

BRITISH STANDARD

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

Part 2: Charts for individual values

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Foreword

Publishing information

This part of BS 5702 was published by BSI and came into effect on 30 April 2008. It was prepared by Technical Committee SS/4, *Statistical process control*. A list of organizations represented on this committee can be obtained on request to its secretary.

Relationship with other publications

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;*
- *Part 3: Charting techniques for short production runs and small batches.*

BS 5702-2 is self-contained in respect to the specific subject matter. It also provides essential links to, and is consistent in approach, format and style with, BS 5702-1 and BS 5702-3, BS 5701 Parts 1 to 4, BS 600 and BS 5703 Parts 1 to 4.

Use of this document

BSI permits the reproduction of Figure B.1 and Figure B.2, on pages 55 and 56 of BS 5702-2. This reproduction is only permitted where it is necessary for the user to record findings on the figures during each application of the standard.

As a guide, this part of BS 5702 takes the form of guidance and recommendations. It should not be quoted as if it were a specification and particular care should be taken to ensure that claims of compliance are not misleading.

Any user claiming compliance with this part of BS 5702 is expected to be able to justify any course of action that deviates from its recommendations.

Presentational conventions

The provisions in this standard are presented in roman (i.e. upright) type. Its recommendations are expressed in sentences in which the principal auxiliary verb is “should”.

Commentary, explanation and general informative material is presented in smaller italic type, and does not constitute a normative element.

Contractual and legal considerations

This publication does not purport to include all the necessary provisions of a contract. Users are responsible for its correct application.

Compliance with a British Standard cannot confer immunity from legal obligations.

1 Scope

This part of BS 5702 gives guidance on the application of control charts to individual observations. It demonstrates the benefits, versatility and usefulness of a simple but powerful pictorial method for monitoring, audit and surveillance with the objectives to control and improve many types of processes. These processes can, for example, be in industry, commerce, public service, health care, environment, food, information technology or finance. Case studies are included to illustrate this adaptability.

It describes how and when to apply, select, construct, interpret and use, control charts:

- generally, to individual measurements of a single characteristic arranged in a meaningful sequence; and
- specifically, to particular cases of attribute data.

This standard distinguishes between the use of control charts to achieve product control as opposed to steering a process (reducing variation and making estimates of, and securing progressive improvements in, process performance).

This standard is aimed at all those concerned with statistical related initiatives based on individual observations and the continuous improvement of business processes.

2 Normative references

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

BS 600:2000, *Guide to the application of statistical methods to quality and standardization*

BS 5702-1, *Guide to statistical process control (SPC) charts for variables – Part 1: Charts for mean, median, range and standard deviation*

BS ISO 3534-2:2006, *Statistics – Vocabulary and symbols – Part 2: Applied statistics*

3 Terms, definitions and symbols

3.1 Terms and definitions

For the purposes of this part of BS 5702, the terms and definitions given in BS ISO 3534-2 apply. Key terms and definitions required for the understanding of this standard are reproduced here.

3.1.1 Process management

3.1.1.1 characteristic

distinguishing feature

NOTE 1 A characteristic can be inherent or assigned.

NOTE 2 A characteristic can be quantitative or qualitative.

NOTE 3 There are various classes of characteristic, such as:

- *physical (e.g. mechanical, electrical, chemical, biological);*
- *sensory (e.g. relating to smell, touch, taste, sight, hearing);*
- *behavioural (e.g. courtesy, honesty, veracity);*
- *temporal (e.g. punctuality, reliability, availability);*
- *ergonomic (e.g. linguistic or physiological or related to human safety);*
- *functional (e.g. range, speed and rate of climb of an aircraft).*

[BS EN ISO 9000:2005]

3.1.1.2 sample statistic

summary measure of some observed value of a sample

NOTE 1 Sample statistics (random variables) are symbolized by upper case Latin letters in italics (e.g. $\bar{X}$ and S) whereas the actual realization of sample statistics (observed values) are symbolized by lower case Latin letters in italics (e.g. $\bar{x}$ and s). This contrasts with population parameters symbolized by lower case Greek letters in italics (e.g. μ and σ).

NOTE 2 Observed values may be combined to form a test result or measurement result. For instance, the density of a bar may involve the combining of observed values of length, diameter and mass.

3.1.1.3 process

set of interrelated or interacting activities which transforms inputs into outputs

NOTE 1 Inputs to a process are generally outputs from other processes.

NOTE 2 Processes in an organization are generally planned and carried out under controlled conditions to add value.

NOTE 3 A process where the conformity of the resulting product cannot be readily or economically verified is frequently referred to as a "special process".

[BS EN ISO 9000:2005]

3.1.1.4 product

result of a process

NOTE 1 There are four generic product categories, as follows:

- *services (e.g. transport);*
- *software (e.g. computer program, dictionary);*
- *hardware (e.g. engine mechanical part);*
- *processed materials (e.g. lubricant).*

Many products comprise elements belonging to different generic product categories. Whether the product is then called service, software, hardware or processed material depends on the dominant element. For example, the offered product “automobile” consists of hardware (e.g. tyres), processed materials (e.g. fuel, cooling liquid), software (e.g. engine control software, driver’s manual), and service (e.g. operating explanations given by the salesman).

NOTE 2 Service is the result of at least one activity necessarily performed at the interface between the supplier and customer and is generally intangible. Provision of a service can involve, for example, the following:

- *an activity performed on a customer-supplied tangible product (e.g. automobile to be repaired);*
- *an activity performed on a customer-supplied intangible product (e.g. the income statement needed to prepare a tax return);*
- *the delivery of an intangible product (e.g. the delivery of information in the context of knowledge transmission);*
- *the creation of ambience for the customer (e.g. in hotels and restaurants).*

Software consists of information and is generally intangible and can be in the form of approaches, transactions or procedures.

Hardware is generally tangible and its amount is a countable characteristic. Processed materials are generally tangible and their amount is a continuous characteristic. Hardware and processed materials often are referred to as goods.

NOTE 3 Quality assurance is mainly focused on intended product.

[BS EN ISO 9000:2005]

3.1.1.5 statistical process control

SPC

activities focused on the use of statistical techniques to reduce variation, increase knowledge about the process and steer the process in the desired way

NOTE 1 SPC operates most efficiently by controlling variation of a process characteristic or an in-process product characteristic that is correlated with a final product characteristic; and/or by increasing the robustness of the process against this variation. A supplier’s final product characteristic can be a process characteristic to the next downstream supplier’s process.

NOTE 2 Although SPC originally was concerned primarily with manufactured goods, it is also equally applicable to processes producing services or transactions, for example, those involving data, software, communications and movement of material.

NOTE 3 SPC involves both process control and process improvement.

3.1.1.6 variation

difference between values of a characteristic

NOTE Variation is often expressed as a variance or standard deviation.

3.1.1.7 inherent process variation

variation in a process when the process is operating in a state of statistical control

3.1.1.8 total process variation

variation in a process due to both special causes and common causes

3.1.1.9 special cause

<process variation> source of process variation other than inherent process variation

NOTE 1 Sometimes special cause is taken to be synonymous with assignable cause. However a distinction is recognized. A special cause is assignable only when it is specifically identified.

NOTE 2 A special cause arises because of specific circumstances that are not always present. As such, in a process subject to special causes, the magnitude of the variation from time to time is unpredictable.

3.1.1.10 random cause

common cause

chance cause (deprecated)

<process variation> source of process variation that is inherent in a process over time

NOTE 1 In a process subject only to random cause variation, the variation is predictable within statistically established limits.

NOTE 2 The reduction of these causes give rise to process improvement. However the extent of their identification, reduction and removal is the subject of cost/benefit analysis in terms of technical tractability and economics.

3.1.1.11 rational subgroup

subgroup, within which variation is presumed due only to random causes

NOTE 1 A subgroup is a set of data taken from a process in such a way as to ensure the greatest similarity among the data in each subgroup and the greatest difference between the data in different subgroups. The larger the subgroup the more sensitive is the control chart to shifts in process level. Ideally each measurement in a subgroup is independent of each other.

NOTE 2 The most common method to obtain a rational subgroup is to form it at a point of time. Data from different time periods would then be in different subgroups. An example would be to take measurements on five consecutive parts from a particular machine every hour. The sample statistics from the subgroups can then be plotted on a control chart in time order. This facilitates the detection of time related variation.

3.1.1.12 stable process

process in a state of statistical control

<constant mean> process subject only to random causes

NOTE 1 A stable process will generally behave as though the samples from the process at any time are simple random samples from the same population.

NOTE 2 This state does not imply that the random variation is large or small, within or outside of specification, but rather that the variation is predictable using statistical techniques.

NOTE 3 The process capability of a stable process is usually improved by fundamental changes that reduce or remove some of the random causes present and/or adjusting the mean towards the preferred value.

NOTE 4 In some processes the mean of a characteristic can have a drift or the standard deviation can increase due, for example, to wear out of tools or depletion of concentration in a solution. A progressive change in the mean or standard deviation of such a process is considered due to systematic and not random causes. The results, then, are not simple random samples from the same population.

3.1.1.13 out of control criteria

set of decision rules for identifying the presence of special causes

NOTE Decision rules may include those relating to points outside of control limits, runs, trends, cycles, periodicity, unusual spread of points within control limits (dispersion large or small) and relationships among values within subgroups.

3.1.2 Control charts

3.1.2.1 control chart

chart on which some statistical measure of a series of samples is plotted in a particular order to help steer the process with respect to that measure and to control and reduce variation

NOTE 1 The particular order is usually time or sample number order based.

NOTE 2 The control chart operates most effectively when the measure is a process variable which is correlated with an ultimate product or service characteristic.

3.1.2.2 Shewhart control chart

control chart with Shewhart control limits intended primarily to distinguish between variation in the plotted measure due to random causes and that due to special causes

3.1.2.3 moving mean control chart

control chart for evaluating the process level in terms of the arithmetic mean of each successive n observations

NOTE 1 This chart is applicable when only one observation per subgroup is available and smoothing is required. Examples are process characteristics such as temperature, pressure and time.

NOTE 2 The current observation replaces the oldest of the latest $n + 1$ observations.

NOTE 3 It has the disadvantage of an un-weighted carry-over effect lasting n points.

3.1.2.4 individuals control chart

$\bar{X}$ control chart

variables control chart for evaluating the process level in terms of the individual observations in the sample

NOTE 1 This chart is usually accompanied by a moving range chart, frequently, with $n = 2$.

NOTE 2 It sacrifices the advantages of averaging in terms of minimizing random variation and the normal distribution central limit theorem assumptions.

3.1.2.5 moving range control chart

variables control chart for evaluating variation in terms of the range of each successive n observations

NOTE The current observation replaces the oldest of the latest $n + 1$ observations.

[BS ISO 3534-2:2006]

**3.1.2.6 cumulative sum chart
cusum chart**

chart where the cumulative sum of deviations of successive sample values from a reference value is plotted to detect shifts in the level of the measure plotted

NOTE 1 The best discrimination of changes in level is achieved when the reference value is equal to the overall mean value.

NOTE 2 The chart can be used in control, diagnostic or predictive mode.

NOTE 3 When used in control mode it can be interpreted graphically by a mask (e.g. V-mask) superimposed on the graph. A signal occurs if the path of the cusum intersects or touches the boundary of the mask.

[adapted from BS ISO 3534-2:2006]

3.1.2.7 median control chart

individuals control chart based on medians

NOTE This chart is based on Tukey's exploratory data analysis techniques.

3.1.2.8 attributes control chart

control chart in which the measure plotted represents countable or categorized data

3.1.2.9 c chart

attributes control chart for number of incidences where the opportunity for occurrence is fixed

3.1.2.10 u chart

attributes control chart for number of incidences per unit where the opportunity is variable

3.1.2.11 np chart

attributes control chart for number of units of a given classification where the sample size is constant

3.1.2.12 p chart

attributes control chart for number of units of a given classification per total number of units in the sample expressed either as a proportion or percent

3.1.3 Control chart components**3.1.3.1 centre line****CL**

line on a control chart representing the intended aim or historical mean of the sample statistic plotted

NOTE The centre line may take one of two forms:

- *standard given centre line, the value of which is pre-specified;*
- *no standard given centre line, the value of which is the historical mean.*

3.1.3.2 control limit

line on a control chart used for judging the stability of a process

NOTE 1 Control lines are drawn on a control chart to represent control limits.

NOTE 2 Control limits provide statistically determined boundaries for the deviations from the centre line of the statistic plotted on a Shewhart control chart due to random causes alone.

NOTE 3 Control limits are based on actual process data and, with the exception of the acceptance control chart, not on specification limits.

NOTE 4 Other than points outside of control limits, out of control criteria can include runs, trends, cycles, periodicity and unusual patterns within the control limits.

3.1.3.3 warning limits

control limits between which the statistic under consideration lies with a high probability when the process is under statistical control

NOTE 1 Warning lines are drawn on a control chart to represent warning limits.

NOTE 2 When the value of the statistic plotted lies outside a warning limit, but within the action limit, increased supervision of the process, to pre-specified rules, is generally required.

3.1.3.4 action limits

control limits between which the statistic under consideration lies with a very high probability when the process is under statistical control

NOTE 1 Action lines are drawn on a control chart to represent action limits.

NOTE 2 When the measure plotted lies beyond an action limit appropriate corrective action is taken on the process.

3.1.3.5 target value

nominal value

aim

preferred or reference value of a characteristic

NOTE The symbol often used for target value is T.

3.1.3.6 specification limit

limiting value stated for a characteristic

3.2 Symbols

A_2	multiplier of mean range used to calculate the control limits for means
c	number of counts (e.g. nonconformities) in a sample
$\bar{c}$	mean number of counts in samples of constant size, n
CL	centre line
C_p	capability index for a process characteristic under statistical control
C_{pkL}	lower capability index for a process characteristic under statistical control
C_{pkU}	upper capability index for a process characteristic under statistical control
D_4	multiplier of mean range used to calculate the upper control limit for ranges

E_2	multiplier of mean range used to calculate the control limits for individuals
L	lower specification limit
LCL	lower control limit
M	median
Q_1	median of lower quartile
Q_3	median of upper quartile
R	range
$\bar{R}$	mean range
R_{IQ}	inter-quartile range
S	standard deviation (sample statistic)
U	upper specification limit
UCL	upper control limit
X	individual observation
$\bar{X}$	mean, sample statistic
$\bar{\bar{X}}$	mean, overall
XmR	standard individual and moving range

4 Role of control charts in process control and improvement

4.1 Principle

To realize the full benefits from the application of statistical process control (SPC) it is important that the meanings of the terms statistical process control and process control charts are understood. Misinterpretation of control can be compounded by the substitution of the term product for process. SPC should be used as a means of improving performance rather than as a judgemental tool.

4.2 Improvement and control

Control is often incorrectly accepted to mean restraint in the containment sense, i.e. the need to keep a process under control. Many SPC operating procedures limit themselves to a set of decision rules for identifying the presence of undesirable special causes which can lead to the incorrect presumption that all out of control signals indicate a detrimental condition.

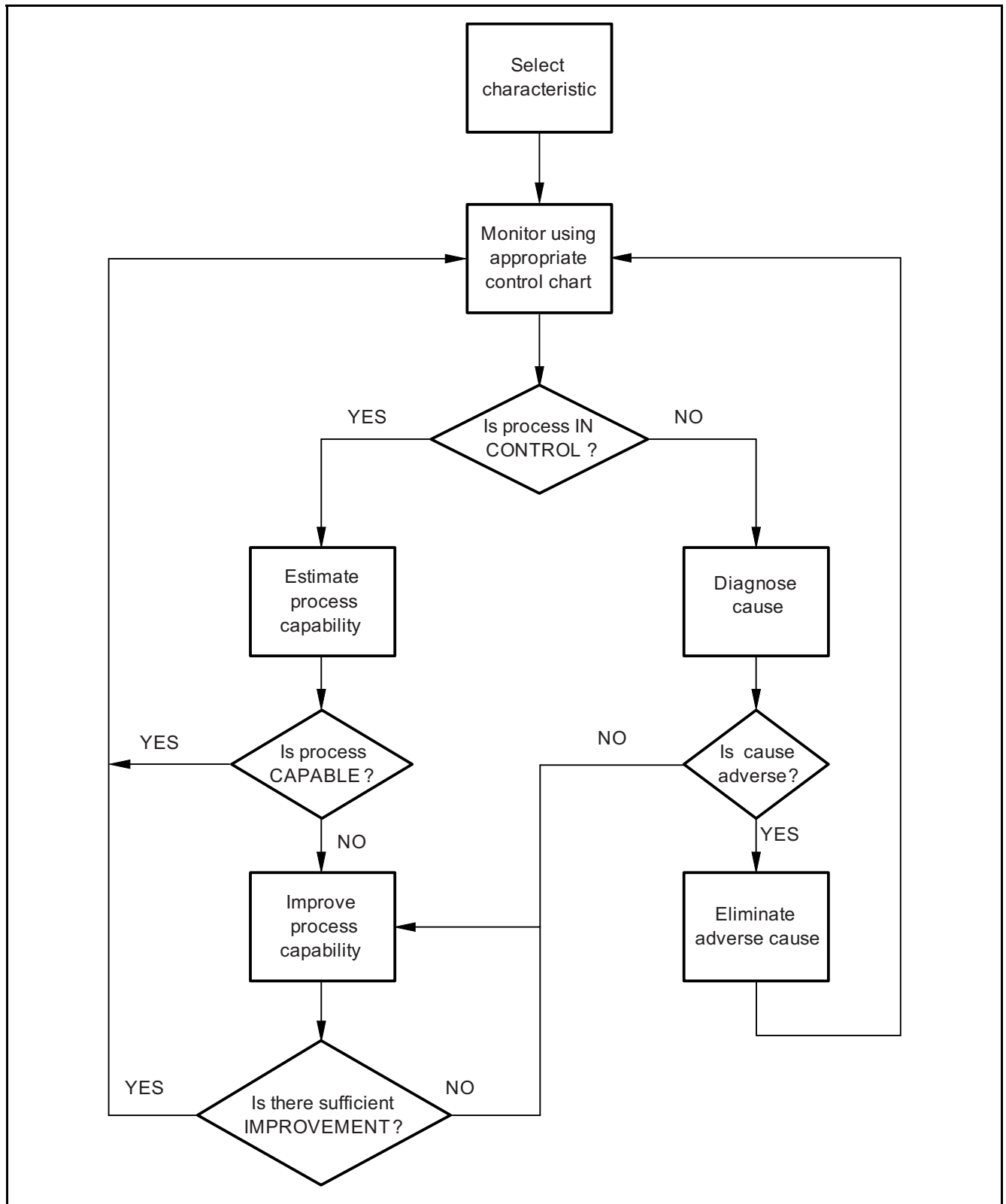
It is necessary to appreciate that such an interpretation of these decision rules relates only to special cause variation. Containment of such special cause variation restores the status quo but does not improve process performance.

An improvement in process performance can only be achieved by a reduction in inherent variation or by an adjustment in the level of the process to the desired value. Such an achievement is also evidenced by an out of control signal.

Figure 1 shows the application sequence that will provide answers to three core questions:

- Is the process in control?
- What is the capability of the process?
- Is there evidence of significant improvement?

Figure 1 Application sequence for process control, performance assessment and improvement

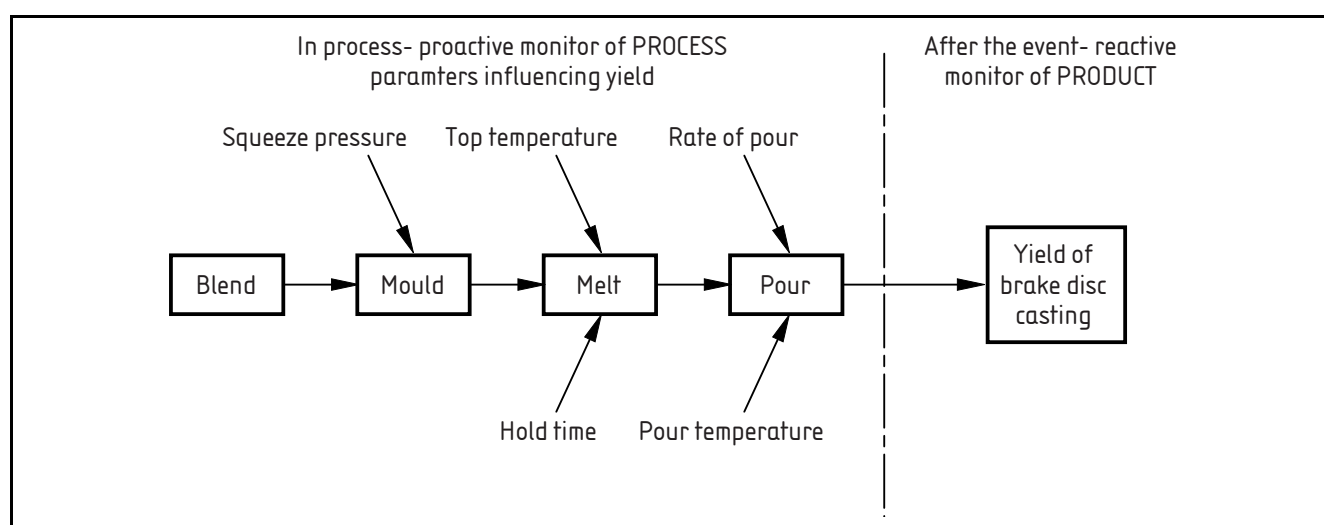


4.3 Monitoring of influential process characteristic in preference to after-the-event output

SPC is often applied solely to the output of a process rather than to the process itself. This concentration on the post-process monitoring of product characteristics can detract from the real purpose of SPC which is to improve the understanding of the process itself, with a view to taking timely action on those process characteristics that influence the quality of the process output.

Figure 2 illustrates that in order to secure high quality brake disc castings it is best to concentrate on in-process characteristics that influence product yield rather than the after-the-event product yield itself.

Figure 2 **Focus on influential process characteristics rather than product yield**



This attention to product output characteristics rather than in-process characteristics, can lead to the belief that the application of SPC is confined exclusively to large volume product applications.

4.4 Process improvement not process judgement

When SPC in general, and control charts in particular, are used as judgemental tools there can be an incentive to use data mainly to demonstrate that processes are acceptable. Information that would be invaluable as a basis for achieving a greater understanding of the process might then be concealed, thus inhibiting the real purpose of the application of SPC.

Such an environment can exist in business organizations that are subject to quality accreditation assessment by third party auditors or their major customers. In multi-national organizations, plants in one country may be inhibited from releasing true data for fear of getting shut down in favour of plants in other countries that may appear to have a better performance. Public services such as the Health Service with its commitment to business targets, star ratings and the publication of comparative score cards can be subjected to such business pressures to dress-up the data. For instance, the disclosure of actual MRSA figures could lead to closure of a ward and adversely affect patient waiting-time ratings.

Organizations that have the mindset to produce real data, and use it to learn and improve, can be penalized if their performance appears to be below that of other organizations.

It is essential to ensure that an SPC system and its control charts are applied in an environment that is sufficiently mature to recognize and avoid such an unproductive judgemental approach.

4.5 SPC is not confined to control charts

The generation of the correct mindset in relation to SPC should take full cognizance of the fact that SPC and associated control charts adopt those activities focused on the use of statistical techniques to:

- a) reduce variation;
- b) increase knowledge about the process;
- c) steer the process in the desired way.

The effective control and improvement of processes require a prior understanding of those process parameters that most significantly affect the output, a need to select their preferred values and then minimize variation.

This indicates that control charts are not standalone tools. They are part of an armoury of statistical tools. Any SPC-based programme, process, or project dedicated to continual improvement will inevitably deploy diagnostic, analytic and presentational tools to support the productive application of control charts. These tools can range from simple tools such as flow charts, Pareto charts, cause and effect diagrams and process capability studies to more advanced tools such as planned experimentation, quality function deployment and measurement systems analysis. Such tools are described in BS 600.

5 Classes of data and selection of appropriate chart

5.1 Data classification

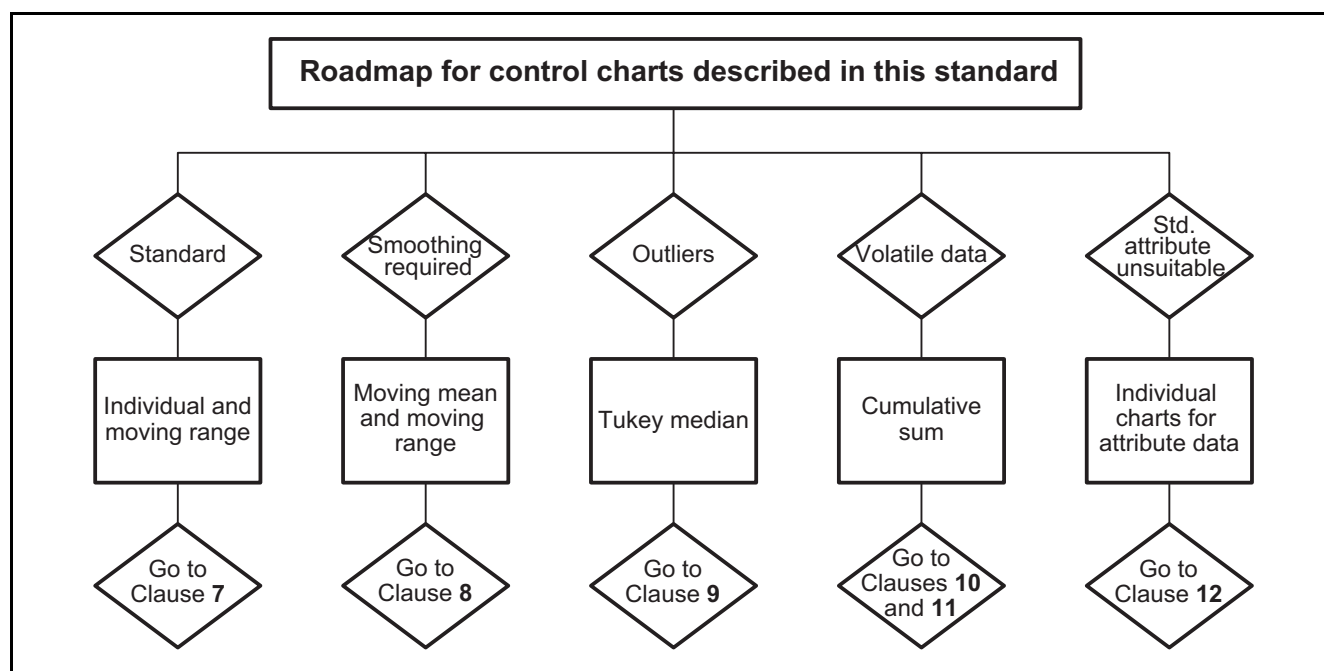
Data are usually classified either as measured data or attribute data.

Continuous data is measured on a continuum of possible values but a degree of discreteness in the result arises due to limitations in the resolution of the overall measuring system. One example is the use of a vernier gauge as compared with a ruler, or a tape measure as opposed to a laser-based system, for measuring length. Another example, for count data, is the taking of a pulse rate over a full minute, rather than over 15 seconds and multiplying by four. Whether or not the discrimination of a particular measuring system is adequate for a given purpose is readily indicated by the number of possible values in a range chart. Inadequate resolution is shown by a range chart with only one, two or three possible values for the range within the control limits.

5.2 Control chart selection

Figure 3 shows a road map for control charts.

Figure 3 Road map for control charts



6 Control charts for individual measurements

6.1 Scope of application

Control charts for individual measurements are intended for situations where it is not feasible to construct control charts based on rational subgroups. This arises when, for example:

- the value of the characteristic does not change, e.g. repetitive readings of:
 - the viscosity, specific gravity or pH of a homogeneous solution,
 - process characteristics, e.g. temperature, pressure and speed.
- the cost of taking a measurement is expensive, e.g. a destructive test.
- the taking of more than one measurement at a given point of time can affect the value of the subsequent measurement(s), e.g. blood pressure testing.
- data are collected periodically, e.g. with monthly financial figures it would take five months to collect each subgroup of five.
- each measurement represents one batch or set of data.
- no rational subgrouping of the data is feasible.

Control charts for individuals can sometimes be used as an alternative to attribute control charts, see Clause 12.

6.2 Statistical and attitudinal aspects

Shewhart control charts, such as those described in BS 5702-1, are based on the means of, and variation within, rational subgroups. This gives rise to mean and range, or mean and standard deviation, control charts.

Such charts have a number of statistical advantages over the use of standard individual measurement charts. These include:

- Greater sensitivity in detecting changes in the process characteristic plotted.
- The isolation of within-subgroup variation from subgroup-to-subgroup variation. This provides the ability to distinguish between inherent short term (within time) variation, and time-to-time variation.
- Facilitating the calculation of valid control limits using standard formulae. This is because the means of subgroups tend to become normal¹⁾ as the subgroup size increases regardless of the lack of normality in the underlying pattern of variation of individuals.

Subgroup sizes in the region of five have been encouraged for statistical reasons. One place to seek to apply such an approach is the output of volume production by, for instance, measuring five consecutive components at pre-specified time intervals (e.g. five consecutive every hour) after completion of a process operation. Piece-to-piece variation is then separated from time-to-time variation. This can divert attention from a business approach in which the more timely manipulation and control of in-process characteristics giving rise to the output is encouraged. It can also give the incorrect impression that the SPC control chart is predominantly a tool for volume production.

Control limits for mean SPC charts are based on within-subgroup variation often with an expectation that this variation would conform to specified component tolerances and that the control charts are primarily intended for control purposes. Expectations have changed significantly and it is no longer accepted that just because a component is within specification, regardless of where its value lies within the tolerance band, it is of equal quality. The objective now is to aim for a preferred value and continually minimize variation. This objective can be achieved by concentrating on the process itself and the influencing process characteristics rather than the output product.

These features support the application of charts for individual measurements in the pursuit of continuous improvement of process performance. Such Shewhart individual and moving range charts are frequently given the name of $\bar{X}mR$ or $I-MR$ control charts. The alternative moving mean and moving range charts are often given the names $MA-MR$ control charts. Other very useful types of chart for dealing with individual results are the Tukey median control chart and the cumulative sum (cusum) chart.

¹⁾ The term normal is used here purely in a statistical sense to describe a symmetrical bell shaped pattern of variation. It is not used in the sense of being usual, natural or standard or not being abnormal. For example, it would not be natural to expect statistical normality in waiting times for service, measurements of eccentricity of a component or impurities in a suspension.

7 Construction and use of standard individual and moving range control charts

7.1 Purpose

The construction and use of a standard individual and moving range control chart is applicable when:

- a) the characteristic is measurable;
- b) the sample size is 1;
- c) the measurements are independent of each other;
- d) the expectation is that the characteristic will exhibit a constant mean and variation;
- e) a timely response is required to any significant change in the value of the characteristic;
- f) the outcome of the individuals is normally distributed;
- g) the individual measurements are taken periodically.

7.2 Construction

7.2.1 Appropriate characteristics

Characteristics chosen for control charting should be those that significantly influence process outputs, not for administrative convenience relating to the ease of measuring and control, e.g. the known relationship between the percentage silicon content and the strength of steel and the effect of squeegee speed, viscosity and dwell time on the quality of a silk screen printing process.

A prior understanding of the influence of which, and to what degree, various process parameters influence the overall performance of the process is required. Such an understanding demands the conducting of designed multi-factorial experiments and quality function deployment analysis before embarking on control charting.

7.2.2 Sampling time and frequency

With the mean and range/standard deviation charts described in BS 5702-1, control limits are based on the variation within each rational subgroup. How such a subgroup is constructed will determine the sensitivity of the ensuing control chart. This method of determining inherent variation in the characteristic is not possible with individual and moving range charts. Here it is based on the difference between successive measurements, the moving ranges. The timing and frequency of the taking of measurements is critical in the determination of short term variation of the characteristic. The making of the appropriate decision in this respect depends on prior knowledge of the behaviour of the process with regard to the measured characteristic, e.g. the taking of blood pressure readings at around the same time of the day will probably show less variation than those taken at unscheduled or random times.