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Capability

Basic concepts and methods

Orientation

This standard is based on ISO 21747. Special guidelines are added as informative annexes.

This issue differs from issue 3 in that the standard no longer applies to new design. For new design, standard STD 105-0009 shall be used.

Contents

1 Scope

The standard contains definitions of various capability indices and the methods used to establish these capability indices.

2 General

The design-engineering documentation (drawing or corresponding) indicates property requirements that apply to the "individual part in finished condition". With this standard, requirements are supplemented by target value and distribution requirements for the relevant property requirements without this being indicated in the basic product documentation.

The standard stipulates the principle of general distribution requirements for the results in the manufacturing processes.

The accuracy with which capability can be determined is dependent on, among other things, the number of units measured.

Normally, a minimum sample of 50 parts is required, but sample sizes down to 30 parts are (sometimes) used. Decision on sample size is made individually by each Business Area/Business Unit on the basis of its production.

The tolerance zone is limited by the tolerance limits specified on the drawing.

The standards on dimensional tolerances, geometrical tolerances, surface roughness, etc., indicate how the tolerance requirements shall be applied and interpreted. The tolerance limits are rejection/adjustment limits.

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For tolerance requirements, there are values within the tolerance zone that are ‘better’ than the limit values. For these, there is an ideal value which gives the best function (at the customer’s) or gives the smallest risk of disturbances in subsequent production. This is the **target value of the property**.

Even if a result at the tolerance limit provides fully satisfactory function, it is thus of value to steer the production towards the target value, at the same time as the requirement for lowest cost is considered.

To comply with a capability index, machines and other equipment must be set to control limits within the tolerance limits.

An example of the application of a control method is SPC (**S**tatistical **P**rocess **C**ontrol). This requires measurement of variables (using indicating measuring instruments) and, in addition, the property must be controllable by the operator.

3 Purpose

The purpose of specifying a process capability index for production is:

1) To reduce the risk of functional disturbances and faults in the finished product by reducing the risk of deviations from the result that is best for the customer

2) To reduce the costs by increasing the process capability and thus obtain a more stable and more predictable production result.

Furthermore, this standard aims at providing clear definitions of concepts used within Volvo in connection with capability work, to provide information on statistical methods and to provide guidelines for the use of these methods.

4 Definitions

Capability

The ability of a machine, process, measuring equipment, etc., to meet the specified property requirement.

Bilateral tolerance

A tolerance for which two tolerance limits – upper and lower – have been specified and are possible to exceed. An example of a bilateral tolerance is diameter Ø 50 ± 0,2.

Unilateral tolerance

A tolerance for which either the upper or the lower tolerance limit has been specified and is possible to exceed. A tolerance is unilateral if it is limited by a natural zero, e.g. a requirement on straightness or run-out.

Multilateral tolerance

A tolerance for which the tolerance definition gives a boundary zone that can be exceeded in several directions. An example of a multilateral tolerance is position with circular or cylindrical tolerance zone.

Mean value

The arithmetic mean and is designated $\overline{X}$. Mathematically, the mean value is defined as follows:

$$\overline{X} = \frac{1}{n} \sum_{i=1}^{n} X_i$$

The 50 % (distribution) quantile, median

The midpoint value of a population is called the 50 % quantile; half of the population is larger than the 50 % quantile and half of the population is smaller than the 50 % quantile.

For a sample used at a capability study, the 50 % quantile is the same as the median, which is the middle value of a number of results arranged according to size. If the number of results is even, the median is the same as the mean value of the two middle values.

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At normal distribution, the median corresponds to the mean value.

When defining capability indices in this standard, the 50 % quantile is used in various formulas. However, in practice, it is quite common to use the mean value as an approximation of the middle value of a sample since the mean value is a stable size. However, in those cases the distribution is highly skewed, it may be preferable to choose the median of the sample.

The 99,865% (distribution) quantile

That value in a result set which statistically is not exceeded by 99,865 % of all values and thus statistically exceeded by 0,135 % of all values.
The 99,865 quantile is designated $X_{99,865\%}$.
At normal distribution, the value for the 99,865 % quantile corresponds to the mean value + three standard deviations.

The 0,135 % (distribution) quantile

That value in a result set which statistically is not exceeded by 0,135 % of all values and thus statistically exceeded by 99,865 % of all values. The 0,135 quantile is designated $X_{0,135\,\%}$.

Dispersion

That area within which 99,73 % of the results are placed and located so that 0,135 % is placed outside each side of the tolerance limits. The dispersion constitutes $X_{99,865\,\%}$ - $X_{0,135\,\%}$ or six standard deviations for a normally distributed result.
Instantaneous distribution is the variation between parts at a given moment over time while the resulting outcome for the process has a greater variation since also any changes with respect to the outcome's location over time are included.

Range of variation

The difference between the largest and smallest value respectively in a data set. The range of variation is designated R.

Standard deviation

A measure of the average square deviation between the individual results and the mean value and gives the size of the dispersion of a normal distribution. Standard deviation is designated S and is calculated from a sample of n parts:

$$S = \sqrt{\frac{1}{n-1} \sum_{i=1}^{n} (x_i - \bar{x})^2}$$

Upper tolerance limit, U

The upper limit value specified by a tolerance for what can be accepted.

Lower tolerance limit, L

The lower limit value specified by a tolerance for what can be accepted.

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5 Definitions and calculations of various capability indices

Covered by this standard are a limited number of measures of capability.
Those covered in this section are:

Pp	process performance index
Cp	process capability index
Cm	machine capability index
Ppk	minimum process performance index
Cpk	minimum process capability index
Cmk	minimum machine capability index
MC	centring value to the target value

Capability indices Pp and Ppk are normally used when determining the possibilities of a process to produce within specified requirements and where the sampling of parts is made in the form of a large sample taken on one occasion. An example of such studies is when a new production process is to be approved for series production.

Capability indices Cp and Cpk are normally used when determining the capability of a continuous production process and where the sampling of parts is made continuously during the production, for example, from control diagrams or from repeated random samples carried out under a lengthy period of time.

Capability indices Cm and Cmk are used when determining the ability of a production machine to produce, for example as acceptance test of new equipment. The sampling of parts is made in a short period of time without changes in machine settings.

The capability index MC is used at all types of capability analyses to determine to what degree a production process of a machine is able to meet the target value of a property.

Calculation of Pp, Cp, and Cm

These capability indices are calculated by comparing the dispersion with the range of variation for the property in question:

$$Pp, Cp, Cm = \frac{U - L}{X_{99,865\%} - X_{0,135\%}}$$

where

U = Upper tolerance limit

L = Lower tolerance limit

$X_{99,865\,\%}$ = the 99,865 % quantile

$X_{0,135\,\%}$ = the 0,135 % quantile

Note – At normal distribution of results, $X_{99,865\,\%} - X_{0,135\,\%} = 6S$.

Pp, Cp and Cm are, in principle, calculated in the same way. What differs is how the sampling is controlled and thus what is intended to be studied.

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Calculation of Ppk, Cpk, and Cmk

These capability indices are calculated by comparing the distance from the median to one tolerance limit with the distance from the median to the $X_{99,865\,\%}$ quantile and the $X_{0,135\,\%}$ quantile respectively. For bilateral tolerances, the smallest of these two values constitutes the minimum capability index:

Bilateral tolerance:

Ppk, Cpk, Cmk = minimum of:

$$\frac{U - X_{50\%}}{X_{99,865\%} - X_{50\%}} \quad \text{and} \quad \frac{X_{50\%} - L}{X_{50\%} - X_{0,135\%}}$$

For a unilateral tolerance with an upper tolerance limit only, e.g. a form tolerance, only the relation between the upper tolerance and the result is interesting; this means that:

$$\text{Ppk, Cpk, Cmk} = \frac{U - X_{50\%}}{X_{99,865\%} - X_{50\%}}$$

Note – At normal distribution of results, the following applies: $X_{99,865\,\%} - X_{50\%}$ and $X_{50\%} - X_{0,135\,\%}$. = 3 S

Ppk, Cpk and Cmk are, in principle, calculated in the same way. What differs is how the sampling is controlled and thus what is intended to be studied.

Calculation of MC

The centering value for the target value MC is calculated as the difference between the location of a result and the target value for the property, expressed as per cent of the tolerance:

$$MC = \frac{X_{50\%} - M}{U - L} \times 100$$

where

$X_{50\%}$ = 50 % (distribution) quantile or median
U = Upper tolerance limit
L = Lower tolerance limit
M = Target value for property, midpoint of tolerance for bilateral tolerance and 0 (zero) for unilateral tolerance where only one maximum value has been specified.

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6 Guidelines for use of standard deviation as a measurement of dispersion

A common way to determine the dispersion of a result is to use standard deviation as a measure of dispersion. To be able to use standard deviation in a statistically ensured manner, the result must be normally distributed.

The calculation of standard deviation for a process is made on incoming measuring data for a large sample, Pp/Ppk, or by collecting measuring data continuously during the process, Cp/Cpk.

Normally, the calculation is made on all incoming measuring data in accordance with the following formula:

$$S = \sqrt{\frac{1}{n-1} \sum_{i=1}^{n} (x_i - \bar{x})^2}$$

If special conditions apply, the standard deviation can as an alternative be estimated on the basis of the range of a variation for a number of sample groups.

Theoretically, these calculations coincide at perfect normal distribution with constant result over time as far as both location and dispersion are concerned.

An estimate of standard deviation Sw is made using the formula:

$$S_w = \frac{\bar{R}}{d_2}$$

where

$\bar{R}$ = mean value of range of variation in sample groups

d_2 = constant whose value is dependent on size of sample group, see table 1

Table 1

Size of sample group, n	Constant d_2
2	1,128
3	1,693
4	2,059
5	2,326
6	2,534
7	2,704
8	2,847
9	2,970
10	3,078

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An estimate of the standard deviation for calculation of the process capability is used only where a dispersion pattern according to type A1 in table 2 is present.

However, also for this type of distribution, a determination of standard deviation S is recommended instead of estimate of S_w since it is difficult to obtain such a distribution type; it will only be approximate. Furthermore, S and S_w coincide in connection with distribution type A1. Should distribution type A1 not be the case or only approximately be the case, the use of S_w risks to underestimate the dispersion and thus overestimate the process capability.

Using Sw as a basis for calculating process capability can, however, be accepted in those cases SPC is used and when the dispersion and location of the result are continuously assessed to ensure distribution of type A1.

Of decisive importance are the changes of the process over time; this is illustrated by the examples in table 2.

Table 2 Process changes over time and resulting distribution type (from ISO 21747:2006)

Characteristic	**Time-dependent distribution models**							
	A1	**A2**	**B**	**C1**	**C2**	**C3**	**C4**	**D**
Location of result	c	c	c	r	r	s	sr	sr
Dispersion of result	c	c	sr	c	c	c	c	sr
Instantaneous distribution type	nd	1m	nd	nd	nd	as	as	as
Outcoming distribution for process	nd	1m	1m	nd	1m	as	as	as
See figure	1	2	3	4	5	6	7	8

Explanations:

c = the parameter remains constant
r = the parameter changes randomly
sr = the parameter changes systematically and/or randomly
nd = normally distributed
1m= one type of distribution only; however, not normally distributed
as = all distribution types

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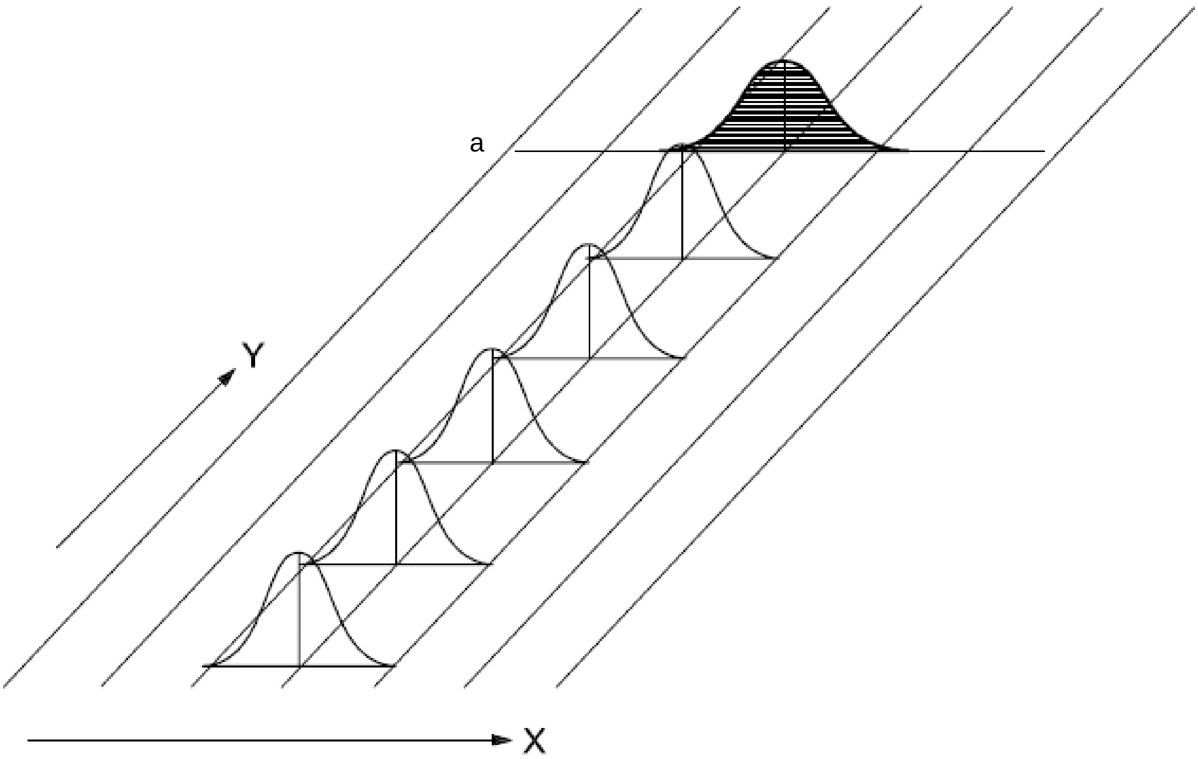
Description:
Location of result: constant over time
Dispersion of result: constant over time
Instantaneous distribution type: normally distributed
Outcoming distribution for process: normally distributed

The process is under statistical control.
Calculation of the process capability can be made by calculating the standard deviation S or by estimating Sw.



X = characteristic value
Y = time axis
a = outcoming distribution for process

Fig. 1 Distribution type A1

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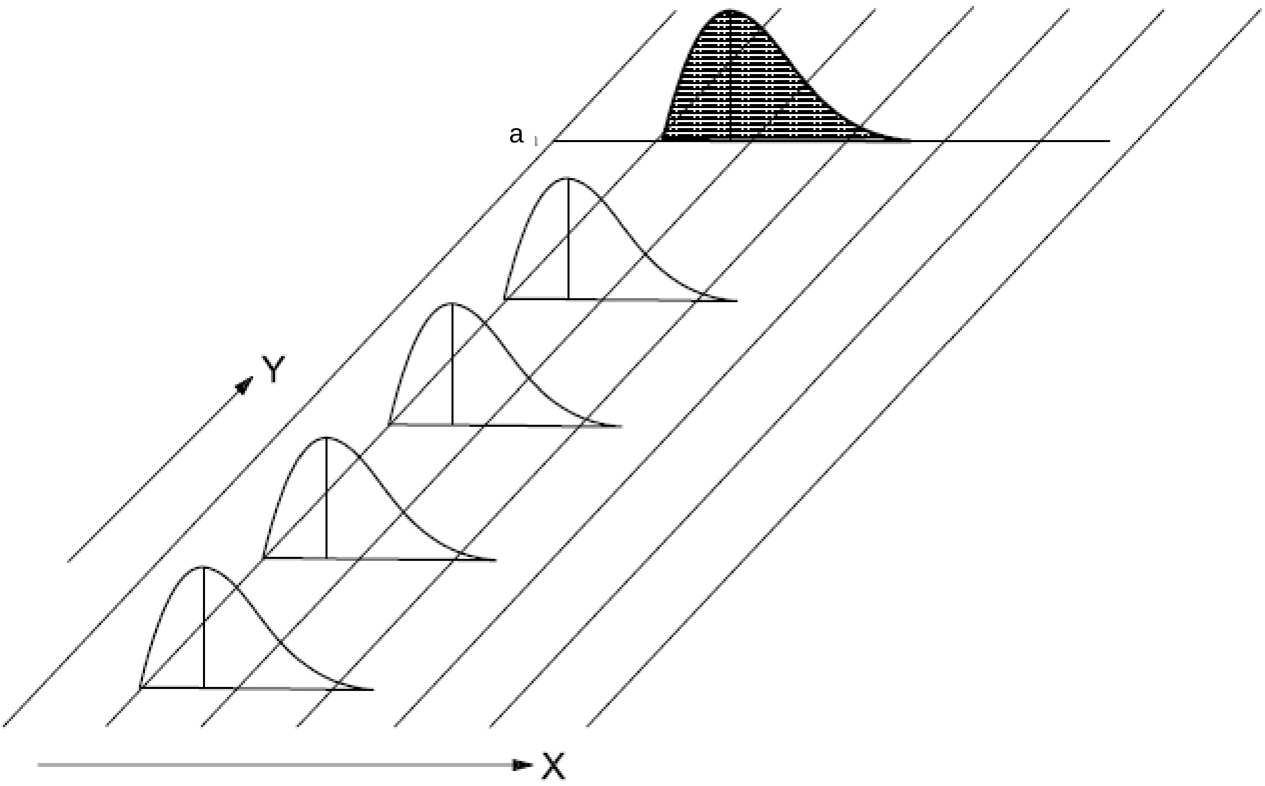
Description:
Location of result: constant over time
Dispersion of result: constant over time
Instantaneous distribution type: one type of distribution, not normally distributed
Outcoming distribution for process: one type of distribution, not normally distributed

The process is under statistical control.
Calculation of the process capability cannot be made by calculating the standard deviation S or by estimating Sw.

See also Annex A.



X= characteristic value
Y = time axis
a = outcoming distribution for process

Fig. 2 Distribution type A2

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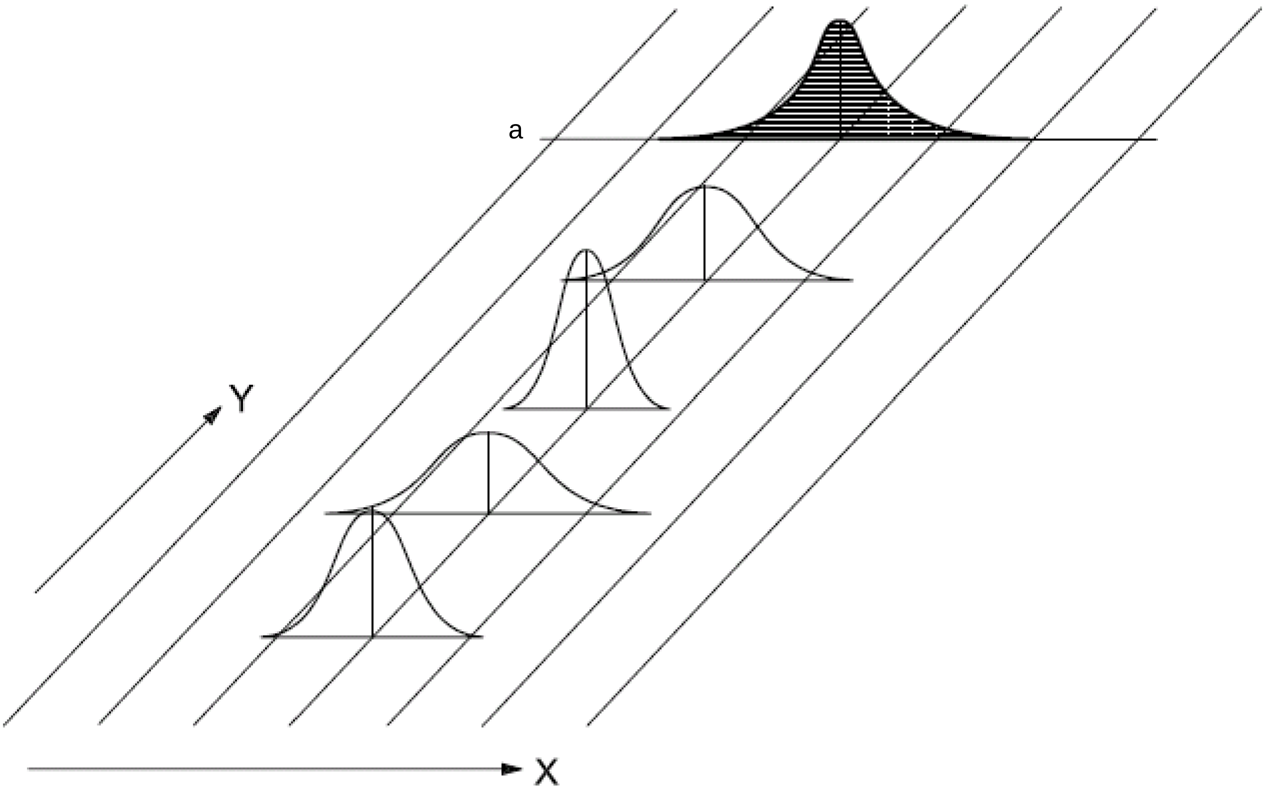
Description:
Location of result: constant over time
Dispersion of result: systematic and/or random variation over time
Instanteous distribution type: normally distributed
Outcoming distribution for process: one type of distribution, not normally distributed (may be approximately normally distributed if the variation in dispersion over time is small)

Calculation of the process capability can only be made approximately by calculating the standard deviation S.
Calculation of the process capability can thus not be made by estimating Sw.



X = characteristic value
Y = time axis
a = outcoming distribution for process

Fig. 3 Distribution type B

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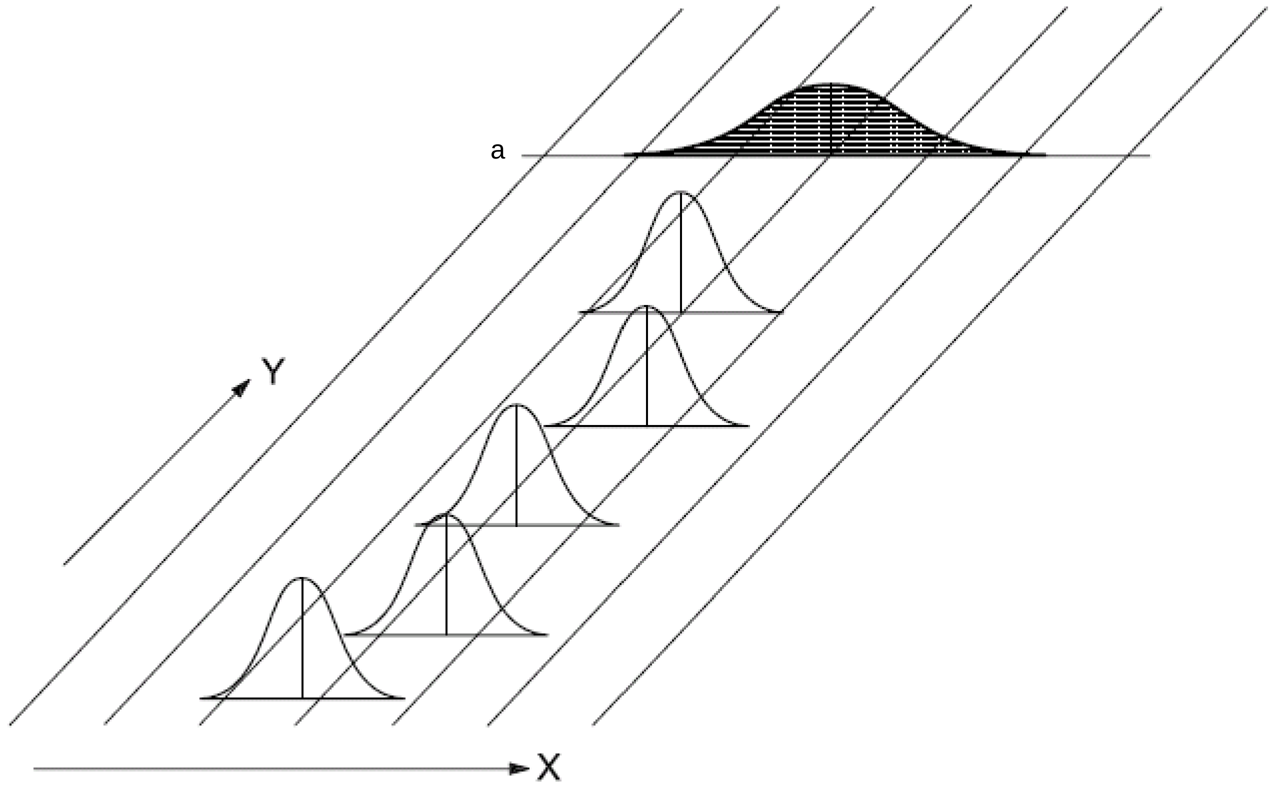
Description:
Location of result: random over time (normally distributed)
Dispersion of result: constant over time
Instantaneous distribution type: normally distributed
Outcoming distribution for process: normally distributed

Calculation of the process capability can be made by calculating the standard deviation S.
Calculation of the process capability cannot be made by estimating Sw.



X = characteristic value
Y = time axis
a = outcoming distribution for process

Fig. 4 Distribution type C1

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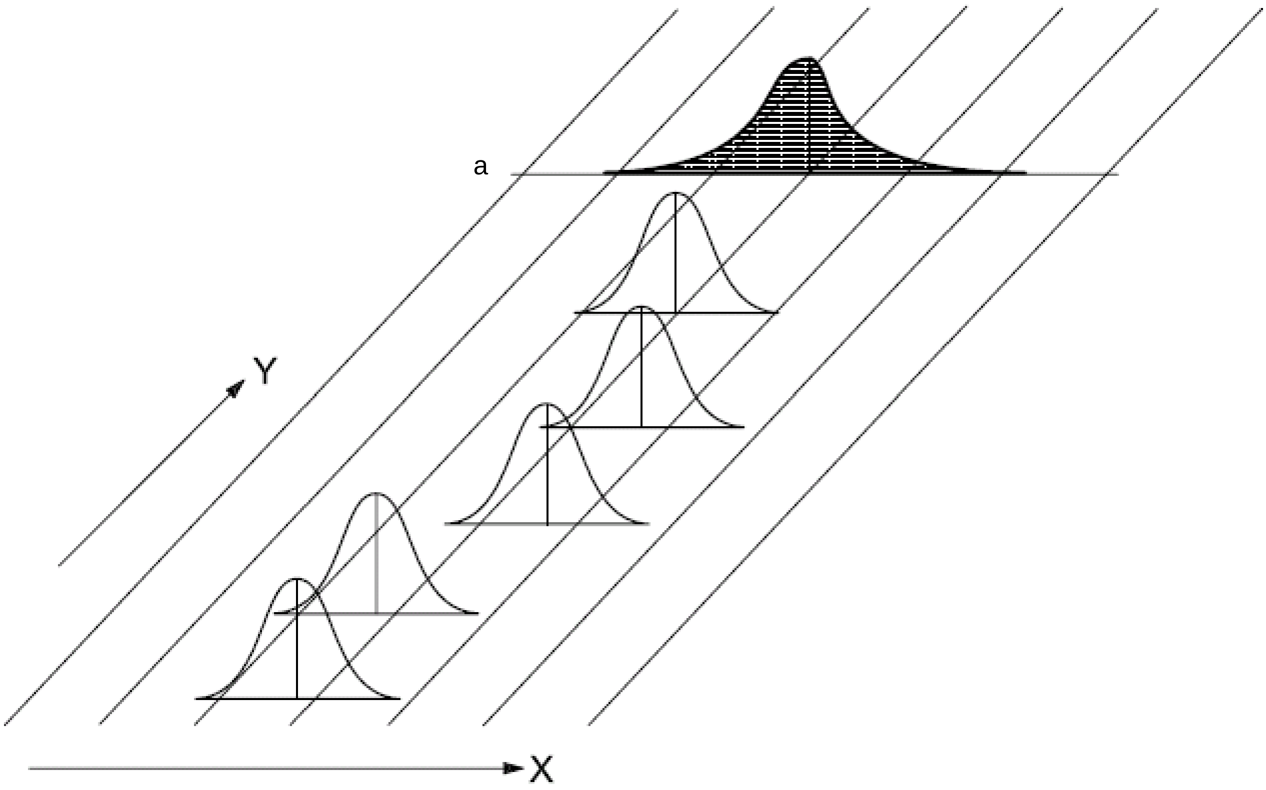
Description:
Location of result: random over time (not normally distributed)
Dispersion of result: constant over time
Instantaneous distribution type: normally distributed
Outcoming distribution for process: one type of distribution, not normally distributed

Calculation of the process capability cannot be made by calculating the standard deviation S or by estimating Sw.



X = characteristic value
Y = time axis
a = outcoming distribution for process

Fig. 5 Distribution type C2

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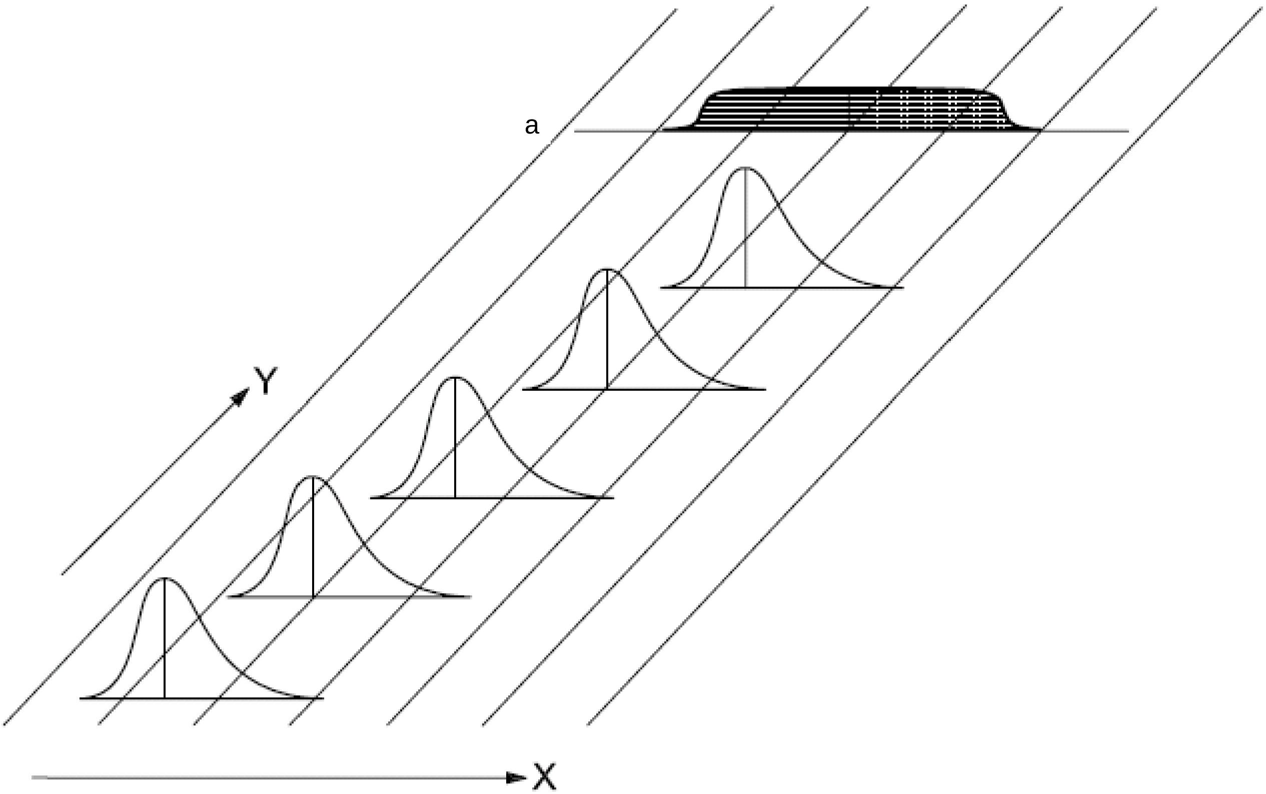
Description:
Location of result: random over time
Dispersion of result: constant over time
Instantaneous distribution type: all distribution types
Outcoming distribution for process: all distribution types

Process capability

Calculation of the process capability <u>cannot</u> be made by calculating standard deviation S or by estimating Sw.

Machine capability

If calculation of the machine capability shall be performed in connection with, e.g., an acceptance test, it is important to try to isolate the influence of the machine on the capability from the influence of other factors. If it is found at this test that the instantaneous distribution type is approximately normally distributed at the same time as there is a trend caused by, e.g., tool wear and this trend is of significant size, then it is possible to isolate this trend away from the machine capability study. This is done by dividing the material into test groups and estimating Sw as a basis for calculating the dispersion.



X = characteristic value
Y = time axis
a = outcoming distribution for process

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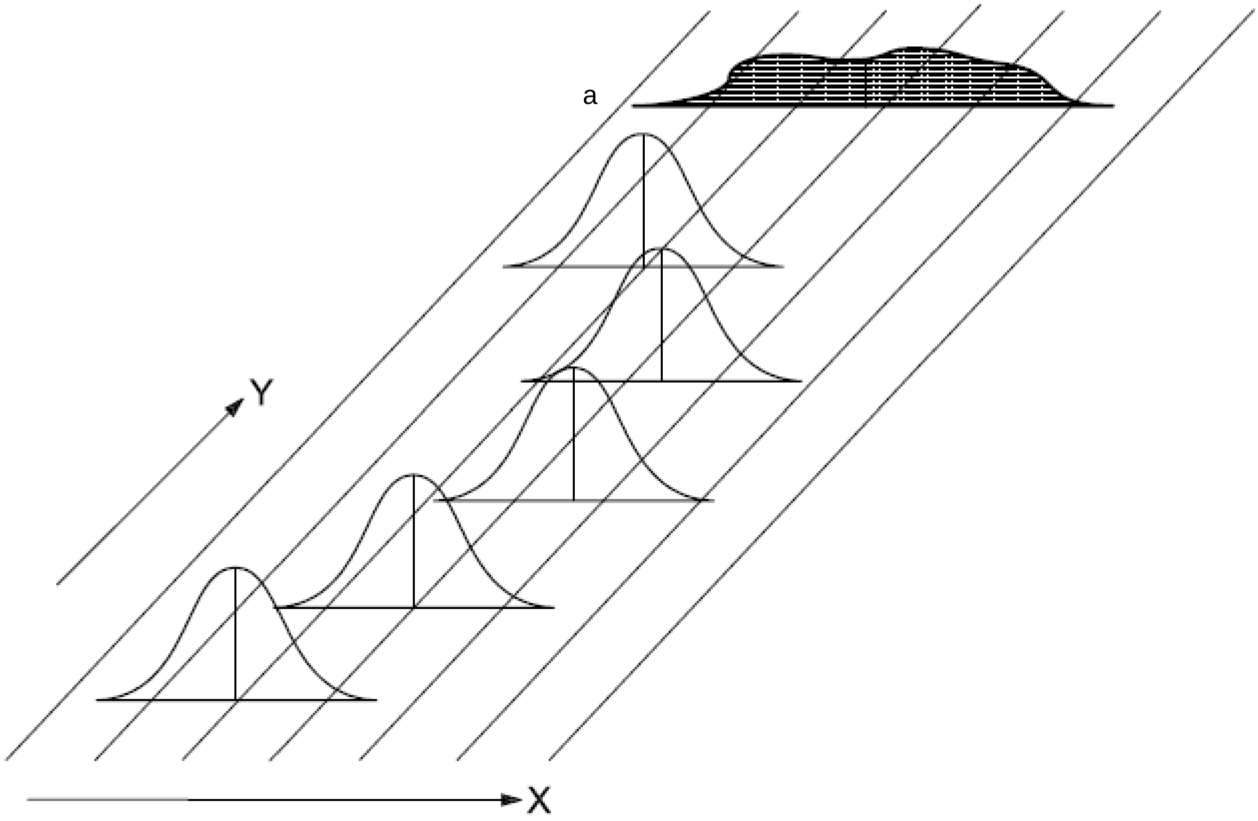
Fig. 6 Distribution type C3

Description:
Location of result: systematic and/or random change over time
Dispersion of result: constant over time
Instantaneous distribution type: all distribution types
Outcoming distribution for process: all distribution types

Calculation of the process capability cannot be made by calculating standard deviation S or by estimating Sw.



X = characteristic value
Y = time axis
a = outcoming distribution for process

Fig. 7 Distribution type C4

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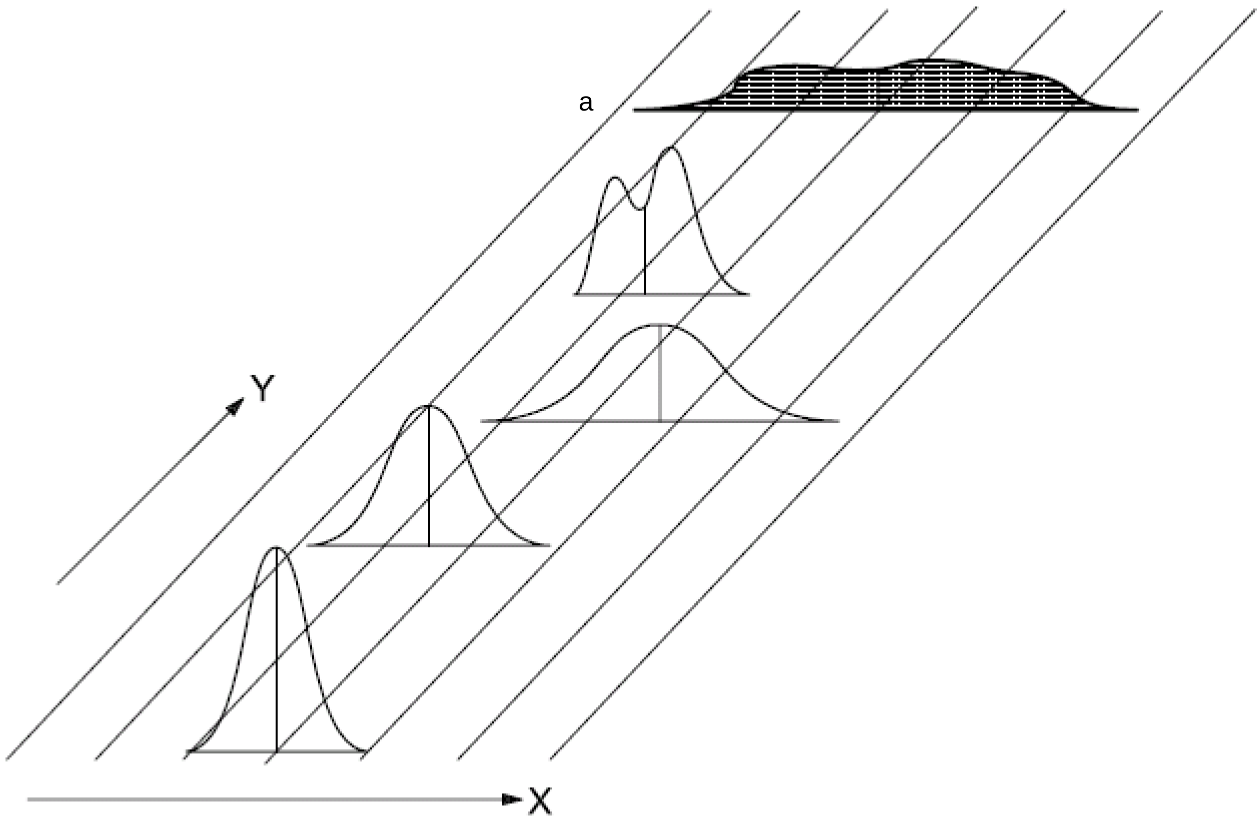
Description:
Location of result: systematic and/or random change over time
Dispersion of result: systematic and/or random change over time
Instantaneous distribution type: all distribution types
Outcoming distribution for process: all distribution types

Calculation of the process capability cannot be made by calculating standard deviation S or by estimating Sw.



X = characteristic value
Y = time axis
a = outcoming distribution for process

Fig. 8 Distribution type D

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7 Requirements on target value and capability index

The process capability shall be continuously evaluated where considered suitable. When prioritizing resources, classification of critical characteristics is guiding when deciding what property requirements that shall be comprised by capability studies.

General requirement on process capability:

When statistically evaluating a process, the corrected capability index Cpk must be at least 1,33 unless otherwise stated to make it possible to continuously meet a tolerance.

In STD 8000,52, the following general requirement for machine capability is indicated:

Unless otherwise agreed, C_{mk} > 2,0 applies to production equipment.

When considered suitable, however, the respective BusinessArea/Business Unit within the Volvo Group may specify its own requirements, which then replace the general requirements stated above.

As to the other capability indices mentioned in section 5, the respective BusinessArea/Business Unit within the Volvo Group determines what requirements to specify as well as what measures to take in those cases a specified capability index is not reached.

8 Measurement of capability index, special cases

8.1 General guidelines for uncertainty of measurement

At capability analyses, measuring results are used; it is essential that the uncertainty of measurement is so low that the actual measuring process does not affect the analysis too much.
Variations in the measuring process affect Pp/Cp and Cm. Ppk, Cpk, Cmk and MC are also influenced by any systematic errors in the measurement.
In connection with capability studies, the repeatability and accuracy of the measuring process with respect to systematic errors shall therefore be considered.

It is recommended to use R & R (Repeatability & Reproducibility) analysis to ensure the repeatability of the measurements and, where considered necessary via systematic comparison with other measuring processes, it shall also be ensured that there are no systematic errors.

8.2 Handling dimensional variations on a part

At capability studies, the ability of a process to repeat the same dimension (Pp/Cp and Cm) is studied or, as an alternative, the ability to repeat a dimension within the tolerance limits (Ppk, Cpk and Cmk). Since the study refers to the ability of the process, it is important not to let variations of other types influence the result. One such type of variations is dimensional variations on one and the same part, e.g., due to deviations from geometrically exact form. An oblong hole (slot) has varying dimensions depending on where in the hole the diameter is measured, but this variation is not part of the process variations or machine variations over time and shall therefore not be included in the capability study.

This is particularly important for requirements where different methods of measurement with dissimilar resulting dimensions are indicated for the upper and lower tolerance limit respectively. Examples of such requirements are so-called envelope requirements according to ISO 14405-1 Dimensional tolerancing – Linear sizes.

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At capability studies of an envelope requirement, dimensions that are compared to the upper tolerance limit when calculating Ppk/Cpk/Cmk are measured with one measuring method while dimensions that are compared to the lower tolerance limit are measured with a different measuring method. The smallest of these corrected capability indices is then the corrected capability index for the relevant characteristic.

In the same way, it may be necessary to measure both maximum and minimum values to obtain a distance dimension between two surfaces when these surfaces are non-parallel.

At capability studies, it is thus important to ensure that the geometric forms are such that only **one** dimension is needed at the study. It is not possible to standardize the limits that specify when a dimensional variation within one part is so large that it is necessary to measure both maximum and minimum dimensions; instead, this is to be covered by internal rules at the respective Business Area/Business Unit.

Figure 9 shows a process that is stable over time, optimally centred and with relatively small dispersion, but where the maximum and minimum dimensions vary on the individual parts.

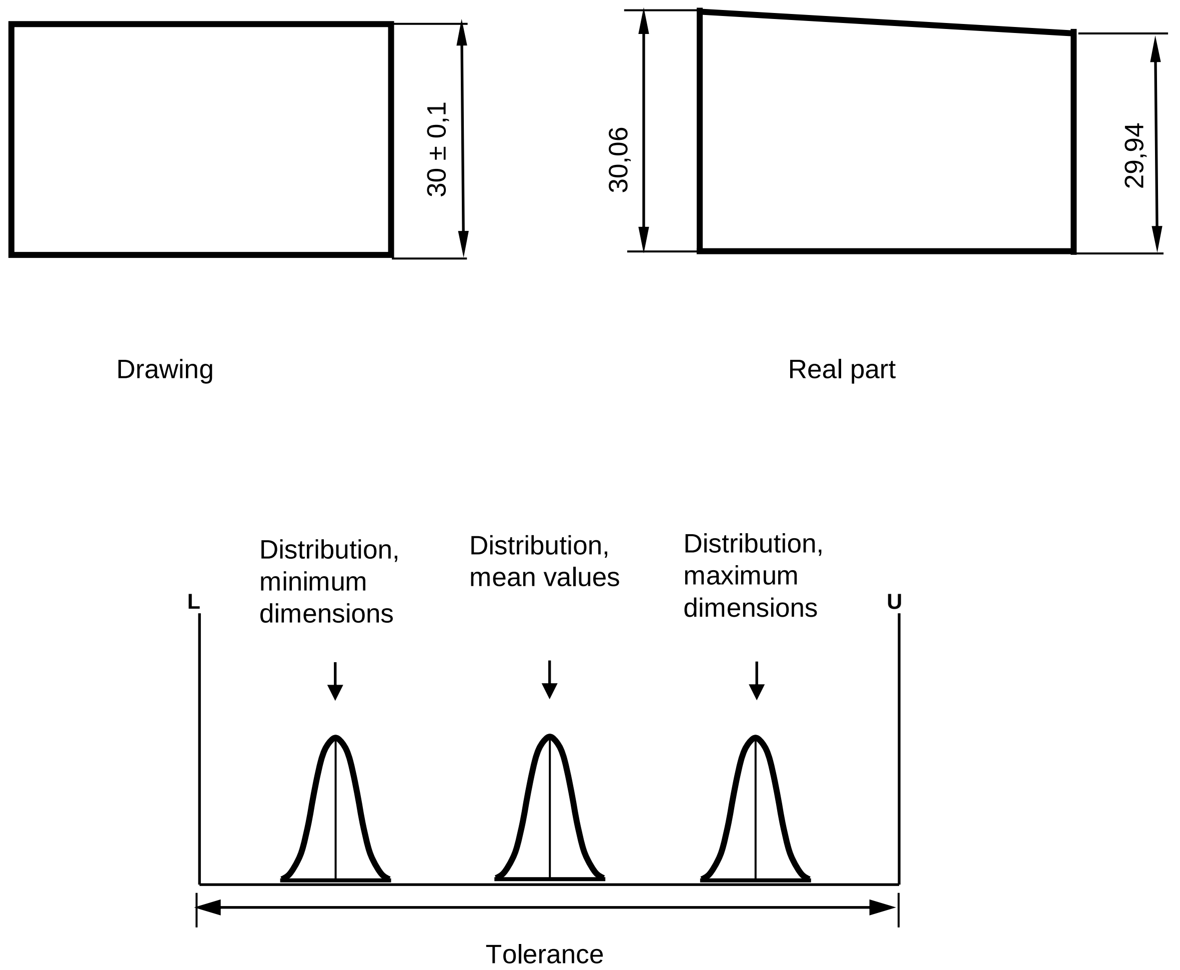

Fig. 9

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At this study, the maximum dimensions, minimum dimensions and the mean value (mean value for maximum and minimum dimensions) for the characteristic are measured.

The location and dispersion of the distribution of the maximum dimensions are used when calculating Ppk/Cpk/Cmk for the upper tolerance limit.

The location and dispersion of the distribution of the minimum dimensions are used when calculating Ppk/Cpk/Cmk for the lower tolerance limit. The smallest of these capability indices is the corrected capability index for the characteristic. The location and dispersion for the distribution of the mean values are used when calculating MC and Pp/Cp/Cm.

8.3 Handling of out-liers

At capability studies, it is important that extreme results, so-called out-liers, which are not representative of the process can be identified and eliminated from the study.

Parts which are not manufactured under production-like conditions, such as setting plates, etc., shall not be included in the capability study.

For current production, where measuring data are continuously registered and stored for continuous assessment of the process capability, it is important that these data are analyzed in such a way that non-representative results are not included in capability studies. Provided the process result is normally distributed and under statistical control, distribution type A1 according to section 6 meaning a limit of ± 4 S from the relevant mean or median value can be used as a guideline for the identification of those results that can be regarded as non-representative.

Out-liers can arise as unexpected events, such as tool-failure, during an otherwise stable process or by incorrect measurement.

If an extreme result can be regarded as a so-called out-lier, a root cause analysis should be performed to identify the reason for the existence of this out-lier even if the out-lier is excluded from the statistical calculation.

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Annex A (informative)

Not normally distributed results

Results which are not normally distributed must be handled with a different mathematical method than normally distributed results. There are several (mathematically defined) distribution types other than normal distribution. In most cases, these can be described as skewed, that is, with a displacement of data so that they are not symmetrically disposed around a mean value, see figure A1.

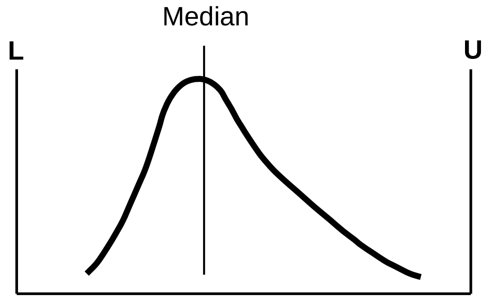

Figure A1 Skewed distribution

For most skewed distributions, it is possible to determine the capability by plotting the values in a so-called extreme value distribution probability paper. An example of such a determination is shown in figure A2.

Computer programmes which contain a number of distribution types are also available. The type of calculation to be used is to be decided by the respective Business Area/Business Unit.

It is important to consider that many of the methods used for determining the dispersion of a result can mean that an inviolable limit can exist physically, e.g. the value 0 (zero) for run-out, while the distribution type is defined for ± infinity.

If a theoretically calculated value exceeds the physically inviolable limit, the physically inviolable limit replaces the theoretically calculated value for, e.g., $X_{0,135\%}$ when calculating the capability.

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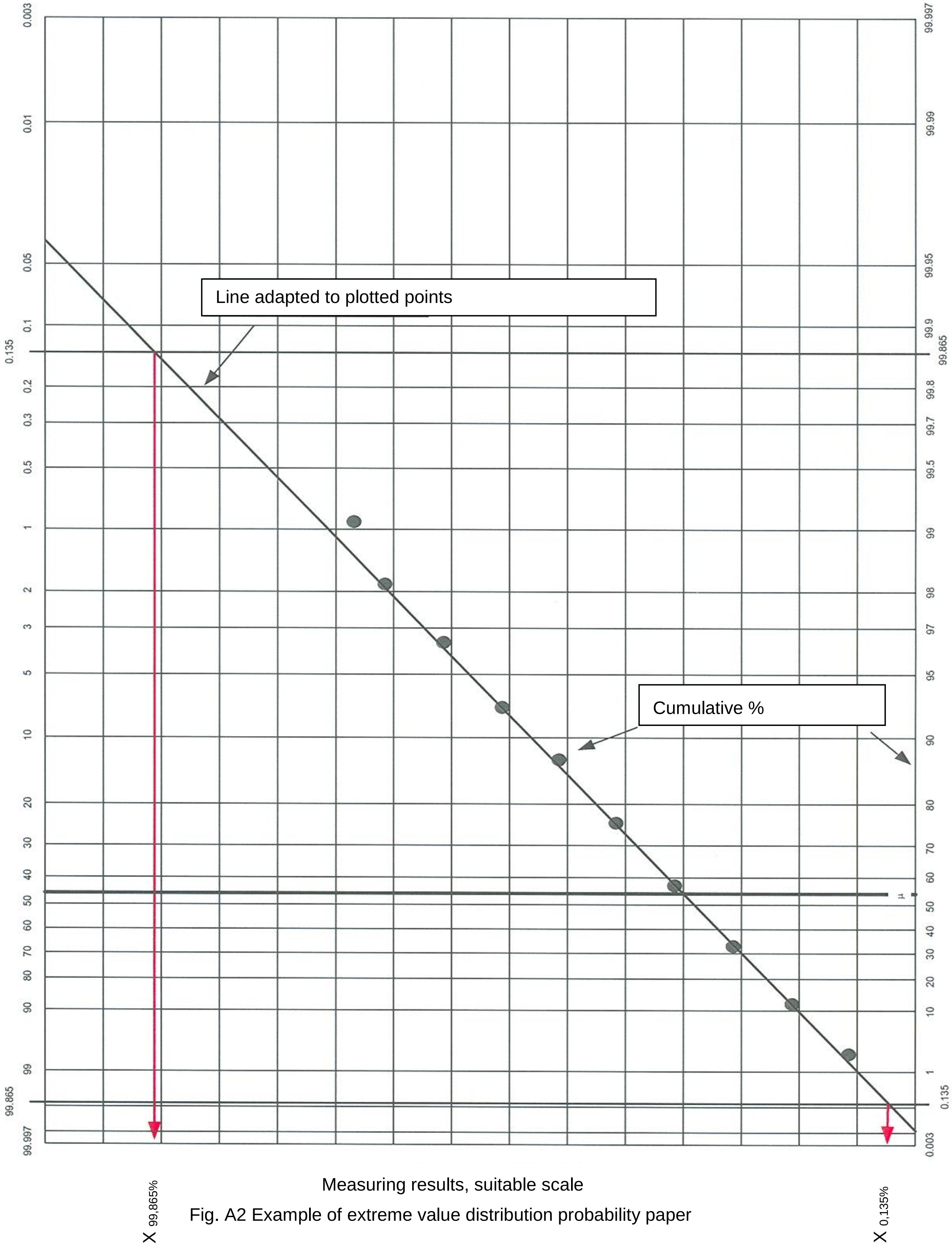

Fig. A2 Example of extreme value distribution probability paper

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Annex B (informative)

Requirements with maximum material requirement

When a tolerance requirement is indicated with maximum material requirement (for definition of maximum material requirement, see STD 112-0001), this means that the tolerance size varies individually for the parts since the use of maximum material requirement permits an increase in the size of the tolerance zone when the dimension of the feature deviates from the maxium material condition.

This, in turn, means that capability studies, which are based on a distribution compared with tolerance sizes and tolerance limits is made more difficult since the tolerance limits are variable and not fixed to the same value for the respective individual part.

For requirements with maximum material requirement, the decisive method is inspection using a fuctional gauge. At capability studies, results from measurements are needed; this means that the geometrical requirements for the feature together with the dimensions of the feature are measured with indicating measuring instruments. To obtain data that can be treated for capability studies, the tolerance size then needs to be normalized to the same value for all measurements.

One way of normalizing the tolerance size is to perform the capability study without considering the maximum material requirement. If the effect of the maximum material requirement is small in comparison to the geometrical tolerance, such a capability study will function well, but if the major part of the tolerance consists of the effect of the maximum material requirement, that is when the addition to the geometrical tolerance that comes from the dimension of the feature is large in comparison to the actual geometrical tolerance, a different type of normalization of the tolerance size is needed.

Another way of normalizing the tolerance zone is the following:

If the tolerance size is normalized in such a way that the tolerance of the individual part is considered as constituting 100 %, then the same tolerance size is obtained for all individuals, that is tolerance 100.

The **utilization** of the individual parts of their respective tolerances can then be calculated as a percentage.

If a number of parts are measured and their respective tolerance utilization has been calculated, we obtain a number of measuring results expressed as a percentage of the tolerance zone. These measuring results can then be used for calculation of the capability index. The entire tolerance zone is set to 100 % and the capability index is then calculated as for a unilateral tolerance.

See example, figure B1.

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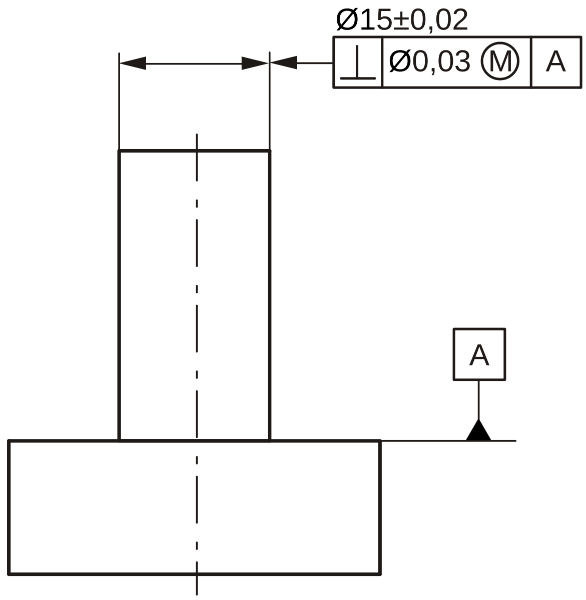

Figure B1 Example – Perpendicularity with maximum material requirement

A part of diameter 15,000 obtains 15,020 - 15,000 = 0,020 in addition to the perpendicularity tolerance and has tolerance size 0,03 + 0,02 = 0,05.

With a perpendicularity deviation of 0,02, this part has utilized 0,02/0,05 = 40 % of the available tolerance zone. At a capability study where the tolerance size has been normalized to 100 %, the measuring value for the part is thus 40 %.

This procedure cannot be used for process control in the strict sense of the word, but gives a useful answer to the question whether the process can be considered as meeting the requirements specified with respect to the capability index.

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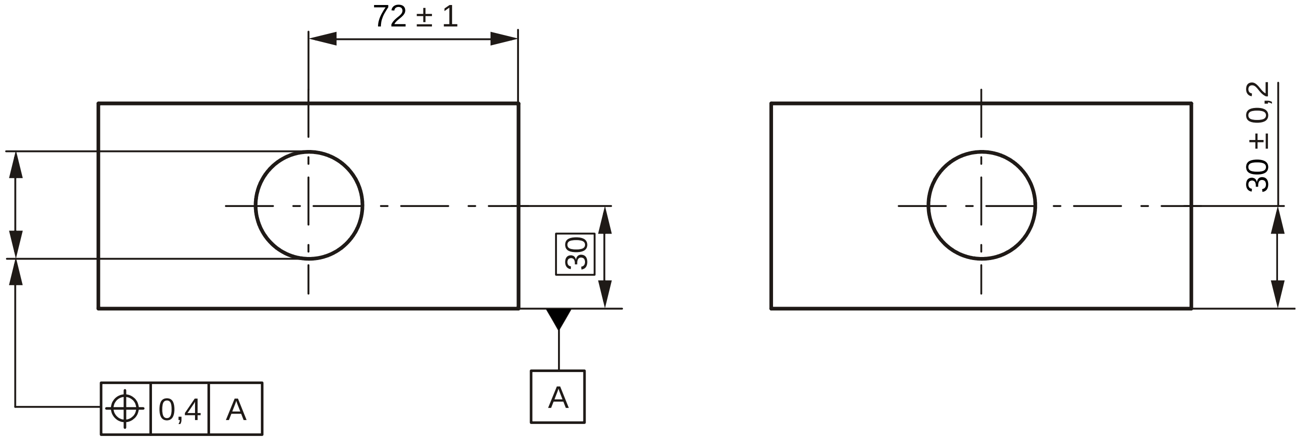
Appendix C (informative)

Capability at position and multilateral tolerance zones

Position in one direction only

When measuring a position tolerance in ordinary measuring equipments, such as coordinate measuring machines, the measuring result is usually obtained as a value, which constitutes the size of the requisite tolerance zone. The tolerance is treated as a unilateral tolerance, even if it can deviate in two or more directions.

When the tolerance for position applies in a specific direction, it can in connection with capability calculation be replaced by a distance dimension with ± tolerance. See example in figure C1.



Drawing

Replacement for drawing requirement for calculation of capability

Fig. C1 Drawing requirement and replacement figure for calculation of capability

When measuring the position according to the drawing in a coordinate measuring machine, the measuring value for two parts with size 29,9 and 30,1 respectively as a distance from the plane to the centre of the hole is presented as 0,2 since both require tolerance zone 0,2 for approval.

Since it is important to obtain information at the capability study as to in what direction the deviation from target value is placed, the position tolerance is recalculated to a distance with ± tolerance and is indicated and measured at the capability study as 30 ± 0,2 instead of a position tolerance.

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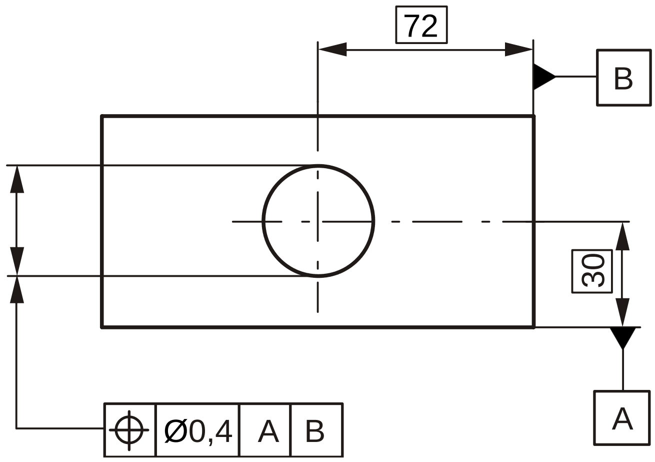
Position with circular tolerance zone

If a position tolerance has been indicated with circular or cylindrical tolerance zone, which is the most common for circular and cylindrical features, it is not possible to recalculate to ± tolerance.

Such a tolerance can be considered as multilateral since a feature may deviate in many directions from the theoretical position. See example in figure C2.



Drawing - Diameter size in the tolerance frame for position indicates that the tolerance zone is circular

Fig. C2

For control purposes, location and dispersion in two axes can be evaluated separately. Determination of capability in, e.g., X- and Y-axis separately, is not suitable since the capability index is related to a tolerance and separate tolerances in two axes mean a square tolerance zone instead of a circular one.

If half the diametral position tolerance is indicated as ± tolerance for the respective axis, the capability of the process will be overrated if a capability index/axis is calculated. Compensation for this is sometimes made by dividing half the diametral position tolerance with the square root of 2 (which gives a ± tolerance in the respective direction of approx. 70 % of half the diametral position tolerance) but risks, on the other hand, to conversely underestimate the capability of the process.

There are different calculation models for an evaluation of capability that takes location and dispersion for both axes into consideration at the same time, see example below.

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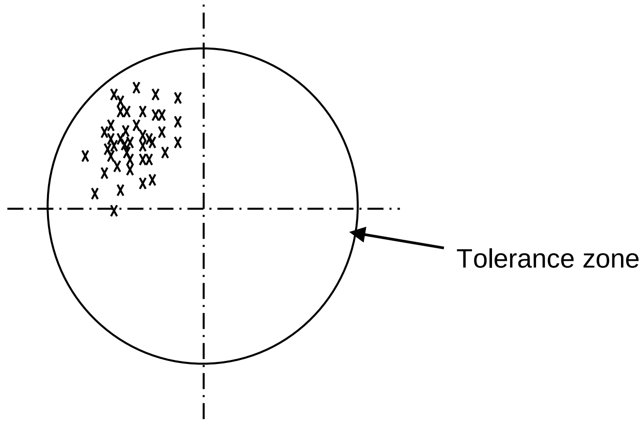
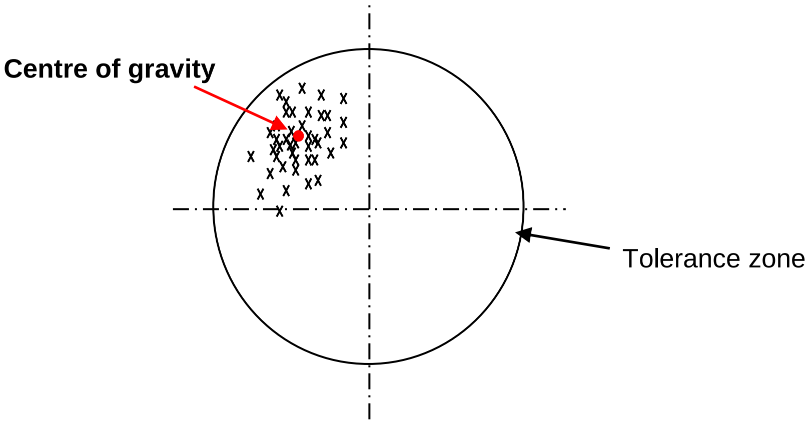
Example of model for determining capability for multilateral tolerance



Position of a number of measured locations relative to indicated circular tolerance zone.



The centre of gravity for the amount of spots is determined.

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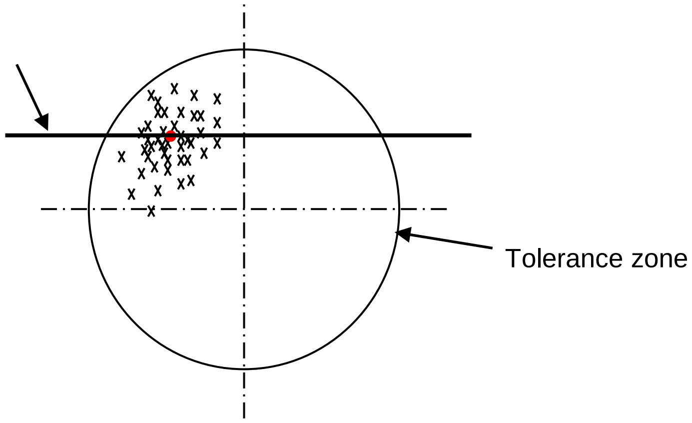
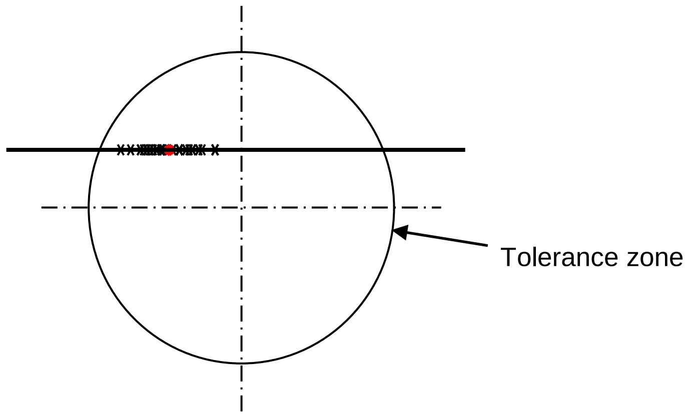
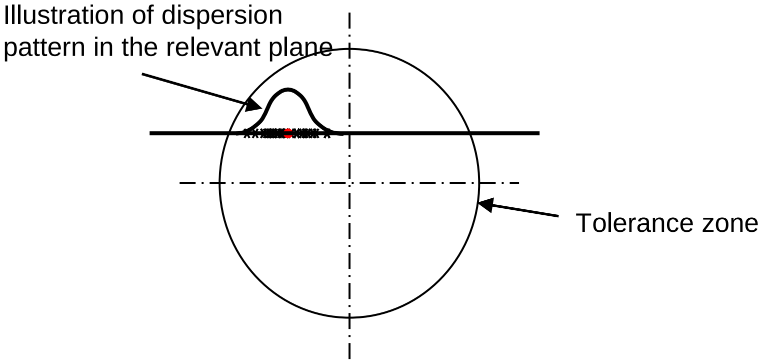
Constructed plane, parallel to the X-axis and through the centre of gravity





All measured locations are projected in the constructed plane.



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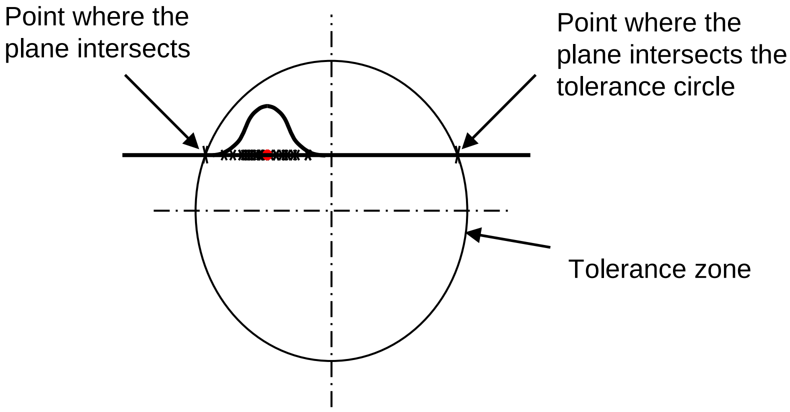
The dispersion for the amount of spots, in the relevant plane, is calculated. In the above example, illustrated via a normal distribution.



The points where the relevant plane intersects the tolerance circle are determined. This means that the distance from the tolerance circle to point of balance can be calculated, in two directions. By dividing these distances by three standard deviations, two Cpk values are obtained.

By means of the calculated standard deviation and the distance between the two points of intersection, which makes up the tolerance zone in the relevant direction, Cp can be calculated for the orientation given by the plane in question.

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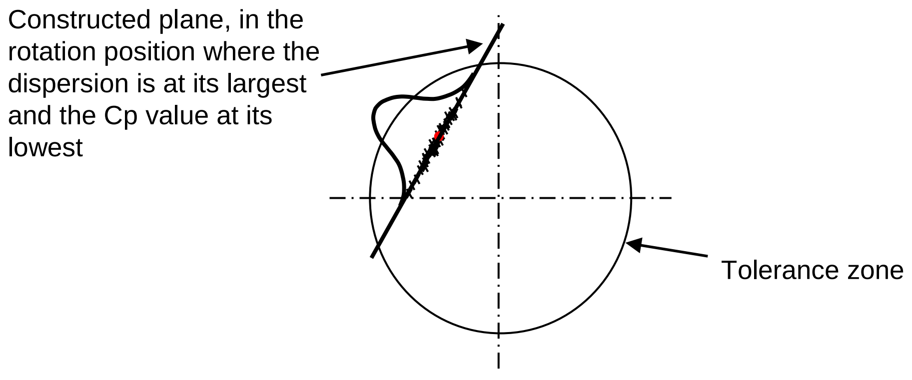
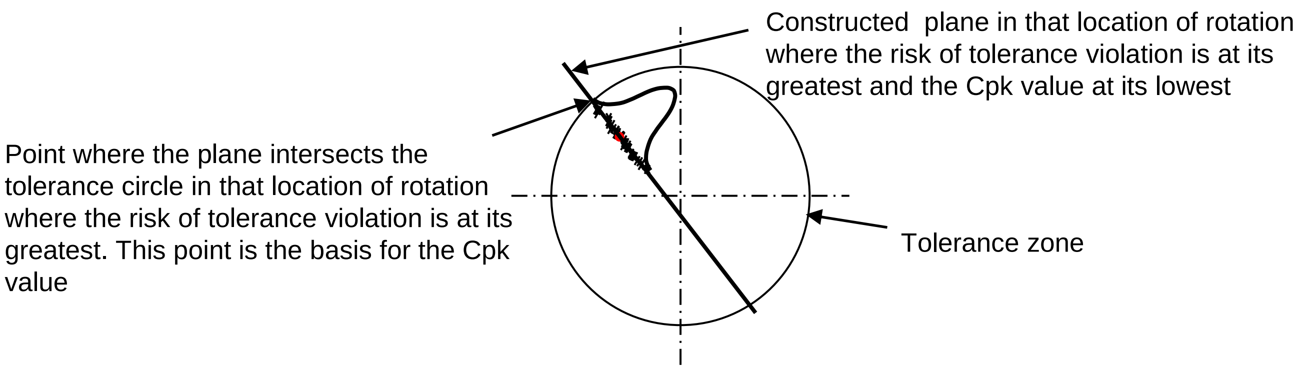
By iteratively rotating the constructed plane through the point of balance in different directions, repeating the projection of the points in the different directions and repeating the evaluation of Cp and Cpk in each iteration, the orientation for the largest dispersion of the amount of points can be produced as a basis for Cp and the orientation where the tolerance violation is at its greatest as a basis for Cpk.





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Annex D (informative)

Interpretation of capability indices

In Annex D, the meaning of some different capability indices is exemplified.

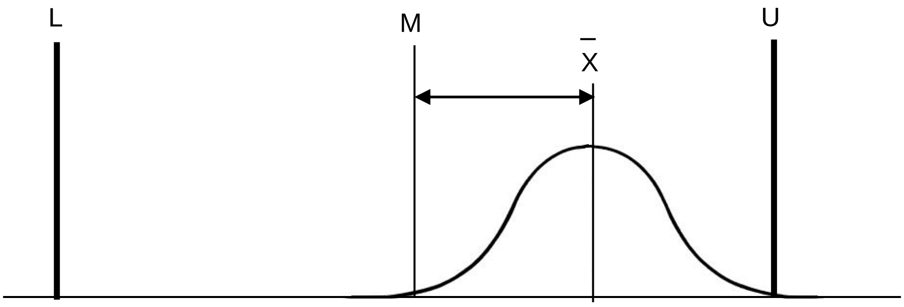
D1 Centering to target value

Target value centering MC is measured as the difference between the mean value of a result and the target value and expressed in per cent of the tolerance zone. MC is negative if the mean value is below the target value.

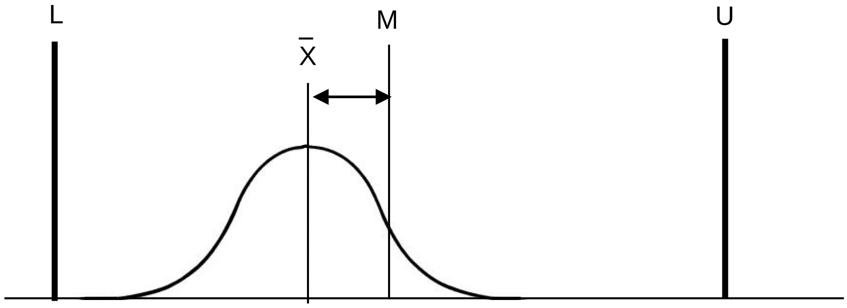
Rules of thumb:

If MC has a minus sign, the mean value is lower than the target value.
If MC = 50 %, the mean value is just on the upper tolerance limit.
If MC = -50 %, the mean value is just on the lower tolerance limit.
If MC is 25 %, the mean value is midway between the upper tolerance limit and the target value.
If MC is higher than 50 % or -50 %, more than half of the results are outside the upper and lower tolerance limit respectively.

See also figure D1.



Tolerance: 50 ± 0,1 Mean value: 50,05 MC = 25 %



Tolerance: 50 ± 0,1 Mean value: 49,975 MC = -12,5 %

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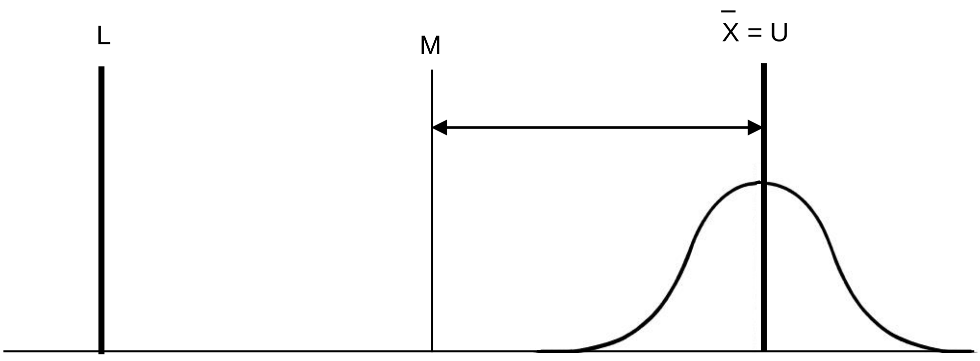


Tolerance: 50 ± 0,1   Mean value: 50,1   MC = 50 %

Figure D1 Example of centering value to target value

D2 Dispersion Pp / Cp / Cm

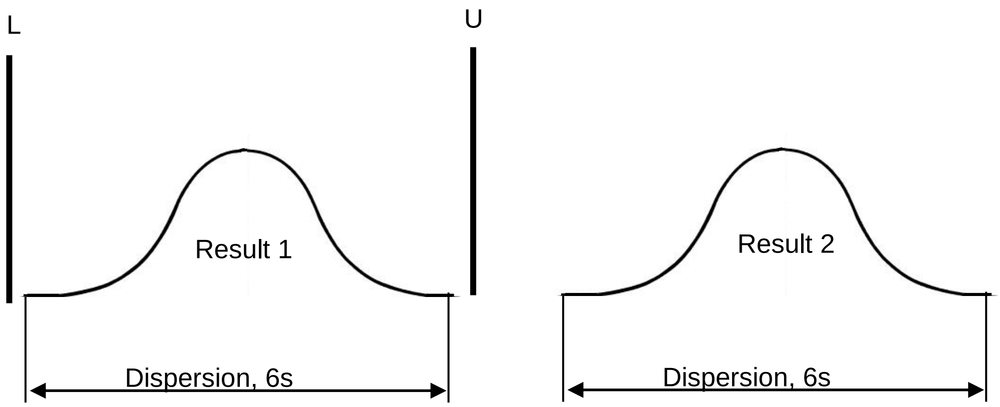
Capability indices Pp, Cp and Cm are measured as dispersion of a result in relation to the size of the tolerance.

The capability index gives a rough idea of the possibilities to be able to meet tolerances, not if the tolerance actually has been met.

Rules of thumb:

If Cp = 1, the dispersion is of the same size as the tolerance zone.
If Cp > 1, the dispersion is smaller than the tolerance zone.
If Cp = 2, the dispersion is half the tolerance zone.
If Cp < 1, the dispersion is larger than the tolerance zone.
If Cp = 0,5, the dispersion is twice as large as the tolerance zone.

See also figure D2.



Results 1 and 2 are normally distributed and have the same dispersion, somewhat smaller than the tolerance zone. Cp is thus the same even if result 1 gives approved parts and result 2 non-approved parts.

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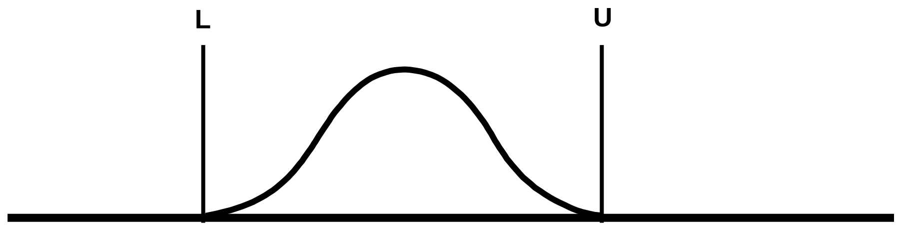
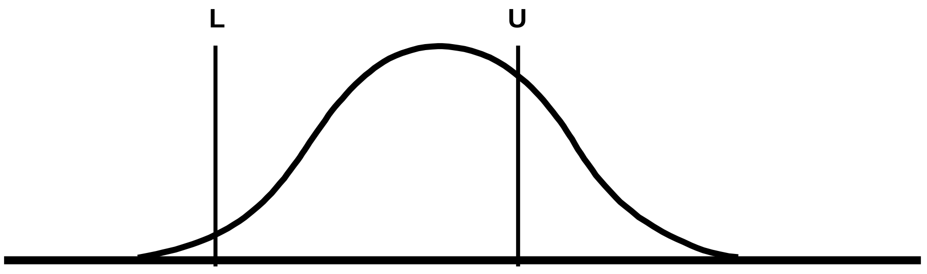
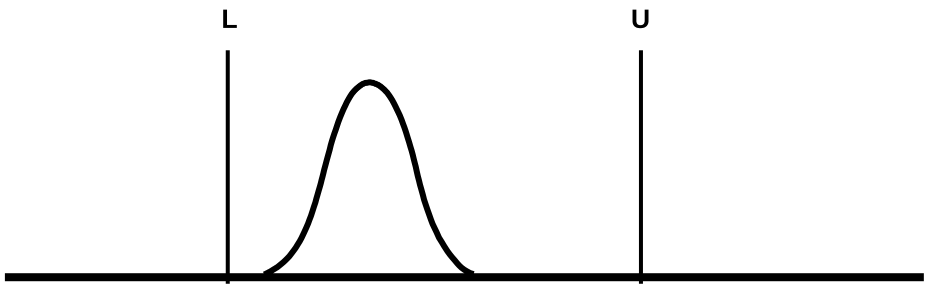


If Cp = 1, the dispersion is of the same size as the tolerance zone



If Cp = 0,5, the dispersion is twice as large as the tolerance zone



If Cp = 2, the dispersion is half the size of the tolerance zone

Fig. D2 Examples of dispersion

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D3 Minimum capability Ppk/Cpk/Cmk

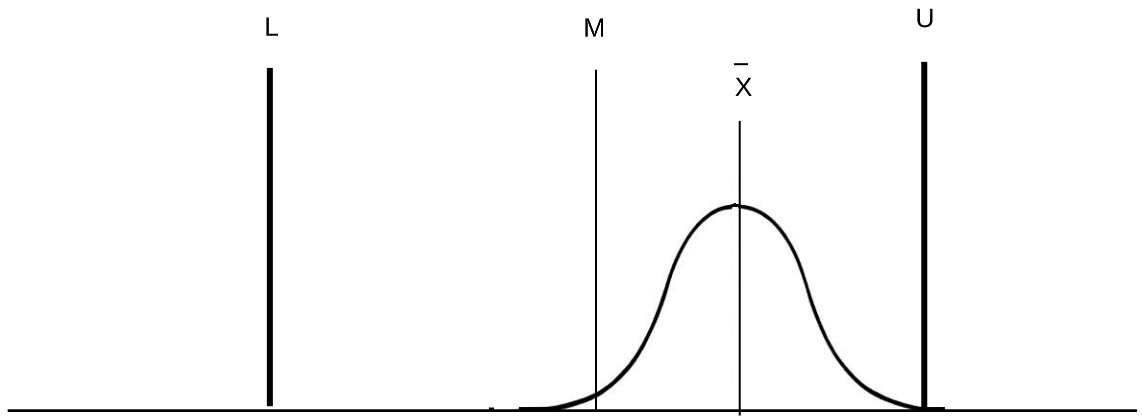
The minimum capability index Ppk, Cpk and Cmk respectively is measured as the distance between the median of a result and the tolerance limit in relation to half the dispersion.

The minimum capability index lets us know whether or not a tolerance is met and how large a share of the result that is outside tolerance or risks being outside tolerance. Minimum capability indices can result as negative numbers.

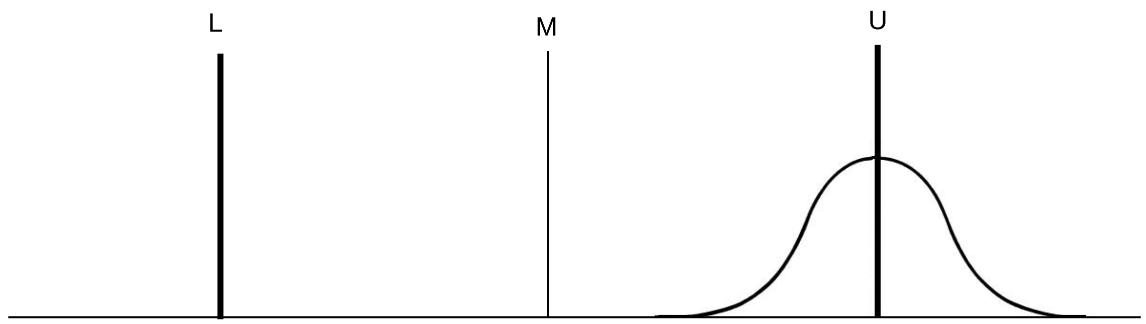
Rules of thumb:

If Cpk = 1, the result is within tolerance but tangent to the tolerance limit.
If Cpk > 1, the distance between the mean value of the result to the tolerance limit is larger than half the dispersion.
If Cpk = 2, the distance between the mean value of the result to the tolerance limit is of the same size as the entire dispersion.
If Cpk < 1, the distance between the mean value of the result to the tolerance limit is less than half the dispersion.
If Cpk = Cp, the result is perfectly centred; the mean value = the midpoint of the tolerance.
If Cpk < 1, the distance between the mean value of the result to the tolerance limit is less than half the dispersion.
If Cpk = 0, the mean value of the result is on the tolerance limit.
If Cpk = -1, the result is outside tolerance and tangent to the tolerance limit.

See also figure D3.



Cpk = 1



Cpk = 0

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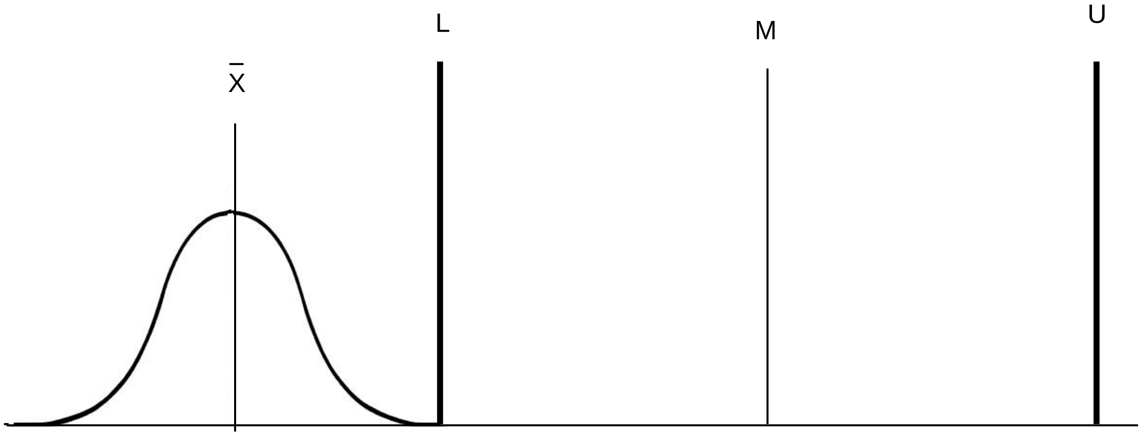

Cpk = -1

Fig. D3 Examples of results and corrected capability indices

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In table D1, the portion outside tolerance is indicated for certain values for minimum capability indices. For unilateral tolerances, only **one** tolerance limit can be exceeded. If the results are well centred, both tolerances can be exceeded in the case of bilateral tolerances.

A perfectly centred result with Ppk/Cpk/Cmk 1,33 for a bilateral tolerance means that the risk of exceeding the tolerance is 0,006 % or 60 PPM.

However, there is normally a certain displacement of the result and this is why it also in the case of bilateral tolerances there is usually a risk of only one tolerance limit being exceeded.

Table D1 shows the portion outside tolerance linked to the minimum capability indices when only one tolerance limit is exceeded.

Table D1 Minimum capability indices and exceeding of tolerance

Ppk/Cpk/Cmk	Portion outside tolerance if only **one** tolerance limit is exceeded
1,5	0 %
1,4	0,001 %
1,33	0,003 %
1,3	0,005 %
1,2	0,016 %
1,1	0,048 %
1,0	0,135 %
0,9	0,35 %
0,8	0,82 %
0,7	1,79 %
0,6	3,59 %
0,5	6,68 %
0,4	11,51 %
0,3	18,41 %
0,2	27,42 %
0,1	38,21 %
0,0	50 %
-0,1	61,79 %
-0,2	72,58 %
-0,3	81,59 %
-0,4	88,49 %
-0,5	93,32 %
-0,6	96,41 %
-0,7	98,21 %
-0,8	99,18 %
-0,9	99,65 %
-1,0	99,865 %