CHAPTER 6
STABILIZING AND IMPROVING A PROCESS WITH CONTROL CHARTS

Sections

Chapter Objectives

- To discuss the need for continual reduction of variation, even when the quality characteristic is within specifications
- To discuss and illustrate the use of control charts to stabilize and improve a process
- To discuss the consequences of over- and under-adjustment of a process
- To illustrate the detection of out-of-control behavior
- To describe how attributes control charts can be used for defect prevention
- To describe how variables control charts can be used for never-ending improvement
- To discuss the purposes of studying control charts

6.1 Introduction

A process that has been defined and documented can be stabilized, and then improved. In great measure this can be accomplished through the use of statistical control charts, discussed in this chapter and in Chapters 7 through 9, as well as other techniques that will be introduced in Chapter 10. Without valid measurements, process improvements are difficult, if not impossible.

Control charts, and the other tools and methods, are best used in an environment that provides a positive atmosphere for process improvement; that is, an environment in which employees know they will not be punished for poor results as long as they follow the best-practice method. Top management must sincerely commit to real process improvement. W. E. Deming points out that "any attempt to use statistical techniques under conditions that rob the hourly worker of his pride in workmanship will lead to disaster." [Deming, 1982, p.116] With this caveat, we may begin to consider the issues of stabilizing and improving a documented and defined process.

6.2 Process Variation

Recall from Chapter 2 that we can classify process variation as the result of either **common causes** or **special causes**. Common variation is inherent in every process. It is comprised of myriad small sources that are always present in a process and affect all elements of the process. Management should not hold workers responsible for such system problems; the system is management's responsibility. If management is unhappy with the amount of common variation in the system, it must act to reduce or eliminate it. Special variation is created by causes which lie outside the system. Frequently their detection, possible avoidance, and rectification are the responsibility of the people directly involved with the process. But sometimes management must try to find these special causes. When found, policy must be set (through the use of change concepts) so that if these special causes are undesirable, they will not recur. If, on the other hand, these special causes are desirable, policy (again, through the use of change concepts) must be set so that they do recur.

6.2.1 Control Charts and Variation

In this chapter, we will see that control charts are used to identify and differentiate between common and special causes of variation. A process is **stable** if it no longer exhibits special variation, but only exhibits common variation. When only common causes of variation are present in a process, management must take action to reduce the difference between customer needs and process performance by endeavoring to move the centerline of the process closer to a desired level (nominal) and/or by reducing the magnitude of common variation. These types of changes will aid in the quest for never-ending improvement.

There are two major types of applications for control charts. The first type of application is for employees to improve their jobs by identifying and resolving special causes of variation, and identifying and removing common causes of variation, through the application of relevant change concepts. On the left side of Table 6.1, three workers enter data into a computer terminal, some of which is conforming to specifications, and some of which is not conforming (defective) to specifications. A control chart used by each worker can be used to distinguish special and common causes of variation; also, the three control charts can be used to determine if any particular worker is a special cause of variation.

The second type of application is for managers and executives to analyze aggregated data over several employees with the same jobs, as in the left side of Table 6.1, or several geographical areas, etc. The right side of Table 6.1 assists a manager in studying the defectives for the entire area or department. It is not possible for managers and executives to identify special causes of variation at this level of analysis, due to the data being aggregated. Aggregated data can easily hide special causes of variation. The purpose of a control chart at the executive and managerial level is to *stop* them from overreacting to random noise (common variation) in the process under study. Managers and executives must realize that for a stable process, there is a 50% chance of any one data point being below average (assuming symmetry of the voice of the process), a 25% chance of any two data points in a row being below average, and a 12.5% chance of any three data points in a row being below average. Managers must stop managing using rules 2, 3, and 4 of the funnel experiment, as described in Chapter 2.

Table 6.1
Types of Control Chart Applications

Worker A defectives	All defectives
Worker B defectives	
Worker C defectives	

6.2.2 The Need for the Continual Reduction of Variation

During the past two centuries, most mass production concerned itself with meeting engineering specifications most of the time; variation was not the central focus. As long as an item or a part served its intended purpose, it was classified as "good" and passed on to its next operation or final use. When excessive variation caused an item to be nonconforming, it was classified as "bad" and downgraded, reworked, discarded, or somehow removed from the mainstream of output. Little if any effort was made to investigate the causes of such variation; it was accepted as a way of life. High output was maintained by overproducing and then sorting the output into items that met specifications and items that did not. It is still common to find firms increasing output by relaxing engineering specifications to include marginally defective items with good ones. [Wheeler. 1992, pp. 1-7] Many have come to accept this sort of process output and continue on in this practice until a superior supplier demonstrates the folly of their ways.

Deming has written, "It is good management to reduce the variation in any quality characteristic, whether this characteristic be in a state of control or not, and even when few or no defectives are being produced." [Deming, 1975, pp. 1-15] When variation is reduced, parts will be more nearly alike, and services rendered will be more predictable. Finished products and services will work better and be more reliable. Customer satisfaction will increase because customers will know what to expect. Process output and capability will be known with greater certainty, and the results of any changes to the process will be more predictable.

Therefore, management must constantly attempt to reduce process variation around desired characteristic specification levels (or nominal levels) to achieve the degree of uniformity required for products and services to function during their life cycle as promised to the customer.

Donald J. Wheeler and David S. Chambers clarify the rationale for the continual reduction of process variation. [Wheeler, 1992, pp. 1-7] A process can be described as existing in one of four states: chaos, the brink of chaos, the threshold state, and the ideal state.

When a process is in a state of **chaos**, it is producing some nonconforming product and it is not in a state of statistical control; that is, special causes of variation are present. There is no way to know or predict the percentage of nonconforming product that the process will generate in the future.

A process on the **brink of chaos** produces 100 percent conforming product; however, the process is not stable: there is variation resulting from special causes. Hence, there is no guarantee that the process will continue to produce 100 percent conforming product indefinitely. Since it is unstable, the process may wander and the product's characteristics may change at any time, entering a state of chaos, possibly at a most inconvenient time.

The **threshold state** describes a stable process that produces some nonconforming product; process variation results from common causes that are an inherent part of the system. The only way to reduce this variation is to improve the process itself. In this state it is possible to predict with some degree of belief what the proportion of nonconformance output will be in the near future.

The **ideal state** describes a stable process producing 100 percent conforming product. It is not a natural state; forces will always exist to push the process away from the ideal state. Wheeler and Chambers liken this phenomenon to entropy, in that there is similarly a trend toward disorder in the universe. It may help to visualize a process in the ideal state as a perfectly swept lawn. There will always be winds to mar its perfect appearance by depositing leaves, twigs, or other debris. Keeping the lawn perfectly swept is a never-ending challenge. In the same way, striving toward an ideal state for a process requires constant attention on management's part.

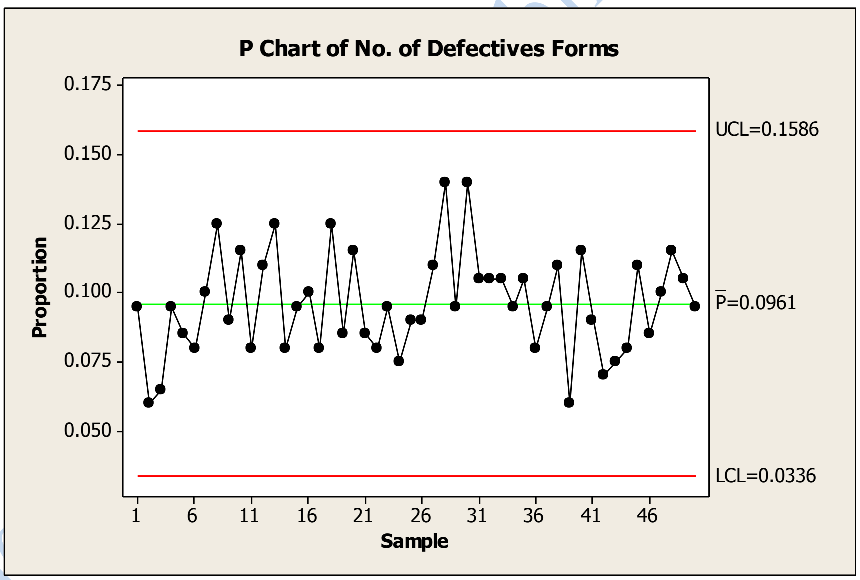
Control charts are statistical tools that make possible the distinction between common and special causes of variation. Consequently, control charts permit management to relentlessly pursue the continuous reduction of process variation and strive toward the ideal state for a process.

6.3 The Structure of Control Charts

Control charts are statistical tools used to analyze and understand process variables, to determine a process's capability to perform with respect to those variables, and to monitor the effect of those variables on the difference between customer (internal and/or external) needs and process performance. Control charts accomplish this by allowing a manager to identify and understand the sources of variation in a process, and hence, to manipulate and control process variables using change concepts to decrease the difference between customers' needs and process performance. This decrease can be managed only if the process under study is stable and capable of improvement.

Most control charts have a common structure, shown in Figure 6.1; they have a **centerline**, representing the process average, and upper and lower **control limits** that provide information on the process variation.

Figure 6.1
Structure of a Control Chart



Control charts are constructed by drawing samples and taking measurements of a process characteristic. Each set of measurements is called a **subgroup**. Control limits are based on the variation that occurs within the sampled subgroups. In this way, variation between the subgroups is intentionally excluded from the computation of the control limits; the common process variation becomes the variation on which we calculate the control limits. The control limit computations assume that there are no special causes of variation affecting the process. If a special cause of variation is present, the control chart, based solely on common variation, will highlight when and where the special cause occurred. Consequently, the control chart makes possible the distinction between common and special variation, and provides management and workers with a basis on which to take corrective action on a process through the application of an appropriate change concept.

Control limits are often called **three-sigma limits.** Recall that the lowercase Greek letter σ ("sigma") is used in enumerative studies to denote the population standard deviation, as described in Chapter 5. In analytic studies, this notation is used to denote a process standard deviation.

When Walter Shewhart described creating a range for allowable variation (common variation), he proposed using as an acceptable economic value the mean of the process characteristic of interest, plus and minus three times its standard deviation (called the **standard error**). [Shewhart, 1980, pp. 276-77] In practice, as pointed out in Chapter 5, virtually all of the process output will be located within a three-sigma interval of the process mean, provided that the process is stable. Further, virtually the entire set of sample means, for a given subgroup size, will be located within a three-standard-error interval around the process mean, provided that the process is stable. This provides us with a basis for distinguishing between common and special variation for the process characteristics to be discussed here and in Chapters 7 and 8.

In general, the centerline of a control chart is taken to be the estimated mean of the process; the upper control limit is the mean plus three times the estimated standard error, and the lower control limit is the mean minus three times the estimated standard error. These are computed from the process output, assuming that no special sources of variation are present. Subgroup means that behave non-randomly with respect to these control limits will be said to be indications of the presence of special causes of variation.

6.4 Stabilizing a Process with Control Charts

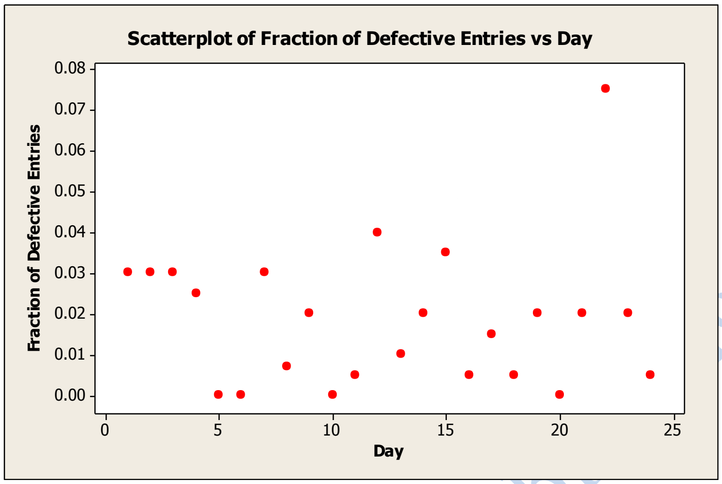
As an example of the use of control charts to detect special variation, consider a data entry operation that makes numerous entries daily. [Gitlow, 1983, pp. 131-141] On each of 24 consecutive days, subgroups of 200 entries are inspected. Table 6.2 shows the resulting raw data; Figure 6.2 is a plot of the fraction of defective entries as a function of time. Table 6.2 seems to indicate that on days 5, 6, 10, and 20 something unusually good happened (0 percent defectives), and on days 8 and 22 something unusually bad happened. A simple control chart will help to determine whether these points were caused by common or special variation.

Table 6.2

Data Entry Operation

Raw Data for Construction of Control Chart			
Day	**Number of Entries Inspected**	**Number of Defective Entries**	**Fraction of Defective Entries**
1	200	6	.030
2	200	6	.030
3	200	6	.030
4	200	5	.025
5	200	0	.000
6	200	0	.000
7	200	6	.030
8	200	14	.0070
9	200	4	.020
10	200	0	.000
11	200	1	.005
12	200	8	.040
13	200	2	.010
14	200	4	.020
15	200	7	.035
16	200	1	.005
17	200	3	.015
18	200	1	.005
19	200	4	.020
20	200	0	.000
21	200	4	.020
22	200	15	.075
23	200	4	.020
24	200	1	.005
Total	**200**	**102**	

Figure 6.2
Plot of Fraction of Defective Entries over Time



When the data consist of a series of fractions that are defective or possess some other characteristic of interest, the appropriate control chart is a **p chart**. This is a depiction of the process output in terms of an attribute of interest - in our example, the fraction defective.

The centerline for a p chart is the mean of the fraction defective, $\bar{p}$, which we calculate as

$$\bar{p} = \left[\frac{\text{Total number of defectives in all subgroups under investigation}}{\text{Total number of units examined in all subgroups under investigation}}\right] \tag{6.1}$$

Control limits are calculated as $\bar{p}$ plus and minus three times the standard error. The standard error for the average proportion, $\sigma_{\bar{p}}$, is given by the expression

$$\sigma_{\bar{p}} = \sqrt{\frac{\bar{p}(1-\bar{p})}{n}} \tag{6.2}$$

where n is the subgroup size.

Using this value, the upper and lower control limits for a p chart are given by:

$$\text{UCL}(p) = \bar{p} + 3\sqrt{\frac{\bar{p}(1-\bar{p})}{n}} \tag{6.3}$$

We can now use Equations (6.1), (6.2), (6.3) and (6.4) to find the numerical values for constructing our p chart:

$$\bar{p} = \frac{102}{4{,}800} = 0.021$$

$$\text{LCL}(p) = \bar{p} - 3\sqrt{\frac{\bar{p}(1-\bar{p})}{n}} \qquad (6.4)$$

Centerline (p) = 0.021

$$\text{UCL}(p) = 0.021 + 3\sqrt{\frac{(0.021)(1-0.021)}{200}} = 0.052$$

= 0.02125 + 3(0.0101)

= 0.051

Upper control limit = 0.051

$$\text{LCL}(p) = 0.021 - 3\sqrt{\frac{(0.021)(1-0.021)}{200}} = 0.052$$

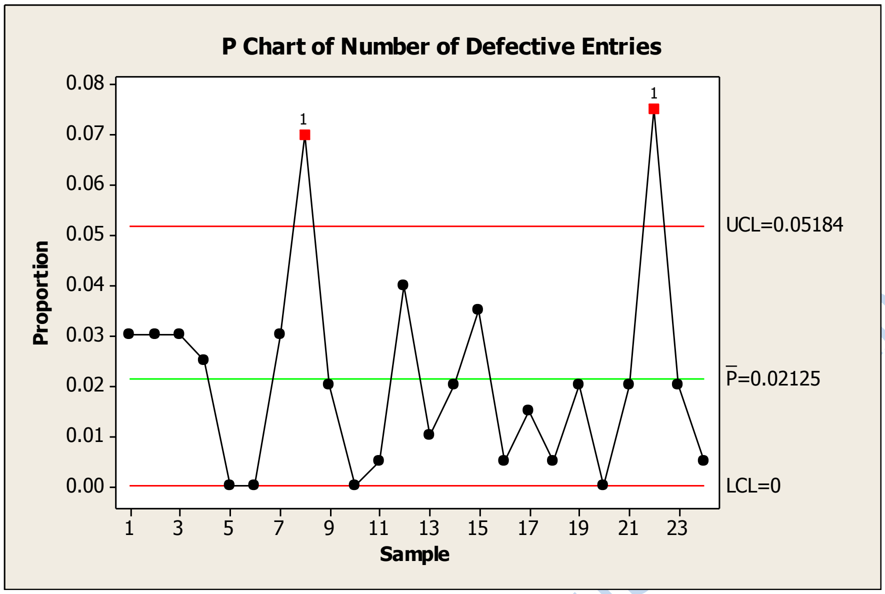
= -0.009

Lower control limit = 0.00

Notice that since a negative fraction defective is not possible, the lower control limit is set at 0.00.

Figure 6.3 shows the completed p chart. Clearly on days 8 and 22 there are special causes of variation. Note, however, that the fractions defective on days 5, 6, 10 and 20 are not beyond the lower control limit. Days with no defectives are not out of control; we have merely observed that the process is capable of producing zero defectives 4 out of 24 days, or 1/6th of the time. Do not look for special causes of variation on these perfect days; they are not special cause days, they are just lucky days; again, the system is capable of producing error free output 1/6 th of the time.

Figure 6.3
p Chart



When a manager or worker determines that the cause of variation is special, he should search for and resolve the cause(s) that may be attributable to such factors as a specific machine, worker or group of workers, a new batch of raw materials, a new supplier, a new process, to name a few possibilities. A stable process results once special cause(s) of variation have been identified and resolved in the process.

In our example, to bring the process under control, management investigates the observations that are out of control (days 8 and 22) in an effort to discover and remove the undesirable special causes of variation in the process. In this case, management finds that on day 8 a new operator was added to the work force without any training. The logical conclusion is that the new environment probably caused the unusually high number of errors. To ensure that this special cause does not recur, the company adds a one-day training program in which data entry operators are acclimated to the work environment.

A team of managers and workers conduct an investigation of the circumstances occurring on day 22. Their work reveals that on the previous night one of the data entry terminals malfunctioned and was replaced with a standby unit. The standby unit is older and slightly different from the ones currently used in the department. Repairs on the regular terminal were not expected to be completed until the morning of day 23. To correct this special source of variation, the team recommends developing a proactive program of preventative maintenance on the terminals to decrease the likelihood of future breakdowns. Employees then implement the solution with the policy commitment of management.

Detrimental special causes of variation can be eliminated from a process, or beneficial special causes of variation can be incorporated into a process, by setting and enforcing policy changes, usually in the form of change concepts. Once this is done, the process has been changed.

The action taken on the process stemming from investigations of days 8 and 22 should eliminate the two special causes of variation. Consequently, the data from days 8 and 22 may now be deleted. After eliminating the days for which the special causes of variation are found (DATAENTRY2), the control chart statistics are recomputed:

$$\bar{p} = \frac{73}{4{,}400} = 0.017$$

$$\mathrm{UCL}(p) = 0.017 + 3\sqrt{\frac{(0.017)(1-0.017)}{200}} = 0.045$$

$$\mathrm{LCL}(p) = 0.017 - 3\sqrt{\frac{(0.017)(1-0.017)}{200}} = -0.010$$

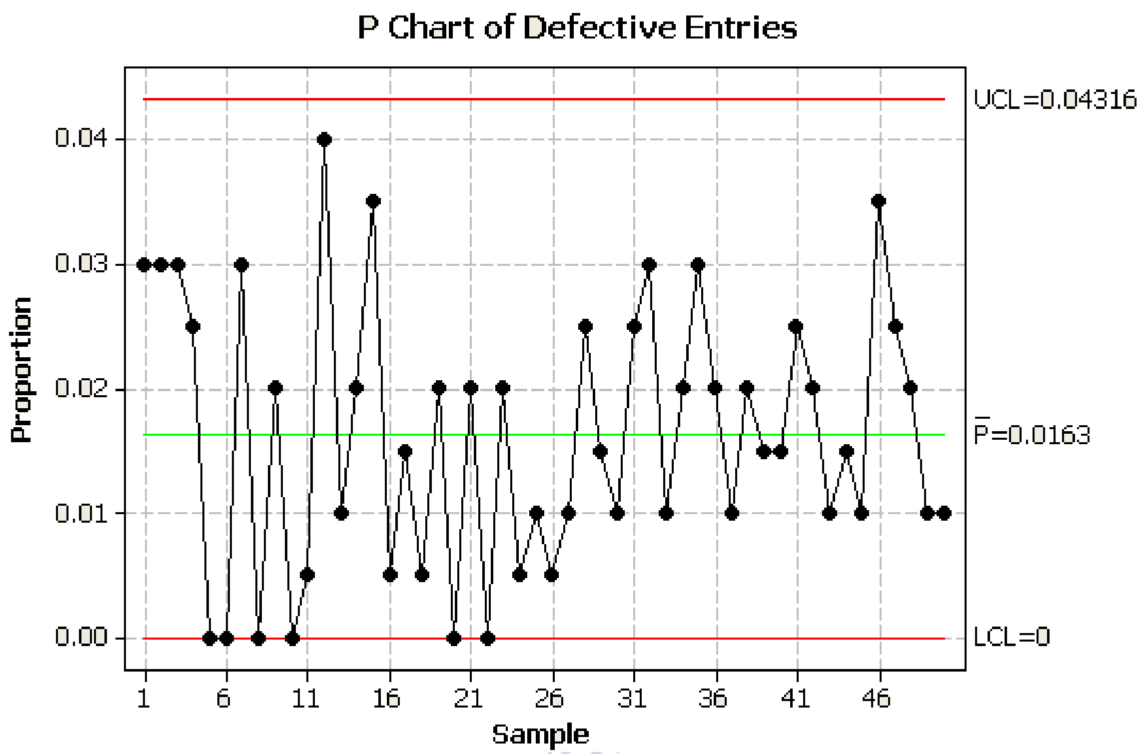
$$= -0.010$$

and hence, the lower control limit = 0.00.

Figure 6.4 shows the revised control chart. The process appears to be stable and in statistical control. Notice that the revised control chart has somewhat narrower control limits than the original. When special causes have been eliminated, the narrower limits that occur may reveal other points that are now out of control. It will then be necessary to again search for special causes. Several such iterations may be required until the process is stable and in statistical control.

At least 20 subgroups should remain to determine that the process is indeed stable. If the elimination of subgroups has left fewer than 20 subgroups remaining, additional data should be collected to ensure that the process is in a state of statistical control.

Figure 6.4
Revised Control Chart for Fraction Defective



6.5 Advantages of a Stable Process

The advantages of achieving a stable process are:

- Management knows the process capability and can predict performance, costs, and quality levels, and consequently, be better able to forecast, plan, and budget.
- Productivity will be at a maximum and costs will be at a minimum.
- Management will be able to measure the effects of changes in the system with speed and reliability.
- If management wants to alter specification limits, it will have the data to back up its decision.

A stable process is a basic requirement for process improvement efforts.

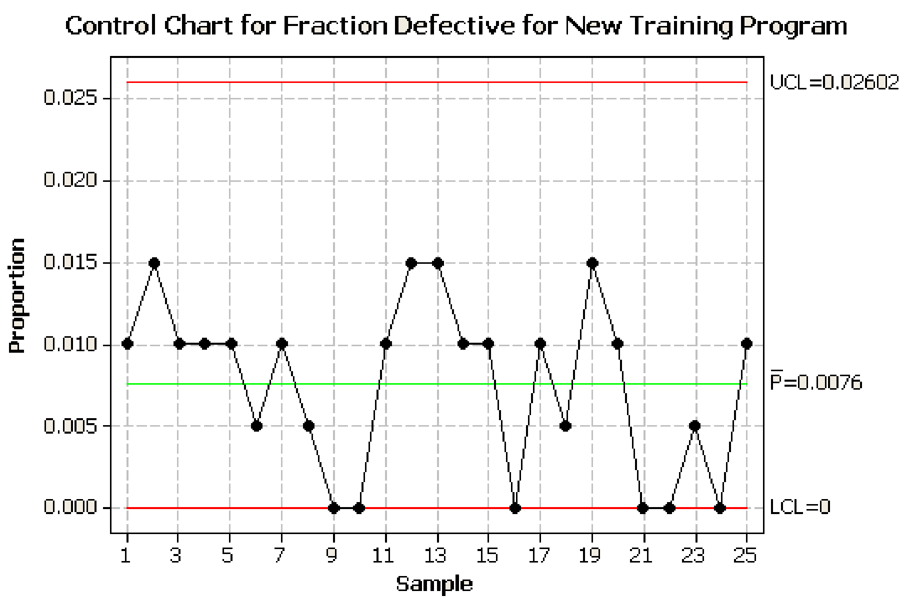
6.6 Improving a Process with Control Charts

Once a process is stable, it has a known capability. A stable process may, nevertheless, produce an unacceptable number of defects (threshold state) and continue to do so as long as the system remains the same. Management owns the system and must assume the ultimate responsibility for changing the system to reduce common variation and to reduce the difference between customer needs and process performance.

There are two areas for action to reduce the difference between customer needs and process performance. First, action may be taken to change the process average. This might include action to reduce the level of defects or process changes to increase production or service. Second, management can act to reduce the level of common variation with an eye toward never-ending improvement of the process. Procedures and inputs (such as composition of the workforce, training, supervision, materials, tools and machinery, and operational definitions) are the responsibility of management. The workers can only suggest changes; they cannot effect changes to the system.

In our example of the data entry firm, an employee-suggested training program was instituted. The program was aimed at reducing the average fraction of errors and the common variation, which would result in narrower control limits. Figure 6.5 shows the data entry control chart after management instituted the new training program (DATAENTRY3). The average proportion of entries with errors decreased from 0.017 to 0.008, and the process variation decreased as well.

Figure 6.5
Control Chart for Fraction Defective after Institution of a New Training Program



6.7 Causes of Variation Out of the Control of the Process Owner

Sometimes the people working in a process detect a cause of variation that is out of the control of the process owner. If this happens, and it surely will happen sooner or later, the people working within the process should look for similar processes, either internal or external to their organization, that have successfully dealt with the special cause of variation. If they find such a process, they can study its flowchart as a starting point for modifying their process: perhaps the similar process will yield a solution to the special cause of variation that makes sense within the context of the process under study. As an example, Miami, Florida has the second highest incidence of lightning in the world. Tampa, Florida has the highest. In the late 1980s, Florida Power and Light Company wanted to improve, or decrease, the minutes of interrupted service per month. A control chart revealed a stable process with an unacceptably high average and standard deviation. Pareto analysis, to be discussed in Chapter 10, revealed that the biggest cause of interrupted services was electrical poles knocked out of service by lightning strikes. The next biggest cause or interrupted service created only a small fraction of the problems caused by lightning strikes. Dr. Noriaki Kano, a professor at the Science University of Tokyo, suggested that they break up FPL into small geographic regions and determine if any region had an effective process for dealing with lightning strikes. The employees studying the problem discovered that Southeastern Dade County had a significantly higher average lightning strike outage rate than any other area. Southeastern Dade County was above the upper control limit for minutes of interrupted service, where the x-axis of the control chart is geographical location for a given time period and the y-axis is minutes of interrupted service for a given time period. Western Broward County had a significantly lower average than any other area. Western Broward County was below the lower control limit for minutes of interrupted service. Employees wondered what would cause such a disparity in the averages. Pareto analysis revealed that the age distribution of linemen (the people who repair electric lines) in Southeastern Dade, with a mean in the mid-50s, was much older than the age distribution is Western Broward County, where the mean was in the mid- 20s. A brainstorming session (discussed in detail in Chapter 10) revealed that the linemen in Southeastern Dade County had been trained in the standards for grounding electrical poles established in the 1950s, while the linemen in Western Broward County had been trained in the standards for grounding electrical poles established in the early 1980s. Employees discovered that the standards for grounding electrical poles had been dramatically improved between the 1950s and 1980s. Subsequently, the linemen in Southeastern Dade County (as well as all other linemen) were trained in the grounding standards established in the 1980s. As a result of this training, the minutes of interrupted service was dramatically decreased throughout the Florida Power and Light system, but especially in Southeastern Dade County. The important point is that a special cause of variation may seem to be out of the control of a process owner, but may be successfully resolved using knowledge from another system.

6.8 Two Possible Mistakes in Using Control Charts

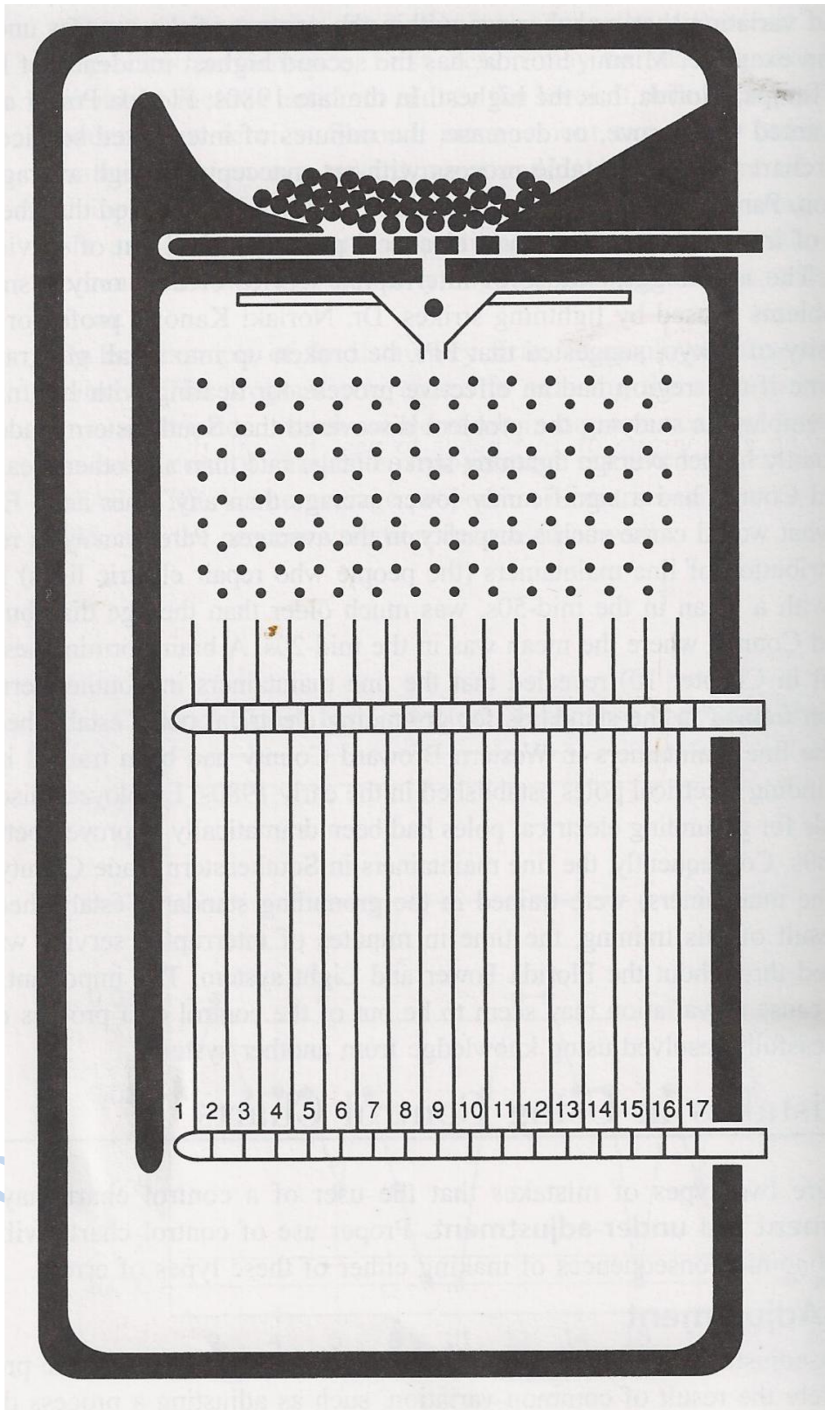
There are two types of mistakes that the user of a control chart may make: **over-adjustment** and **under-adjustment**. Proper use of control charts will minimize the total economic consequences of making either of these types of errors.

6.8.1 Over-adjustment

An over-adjustment error occurs when the user reacts to swings in the process data that are merely the result of common variation, such as adjusting a process downward if its past output is above average or adjusting a process upward if its past output is below average. When a process is over-adjusted, it resembles a car being over-steered, veering back and forth across the highway. In general, processes should be adjusted not on the basis of time-to-time observations, but on the basis of information provided by a statistical control chart.

Examining a frequently used demonstration device known as a **Quincunx board**, shown in Figure 6.6, one can see the effects of over-adjustment. The Quincunx board is a rectangular box with an upper chamber containing a large number of beads. A horizontal sliding bar feeds one or more beads at a time into a triangular hopper which then allows the beads to fall at a specified lateral point directly above 10 rows of pegs. Each time a bead hits a peg, it will bounce right or left so that its position after falling through the 10 rows of pegs is a result of 10 random events. It does not seem unreasonable to expect that many beads would tend to fall almost directly beneath the point at which they were released. But some beads may tend to wander a bit and end up to the right or left of their release point.

Figure 6.6
A Quincunx Board

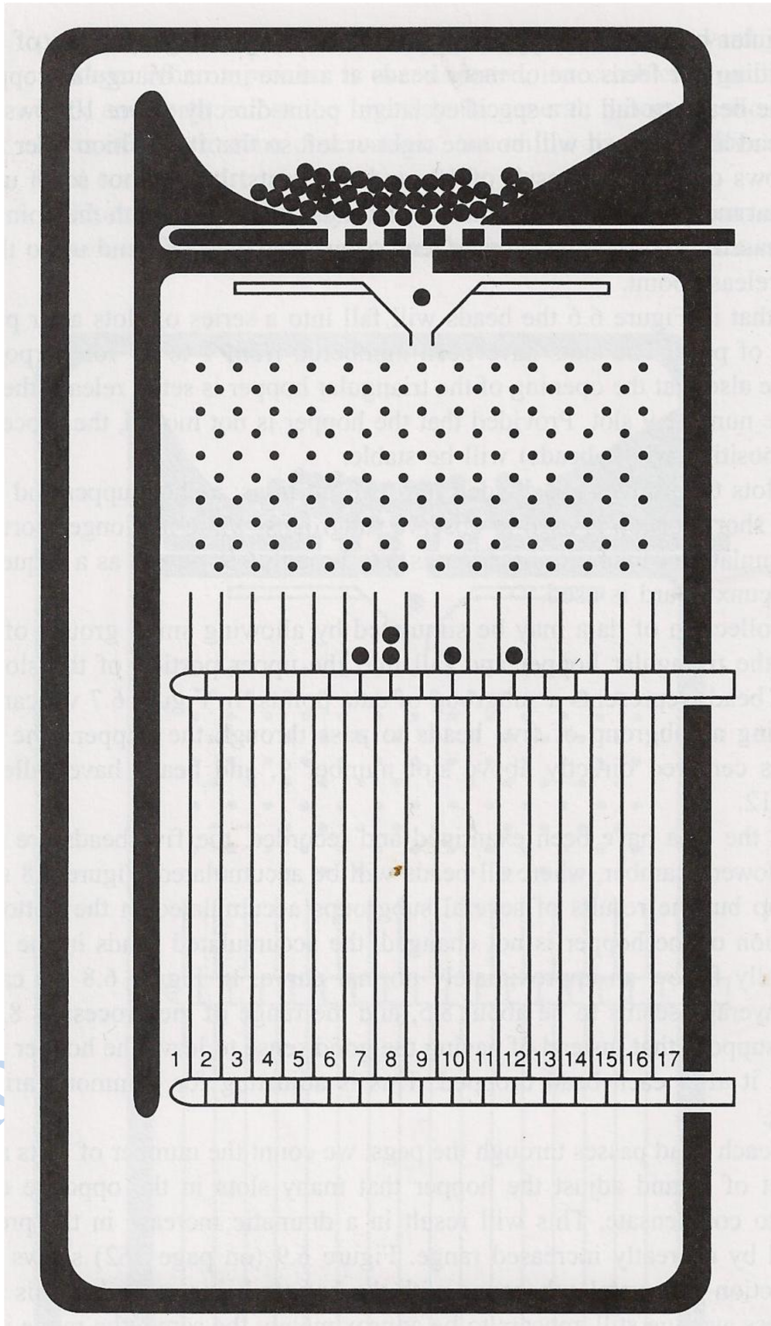


Note that in Figure 6.6 the beads will fall into a series of slots after passing through the rows of pegs. The slots have been numbered from 1 to 17 for purposes of illustration. Note also that the opening of the triangular hopper is set to release the beads directly above the number 9 slot. Provided that the hopper is not moved, the process output (i.e., the slot position of the beads) will be stable.

The slots themselves are divided into two portions: a short upper and a longer lower one. The short portion is used to observe subgroups, while the longer portion is used for the accumulation of subgroups. Figures 6.6 through 6.9 viewed in sequence show how the Quincunx board is used.

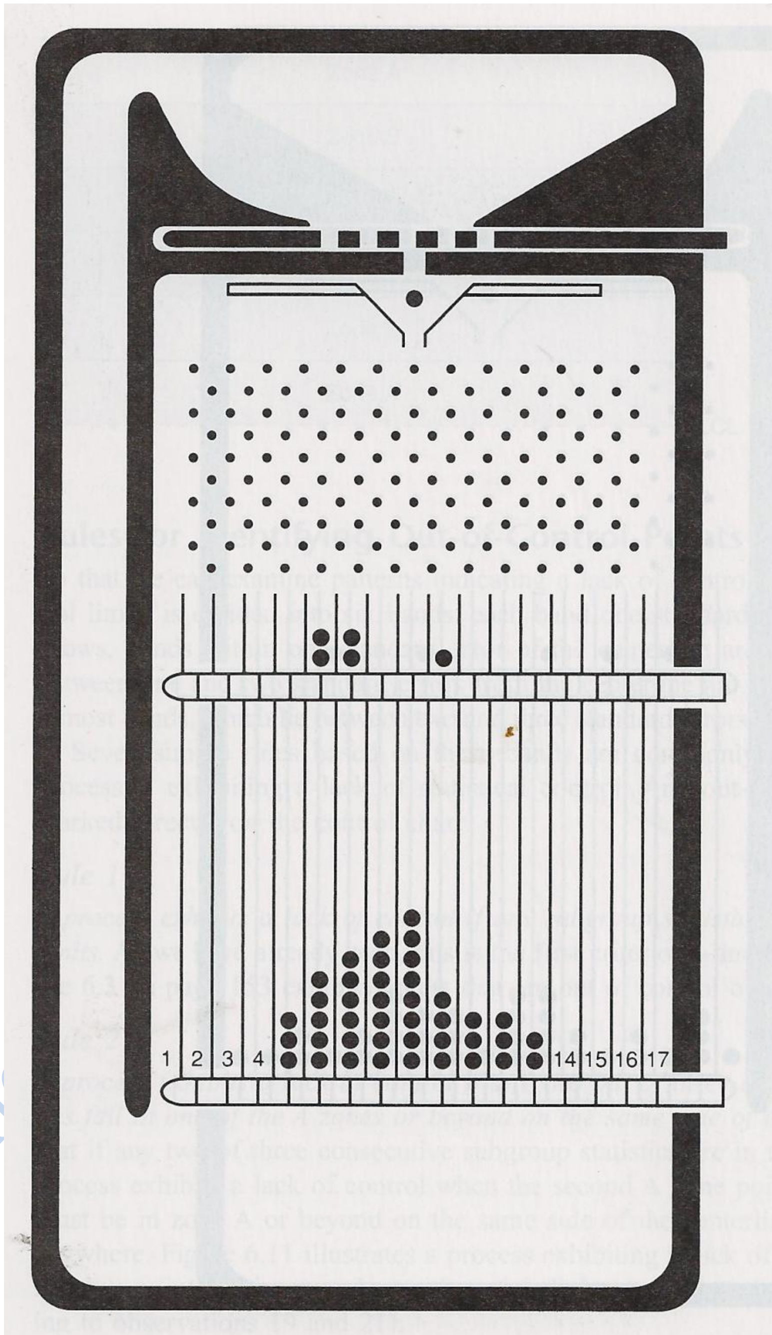
The collection of data may be simulated by allowing small groups of beads to pass through the triangular hopper and fall into the upper portion of the slots. Each small group of beads represents a subgroup of data points. In Figure 6.7 we can see the result of allowing a subgroup of five beads to pass through the hopper. The bottom of the hopper is centered directly above slot number 9, and beads have fallen into slots 7 through 12.

Figure 6.7
Quincunx Bead Falling



When the data have been examined and recorded, the five beads are allowed to fall into the lower chamber, where all beads will be accumulated. Figure 6.8 shows not only this group but the results of several subgroups accumulated in the bottom chamber. If the position of the hopper is not changed, the accumulated beads in the lower chamber will usually follow an approximately normal curve. In Figure 6.8 we can see that the process average seems to be about 8.5, and the range of the process is 8 (13 – 5 = 8).

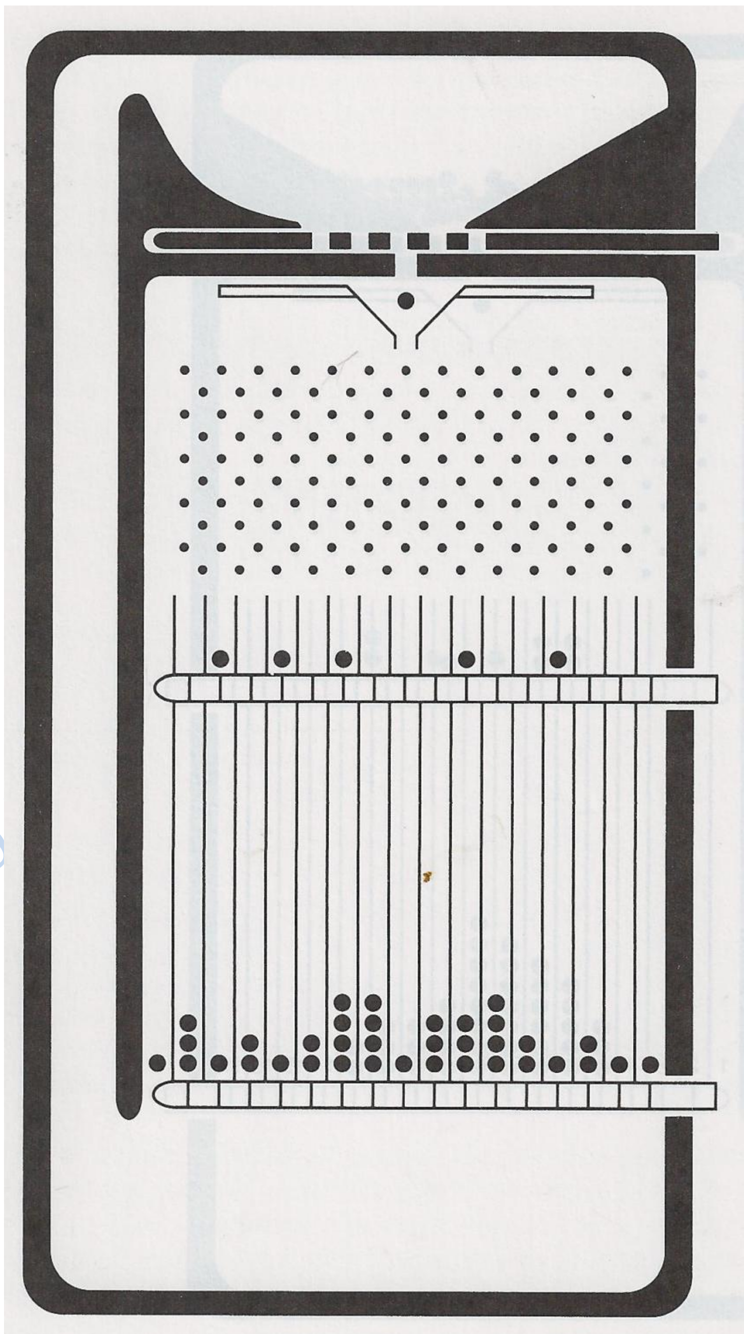
Figure 6.8
Quincunx Subgroups



Now suppose that instead of having the good sense to leave the hopper alone, we were to adjust it after each bead dropped. This is adjusting for common variation, or over-adjusting.

After each bead passes through the pegs, we count the number of slots above or below the target of 9, and adjust the hopper that many slots in the opposite direction in an attempt to compensate. This will result in a dramatic increase in the process variation indicated by a greatly increased range. Figure 6.9 shows the results for the collection of several subgroups with the hopper being moved in this manner. While the process average still appears to be approximately the same, the range is now 16. This is the penalty for adjusting on the basis of common variation. This dangerous situation is illustrated by Rule 2 of the Funnel Experiment discussed in Chapter 1.

Figure 6.9
Results of Compensating for Bead Motion from Trial to Trial



Under-adjustment, or lack of attention, results when a process is out of control and no effort is made to provide the necessary regulation. The process swings up and down in response to one or more special causes of variation, which may have compounding effects.

Avoiding both of these mistakes all of the time is an impossible task. That is, never adjusting the process -- so that we never make the mistake of over-adjusting -- could result in severe under-adjustment. On the other hand, if we made very frequent adjustments to avoid the problem of under-adjustment, we would probably be over-adjusting. Control charts provide an economical means to minimize the total loss that results from these two errors. Consequently, control charts provide management with guidance on when to take action on a process and when to leave it alone.

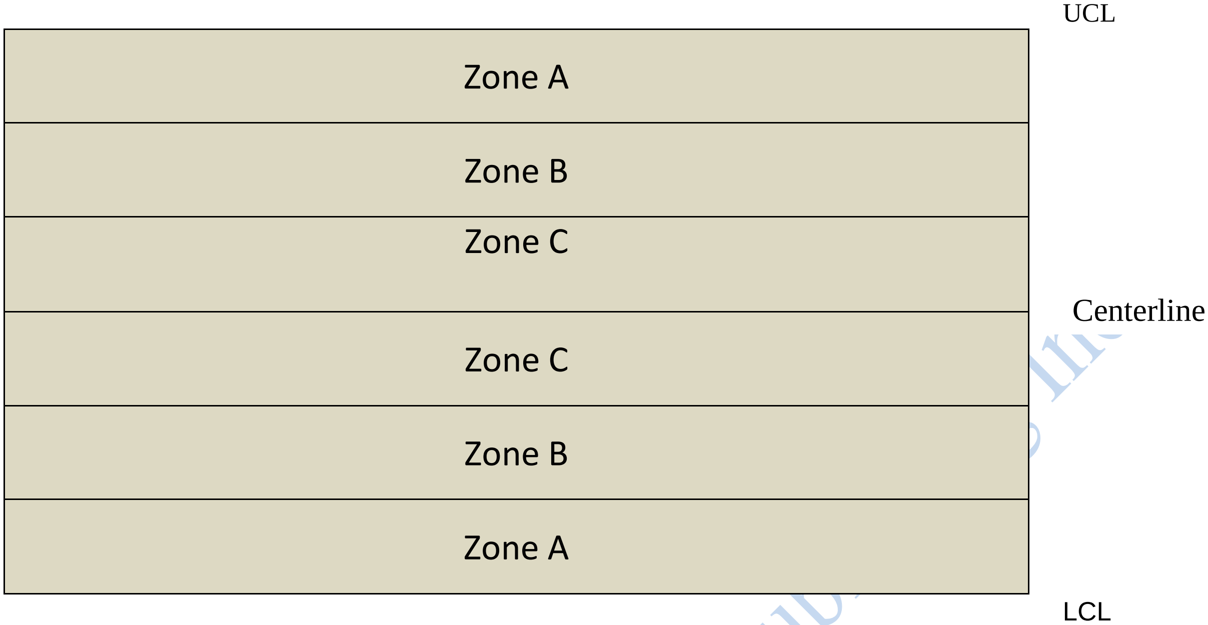
6.9 Some Out-of-Control Evidence

We know that a process exhibits a lack of statistical control if a subgroup statistic falls beyond either of the control limits. But it is possible for all subgroup statistics to be within the control limits while there are other factors that indicate a lack of control in the process. Stable processes always exhibit random patterns of variation. Accordingly, most data points will tend to cluster about the mean value, or centerline, with an approximately equal number of points falling above and below the mean. A few of the values will lie close to the control limits. Points will rarely fall beyond a control limit. Also there will seldom be prolonged runs upward or downward for a number of subgroups. If one or more of these conditions is violated in a control chart, the chart does not exhibit statistical control. Hence, for a process that is out of control, there will be an absence of points near the centerline, an absence of points near the control limits, one or more points located beyond the control limits, or runs or nonrandom patterns among the points.

6.9.1 Rules for Identifying Out-of-Control Points

So that we can examine patterns indicating a lack of control, the area between the control limits is divided into six bands, each band one standard error wide. As Figure 6.10 shows, bands within one standard error of the centerline are called the C zones; bands between one and two standard errors from the centerline are called B zones; and the outermost bands, which lie between two and three standard errors from the mean, are A zones.

Figure 6.10
A, B, and C Zones for a Control Chart

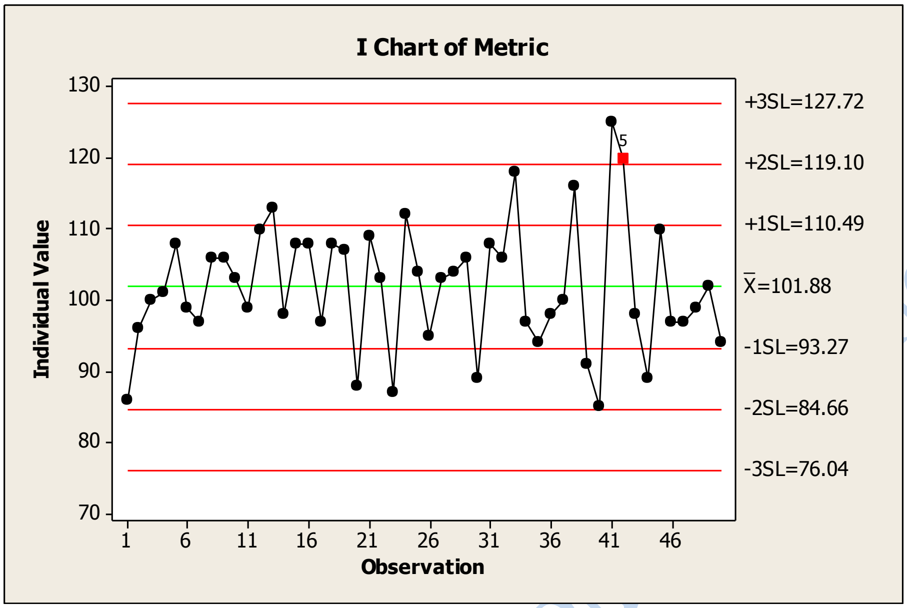


Seven simple rules based on these bands are commonly applied to determine if a process is exhibiting a lack of statistical control. Any out-of-control points found are marked with a square with a number next to it directly on the control chart.

Rule 1. *A process exhibits a lack of control if any subgroup statistic falls outside of the control limits.* As we have already seen, this is the first criterion -- and the most obvious one. Figure 6.3 exhibits points (indicated by an square with the number 1 next to it) that are out of control by virtue of this rule.

*Rule 2***.** *A process exhibits a lack of control if any two out of three consecutive subgroup statistics fall in one of the A zones or beyond on the same side of the centerline.* This means that if any two of three consecutive subgroup statistics are in the A zone or beyond, the process exhibits a lack of control when the second A zone point occurs. The two points must be in zone A or beyond on the same side of the centerline; the third point can be anywhere. Figure 6.11 illustrates a process exhibiting a lack of control by virtue of Rule 2 relating to observations 41 and 42.

Figure 6.11
Lack of Control by Virtue of Rule 2 (Noted by “5”)



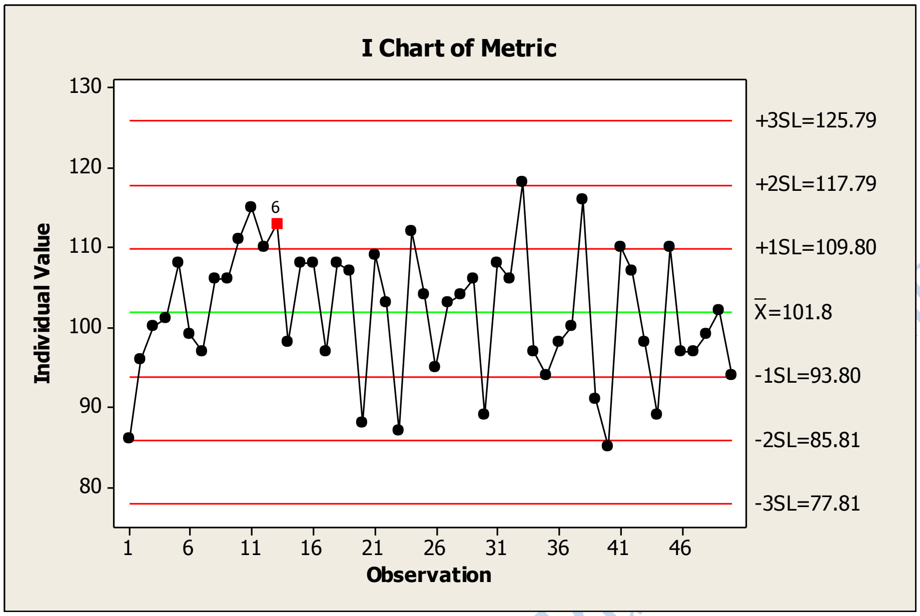
When applying Rule 2 or any other indicator of a lack of control, it is always best to look for patterns demonstrating evidence of a lack of control by looking backward along the control chart. This makes any patterns or trends more obvious and makes it easier to find the beginning of a pattern or trend.

Rule 3. A process exhibits a lack of control if four out of five consecutive subgroup statistics fall in one of the B zones or beyond on the same side of the centerline. This means that if any four out of five consecutive subgroup statistics are in either one of the B zones or beyond on the same side of the centerline while the fifth is not, the fourth point in the B zone or beyond is deemed to be providing evidence of a lack of control. It should be marked with a square.

Figure 6.12 illustrates an out of control pattern flagged by Rule 3. Observations 13, 12, 11, and 10 are in zone B or beyond. This means that observation number 13 is an indication of a lack of control.

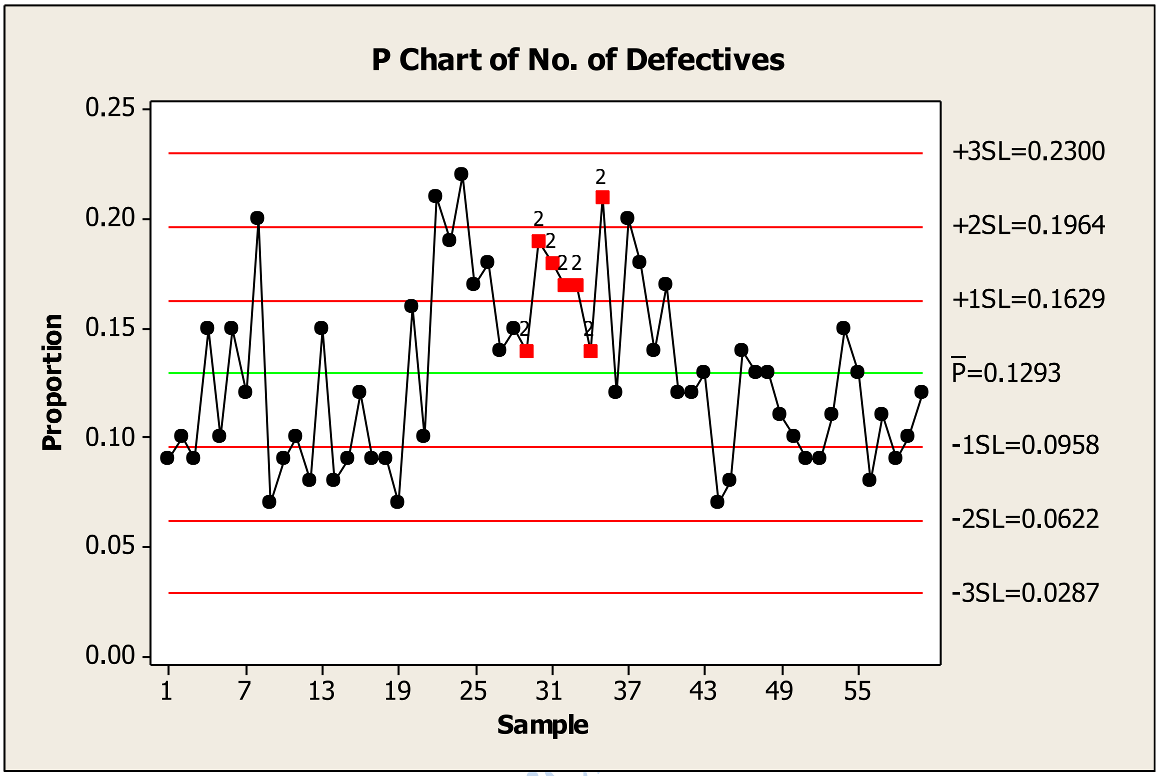
Subgroup statistics 10, 11, 12, and 13 all lay in zone B or beyond. They constitute four out of five points in zone B or beyond.

Figure 6.12
Lack of Control by Virtue of Rule 3 (Notes by "6")



Rule 4. A process exhibits a lack of control if eight or more consecutive subgroup statistics lie on the same side of the centerline. The eighth and subsequent subgroup statistics are said to provide evidence of a lack of control by virtue of this rule. Figure 6.13 shows a process exhibiting a lack of control by virtue of this rule.

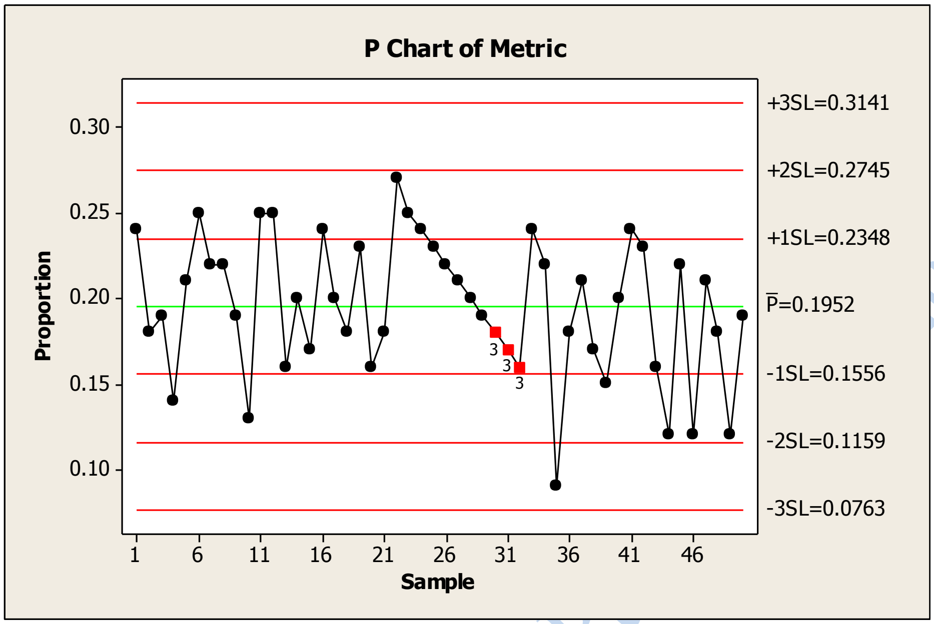
Figure 6.13
Lack of Control by Virtue of Rule 4 (Noted by "2")



Rules 1 through 4 assume that the distribution of the control chart statistic is continuous, stable, and normally distributed. However, we really do not require the assumption of normality to apply Rules 1 through 4, due to the Empirical Rule discussed earlier in Chapter 5. For example, if the control chart statistic is continuous, stable, and non-symmetrically distributed, as is frequently the case with the range chart, the Empirical Rule still justifies the use of Rules 1 through 4 to detect out-of-control points.

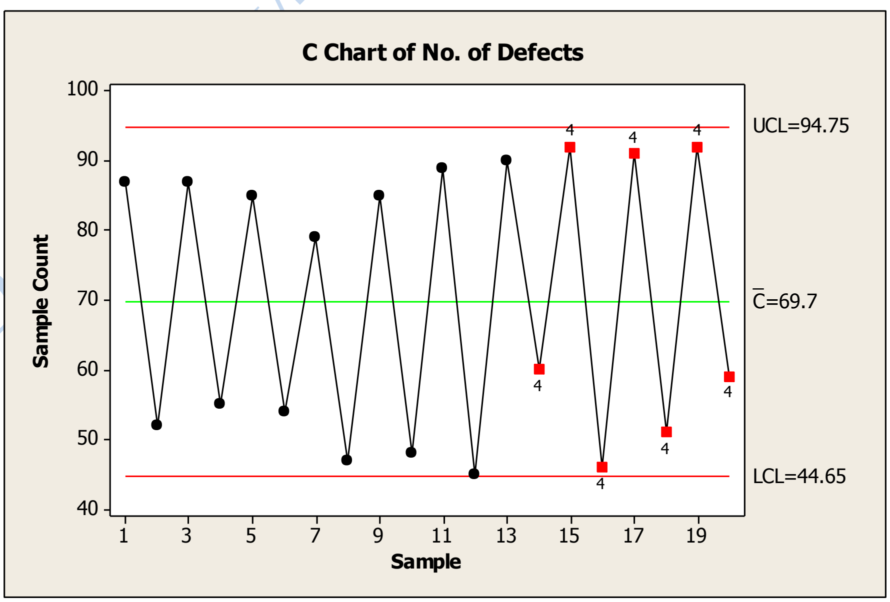
*Rule 5***.** *A process exhibits a lack of control if eight or more consecutive subgroup statistics move upward in value or if eight or more consecutive subgroup statistics move downward in value.* The eighth and subsequent subgroup statistics that continue moving up (or down) are said to provide evidence of a lack of control. Figure 6.14 shows a process exhibiting a lack of control by virtue of this rule.

Figure 6.14
Lack of Control by Virtue of Rule 5 (Noted by “3”)



Rule 6. A process exhibits a lack of control if an unusually small number of runs above and below the centerline are present (a saw-tooth pattern). Figure 6.15 shows a process exhibiting a lack of control by virtue of this rule.

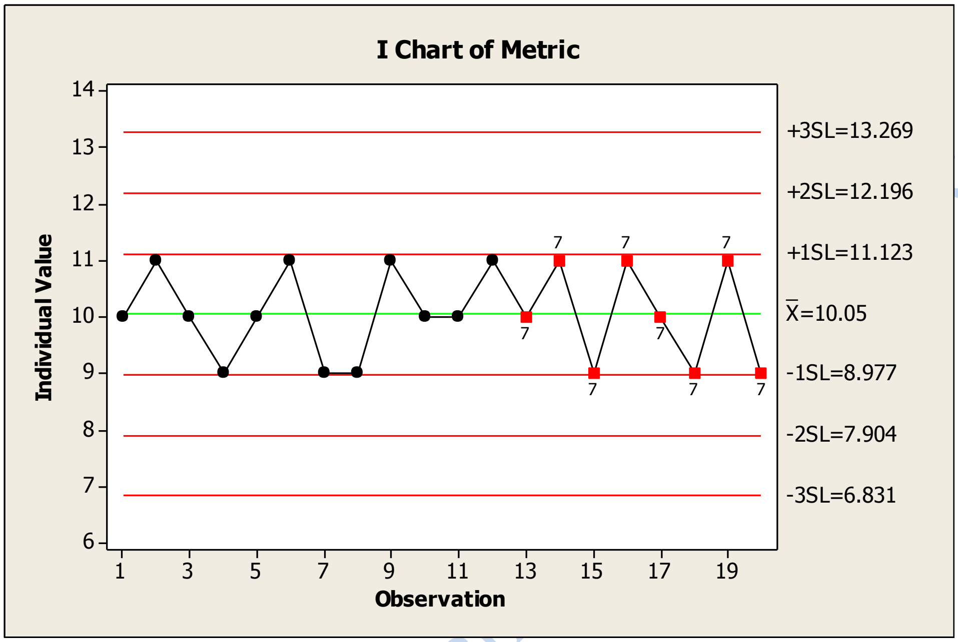
Figure 6.15
Lack of Control by Virtue of Rule 6 (Noted by “4”)



Rule 7. A process exhibits a lack of control if 13 consecutive points fall within zone C on either side of the centerline. The thirteenth and subsequent subgroup statistics are said

to provide evidence of a lack of control by virtue of this rule. Figure 6.16 shows such a process.

Figure 6.16
Lack of Control by Virtue of Rule 7 (Noted by "7")



It should be pointed out that Rules 6 and 7 are used to determine whether a process is unusually noisy (high variability) or unusually quiet (low variability).

6.9.2 False Out-of-Control Signals

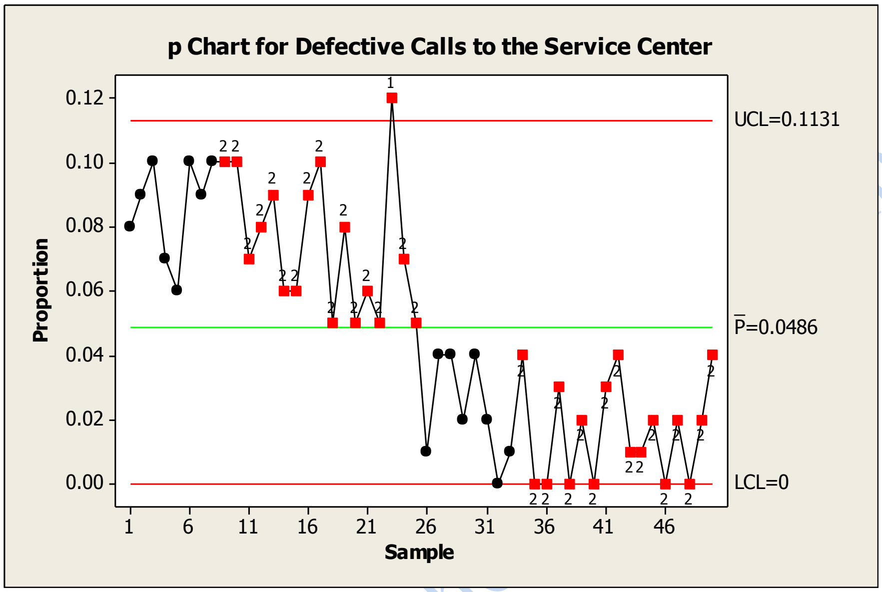
Occasionally, a control chart presents out-of-control signals, one or more of which are "false" signals. Table 6.3 presents data from a service center indicating the number of improperly handled calls per day, from a daily sample of 100 calls, for 50 days. The data are arranged horizontally in five rows. The data point for the first day was 8 defective calls and the data point for the eleventh day was 7 defective calls.

Table 6.3 Number of Defective Calls to a Service Center

8	9	10	7	6	10	9	10	10	10
7	8	9	6	6	9	10	5	8	5
6	5	12	7	5	1	4	4	2	4
2	0	1	4	0	0	3	0	2	0
3	4	1	1	2	0	2	0	2	4

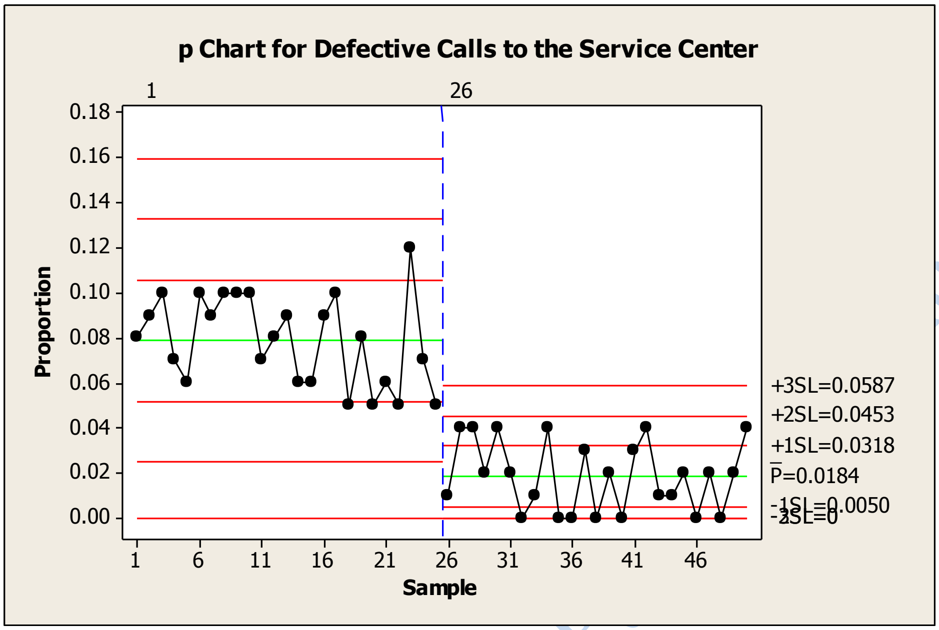
Figure 6.17 shows a p chart for the data in Table 6.3. There is one data point above the upper control limit (a violation of Rule 1, signified by a 1) and many data points that are 8 or more points in a row above or below average (a violation of Rule 4, signified by 2).

Figure 6.17
p chart for Defective Calls to the Service Center



Many analysts might begin to search for both types of special causes (indicated by 1 and 2) shown in Figure 6.17. However, this would be a mistake. In this case, the out-of-control point above the upper control limits is a false signal caused by the shift down in the process average at point 26 caused by the introduction of a training program for staff answering phones. A revised control chart that takes into account the change in the processes from one without training to one with training is shown in Figure 6.18.

Figure 6.18
Revised p chart for Defective Calls to the Service Center



We can now see that the out-of-control point above the upper control limit disappears when only the before-training process is considered. The lesson here is that a process expert may have to be consulted when searching for special causes of variation.

6.10 Quality Consciousness and Types of Control Charts

Quality consciousness should follow a logical pattern. It generally begins with a lack of quality consciousness, moves on to **defect detection** (also called mass inspection), moves from there to **defect prevention**, then through the **never-ending improvement** of current products and services, and ultimately leads to the realization that the only path to continued prosperity must include innovations in future products and services.

6.10.1 No Quality Consciousness: Accept Everything without Question

The lowest level of quality consciousness is to accept everything from a vendor, without question. For example, most people do not count to check if there are 144 toothpicks in a box or if there are 500 sheets of paper in a ream as stated on the package. This type of quality consciousness is borne out of a lack of awareness of quality, or past satisfaction and a consequent lack of concern about poor quality.

6.10.2 Defect Detection: Mass Inspection to Sort Conforming and Non-Conforming Output

The purpose of defect detection is to sort conforming and nonconforming products or services through mass inspection (Deming's Point 3, discussed in Chapter 2). Defect detection assumes that defects will be produced; they are expected and anticipated. In this stage of quality consciousness, no feedback loops or tools are available for correcting the factors that created the defectives in the first place. Once a defect is produced, it is too late to do anything but remove it from the process output. The costs associated with its production, distribution, and perhaps most important of all, worker morale and good will are usually unrecoverable. Worse yet, if the product or service has found its way to an internal or external customer, the good of the supplier has been tarnished.

6.10.3 Defect Prevention: Attribute Control Charts

The purpose of defect prevention is to achieve zero defects. This stage of quality consciousness assumes that if all products and services are within specification limits, then all output will meet customers' needs and wants. This is the goal post view of quality, discussed in Chapter 1. The initial entry into defect prevention generally involves the use of control charts based on attribute data, such as conforming versus nonconforming with respect to some specification limit(s).

The most common types of **attribute control charts** are:

- **p chart**: used to control the fraction of units with some characteristic (such as the fraction defective).
- **np chart**: used to control the number of units with some characteristic (such as the number of defectives per batch, assuming a constant batch size).
- **c chart**: used to control the number of events (such as defects) in some fixed area of opportunity (such as a single unit or a period of time).
- **u chart**: used to control the number of events (such as defects) in a changeable area of opportunity (such as square yards of paper drawn from an operational paper machine).
- **I-MR (Individuals and Moving Range) charts**: used to control the count for a number of discrete events when the assumptions for the other attribute charts cannot be met. I-MR charts are discussed in chapter 8.

Attribute control charts, which will be discussed in detail in Chapter 7, can help move processes toward a zero percent defective rate. However, they do not provide specific information on the cause(s) of the defectives. Furthermore, as the percent defective approaches zero, larger and larger sample sizes will be needed to detect defective process output. For example, if a process is generating an average of one defective in every million units produced, then the average sample size needed to find one defective unit is one million units. Hence, attribute control charts become ineffective as the proportion of defective output approaches zero. Control charting must continue, but in the face of the limitations of attribute control charts, a better means of process improvement and evaluation is required. This should lead management to the next level of quality consciousness -- never-ending improvement.

6.10.4 Never-Ending Improvement: Variables Control Charts

The purpose of never-ending improvement is to modify current processes used for products and services to continuously reduce the difference between customer needs and process performance. This is the Taguchi Loss Function view of quality, discussed in Chapter 1. Never-ending improvement necessitates using control charts based on variables data. These types of control charts allow for the never-ending reduction of unit-to-unit variation, even though all output is well within specification limits. For example, in the manufacture of steel push rods, all may come from a stable process and all may conform to specifications; an attribute control chart would show zero percent defective in almost every sample. However, by taking actual measurements on rod lengths (variables data), management is able to collect information that will enable them to consistently strive for the reduction of unit-to-unit variation, even within specification limits.

The most common types of **variables control charts** are:

- **I (individuals) chart**: used to control the process average for subgroups of one data point per subgroup.
- $\bar{x}$ **chart**: used to control the process average for subgroups of two or more data points.
- **R chart**: used to control the process range when between 2 and 10 data points exist per subgroup.
- **MR (moving range) chart**: used to control the process range when only one data point exists per subgroup.
- **s chart**: used to control the process standard deviation when more than 10 data points exist per subgroup.

Using variables control charts, management may continuously seek to reduce variation, center a process on nominal, and decrease the difference between customer needs and process performance. Chapter 8 discusses in detail the uses and applications of these variables control charts.

6.10.5 Innovation (Quality Creation)

Innovation can be thought of as having two primary purposes: to create a dramatic breakthrough in decreasing the difference between customers' needs and process performance; and to discover customers' future needs. Ideas for innovation with respect to customers' future needs generally cannot come from direct queries to customers; rather, they must come from the producer. In this regard, consumer research is backward- looking; that is, asking customers what they want usually can only help producers improve existing products or services; frequently, it cannot help producers anticipate the customers' future needs. As a rule, consumers do not know what innovations they will want in the future. For example, consumers did not know that they wanted an iPhone with a built in camera or the iCloud before such products existed. The producer studying the problems customers have when using products and services must discover these types of breakthroughs. In 1974, the camera market was saturated with cameras that satisfied customers' current needs; cameras were reliable, were relatively inexpensive to use, and produced good pictures. This created a nightmare for the camera industry. Consequently Konica decided to ask consumers what more they would like in a camera. Consumers replied that they were satisfied with their cameras; asking consumers what more they would like in a camera did not yield the information Konica needed to create a breakthrough. In response to this situation, Konica studied negatives at film processing laboratories and discovered that often the first few pictures on rolls of film were overexposed, indicating that users had difficulty in loading cameras. This presented an opportunity to innovate camera technology. In response to this analysis, Konica developed the automatic-loading camera. This is an excellent example of innovation of a product or service. The customer could not have been expected to think of this innovation. Digital cameras have essentially replaced cameras that use conventional film, presenting another set of challenges for this industry -- yet consumers have never asked for these products.

6.11 Three Uses of Control Charts

As we have seen, control charts fall into two broad categories: attribute and variables. In both cases, a particular quality characteristic is measured and then examined. That examination can be used to: (1) evaluate the history of the process, (2) evaluate the present state of the process, or (3) predict the near future state of a process in conjunction with the opinion of a process expert.

6.11.1 Evaluating the Past

The retrospective examination of the process's completed output using a control chart answers the question of whether the process has been in statistical control. A lack of control, or the presence of special causes of variation, is indicated when one or more of the control chart points is beyond the control limits or is otherwise in violation of one of the several rules introduced in this chapter. Chapter 9 more fully discusses patterns indicating a lack of control. When no special causes of variation are present, the characteristic measured is said to be in statistical control or stable.

6.11.2 Evaluating the Present

Control charts have two main functions when evaluating the present condition of a process. The first function is to maintain a state of statistical control during a process's operation. Control charts can be used to generate “special cause” signals during normal operation. The signal might, for example, call attention to tool wear or changes in humidity that might require intervention in the process. In this sense, control charts are useful in maintaining an existing state of process stability. The second function is to stop management from over reacting to common causes of variation and treating them as special causes of variation for aggregated data. Recall, if a control chart is computed from aggregated data (data from multiple sources such a multiple production lines), then it is not an effective tool to detect special causes of variation. Rather, a control chart for aggregate data serves the purpose of stopping management of the process being control charted from tampering with the process.

6.11.3 Predicting the Near Future

Finally, control charts can be used to predict the near future condition of a process, based on statistical evidence of a process's stability and process knowledge concerning future conditions that could affect the process. For example, if a process is stable and a process expert foresees no future sources of special variation, then the expert can predict that the process will remain stable in the near future, thereby, making it possible to forecast, plan, and budget in a more responsible manner.

6.11.4 Tips on Using Control Charts

There are two means commonly employed by consultants to determine if control charts are being used on the shop floor or the service center area of an organization. The first is to determine if any dust appears on a control chart: the presence of dust usually indicates that the control charts are not being used by employees. The second is to identify the last plotted point on a control chart: if the last plotted point is not the most recently completed time period, then the control chart is probably not being used by employees.

6.12 Summary

In this chapter, we have focused on the importance of stabilizing and improving a process, and presented an overview of the techniques for accomplishing this.

All processes exhibit variation. We can distinguish between common causes of variation, affecting all elements of a process, and special variation, created by causes outside the system. In general, only management can reduce common variation, while workers and others more directly involved with the process are best suited to identifying sources of special variation.

Control charts enable us to identify and differentiate between these two sources of variation. As a result, we are able to eliminate special variation, stabilizing the process, and then focus on reducing common variation and hence improving the process. The continual reduction of variation, even within specifications, is critical to increasing quality, predictability, and customer satisfaction.

A process can be described as existing in one of four states: chaos, the brink of chaos, the threshold state, and the ideal state. When a process is in a state of chaos, it is producing some nonconforming product and it is not in a state of statistical control. A process on the brink of chaos produces 100 percent conforming product; however, the process is not stable. The threshold state describes a stable process that produces some nonconforming product; process variation results from common causes that are an inherent part of the system. The ideal state describes a stable process producing 100 percent conforming product.

All control charts have a centerline, representing the process average, and upper and lower control limits that provide information on the process variation. Control charts are constructed by drawing samples and taking measurements of a process characteristic. Each set of measurements is called a subgroup. Control limits, often called three-sigma limits, are based on the variation that occurs within the sampled subgroups. In this way, variation between the subgroups is intentionally excluded from the computation of the control limits; the common process variation becomes the variation on which we calculate the control limits.

When the observations are plotted on the control chart, points exhibiting non-random behavior, such as falling outside the control limits, are indications of special causes of variation. Once these causes are identified and eliminated from the system, the corresponding data points can be deleted and the control limits recalculated. This iterative procedure is continued until there are no indications of special variation, so that we now have a stable process.

The advantages of achieving a stable process are: management knows the process capability and can predict performance, costs, and quality levels; productivity will be at a maximum, and costs will be minimized; management will be able to measure the effects of changes in the system with greater speed and reliability; and if management wants to alter specification limits, it will have the data to back up its decision. A stable process is a basic requirement for process improvement efforts.

Once we have a stable process, there are two areas for action to reduce the difference between customer needs and process performance. First, action may be taken to change the process average. This might include action to reduce the level of defects or process changes to increase production or service. Second, management can act to reduce the level of common variation with an eye toward never-ending improvement of the process.

There are two types of mistakes that the user of a control chart may make: over-adjustment and under-adjustment. Proper use of control charts will minimize the total economic consequences of making either of these types of errors.

Stable processes always exhibit random patterns of variation. Accordingly, most data points will tend to cluster about the mean value, or centerline, with an approximately equal number of points falling above and below the mean. A few of the values will lie close to the control limits. Points will rarely fall beyond a control limit. Also there will seldom be prolonged runs upward or downward for a number of subgroups. If one or more of these conditions is violated in a control chart, the chart does not exhibit statistical control. By dividing the control chart into one-sigma width bands, called the A, B, and C zones, seven rules can be articulated which enable us to identify points which are out of control. Any out-of-control points found are marked with an X directly on the control chart.

In moving from no quality consciousness to never-ending improvement and innovation, we pass through several stages. Defect detection uses mass inspection to sort good units from bad units. Defect prevention uses attribute control charts to promote the goal post view of quality. Never-ending improvement uses variables control charts to promote the Taguchi Loss Function view of quality. The only path to continued prosperity must include innovations in future products and services. Innovation can be thought of as having two primary purposes: to create a dramatic breakthrough in decreasing the difference between customers' needs and process performance; and to discover customers' future needs.

The retrospective examination of the process's completed output using a control chart answers the question of whether the process has been in statistical control. When evaluating the present condition of a process, control charts have two main functions: to maintain a state of statistical control during a process's operation, and to stop management from over reacting to common causes of variation and treating them as special causes of variation for aggregated data. For the near future, control charts can be used to predict the condition of a process, based on statistical evidence of a process's stability and process knowledge concerning future conditions that could affect the process.

EXERCISES

6.1 Steel pails are manufactured at a high rate. Periodic samples of 50 pails are selected from the process. Results of that sampling are:

Sample No.	Subgroup Size	No. Defective
1	50	5
2	50	6
3	50	3
4	50	6
5	50	8
6	50	5
7	50	4
8	50	5
9	50	6
10	50	7
11	50	4
12	50	4
13	50	3
14	50	5
15	50	4
16	50	2
17	50	4
18	50	5
19	50	1
20	50	6

a. Calculate the string of successive proportions of defective pails.
b. Calculate the centerline and control limits for the p chart.
c. Draw the p chart.
d. Is the process stable? How do you know?

6.2 A medical transcription service enters medical data on patient files for hospitals. The service is studying ways to improve the turnaround time (defined as the time between receiving data and time the client receives completed files). Upon studying the process, it is determined that turnaround time is increased by transmission errors. A transmission error is defined as data transmitted that does not go through as planned, and needs to be re-transmitted. Each day a sample of 125 record transmissions are randomly selected and evaluated for errors. The table below presents the number and proportion of transmissions with errors in samples of 125 records transmitted.

TRANSMIT

Date	Number of Errors	Proportion of Errors
August:		
1	6	0.048
2	3	0.024
5	4	0.032
6	4	0.032
7	9	0.072
8	0	0.000
9	0	0.000
12	8	0.064
13	4	0.032
14	3	0.024
15	4	0.032
16	1	0.008
19	10	0.080
20	9	0.072
21	3	0.024
22	1	0.008
23	4	0.032
26	6	0.048
27	3	0.024
28	5	0.040
29	1	0.008
30	3	0.024
September:		
3	14	0.112
4	6	0.048
5	7	0.056

6	3	0.024
9	10	0.080
10	7	0.056
11	5	0.040
12	0	0.000
13	3	0.024

a. Construct a p chart.
b. Is the process in a state of statistical control? Why?

6.3 The following 32 days of data represent the findings from a study conducted at a factory that manufactures film canisters. Each day 500 film canisters were sampled and inspected. The number of film canisters that are defective are recorded each day below.

CANISTER

Day	No. Defective Canisters
1	26
2	25
3	23
4	24
5	26
6	20
7	21
8	27
9	23
10	25
11	22
12	26
13	25
14	29
15	20
16	19
17	23
18	19
19	18
20	27
21	28
22	24
23	26
24	23
25	27
26	28
27	24

28	22
29	20
30	25
31	27
32	19

a. Construct a p chart using the first 25 data points to calculate trial limits.
b. Is the process in a state of statistical control? Why?
c. If the process is in control, extend the limits and record data for days 26 through 32.

6.4 A jewelry manufacturing company has a data processing department with 115 terminals in various locations in its building. A technician is responsible for investigating and correcting problems with the terminals. She is concerned with the rate at which terminals develop problems; she collects the following data to see if the system is in a state of statistical control.

JEWELRY

Day	Number With Problems	Proportion With Problems
1	2	0.0174
2	5	0.0435
3	3	0.0261
4	13	0.1130
5	8	0.0696
6	6	0.0522
7	12	0.1043
8	1	0.0087
9	1	0.0087
10	5	0.0435
11	7	0.0609
12	10	0.0870
13	5	0.0435
14	6	0.0522
15	9	0.0783
16	3	0.0261
17	4	0.0348
18	8	0.0696
19	4	0.0348
20	2	0.0174
21	2	0.0174
22	4	0.0348
23	7	0.0609
24	10	0.0870
25	6	0.0522

26	5	0.0435
27	5	0.0435
28	9	0.0783
29	1	0.0087
30	4	0.0348

a. Construct a control chart for these data.
b. Is the process in a state of statistical control? Why?
c. If the process is not in a state of control, eliminate out of control points and recalculate the control limits.

6.5 A commuter railroad in a large northeastern city runs 122 trains from suburban areas into the city each weekday. A survey of rider satisfaction indicates that commuters are very concerned with trains arriving on time. Before making changes to the system to increase the proportion of on-time arrivals, the railroad wants to know whether the proportion of on-time arrivals is in a state of statistical control. The number of late trains for 30 weekdays is as follows:

RRLATE

Day	Number Late	Day	Number Late
1	3	16	7
2	1	17	3
3	1	18	4
4	4	19	7
5	5	20	5
6	4	21	2
7	6	22	6
8	3	23	2
9	4	24	4
10	5	25	4
11	6	26	5
12	1	27	4
13	7	28	6
14	4	29	1
15	4	30	2

a. Construct a p chart for these data.
b. Is the process in a state of statistical control? Why?
c. If the process is not in a state of control, eliminate out of control points and recalculate the trial control limits.

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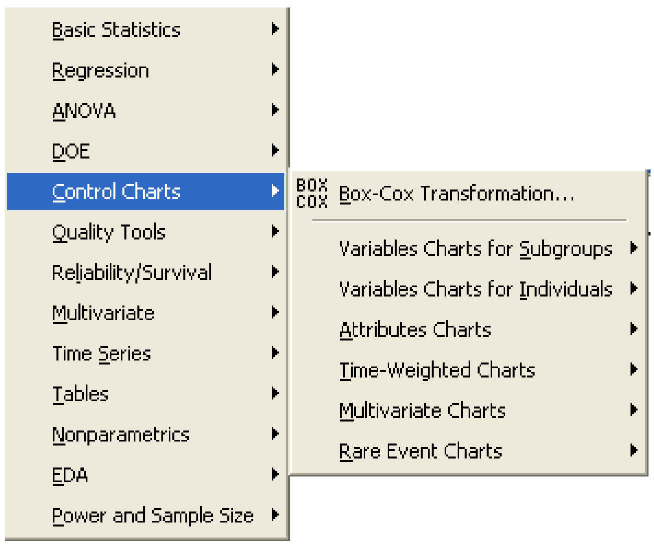
Appendix A6.1
Using Minitab for Control Charts: An Overview

The concept of a control chart has been introduced in this chapter along with rules for detecting out-of-control patterns. The Minitab statistical software package will be used to perform the computations for control charts in this text.

To use Minitab to obtain a control chart, select **Stat | Control Charts**. The list of different types of control charts available is displayed in Figure A6.1.

Figure A6.1
List of Control Charts Available in Minitab



Each control chart provides tests for special causes, usually in the Options box for the test. Note that the default choices for the 8 tests provided are not identical to the rules given in this chapter. The new values provided stay in effect until Minitab is restarted.

Figure A6.2
Tests Tab of the X-bar and R Chart – Options Dialog Box