Introduction

The Shewhart control chart is a graphical and analytical tool for deciding whether a process is in a state of statistical control. You can use the SHEWHART procedure to display many different types of control charts, including all commonly used charts for variables and attributes. In addition, you can use the SHEWHART procedure to

- create charts from either raw data (actual measurements) or summarized data

- analyze multiple process variables

- specify control limits in terms of a multiple of the standard error of the plotted summary statistic or as probability limits

- adjust control limits to compensate for unequal subgroup sizes

- estimate control limits from the data, compute control limits from specified values for population parameters (known standards), or read limits from an input data set

- create historical control charts that display distinct sets of control limits for multiple time phases

- perform tests for special causes based on runs patterns (Western Electric rules)

- estimate the process standard deviation using various methods (variable charts only)

- accept numeric-valued or character-valued subgroup variables

- display subgroups with date and time formats

- save chart statistics and control limits in output data sets

- tabulate chart statistics and control limits

- generate charts on line printers or on graphics devices. Charts produced on line printers can use special formatting characters that improve the appearance of the chart. Charts produced on graphics devices can be annotated, saved, and replayed.

Uses of Shewhart Charts

The Shewhart chart is named after Walter A. Shewhart (1891-1967), a physicist at the Bell Telephone Laboratories, who introduced the method in 1924 and elaborated upon it in his book *Economic Control of Quality of Manufactured Product*, (1931).

The concepts underlying the control chart are that the natural variability in any manufacturing process can be quantified with a set of control limits and that the variation exceeding these limits signals a change in the process.

In industry, the Shewhart chart is the most commonly applied statistical quality control method for studying the variation in output from a manufacturing process. Shewhart charts are typically used to distinguish variation due to *special causes* from variation due to *common causes*. Special causes, also referred to as *assignable causes*, are local, sporadic problems such as the failure of a particular machine or a mistakenly recorded measurement. Common causes are problems inherent in the manufacturing system as a whole. Examples of common causes are inadequate product design, inherited defective material, and excessive humidity.

When the special causes have been identified and eliminated, the process is said to be in *statistical control*. Once statistical control has been established, Shewhart charts can be used to monitor the process for the occurrence of future special causes and to measure and reduce the effects of common causes.

Deming (1982) emphasized that the improvement of a process can begin only after statistical control has been established. Deming also noted that control chart techniques are applicable to quality improvement in service industries as well as manufacturing industries.

Characteristics of Shewhart Charts
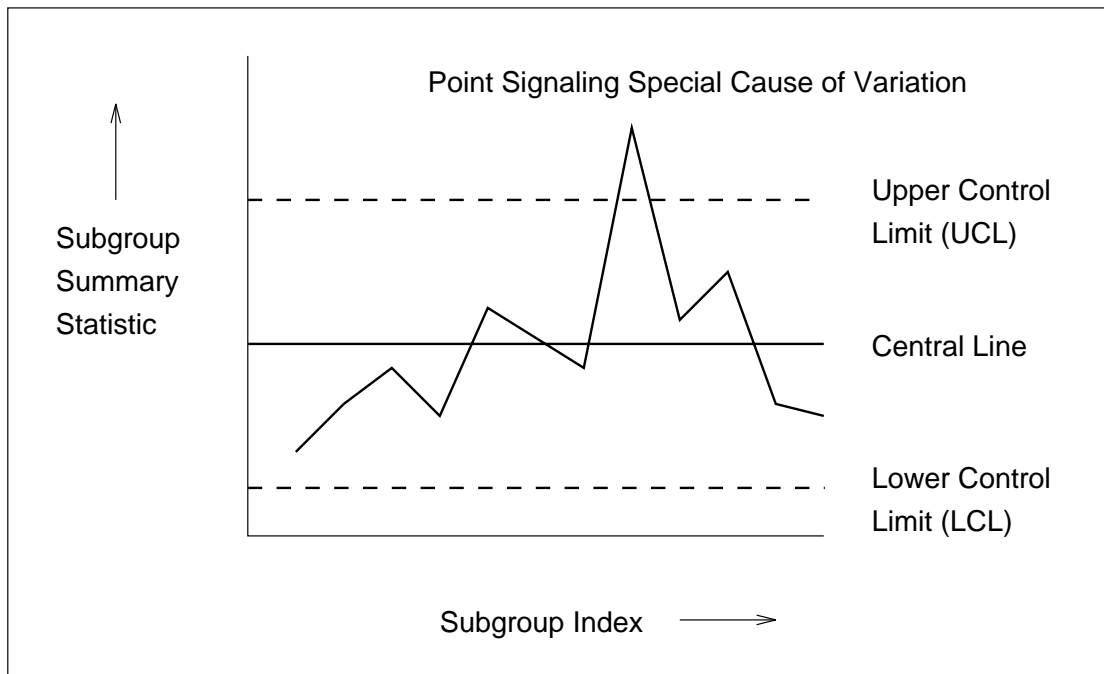
Figure 1 illustrates a typical Shewhart chart.

Figure 1. A Shewhart Control Chart

All Shewhart charts have the following characteristics:

- Each point represents a *summary statistic* computed from a sample of measurements of a quality characteristic. For example, the summary statistic might be the average value of a critical dimension of five items selected at random, or it might be the proportion of nonconforming items in a sample of 100 items.

- The *vertical axis* of a Shewhart chart is scaled in the same units as the summary statistic.

- The samples from which the summary statistics are computed are referred to as *rational subgroups* or *subgroup samples*. The organization of the data into subgroups is critical to the interpretation of a Shewhart chart. Shewhart (1931) advocated selecting rational subgroups so that variation within subgroups is minimized and variation among subgroups is maximized; this makes the chart more sensitive to shifts in the process level. Various approaches to subgrouping are discussed by Grant and Leavenworth (1980), Montgomery (1996), and Kume (1985).

- The *horizontal axis* of a Shewhart chart identifies the subgroup samples. Frequently, the samples are indexed according to the order in which they were taken or the time at which they were taken. Subgroup samples can also be assigned labels that indicate some other type of classification (for example, lot number).

- The *central line* on a Shewhart chart indicates the average (expected value) of the summary statistic when the process is in statistical control.

- The *upper and lower control limits*, labeled UCL and LCL, respectively, indicate the range of variation to be expected in the summary statistic when the process is in statistical control. The control limits are commonly computed as 3σ limits[*] representing three standard errors[†] of variation in the summary statistic above and below the central line. However, the limits can also be determined using a multiple of the standard error other than three, or from a specified probability (α) that a single summary statistic will exceed the limits when the process is in statistical control. Limits determined by the latter method are referred to as *probability limits*.

  The control limits are also determined by the subgroup sample size because the standard error of the summary statistic is a function of sample size. If the sample size is constant across subgroups, the control limits are typically horizontal lines, as in Figure 1. However, if the sample size varies from subgroup to subgroup, the limits are usually adjusted to compensate for the effect of sample size, resulting in step-like boundaries.

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[*]In this context, the symbol σ always stands for the standard error of the subgroup summary statistic that is plotted on the chart. Elsewhere in this chapter, σ is also used to denote the standard deviation of a process, also referred to as the population standard deviation. This dual usage is standard practice.

[†]The term *standard deviation* is also used by some authors to refer to this quantity; see, for example, Montgomery (1996). This chapter uses the term *standard error* for the dispersion of the distribution of a statistic and the term *standard deviation* for the dispersion of a distribution of individual measurements.

Control limits can be estimated from the data being analyzed, or they can be standard, previously determined values. Estimated limits are often used when statistical control is being established, and standard limits are often used when statistical control is being maintained.

- *A point outside the control limits* signals the presence of a special cause of variation. Additionally, *tests for special causes* (also referred to as *Western Electric rules* and *runs tests*) can signal an out-of-control condition if a statistically unusual pattern of points is observed in the control chart. For example, one pattern used to diagnose the existence of a trend is seven consecutive steadily increasing points.

  When the process is in statistical control, a point may fall outside the control limits purely by chance, resulting in a false out-of-control signal. However, when the Shewhart chart correctly signals the presence of a special cause, additional action is needed to determine the nature of the problem and eliminate it.

Classification of Shewhart Charts

Shewhart charts are broadly classified according to the type of data analyzed.

- Shewhart charts for *variables* are used when the quality characteristic of a process is measured on a continuous scale.

- Shewhart charts for *attributes* are used when the quality characteristic of a process is measured by counting the number of nonconformities (defects) in an item or the number of nonconforming (defective) items in a sample.

Shewhart charts for variables are further classified according to the subgroup summary statistic plotted on the chart.

- $\bar{X}$ and R charts display subgroup means (averages) and ranges. Typically the two charts are presented on the same page, with the $\bar{X}$ chart aligned above the R chart to facilitate the simultaneous analysis of the central tendency and variability of the process.

- $\bar{X}$ and s charts display subgroup means (averages) and standard deviations. Typically the two charts are presented on the same page, with the $\bar{X}$ chart aligned above the s chart.

- Median and range charts display subgroup medians and ranges. Typically the two charts are presented on the same page, with the median chart aligned above the R chart.

- Charts for individual measurements and moving ranges display individual measurements and moving ranges of two of more successive measurements. In this case the subgroup sample consists of a single observation.

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Likewise, Shewhart charts for attributes are classified according to the subgroup summary statistic plotted on the chart:

- A p chart displays the proportion of nonconforming (defective) items in a subgroup sample.

- An np chart displays the number of nonconforming (defective) items in a subgroup sample.

- A u chart displays the number of nonconformities (defects) per unit in a subgroup sample consisting of an arbitrary number of units.

- A c chart displays the number of nonconformities (defects) in a unit (here, a subgroup sample typically consists of one unit).

You can create all of the preceding types of Shewhart charts with the SHEWHART procedure. In addition, you can create a wide variety of nonstandard Shewhart charts, including

- a trend chart displaying a time trend plot and an $\bar{X}$ chart (or median chart) that has been created removing the time trend from the data. The trend chart and $\bar{X}$ chart are presented on the same page, with the $\bar{X}$ aligned above the trend chart, to facilitate the detection of special causes after accounting for the time trend effect. Trend charts are applicable when a time trend (for instance, due to tool wear) is observed in a preliminary $\bar{X}$ chart of the original data.

- a box chart displaying a box plot (box-and-whisker plot) for each subgroup and control limits for the subgroup means. This chart facilitates detailed analysis of the subgroup distributions and is applicable with large subgroup sample sizes (ten or more).

Learning to Use the SHEWHART Procedure

Although the SHEWHART procedure provides a large number of options, you can use the procedure to create a basic Shewhart chart with as few as two SAS statements:

- the PROC SHEWHART statement, which starts the procedure and specifies the input SAS data set

- a chart statement, which specifies the type of Shewhart chart you want to create and the variables in the input data set that you want to analyze

For example, you can use the following statements to create $\bar{X}$ and R charts with 3σ limits for measurements read from a SAS data set named DRUMS:

```
proc shewhart data=drums graphics;
   xrchart flwidth*hour;
run;
```

The keyword XRCHART in the chart statement specifies that $\bar{X}$ and R charts are to be created. The following SAS variables are specified in the XRCHART statement:

- A SAS variable (FLWDITH), whose values are the process measurements, is specified before the asterisk. This variable is referred to as the *process*.

- A SAS variable (HOUR), whose values classify the measurements into subgroups, is specified after the asterisk. This variable is referred to as a *subgroup-variable*.

The same form of specification is used with other chart statements to create different types of Shewhart charts. The following table lists the keywords for the 13 chart statements that are available with the SHEWHART procedure:

Table 1. Chart Statements in the SHEWHART Procedure

Keyword	Chart(s) Displayed	"Getting Started" Page
BOXCHART	box chart with optional trend chart	1050
CCHART	c chart	1106
IRCHART	individual and moving range charts	1144
MCHART	median chart with optional trend chart	1184
MRCHART	median and R charts	1220
NPCHART	np chart	1264
PCHART	p chart	1304
RCHART	R chart	1348
SCHART	s chart	1384
UCHART	u chart	1420
XCHART	$\bar{X}$ chart with optional trend chart	1458
XRCHART	$\bar{X}$ and R charts	1502
XSCHART	$\bar{X}$ and s charts	1552

If you are using the SHEWHART procedure for the first time, you should

- read Chapter 31, "PROC SHEWHART and General Statements"

- read the "Getting Started" section in the chapter for the chart statement you need to create your chart. Table 1 lists the pages for these sections.

Once you have learned to use a particular chart statement, you will find it straightforward to use the remaining chart statements since their syntax is nearly the same. A separate, self-contained chapter is provided for each chart statement.