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SPC'S EFFECTIVENESS PREDICTION AND ANALYSIS

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> *History knows many more armies ruined by want and disorder than efforts of their enemies.*
> *—A. J. deRishelieu, Cardinal & Statesman (1585–1642)*

Philadelphia

SUMMARY

The article presents a simple measure for process state evaluation—ratio of the inherent variation to the total variation—and a procedure for its calculation. The ratio could be used as a guide for local adjustment required to eliminate assignable causes, or for an action on the system intended for global process improvement. The procedure is illustrated by numerous case studies applicable to different industries and processes.

KEY WORDS

capability study, control charts, statistical process control

INTRODUCTION

Over the past several decades, statistical process control (SPC) has become increasingly important in any manufacturing environment. There are at least two main reasons for SPC's popularity: rethinking the quality strategy, and addressing customers' demands. A radical review of the strategy implies transition from quality control (QC) to quality assurance (QA), that is, from defect *detection* based on final inspection, to a defect *prevention* system, of which SPC is the cornerstone. Comparative analysis of these competing systems is presented in Table 1.

Table 1. Comparative analysis of the competing systems.

Defect Detection	*Defect Prevention*
• Represents a kind of postmortem, as it is applied after the production phase is over	• Relies on monitoring process parameters to prevent defective items from being produced
• Even 100% inspection never gives 100% detection of defects	• Is based on sampling and provides a reliable basis for process management
• Is accompanied by an unavoidable 'Them and Us' conflict between shop floor personnel and 'white coated QC inspectors'. We are responsible for Productivity, They—for Quality!	• Turns all employees into members of a united QA team ('Us and Us' spirit of cooperation)
• Is expensive and time-consuming	• Is relatively inexpensive, and is performed in real time
• Takes into account only specification limits, and pays no attention to a target value	• Recognizes that there is an economic loss for any deviation from a target, and therefore tries to direct the products characteristic toward this target

The following quotation is an excellent demonstration of using SPC to meet customer demands. "We turned to Database for Quality because many of our customers now require statistical reporting," said J. Smith, Huron's SPC coordinator (*Quality* 1996, p. 20). Indeed, many years ago, a lot of companies pushed and demanded SPC as a part of a supplier quality package from their supplier base. Now the SPC data 'have become part and parcel of the quality requirements that major corporations impose on their suppliers' (Hoyer and Ellis 1996, p. 65). Transition from QC to QA unavoidably involves translation of formal quality requirements from the language of inspection (per cent defectives, number of defects) to that of SPC (capability indices, control charts).

At the same time there are many companies that have not yet started to use SPC. The main reason for the lack of practical implementation is usually the belief by top and middle managers that SPC cannot benefit their organizations because their processes are "somehow different" from other systems. We do believe that SPC should be a vital part of any organization, and any process is a potentially good candidate for SPC application. The reason is very simple: there is no alternative to real time in-process verification. Even if not explicitly formulated, feedback adjustment (FA) governs any process. If you do not use the SPC technique involving FA based on the results of process verification, you'll be forced in any case to manage your process by means of FA based on customers' responses. This *ex post facto* policy is both hazardous and costly, because when a customer is talking, it usually means bad news.

It should be noted that there is some bad popular press concerning statistical methods (Saniga 1997, p. 151), that is, there are practitioners who have now written off the introduction of SPC as an unsuccessful experience, because they tried it and their processes didn't get better (Saniga 1997, p. 151). In order to understand this interesting phenomenon, we should analyze some aspects of SPC's role in quality improvement.

BACKGROUND: DECOMPOSITION OF TOTAL PROCESS VARIATION

Quality improvement can usually be achieved by reducing either the process's failure rate or its output variability (or both). The former represents a major concern of reliability programs, and is beyond the scope of this article. We'll focus on the variability in the data used as a basis for effective process management. Lack of consistency undermines quality as measured by the deviation of a functional characteristic from its target value. These variations will generally result in reduced product performance and may lead to early product failures (Wheeler 1990, p. 253).

In any process, a certain amount of variation will always exist due to the second law of thermodynamics: a system influenced by random factors evolves toward the maximum entropy (disorganization). By contrast, the goal of quality control is to run the process consistently on target. The actual process state represents some kind of a compromise between these opposing tendencies. Obviously, a state of virtually uniform product could only be achieved through the study of the sources of process variation. The fundamental decomposition of the total variation of process output into its components is one of the great contributions that Dr. Shewhart gave to the world (Deming 1986, p. 310). He first made the distinction between controlled and uncontrolled variation due to so-called common and assignable (special) causes, respectively (see Figure 1), and indicated that the gap between the process capability and performance is due to assignable causes only.

The common or random causes are a reflection of the inherent variability of the process being operated as intended. This variability represents the result of normal variations in materials, performance, test procedures, and environment, intrinsic to the production system. Possible sources of inherent process variation are shown in Figure 2. Obviously, some of sources could be unrelated to any given process. Conventional procedure of inherent variability analysis implies identification, separation, and assessment of sources of variation by means of R&R studies (measurement variation), capability studies, and control charts (non-homogeneity and time-to-time variation).

When only random variations are present in the process, it is considered to be in statistical control, otherwise it is said to be out of statistical control due to some assignable cause which is usually associated with mistakes of poorly trained inspectors, miscalibrated gages, machinery that is out of order, tool wear, power failures, severe environmental conditions, poor raw materials, and so on. Any assignable cause should be recognized and removed from the process as soon as possible, while the process itself should be restored to its in-control state by means of an appropriate adjustment. Furthermore, some actions should be taken in order to prevent this assignable cause from recurring. Unfortunately, in practice the distinction between the two sorts of variation is not always obvious, so it is a hazard to use judgment to distinguish between special causes and common causes (Deming 1986, p. 320). Confusion between different causes could result in two kinds of errors: overadjustment (personnel reacting to process variations that are merely the result of common causes) and underadjustment (an appreciable process change due to an assignable cause is not detected).

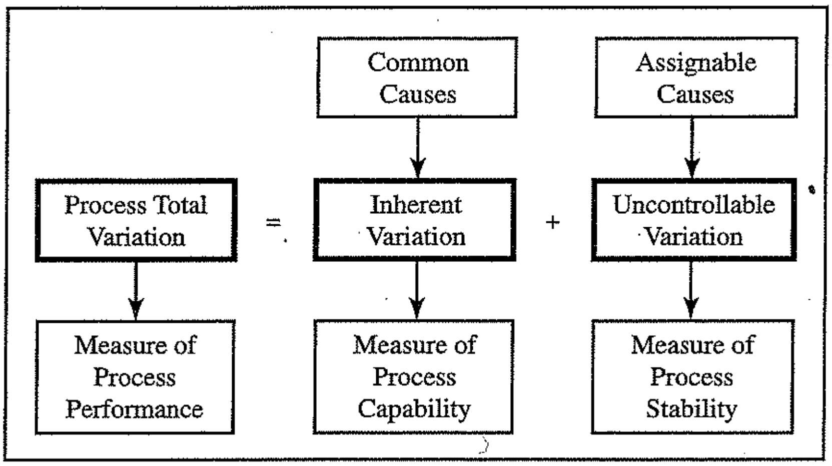


Figure 1. Shewhart decomposition of total process variation.

Control charts, suggested and proposed by Shewhart in the 1920s, represent a simple but powerful statistical tool used to track the process variations and distinguish between inherent variation and excessive one due to external factors. We are sure that most readers are aware of these charts, which now represent a prominent, perhaps even dominant, feature of SPC, therefore we will dwell neither on the chart's principles nor their details. The interested reader is referred to many excellent textbooks on SPC for a full explanation of charting techniques.

Control charts have been widely used for process monitoring because they provide us with an insight into the variation model developed by Shewhart. Seeing is believing means that when personnel actually see control charts, they can understand the process' behavior. Actually, any control chart represents a kind of process identification card or signature. 'Hi, it's me!' says the process in its graphical representation.

SHORT-TERM AND LONG-TERM SPC OBJECTIVES IN QUALITY IMPROVEMENT

In accordance with the Shewhart concept of total variation decomposition, SPC techniques are intended for testing and improvement of two major process characteristics: stability and capability. As a rule, the process is neither

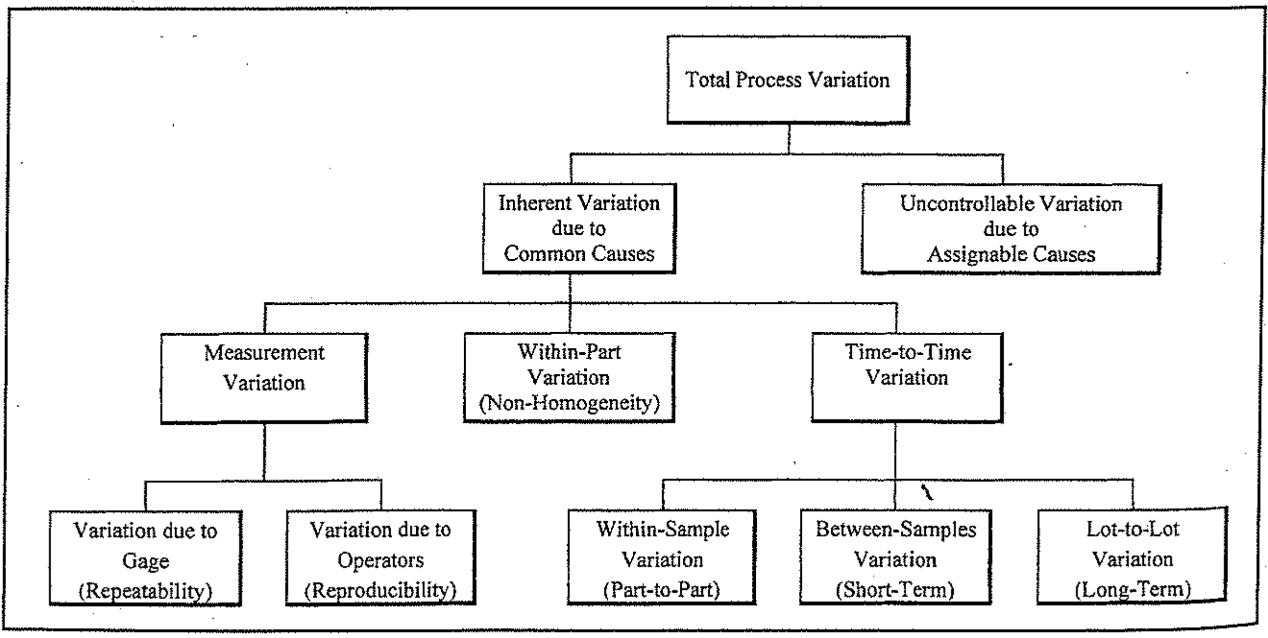


Figure 2. Possible sources of inherent process variation.

stable nor capable during its early stages. This means we are not operating the process in the manner in which it was designed to be run, and continued operation under such conditions is merely wasteful. The inherent variation value cannot be evaluated yet due to continuous disruptions within the core process. Abnormal variation is dominant, therefore process set-ups start with an empirical effort necessary to bring about and maintain stability.

Usually at this stage the most powerful assignable causes can be readily detected and identified, because the excessive variation due to these causes is very large in magnitude. Rapid and successful traceability (identification of main sources of an out-of-control state by linking the subgroup identifier to information about process performance condition) encourages process galloping toward purification and quick removal of obvious assignable causes. These local actions are usually within the ability of the operators or local supervision (SPC Reference Manual 1995, p. 65) and imply, as a rule, tool replacement, machine or gage recalibration, Poka-Yoke (mistake-proofing devices) implementation, and so forth. Management is less involved in resolution. Its participation is required, for example, when personnel retraining is required, when standardization as a countermeasure against assignable cause is necessary, when raw materials or parts are unacceptable and dealing with vendors is on the agenda, etc. Compensation and regulation through feedback and feedforward control represent an alternative to the above mentioned countermeasures when we are not able to remove assignable causes. Obviously, compensation without any attempt to attack the root cause represents some kind of cosmetic solution.

So-called no standard given control charts are used for process stability testing and analysis at this stage, when both the chart centerline and trial control limits are based on the subgroup data plotted on the chart. Any salient point, for which an assignable cause has been found and removed (or compensated), should be excluded from calculations and the chart should be recalculated.

As a rule, neither removal nor compensation of obvious sources of assignable causes is enough for achieving a stable process state. A process may be (and, as a rule, will be) affected by some hidden causes. There may be combinations of process conditions that might cause some excessive variation. Sources of normal and abnormal variations could overlap, impending decomposition of process total variation. Therefore control chart analysis should be supported by follow-up investigation. An assignable cause identification and definition of the actions to be taken in such a case depend upon the experience of technical staff and require good understanding of SPC's fundamental principles. Problem-solving skills can be enhanced by using different run tests for nonrandom pattern recognition on the Shewhart charts, more sophisticated charts, design of experiments (DOE), and so on.

Unfortunately, experience shows that disregard or inaction (or both) sometimes represent a palliative to all the above: since some assignable cause could not be readily identified, it is attributed to an inherent source, which we must live with (so-called 'It's O.K.' philosophy); or an out-of-control situation has been detected and its cause has been identified but no action has been taken (typical situation when the shop floor is a battlefield between employees and management).

Suppose that the process is well understood, and personnel take an active part in SPC implementation. The process was brought into a state of statistical control, but it still fails to meet the customer's requirements. The short-term period of fast SPC achievements by means of local actions is over, and now the process inherent variability is itself of interest. Both Juran and Deming (Deming 1986) warn against confusion of removing assignable causes with process improvement. They emphasize that the former only brings the system back to where it should have been in the first place, while the latter represents the long-term program of never-ending gradual reduction of inherent process variability. The capable process is also subject to continuous improvement so as to meet customer expectations in a more economical fashion, and thus enhance competitive position (see Table 2).

Table 2. Responsibilities for assignable causes elimination and inherent variability reduction.

	Responsibility			
	Employees	***First-line Supervision***	***Middle Management***	***Top Management***
Common Causes	░	░	▓	█
Assignable Causes	▓	█	░	░

□ ░ ░ ▒ ▒ ▓ ▓ █ █

Low responsibility High responsibility

Usually, the system-related common causes (such as raw materials, machinery, control equipment, technology, working conditions) are beyond the abilities of operators and their local supervision to correct. Instead, they require management involvement to make basic changes in the process. At the same time, machine performance depends on operators (settings could be inaccurate, workstation could be dirty through his fault, and so on). Thus both short-term and long-term SPC require participation of the whole company from top management to shop floor personnel, the only difference is the degree of responsibility for assignable causes elimination and inherent variability reduction.

As a rule, capability studies identify processes that are candidates for improvement. Any action on a system implies that we introduce an assignable cause, that is we redo the process by sending it out of control. Therefore, the action's effects should be carefully monitored by the control charts, which become a way of verifying the effectiveness of the obtained results. The action's effectiveness could be significantly enhanced using DOE methodology. So-called standard given control charts are used for process stability testing and analysis at this stage, when both the chart centerline and trial control limits are based on representative prior data. No salient points lead to the chart's recalculation, but after the action is performed, the reduced inherent process variation should be assessed and used as the basis of new control limits for future operations.

As we see, although the main goal of SPC—reduction of variation—remains constant throughout the process life cycle, both the SPC's objectives and technique are subject to significant transformations.

- Stability achievement by removing assignable causes is dominant during process set-up, whereas capability improvement by means of inherent variability reduction becomes the primary task later
- As a rule, numerous assignable causes during the initialization period indicate opportunities for short-term and relatively easy reduction of total process variation; after that the curve of improvement leveled off and became stable at an unacceptable level (Deming 1986, p. 324), so further improvement is associated with a long-term SPC program assisting the pursuit of never-ending quality improvement
- SPC allows us to be proactive with a stable process, rather than reactive as is typical for earlier stages
- The control chart technique is different for process set-up and routine operation
- Change in relationship between SPC and DOE while transition from process stabilization to attempts of capability improvement: DOE is a tool supporting follow-up investigation after SPC's warning signal during the initialization period, and SPC is a verification tool for the DOE results during the process' mature age

RATIO OF THE INHERENT VARIATION TO THE TOTAL VARIATION AS A GUIDE TO SPC IMPLEMENTATION

It follows from the previous section that transition from short-term to long-term SPC is associated with gradually decreased contribution of assignable causes in total process variation. Thus the ratio of the controlled process variation to the total variation could be used as a guide to local adjustment required to eliminate assignable causes of variation, or an action on the system required for global process improvement by means of inherent variability reduction.

The ratio could be used for some primary tasks associated with successful SPC implementation.

- Objective accurate evaluation of current process state—transition from binomial judgment (stable, unstable) to continuous numerical measure, which varies between 0 and 1
- Choice of appropriate SPC technique (short-term, long-term) for a given process state in accordance with calculated ratio value
- Timing prediction of SPC's effectiveness (possible fast achievements, gradual process improvement)
- Understanding of current and future degree of responsibility of management and employees for process total variation reduction

The ratio represents analog to the coefficient of determination (squared coefficient of correlation) used in regression analysis for a model's predictive power assessment. The coefficient's value is computed by dividing the so-called explained variation by the total variation, associated with spread of the predicted values and real data, respectively, about the same mean value. In our case, the ratio of the inherent process variation to the total variation could be calculated by means of a similar procedure based on the sampling data used for the Shewhart charts. Two assumptions underlying the procedure are: 1) the process' inherent variation is independent of the uncontrollable variation due to assignable causes; 2) the control chart associated with process spread is in control.

If the first assumption is fulfilled, the total process variance can be written as a sum of variances associated with its components.

$$\sigma^2_{\text{Total}} = \sigma^2_{\text{Inherent}} + \sigma^2_{\text{Uncontrollable}} \tag{1}$$

If the second assumption is fulfilled, the inherent process variation could be estimated using an R-chart or S-chart. The procedure implies

1. Estimation of the total process variation from all the data
    - 1.1 If control charts for $\bar{x}$ and R (or S) have been used

$$\hat{\sigma}^2_{Total} = \sum_{i=1}^{k}\sum_{j=1}^{n}(X_{ij}-\overline{X})^2 \tag{2}$$

where: X_{ij} is the jth observation in the ith sample; $\overline{X}$ is the process grand average; n is a sample size; k is number of samples.

    - 1.2 If control charts for individuals have been used

$$\hat{\sigma}^2_{Total} = \sum_{i=1}^{n}(X_i-\overline{X})^2 \tag{3}$$

where: X_i is the ith observation; ($\overline{X}$ is the process average; n is number of observations.

2. Estimation of the inherent process variation
    - 2.1 If the R-chart has been used

$$\hat{\sigma}^2_{Inherent} = \left(\frac{\overline{R}}{d_2}\right)^2 \tag{4}$$

where: ($\overline{R}$ is the average range; d_2 is the constant value depending on the sample size.

    - 2.2 If the S-chart has been used

$$\hat{\sigma}^2_{Inherent} = \left(\frac{\overline{S}}{c_4}\right)^2 \tag{5}$$

where: (S is the average standard deviation; c_4 is the constant value depending on the sample size.

    - 2.3 If charts for individuals have been used

$$\hat{\sigma}^2_{Inherent} = \left(\frac{\overline{MR}}{1.128}\right)^2 \tag{6}$$

where: $\overline{MR}$ is the average moving range

3. Estimation of ratio of the inherent process variation to the total process variation

$$0 \le R_{SPC} = \frac{\hat{\sigma}^2_{Inherent}}{\hat{\sigma}^2_{Total}} \le 1 \tag{7}$$

CASE STUDIES

We found some tips in the literature about the ratio values given by some experienced quality control professionals. For example, Deming attributes 94 percent of total process variation to common causes and the remaining 6 percent to assignable ones (Deming 1986). According to the *SPC Reference Manual* of the American Automotive Industry (1995), the percentage is 85/15, and most SPC researchers agree with this. The most extreme split we found was 80/20 (McKennon 1988). All authors indicate that these values reflect their personal experience rather than results of some study.

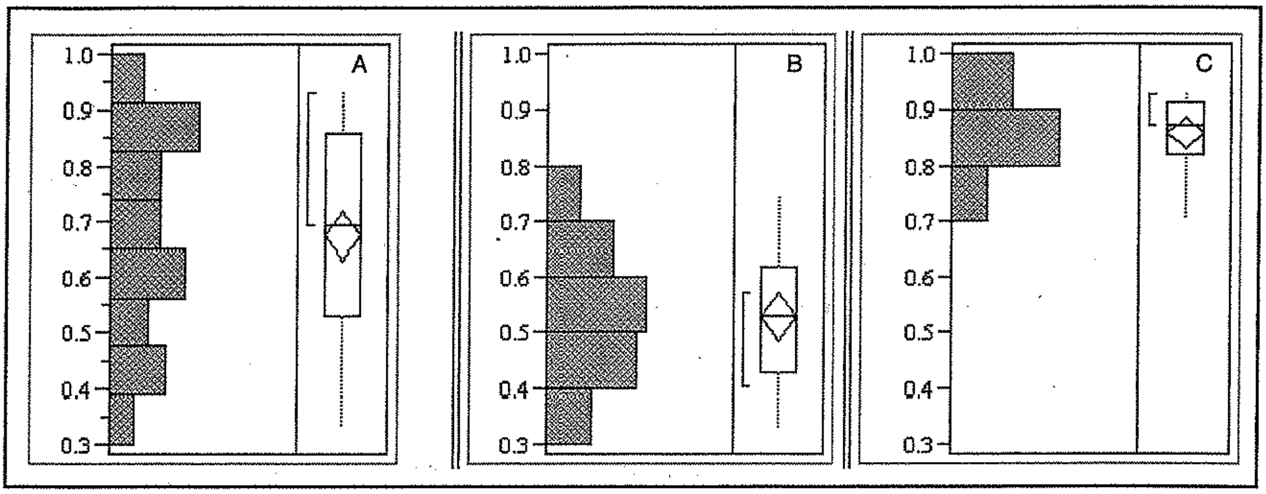


Figure 3. Histograms, normal and fitted curves, box-and-whisker plots of the ratio of the inherent process variation to the total variation for all analyzed processes (A), for processes in initialization period (B), and processes in the state of routine operating (C).

To give an idea of the ratios' true values in practice, the proposed procedure was applied to 66 real (not simulated) cases described in the textbooks listed in the Appendix. Only cases where at least one of the Shewhart charts indicated an excessive process variation were taken into consideration. The sample size for the data sets was from 1 through 6, that is both charts for individuals and the charts associated with sample statistics have been included in the empirical study.

A histogram of the calculated values appears in Figure 3. The computed P-value of the Shapiro-Wilkinson test for normality is 0.004, that is the normality assumption could be rejected at the conventional level of significance a = 0.05. The apparent nonsmooth bimodal pattern seems to indicate a mixture of at least two populations. To identify these populations careful analysis of the sources has been performed.

We focused attention on the authors' descriptions of the process state associated with the period of data collection. The question was whether it was process set-up (the process was being run for the first time, it was an initial study of process performance without any production history), or it was process routine operating (situation when it was known that the variability of existing process was more than desired so it was decided to embark on a SPC program). Since some researchers do not clearly state at what stage the data have been collected, we excluded these cases from further consideration. Therefore the total sets number is not additive in relation to the number of process set-up cases (30) and routine operating ones (23).

The histograms of the calculated values with both normal and fitted curves are shown in Figure 3. The computed P-values of the Shapiro-Wilkinson test for normality are 0.31 and 0.01, that is, the normality assumption could not be rejected at $\alpha = 0.05$ for process set-up, whereas for routine operating it could be rejected. The latter could be described much better by the right-skewed distribution, limited on the right by 100 percent. Values of mean and standard deviation for two stages are presented in Table 3.

Considering the values presented in Table 3, one can conclude

- The conjecture of most researchers that about 85 percenat of the total variation could be attributed to common causes, with the remaining 15 percent to assignable causes, is absolutely correct but in relation to process routine operating only; for unstable processes this relation is in average 50/50
- Process set-up and routine operating are not mutually exclusive states from the introduced measure (RSPC) point of view. In our opinion, it is caused by some hidden assignable causes in the state of

Table 3. Distribution of ratio of the inherent process variation to the total variation.

	Distribution Shape	*Mean*	*Standard Deviation*
Set-up	Normal	53.0	12.0
Routine Operating	Right-Skewed	86.1	6.4

routine operating. Therefore the process characterized by the ratio values within 0.7–0.85 range (common region belonging to both status), should be called quasi-stable.

CONCLUSION

1. Unsuccessful SPCs Implementation Experience

In the introduction we wrote about companies that have implemented SPC but their processes did not improve, and therefore they now declare that the effectiveness of this technique is questionable in principle. Experience shows that in most of these cases SPC was implemented during the routine operating stage, when actually any management activity has already been completed. In other words, the process seems to be both stable and capable (and it really is). Top management's point of view is: 'It looks well behaved, why should we dig deeper?' Control charts are used for stable process monitoring. Since they almost never go out of control, everything is O.K.

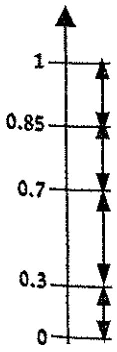
First, we would seriously question whether this process should be charted. Second, using control charts in routine operating only for periodical stability testing is like driving in low gear at high speed—both are used only for starting and accelerating. Third, a perfect state of control is never attainable in a production processes (the ratio value equal to 1 is a vain dream), therefore in a state of routine operating local actions can correct typically less than 15 percent of process problems, whereas the majority—the other 85 percent—are the result of common causes and are correctable only by action on the system. However, management's slogan is 'Hands off! Stop tinkering the process!' so nothing gets done.

2. SPC at Any Price

We have also written about the second reason for SPC's wide implementation—customer pressure. As a rule, in such a case control charts are used by management as a kind of additional report card instead of quality improvement and capability indices as abstract benchmarks. According to Saniga (1997) it is better than doing nothing, but in our opinion it may discredit SPC. Employees may think that SPC is a game that management plays. SPC becomes a byword on the shop floor, and the result is full frustration.

3. Measure for Current Process State Evaluation

The suggested ratio of the inherent process variation to the total variation represents a rather adequate basis for current process state evaluation and it seems to be a good indicator of appropriate SPC tactics, that is whether the process' problems are likely to be correctable locally or require actions on the system.



RSPC

DOE and long-term SPC techniques should be used for inherent variability reduction.

The process is quasi-stable, sources of hidden assignable causes should be attacked using more sophisticated short-term SPC techniques.

The process set-up is not yet finished.

There is no process.

APPENDIX

The following items were included in the case studies: diameter of the piston-rings, output voltage of power supply, thickness of printed board thickness, cigar lighter detent (Montgomery 1991, 207, 212, 266, 267, 272); weight of display panels, inside and outside diameters of cylinder bores, weight per bag of dog food, thickness of soft gasket sheets (Devor, Chang and Sutherlend 1992, 99, 165, 186, 190, 303); thread diameter (Breyfogle 1990, 295); critical dimension of part of power transmission, length of lithographic plate (Oakland 1987, 97, 107); mica thickness data, depth of cut for air-receiver magnetic assembly, gross-weight of ice-cream fill, component content in a plastic monomer (Ott and Schilling 1988, 31, 61, 70, 80); vial weight, fill data for paint cans, cut circuit board length, hardness depth of camshaft (Gitlow, Gitlow, Oppenheim and Oppenheim 1989, 180, 203, 298, 440); rotor pin diameter (Hutchins 1990, 83); engine crankshaft characteristic, compatibility of mold sand, surface finish, bearing diameter, thickness of coating, hardness of iron casting, diameter concentricity, mold density (Kane 1989, 76, 84, 85, 86, 87, 88, 89, 144, 157, 159, 162, 298, 302); viscosity of chemical component (Lindgren and McElrath, 1969, 135); bag weight of powdered material, machine direction strength (Feller 1988, 19, 43); length for meter sticks, thickness measurements, weight of candy bar, cardboard thickness, moisture level in apple dehydrating unit (Kolaric 1995, 294, 313, 325, 326, 328); weight of Torino frozen pizzas, length of photocopier cylinders, diameter of cable insulators, dimension in a machine company (Hansen and Ghare 1987, 97, 117, 118, 119); depth of keyway, acid content (Besterfield 1990, 86, 125); cutoff length of studs (Feigenbaum 1983, 411); fill weight of containers, bearing diameters, particle size (Leitnaker, Sanders and Hild 1996, 192, 210, 338); flow point of resin (Juran and Gryna 1988, 24.19); gap dimension (Grifith 1996, 26); plastic strength data (Wetherill and Brown 1991, 90); weight of canned tomatoes, slot width of terminal block, material strength, thickness of pads on half-ring engine mount, percent of unreacted CaO, 'on' temperature of the thermostat (Grant and Leavenworth 1972, 41, 146, 155, 166, 179, 343).

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