
Guide to statistical process control (SPC) charts for variables —

Part 1: Charts for mean, median, range and standard deviation

ICS 21.060.10; 21.060.20

Confirmed November 2008

Committees responsible for this British Standard

The preparation of this British Standard was entrusted to Technical Committee SS/4, Statistical process control, upon which the following bodies were represented:

- BEAMA Limited
- British Standards Society
- Cable and Wireless Communications plc
- Clay Pipe Development Association Limited
- Federation of Small Businesses
- Gauge and Tool Makers' Association
- General Domestic Appliances Limited
- Institute of Quality Assurance
- Royal Statistical Society
- Society of Motor Manufacturers and Traders Limited

This British Standard, having been prepared under the direction of the Management Systems Sector Committee, was published under the authority of the Standards Board and comes into effect on 15 April 2001

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Amendments issued since publication

Amd. No.	Date of issue	Comments

The following BSI references relate to the work on this standard:
Committee reference SS/4
Draft for comment 94/408916 DC

ISBN 0 580 33229 2

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Foreword

This part of BS 5702 has been prepared by Technical Committee SS/4.

It is envisaged that, ultimately, BS 5702 will consist of the following parts:

- *Part 0: General introduction to control charts for measurements;*
- *Part 1: Charts for mean, median, range and standard deviation;*
- *Part 2: Charts for individual values and moving range and for moving averages and moving ranges/standard deviations;*
- *Part 3: Charting techniques for short production runs and small batches;*
- *Part 4: Charting techniques for special situations.*

A new British Standard on process capability is in the course of preparation and this subject is not included in this standard.

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Summary of pages

This document comprises a front cover, an inside front cover, pages i and ii, pages 1 to 36, an inside back cover and a back cover.

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Introduction

The business aim of statistical process control (SPC) is to control and improve quality, increase productivity and reduce cost. This is achieved through the analysis of the variation of a process or its outputs in order to take appropriate actions to:

- achieve and maintain a state of statistical control;
- provide a quantitative measure of process performance;
- improve process capability.

The variation in a quality characteristic of a process is due to two types of causes:

- *assignable (special)*: systematic cause or causes that are not part of the process all the time but arise due to special circumstances;
- *random (common)*: non-systematic causes that are inherent in the process.

The principal tool of SPC is the control chart. There are two main types of control chart, Shewhart and cusum (Cumulative SUM).

NOTE Cusum charts are dealt with in BS 5703.

The Shewhart control chart provides a graphical representation of a process showing plotted values of a representative statistic of the characteristic (e.g. count, mean, range, standard deviation), a centre line, and one or more control lines. The control line(s) and centre line are used as a basis for judging the stability of the process, namely, whether or not the process is in statistical control. Control limits are derived from the performance of the process and are not to be confused with specification limits or specified tolerances.

Shewhart control charts provide a common international language for communicating technical information on the performance of a process. Control charts are effective tools in understanding process behaviour. They distinguish between random and assignable causes of variation. When no assignable causes are present, the process is said to be in statistical control.

When a process is in statistical control its performance is predictable and can be assessed. This performance can be improved by reducing random cause variation and improving process centring (targeting).

The control chart has wide applicability throughout an organization, ranging from marketing, sales, finance, administration to manufacturing or service.

There are essentially two main classes of Shewhart control chart, namely attribute charts and variable charts. Attributes charts are dealt with in BS 5701. This part of BS 5702 deals solely with the control aspects of Shewhart-type variables charts for mean, median, range and standard deviation, using both Shewhart and probabilistic control limits.

1 Scope

This part of BS 5702 describes a method of statistical process control that involves charting measurements of a given characteristic. It sets out accepted methods of sampling and charting that are easy to use and that often can safely and profitably replace routine inspection. These charts indicate both the level and variability of the characteristic.

The control aspects of Shewhart-type variables charts for mean, median, range and standard deviation, using both Shewhart and probabilistic control limits, are described.

Guidance is given to persons concerned with making decisions on products and processes. The charting techniques outlined may be employed to establish and maintain process control over the charted characteristic.

No attempt is made to deal at length with the statistical principles underlying the methods described in this standard.

2 Normative references

The following normative documents contain provisions which, through reference in this text, constitute provisions of this part of BS 5702. For dated references, subsequent amendments to, or revisions of, any of these publications do not apply. For undated references, the latest edition of the publication referred to applies.

BS ISO 3534-1:1993, *Statistics — Vocabulary and symbols — Part 1: Probability and general statistical terms*.

BS ISO 3534-2:1993, *Statistics — Vocabulary and symbols — Part 2: Statistical quality control*.

BS EN ISO 8402:1995, *Quality management and quality assurance — Vocabulary*.

3 Definitions

For the purposes of this part of BS 5702, the definitions given in BS EN ISO 8402:1995, BS ISO 3534-1:1993, BS ISO 3534-2:1993 and the following apply.

3.1

control line (action line)

line drawn on a control chart to indicate a control limit

NOTE 1 Users of probabilistic control limits usually employ the term "action line" instead of "control line", a practice which has also been adopted in this standard in the discussion of probabilistic control charts.

NOTE 2 In loose day-to-day usage the terms "control line" and "control limit" are often used indiscriminately, meant to denote the same thing. In this standard the terms are used with their specific meaning. The term "control limits" is defined in BS ISO 3534-2 (see 3.4.1). They are calculated numerical values that define the location of the control lines on the chart.

3.2

random causes (of variation)

factors, generally many in number but each of relatively small importance, contributing to variation, which have not necessarily been identified

NOTE Synonyms used to designate the factors responsible for inherent variation in characteristics of product items are "chance causes" and "common causes". In this standard the term "random causes" is used exclusively.

3.3

assignable cause (of variation)

factor (usually systematic) that can be detected and identified as contributing to a change in a quality characteristic or process level

NOTE Synonymous term used to designate variation attributable to a specific factor is "special cause". However, this standard will only use the term "assignable cause".

3.4

control chart

chart normally consisting of two plots – one to depict how over time the subgroup averages vary in relation to the target process mean, the other to indicate the extent of the variation within the subgroups over time

3.5

process

any activity that operates upon an input and as a result produces an output

4 Symbols

The following symbols and abbreviated terms are used in this part of BS 5702.

CL	Centre line
UCL	Upper centre line
LCL	Lower control line
UWL	Upper warning line
LWL	Lower warning line
UAL	Upper action line (see Annex B)
LAL	Lower action line (see Annex B)
i	Counter for items in a subgroup
j	Counter for subgroups in a sequence
k	Number of subgroups
n	Subgroup size
n_j	Number of items in the j^{th} subgroup
X	Individual value of the characteristic for items in a subgroup
X_{ij}	Value of the characteristic for the i^{th} item of the j^{th} subgroup
$X_{\max}$	Highest value in a subgroup
$X_{\min}$	Lowest value in a subgroup
$\bar{X}$	Arithmetic mean of the characteristic for all items in a subgroup
$\bar{\bar{X}}$	Arithmetic mean of a number of values of $\bar{X}$ (i.e. arithmetic mean of the characteristic for all subgroups combined)
R	Subgroup range ($X_{\max} - X_{\min}$)
$\bar{R}$	Arithmetic mean of subgroup range values
$\tilde{X}$	Subgroup median
$\bar{\tilde{X}}$	Arithmetic mean of subgroup median values
μ	True process mean value
μ_0	Nominal value for the process mean
μ_R	Process arithmetic mean of the range in subgroups of size n
μ_s	Process arithmetic mean of the standard deviation in subgroups of size n
σ	True process standard deviation
σ_0	Assumed true process standard deviation
$\hat{\sigma}$	Unbiased estimate of the process standard deviation
σ_e	Standard error of the plotted characteristic (see NOTE 3 below)
σ_R	Process standard deviation of the range in subgroups of size n
σ_s	Standard deviation of the process standard deviation in subgroups of size n
s	Subgroup standard deviation
$\bar{s}$	Arithmetic mean of a number of subgroup standard deviations (see NOTE 1 below)
$\bar{s}'$	Square root of the arithmetic mean of s^2 over a number of subgroups (see NOTE 1 below)

NOTE 1 The symbol $\bar{s}$ represents the arithmetic mean of a number of individual subgroup standard deviations and is used to obtain a (biased) estimate of the process standard deviation. An alternative method which is less biased is to take the square root of the arithmetic mean of the squares of the subgroup standard deviations. The correct, but awkward, expression for the latter would

therefore be $\sqrt{\bar{s}^2}$. In this part of BS 5702 the symbol $\bar{s}'$ is used in place of $\sqrt{\bar{s}^2}$. (See also 7.2.2.2.1.)

NOTE 2 The symbol $\hat{\sigma}$ is the notation generally employed to denote an estimate of a population standard deviation and it should be noted that the use of this symbol in this part of BS 5702 is more specific than this.

NOTE 3 In several places of this part of BS 5702 the term "standard error" has been used (and denoted by σ_e). In the context of this part of BS 5702 the term represents the standard deviation of the distribution of a statistic, e.g. the standard deviation of the subgroup means, the subgroup medians or the subgroup ranges.

5 Preparation for control charting

5.1 General

Any statistical method will fail to achieve a desired objective unless management has prepared a responsive environment. Open communication should be developed. A team approach should be used, and training and resources should be provided to support improvement actions. This clause outlines the steps to be taken to ensure that a suitable environment for control charting is established.

5.2 Analysis of the process

5.2.1 *Concept of process*

The definition of “process” for the purposes of this standard is given in **3.5**.

The process should be understood in terms of its relationship to other operations in the system and in terms of the individual process elements. Irregularities may arise from a variety of causes associated with equipment, materials, methods, human factors, etc., and these may have effects at different stages. Methods of presentation such as process flow diagrams may help to clarify such relationships.

5.2.2 *Minimization of variation*

Unnecessary external causes of variation should be reduced before charting begins. This could simply mean ensuring that the process is being operated as intended, or it could mean conducting a designed experiment with known input materials, constant control settings, etc. The purpose is to avoid problems that should be corrected beforehand, including excessive process adjustment or over-control. In all cases a process log should be kept, noting all relevant events such as tool changes, new raw material lots, etc.

5.2.3 *Identification of output*

The process should be considered as a single stream having a single set of causes. If there are two or more distinct streams, the usual practice is for each to be treated separately in the control programme because they come from different systems, e.g. different conveyor or machine lines. Alternatively, methods of control that recognize the differences between streams may be used.

5.3 Choice of characteristics

5.3.1 *Determination of characteristics to be managed*

Attention should be concentrated on those characteristics that are most promising for process improvement or which give the clearest indications of subsequent performance. Several considerations are appropriate as follows.

- a) *The customer's needs*: the requirements of subsequent processes that use the product or service as an input, as well as those of the end user should be determined.
- b) *Current and potential problem areas*: evidence of waste or poor performance, e.g. scrap, rework, returns from customers, excessive overtime, missed targets, and areas of risk, such as proposed changes to the design of the product or service should be monitored.
- c) *Related characteristics*: characteristics that are difficult to measure may be represented by surrogate characteristics that are directly related but more easily measured, e.g. volume may be represented by weight; in addition, charting of one characteristic may be sufficient to control several closely related characteristics.

5.3.2 *Defining measured characteristics*

The characteristics to be measured should be clearly defined, so that findings can be effectively communicated to all concerned. This involves specifying the information to be gathered, where, how and under what conditions. The method of measurement should be analysed to note any factors that may give rise to errors. The measurement equipment itself should be predictable for both accuracy and precision (see BS ISO 5725). Studies should be undertaken to assess the precision of the measurements and improve it where necessary. Imprecise measurements can increase the *apparent* variation of a process.

5.3.3 *Determination of the point of measurement*

The earliest point at which measurement can be carried out for the characteristic under consideration should be determined in order to obtain, as soon as possible, information regarding variability that arises in the process.

5.4 Collection of data

5.4.1 Data gathering

A data-gathering plan should be developed and used as the basis for collecting, recording and plotting the data on a chart. Variables charts should be constructed from measurements of a particular process parameter or product (i.e. process output) characteristic. These data should be obtained from small rational subgroups of constant size (see 5.4.2.1).

5.4.2 Selection of subgroups

5.4.2.1 Rational subgroup

As the first key step in variables control charting, “rational subgroups” should be established. These will determine the effectiveness and efficiency of the control chart that uses them.

The subgroups should be chosen so that the variation within a subgroup will consist only of inherent process variability. Any assignable variation between subgroups would reflect changes in the process that should be investigated for appropriate action.

For an initial study of a process, the subgroups should consist of two or more items from a single process stream. All items within each subgroup should be produced under similar production conditions over a very short time interval; hence, variation within each subgroup should primarily reflect the inherent random variation. Where these conditions are not met, the resulting control chart may not indicate assignable causes of variation effectively. For each process stream, subgroup sizes should remain constant.

Statistics from subgroups should generally be plotted in order of occurrence. The specific objective of the control chart will influence the choice of subgroup, e.g. if the objective is to evaluate differences between suppliers, then only data from a single supplier should be included within a subgroup. The individual chart ($\bar{X}$ chart) may be used when the data cannot be organized into rational subgroups.

If there is a strong positive correlation between consecutive items in a subgroup (to be covered in Part 4 of BS 5702), some random causes may not manifest themselves within the confines of one subgroup if this is made up of consecutive items. If there is evidence of such correlation, it may be appropriate to spread out the measurements to capture the full extent of the random variation.

5.4.2.2 Subgroup size

The subgroup size, that is the number of items, n , included in each of the rational subgroups, will sometimes be dictated by circumstances. Where testing or measurement is expensive or time consuming, or if items need to be destroyed, $n = 2$ may be an enforced choice. At the other extreme, where automatic testing or inspection is performed by instrumentation with direct transfer to electronic data processing, $n = 25$ or more may be feasible.

Between these extremes, some factors affecting the choice of n include the following:

- a) where the process location is monitored by subgroup medians, an odd subgroup size is preferable to an even number, so that the median corresponds to the middle value of the ordered subgroup values and does not have to be the average of the two middle values;
- b) for the calculation of the arithmetic mean, $n = 5$ or 10 can eliminate the need for division; thus, for $n = 10$ the decimal point for the sample total ΣX is shifted one place to the left, whilst for $n = 5$ the total is doubled before shifting the decimal point;
- c) although large subgroup sizes provide a more precise estimate of the current state of the process, time and cost factors work in the opposite sense;
- d) even when the process characteristic is not normally¹⁾ distributed, the distribution of the arithmetic mean in subgroups of size n rapidly approaches normality as n increases, as a result of which the probabilities associated with probabilistic $\bar{X}$ charts become approximately correct.

For values of n greater than about 8, R charts become relatively inefficient and s charts should be used.

For a combination of these reasons $n = 5$ is widely used and, in the absence of other overriding considerations, can at least be regarded as a useful starting point. (The subgroup size can be revised later if experience shows this to be advisable.)

¹⁾ The mathematical usage of the word “normally” is intended throughout this document.

5.4.2.3 Subgroup frequency

Subgroups should be collected often enough to detect changes in the process within a reasonable time of their occurrence. The times at which they are taken should reflect the potential causes of change, e.g. changes of shift, relief operators, warm-up trends or different material lots. To ensure the capture of such process changes, a useful rule of thumb is to take at least six subgroups between anticipated changes in a process.

During an initial process study, the subgroups may be taken consecutively or at very short intervals to detect whether the process shifts or shows other instability. When the process appears stable the period between subgroups can be increased.

5.4.2.4 Number of subgroups

When deciding the number of subgroups, it should be borne in mind that this number should satisfy two requirements.

- a) From the point of view of the process, the number of subgroups should be sufficiently large for the major sources of variation to have had an opportunity to manifest themselves on the chart.
- b) As a statistical consideration there should be 25 or more subgroups containing in all 125 or more readings to give a good test for stability and, if stability has been demonstrated, to give a good estimate of the process location and a reasonable estimate of the process variability.

NOTE A sampling regime may sometimes be established using previous data. Such data should always be used with caution and only if they are recent and if the basis of sampling is clearly understood.

5.4.3 Calculation of $\bar{X}$ and R for each subgroup

The average, $\bar{X}$, and the range, R , for each subgroup reflect the overall process location and its variability, respectively.

The subgroup average is the arithmetic mean of the individual values within the subgroup and should be calculated from the following formula:

$$\bar{X} = \frac{X_1 + X_2 + \dots + X_n}{n} \quad (1)$$

where $X_1, X_2, \dots$ are the individual values and n is the subgroup size.

The range should be calculated as follows:

$$R = X_{\max} - X_{\min} \quad (2)$$

NOTE As a measure of variability, an alternative to the range is the standard deviation, s . (See 6.2.2.)

5.4.4 Charting raw data

Control charts should be constructed and analysed in accordance with Annex A. They should be constructed with the $\bar{X}$ plot above the R plot and a data block at the bottom. The values of $\bar{X}$ and R should be represented on the vertical axis, while the sequence of subgroups should be represented on the horizontal axis. Chart layout should be in accordance with Figure 1.

The chart should be sufficiently long to provide a history of the process. The scales selected should enable all the information to be clearly visible. As a rough guide, the maximum and minimum scale values selected typically cover twice the distance between the upper and lower control lines. This ensures that very few plotted points will fall beyond the scale. Additionally, Table 1 recommends appropriate scales for different subgroup sizes.

Process Control Chart									
Part Name	Characteristic	Specification	Sampling - Frequency	Op.	Machine Number	Distribution of $\bar{X}$			
Average $\bar{X}$					Remarks				
Range R									
Shift									
Time									
Date									
X 1									
X 2									
X 3									
X 4									
X 5									
ΣX									
$\bar{X}$									
R									
					$\bar{\bar{X}} =$ $\bar{\bar{R}} =$ $UCL_{\bar{X}} = \bar{\bar{X}} + A_2 \bar{\bar{R}} =$ $LCL_{\bar{X}} = \bar{\bar{X}} - A_2 \bar{\bar{R}} =$ $UCL_R = D_4 \bar{\bar{R}} =$ $LCL_R = D_3 \bar{\bar{R}} =$				
					Contents Sample size A_2 D_3 D_4 n $\bar{\bar{R}}$ $\bar{\bar{R}}$ $\bar{\bar{R}}$ 2 1.880 0 3.267 3 1.023 0 2.574 4 0.729 0 2.282 5 0.577 0 2.114 6 0.483 0 2.004 7 0.419 0.076 1.924				

Figure 1 — Recommended control chart layout for $\bar{X}/R$ chart

Table 1 — $\bar{X}$ scale as a function of subgroup size

Subgroup size n	Scale interval (in multiples of $\bar{R}$)
2	7.1
3	4.7
4	3.9
5	3.4

The data block should include space for each of the individual readings. It should also include a space for the sum of the readings (ΣX), $\bar{X}$ and R , and the date and time or some other identification of the subgroup. For each subgroup the data values and the plot points for $\bar{X}$ and R should be aligned vertically.

Any relevant data should be logged on the chart to assist in diagnosis and in searching for causes of variability. It may be necessary to record on the chart any kind of process change such as trial loads, material or tool changes or to show times of production or even specific machine numbers or operators' names. The need to *speedily* identify times or sources of production should also be considered since some causes of problems may be transient.

6 Types of variables charts

6.1 General

Control charts can be presented using a variety of measures to permit assessment of changes in level and variability. Mean ($\bar{X}$) plots or median $\tilde{X}$ plots may be used to monitor the level, whereas standard deviation (s) or range (R) plots may be used to monitor the variability. The decision which to use should be made on the basis of the criteria set out in 6.2.1 and 6.2.2. In some applications only one measurement can be made at each sampling time; in these cases the individual measurements may be recorded on the control chart and a number of consecutive observations may be grouped to obtain running estimates of variability. This will be considered in BS 5702-2. (See also BS 5700)

6.2 Statistical measures

6.2.1 Measures of location

The most common choice as a measure of location is $\bar{X}$. The median $\tilde{X}$ may be the preferred measure of location when the subgroup data come from an asymmetric distribution. It may also be preferred when ease of computation is paramount.

6.2.2 Measures of variability

The range, R , is the most commonly used measure of variability in industrial applications of statistical process control. It is easy to calculate and it is a relatively efficient measure of variability for small subgroup sizes (especially below 8).

A more efficient indicator of process variability, especially with larger subgroup sizes, is the standard deviation s . It has a drawback that its calculation is more complex than that of the range. The standard deviation of a subgroup is defined as follows:

$$s = \sqrt{\frac{\Sigma(X_i - \bar{X})^2}{(n-1)}} \quad (3)$$

When using certain types of calculator, the following equivalent formula may be preferred for the calculation of s :

$$s = \sqrt{\frac{n\Sigma X_i^2 - (\Sigma X)^2}{n(n-1)}} \quad (4)$$

However, with most scientific calculators, s may be calculated directly using the σ_{n-1} key.

The standard deviation should be used as a measure of variability where:

- a) the data are recorded by computer, so that a calculation routine for s can easily be incorporated; or
- b) the ready availability of a pocket calculator (with a standard deviation function) makes computation of s a routine matter; or
- c) large subgroup sizes are used.

7 Setting up the control chart

7.1 Collection and analysis of preliminary data

Before setting up the control chart it is necessary to collect and analyse some preliminary data under normal operating conditions for the process. The preliminary data should be used to obtain estimates of the process level and variability against which future observations may be tested. At least 25 subgroups in the preliminary data set are recommended, although, if it is necessary to set up the programme with minimal delay, as few as 10 may be used in the preliminary data, pending the accumulation of more data.

If a collection of past data is already available that reflects the current operation of the process, and it is in a form that permits subgrouping on the basis decided upon, these past data may be used at once without waiting for the accumulation of new data.

Once control lines have been established, the preliminary data should be examined to make sure that no points lie outside the control lines (i.e. that no assignable causes were operating while the preliminary data were being collected). Reasons should be sought for any aberrant data, and the cause(s) removed, if possible.

Whilst there are other, more rigorous, statistical procedures for initial analysis, the trial control lines offer an effective and simple tool.

New control lines may be re-computed from a new trial period or assessed from the random causes system after all removable assignable causes have been addressed.

When a sufficient number of subgroups has been collected, the positions of the control lines should be computed in accordance with 7.2.

Preliminary data should be collected and analysed in accordance with the flowchart shown in Figure 2.

7.2 Establishment of centre line and control lines

7.2.1 Location of centre line and control lines

A control chart should be set up by establishing the location of up to six lines (or, if warning lines are included, up to 10 lines), i.e. a centre line (CL), and an upper and/or lower control line (UCL and LCL, respectively) for each of the two plots in the chart.

NOTE In Shewhart-type control charts warning lines are not usually applied. However, when used in probabilistic charts (and exceptionally in Shewhart charts) they are designated upper warning line (UWL) and lower warning line (LWL). In probabilistic charts the control lines are known as the upper action line (UAL) and the lower action line (LAL) (see Annex B).

For the plot of subgroup averages ($\bar{X}$) or for the median plot ($\tilde{X}$) the location of the centre line should be set by the target value, for which the overall average from a previous chart or from a preliminary evaluation is often adopted, i.e. the target value should be $\bar{\bar{X}}$ or $\tilde{\bar{X}}$. However, the following are some questions that should be considered before adopting $\bar{\bar{X}}$ or $\tilde{\bar{X}}$.

- a) Is there a logical or target value for the application, such as:
 - the nominal value from a specification;
 - a technologically sound aim value for a process variable that is known to give good operational performance?
- b) When the control chart indicates departure from target, is the adjustment or correction of the system a simple and straightforward matter without undesirable side effects (such as increasing the variation, destabilizing other important variables, or the risk of making erroneous corrections)?