sponsor to take ownership of the control process after the team disbands and the main project sponsor accepts the new system. A detailed Business Process Change Control Plan should be prepared and kept up to date until the Black Belt, sponsor, and process owner are confident that the improvements are permanent.

- *Brainstorming.* The Six Sigma team should brainstorm to expand the list presented above with ideas from their own organization.
- *Force-field diagram.* A force-field diagram can be very useful at this point. Show the forces that will push to undo the changes, and create counter-forces that will maintain them. The ideas obtained should be used to develop a process control plan that will assure that the organization continues to enjoy the benefits of the Six Sigma project.
- *Process decision program chart.* The PDPC is a useful tool in developing a contingency plan.
- *Failure mode and effect analysis.* Using FMEA in the improve phase was discussed in detail in Chapter 16, but it is every bit as useful in control planning.

USING SPC FOR ONGOING CONTROL

Assuming that the organization's leadership has created an environment where open and honest communication can flourish, SPC implementation becomes a matter of 1) selecting processes for applying the SPC approach and 2) selecting variables within each process. This section describes an approach to this activity.

Variable selection

PREPARING THE PROCESS CONTROL PLAN

Process control plans should be prepared for each key process. The plans should be prepared by teams of people who understand the process. The team should begin by creating a flow chart of the process using the process elements determined in creating the house of quality (see the QFD discussion in Chapter 3). The flow chart will show how the process elements relate to one another and it will help in the selection of control points. It will also show the point of delivery to the customer, which is usually an important control point. Note that the customer may be an internal customer.

For any given process there are a number of different types of process elements. Some process elements are *internal* to the process, others *external.* The rotation speed of a drill is an internal process element, while the humidity in the building is external. Some process elements, while important, are easy to hold constant at a given value so that they do not change unless deliberate action is taken. We will call these *fixed* elements. Other process elements vary of their own accord and must be watched; we call these *variable* elements. The drill rotation speed can be set in advance, but the line voltage for the drill press may vary, which causes the drill speed to change in spite of its initial setting (a good example of how a correlation matrix might be useful). Figure 18.1 provides a planning guide based on the internal/external and fixed/variable classification scheme. Of course, other classification schemes may be more suitable on a given project and the analyst is encouraged to develop the approach that best serves his or her needs. For convenience, each class is identified with a Roman numeral; I = fixed–internal, II = fixed–external, III = variable–internal and IV = variable–external.

In selecting the appropriate method of control for each process element, pay particular attention to those process elements which received high importance rankings in the house of quality analysis. In some cases an important process element is very expensive to control. When this happens, look at the QFD correlation matrix or the statistical correlation matrix for possible assistance. The process element may be correlated with other process elements that are less costly to control. Either correlation matrix will also help you to minimize the number of control charts. It is usually unnecessary to keep control charts on several variables that are correlated with one another. In these cases, it may be

	INTERNAL	EXTERNAL
	I	II
FIXED	• Setup approval • Periodic audits • Preventive maintenance	• Audit • Certification
	III	IV
VARIABLE	• Control charts • Mistake-proof product • Mistake-proof process • Sort the output	• Supplier SPC • Receiving inspection • Supplier sorting • Mistake-proof product

Figure 18.1. Guide to selecting and controlling process variables.

possible to select the process element that is least expensive (or most sensitive) to monitor as the control variable.

As Figure 18.1 indicates, control charts are not always the best method of controlling a given process element. In fact, control charts are seldom the method of choice. When process elements are important we would prefer that they *not vary at all!* Only when this cannot be accomplished economically should the analyst resort to the use of control charts to monitor the element's variation. Control charts may be thought of as a control mechanism of last resort. Control charts are useful only when the element being monitored can be expected to exhibit measurable and "random-looking" variation when the process is properly controlled. A process element that always checks "10" if everything is okay is not a good candidate for control charting. Nor is one that checks "10" or "12," but never anything else. Ideally, the measurements being monitored with variables control charts will be capable of taking on any value, i.e., the data will be continuous. Discrete measurement data can be used if it's not too discrete; indeed, all real-world data are somewhat discrete. As a rule of thumb, at least ten different values should appear in the data set and no one value should comprise more than 20% of the data set. When the measurement data become too discrete for SPC, monitor them with checksheets or simple time-ordered plots.

Of course, the above discussion applies to measurement data. Attribute control charts can be used to monitor process elements that are discrete counts.

Any process control plan must include instructions on the action to be taken if problems appear. This is particularly important where control charts are being used for process control. Unlike process control procedures such as audits or setup approvals, it is not always apparent just what is wrong when a control chart indicates a problem. The investigation of special causes of variation usually consists of a number of predetermined actions (such as checking the fixture or checking a cutting tool) followed by notifying someone if the items checked don't reveal the source of the problem. Also verify that the arithmetic was done correctly and that the point was plotted in the correct position on the control chart.

The reader may have noticed that Figure 18.1 includes "sort the output" as part of the process control plan. Sorting the output implies that the process is not capable of meeting the customer's requirements, as determined by a process capability study and the application of Deming's all-or-none rules. However, even if sorting is taking place, SPC is still advisable. SPC will help assure that things don't get any worse. SPC will also reveal improvements that may otherwise be overlooked. The improvements may result in a process that is good enough to eliminate the need for sorting.

PROCESS CONTROL PLANNING FOR SHORT AND SMALL RUNS

A starting place for understanding statistical process control (SPC) for short and small runs is to define our terms. The question "what *is* a short run?" will be answered for our purposes as an environment that has a large number of jobs per operator in a production cycle, each job involving different product. A production cycle is typically a week or a month. *A small run* is a situation where only a very few products of the same type are to be produced. An extreme case of a small run is the one-of-a-kind product, such as the Hubble Space Telescope. Short runs need not be small runs; a can manufacturing line can produce over 100,000 cans in an hour or two. Likewise small runs are not necessarily short runs; the Hubble Space Telescope took over 15 years to get into orbit (and even longer to get into orbit and working properly)! However, it is possible to have runs that are both short *and* small. Programs such as Just-In-Time inventory control (JIT) are making this situation more common all of the time.

Process control for either small or short runs involves similar strategies. Both situations involve markedly different approaches than those used in the classical mass-production environment. Thus, this section will treat both the small run and the short run situations simultaneously. You should, however, select the SPC tool that best fits your particular situation.

Strategies for short and small runs

Juran's famous trilogy separates quality activities into three distinct phases (Juran and Gryna, 1988):

- Planning
- Control
- Improvement

Figure 18.2 provides a graphic portrayal of the Juran trilogy.

When faced with small or short runs the emphasis should be placed in the planning phase. As much as possible needs to be done *before* any product is made, because it simply isn't possible to waste time or materials "learning from mistakes" made during production. It is also helpful to realize that the Juran trilogy is usually applied to *products*, while SPC applies to *processes.* It is quite possible that the element being monitored with SPC is a process element and not a product feature at all. In this case there really is no "short run," despite appearances to the contrary.

A common problem with application of SPC to short/small runs is that people fail to realize the limitations of SPC in this application. Even the use of SPC to *long production runs* will benefit from a greater emphasis on pre-production planning. In the best of all worlds, SPC will merely confirm that

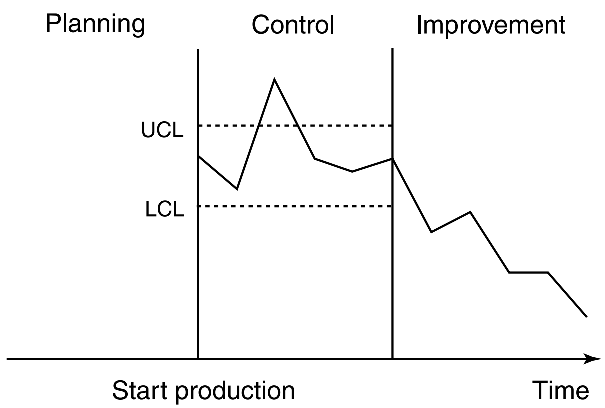


Figure 18.2. Juran's trilogy.

the correct process has been selected and controlled in such a way that it consistently produces well-designed parts at very close to the desired target values for every dimension.

PREPARING THE SHORT RUN PROCESS CONTROL PLAN (PCP)

Plans for short runs require a great deal of up-front attention. The objective is to create a list of as many potential sources of variation as possible and to take action to deal with them *before* going into production. One of the first steps to be taken is to identify which processes may be used to produce a given part; this is called the "Approved Process List." Analogously, parts that can be produced by a given process should also be identified; this is called the "Approved Parts List." These determinations are made based on process capability studies (Pyzdek, 1992a). The approach described in this guide uses process capability indices, specifically C_{pk} (the number of standard deviations between the mean and the nearest specification limit). The use of this capability index depends on a number of assumptions, such as normality of the data etc.; Pyzdek (1992b) describes the proper use, and some common abuses, of capability indices.

Because short runs usually involve less than the recommended number of pieces the acceptability criteria are usually modified. When less than 50 observations are used to determine the capability I recommend that the capability indices be modified by using a $\pm 4\sigma$ minimum acceptable process width (instead of $\pm 3\sigma$) and a minimum acceptable C_{pk} of 1.5 (instead of 1.33). Don't bother making formal capability estimates until you have at least 20 observations.

(You can see in Chapter 12 that these observations need not always be from 20 separate parts.)

When preparing for short runs it often happens that actual production parts are not available in sufficient quantity for process capability studies. One way of dealing with this situation is to study process elements separately and to then sum the variances from all of the known elements to obtain an estimate of the best overall variance a given process will be able to produce.

For example, in an aerospace firm that produced conventional guided missiles, each missile contained thousands of different parts. In any given month only a small number of missiles were produced. Thus, the CNC machine shop (and the rest of the plant) was faced with a small/short run situation. However, it was not possible to do separate pre-production capability studies of each part separately. The approach used instead was to design a special test part that would provide estimates of the machine's ability to produce every basic type of characteristic (flatness, straightness, angularity, location, etc.). Each CNC machine produced a number of these test parts under controlled conditions and the results were plotted on a short run $\bar{X}$ and R chart (these are described in Chapter 12). The studies were repeated periodically for each machine.

These studies provided pre-production estimates of the machine's ability to produce different characteristics. However, these estimates were always *better* than the process would be able to do with actual production parts. Actual production would involve different operators, tooling, fixtures, materials, and other common and special causes not evaluated by the *machine capability study*. Preliminary Approved Parts Lists and Preliminary Approved Process Lists were created from the capability analysis using the more stringent acceptability criteria described above (C_{pk} at least 1.5 based on a $\pm 4\sigma$ process spread). When production commenced the actual results of the production runs were used instead of the estimates based on special runs. Once sufficient data were available, the parts were removed from the preliminary lists and placed on the appropriate permanent lists.

When creating Approved Parts and Approved Process lists always use the most stringent product requirements to determine the *process requirement.* For example, if a process will be used to drill holes in 100 different parts with hole location tolerances ranging from 0.001 inches to 0.030 inches, the process requirement is 0.001 inches. The process capability estimate is based on its ability to hold the 0.001 inch tolerance.

The approach used is summarized as follows:

1. Get the process into statistical control.
2. Set the control limits *without regard to the requirement.*
3. Based on the calculated process capability, determine if the most stringent product requirement can be met.

Process audit

The requirements for all processes should be documented. A process audit checklist should be prepared and used to determine the condition of the process prior to production. The audit can be performed by the operator himself, but the results should be documented. The audit should cover known or suspected sources of variation. These include such things as the production plan, condition of fixtures, gage calibration, the resolution of the gaging being used, obvious problems with materials or equipment, operator changes, and so on.

SPC can be used to monitor the results of the process audits over time. For example, an audit score can be computed and tracked using an individuals control chart.

Selecting process control elements

Many short run SPC programs bog down because the number of control charts being used grows like Topsy. Before anyone knows what is happening they find the walls plastered with charts that few understand and no one uses. The operators and inspectors wind up spending more time filling out paperwork than they spend on true value-added work. Eventually the entire SPC program collapses under its own weight.

One reason for this is that people tend to focus their attention on the *product* rather than on the *process*. Control elements are erroneously selected because they are functionally important. A great fear is that an important product feature will be produced out of specification and that it will slip by unnoticed. This is a misunderstanding of the purpose of SPC, which is to provide a means of *process* control; SPC is not intended to be a substitute for inspection or testing. The guiding rule of selecting control items for SPC is:

> SPC control items should be selected to provide a maximum amount of information regarding the state of the process at a minimum cost.

Fortunately most process elements are correlated with one another. Because of this one process element may provide information not only about itself, but about several others as well. This means that a small number of process control elements will often explain a large portion of the process variance.

Although sophisticated statistical methods exist to help determine which groups of process elements explain the most variance, common sense and knowledge of the process can often do as well, if not better. The key is to think about the process carefully. What are the "generic process elements" that affect all parts? How do the process elements combine to affect the product? Do several process elements affect a single product feature? Do changes in one process element automatically cause changes in some other process elements? What process elements or product features are most sensitive to unplanned changes?

EXAMPLE ONE

The CNC machines mentioned earlier were extremely complex. A typical machine had dozens of different tools and produced hundreds of different parts with thousands of characteristics. However, the SPC team reasoned that the machines themselves involved only a small number of "generic operations": select a tool, position the tool, remove metal, and so on. Further study revealed that nearly all of the problems encountered after the initial setup involved only the ability of the machine to position the tool precisely. A control plan was created that called for monitoring no more than one variable for each axis of movement. The features selected were those farthest from the machine's "home position" and involving the most difficult to control operations. Often a single feature provided control of more than one axis of movement, for example, the location of a single hole provides information on the location of the tool in both the X and Y directions.

As a result of this system no part had more than four features monitored with control charts, even though many parts had thousands of features. Subsequent sophisticated multivariate evaluation of the accumulated data by a statistician revealed that the choices made by the team explained over 90% of the process variance.

EXAMPLE TWO

A wave solder machine was used to solder printed circuit boards for a manufacturer of electronic test equipment. After several months of applying SPC the SPC team evaluated the data and decided that they needed only a single measure of product quality for SPC purposes: defects per 1,000 solder joints. A single control chart was used for dozens of different circuit boards. They also determined that most of the process variables being checked could be eliminated. The only process variables monitored in the future would be flux density, solder chemistry (provided by the vendor), solder temperature, and final rinse contamination. Historic data showed that one of these variables was nearly always out of control when process problems were encountered. Other variables were monitored with periodic audits using checksheets, but they were not charted.

Notice that in both of these examples all of the variables being monitored were related to the *process*, even though some of them were product features.

The terms "short run" and "small run" refer to the product variables only; the process is in continuous operation so its run size and duration is neither small nor short.

The single part process

The ultimate small run is the single part. A great deal can be learned by studying single pieces, even if your situation involves more than one part.

The application of SPC to single pieces may seem incongruous. Yet when we consider that the "P" in SPC stands for *process* and not product, perhaps it is possible after all. Even the company producing one-of-a-kind product usually does so with the same equipment, employees, facilities, etc. In other words, they use the same *process* to produce different *products.* Also, they usually produce products that are similar, even though not identical. This is also to be expected. It would be odd indeed to find a company fabricating microchips one day and baking bread the next. The processes are too dissimilar. The company assets are, at least to a degree, product-specific.

This discussion implies that the key to controlling the quality of single parts is to concentrate on the process elements rather than on the product features. This is the same rule we applied earlier to larger runs. In fact, it's a good rule to apply to all SPC applications, regardless of the number of parts being produced!

Consider a company manufacturing communications satellites. The company produces a satellite every year or two. The design and complexity of each satellite is quite different than any other. How can SPC be applied at this company?

A close look at a satellite will reveal immense complexity. The satellite will have thousands of terminals, silicon solar cells, solder joints, fasteners, and so on. Hundreds, even thousands of people are involved in the design, fabrication, testing, and assembly. In other words, there are *processes* that involve massive amounts of repetition. The processes include engineering (errors per engineering drawing); terminal manufacture (size, defect rates); solar cell manufacture (yields, electrical properties); soldering (defects per 1,000 joints, strength); fastener installation quality (torque) and so on.

Another example of a single-piece run is software development. The "part" in this case is the working copy of the software delivered to the customer. Only a singe unit of product is involved. How can we use SPC here?

Again, the answer comes when we direct our attention to the underlying process. Any marketable software product will consist of thousands, perhaps millions of bytes of finished machine code. This code will be compiled from thousands of lines of source code. The source code will be arranged in modules; the modules will contain procedures; the procedures will contain functions;

and so on. Computer science has developed a number of ways of measuring the quality of computer code. The resulting numbers, called computer metrics, can be analyzed using SPC tools just like any other numbers. The processes that produced the code can thus be measured, controlled and improved. If the process is in statistical control, the process elements, such as programmer selection and training, coding style, planning, procedures, etc. must be examined. If the process is not in statistical control, the special cause of the problem must be identified.

As discussed earlier, although the single part process is a small run, it isn't necessarily a short run. By examining the process rather than the part, improvement possibilities will begin to suggest themselves. The key is to find the process, to define its elements so they may be measured, controlled, and improved.

Other elements of the process control plan

In addition to the selection of process control elements, the PCP should also provide information on the method of inspection, dates and results of measurement error studies, dates and results of process capability studies, subgroup sizes and methods of selecting subgroups, sampling frequency, required operator certifications, pre-production checklists, notes and suggestions regarding previous problems, etc. In short, the PCP provides a complete, detailed roadmap that describes how process integrity will be measured and maintained. By preparing a PCP the *inputs* to the process are controlled, thus assuring that the *outputs* from the process will be consistently acceptable.

PRE-CONTROL

The PRE-Control method was originally developed by Dorian Shainin in the 1950s. According to Shainin, PRE-Control is a simple algorithm for controlling a process based on the tolerances. It assumes the process is producing product with a measurable and adjustable quality characteristic which varies according to some distribution. It makes no assumptions concerning the actual shape and stability of the distribution. Cautionary zones are designated just inside each tolerance extreme. A new process is qualified by taking consecutive samples of individual measurements until five in a row fall within the central zone before two in a row fall into the cautionary zones. To simplify the application, PRE-Control charts are often color-coded. On such charts the central zone is colored green, the cautionary zones yellow, and the zone outside of the tolerance red. PRE-Control is not equivalent to SPC. SPC is designed to identify special causes of variation; PRE-Control starts with a process that is known