INTERNATIONAL STANDARD

ISO 26303

Second edition
2022-03

Machine tools — Short-term capability evaluation of machining processes on metal-cutting machine tools

Machines-outils — Évaluation de la capacité des procédés d'usinage des machines-outils travaillant par enlèvement de métal

Reference number
ISO 26303:2022(E)

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Published in Switzerland

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Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular, the different approval criteria needed for the different types of ISO documents should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights. Details of any patent rights identified during the development of the document will be in the Introduction and/or on the ISO list of patent declarations received (see www.iso.org/patents).

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For an explanation of the voluntary nature of standards, the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the World Trade Organization (WTO) principles in the Technical Barriers to Trade (TBT), see www.iso.org/iso/foreword.html.

This document was prepared by Technical Committee ISO/TC 39, *Machine tools*, Subcommittee SC 2, *Test conditions for metal cutting machine tools*.

This second edition cancels and replaces the first edition (ISO 26303:2012), which has been technically revised. The main changes compared with the previous edition are as follows:

— additional explanations have been added in 6.6 "Measurement" and for Formula (23);

— the indices of variables in Formulae (3) and (18) have been corrected;

— agreement forms 2 to 4 of Annex B, analysis form 2 of Annex C, agreement forms 3 and 4 of Annex D and analysis forms 1 and 2 of Annex D have been corrected;

— the references in Figure 2 have been revised;

— Figure A.1 has been improved;

— the status of Annexes B and C has been changed to informative;

— the formulae in analysis form 4 of Annex C and in analysis form 4 of Annex D have been corrected;

— the Bibliography has been updated.

Any feedback or questions on this document should be directed to the user's national standards body. A complete listing of these bodies can be found at www.iso.org/members.html.

Introduction

The evaluation of the short-term capability of the machining process is a different approach in machine tool assessment compared with machine tool performance testing methods, which are covered by a number of International Standards, e.g. ISO 230 (all parts) and other machine tool type specific standards. The main differences are machining a sample batch of test pieces and definition of the relevant influencing factors as well as the statistical conditioning and analysis of the workpiece quality related data obtained during such tests.

This document is the result of a project guided closely by an international working group, and summarized in order to make the information available to as many interested parties as possible.

Especially for large batch production, short-term process capability estimates, as well as capacity measures, are very often applied in addition to testing of machine tool performances. In fact, machine tool users increasingly employ statistical process control (SPC) techniques in their activities and frequently ask the machine suppliers/manufacturers to become system suppliers as well, giving them responsibilities for the machining process too.

Statistical methods in process management are covered by ISO 22514 (all parts).

For the purposes of machine tool acceptance based on the test of its capability in machining a specified workpiece, both requirements and methods stated by individual users differ widely, due to the absence of a recognized International Standard. Long-winded discussions and adaptation processes during the acceptance tests are, therefore, often necessary, delaying delivery to the customer and causing great time- and cost-related expenditure. This document provides a unified procedure for the acceptance test of a machine tool based on its short-term process capability. It introduces:

— the short-term capability of a given process, which employs the machine tool under test, the machining process, tooling and clamping applied, as well as the workpiece properties;

— the estimate of relevant machine capability indexes.

This document adapts to and conforms to the specifications established in ISO 22514 (all parts). However, the term “process performance index” specified in ISO 3534-2:2006 and used in ISO 22514-3:2020 corresponds for normal distribution to the term “short-term capability” in this document. The term “short-term capability” has been widely used in the machine tool industry for many years; therefore, ISO/TC 39/SC 2 decided to maintain this term.

Combined with the statistical evaluation, many influencing factors significantly restrict the fraction of tolerance interval covered by machine tool variations. As a consequence, the machine capability indices are specified in conjunction with the test conditions and the required tolerance limits.

Machine tools — Short-term capability evaluation of machining processes on metal-cutting machine tools

1 Scope

This document specifies procedures for acceptance of metal-cutting machine tools based on the tests of their capability in machining a specified workpiece (i.e. indirect testing). It gives recommendations for test conditions, applicable measurement systems and the requirements for machine tools.

This document is consistent with ISO 22514 (all parts) describing statistical methods for process management and deals with the specific application of those methods to machine tools and machining of a sample batch of test pieces. This document covers neither functional tests, which are generally carried out before testing the accuracy performance, nor the testing of the safety conditions of the machine tool.

Annex A gives additional information related to statistical evaluation, Annexes B and C provide agreement and evaluations forms for short-term capability tests, while Annex D gives an example.

NOTE 1 Direct testing aims to investigate individual machine tool properties, such as geometric or positioning accuracy. Short-term capability evaluation is meant to prove that a machine tool has the capability to fulfil a specific process task. It is, therefore, important to recognize that the short-term capability test is focused only on the manufactured product. This means that direct testing methods are more suited for the determination of error sources on the machine tool and for deriving constructive improvements of a machine tool that is used in a wide production spectrum; a short-term capability test is less suited for detection of error sources of the machine tool. Therefore, it is expected that short-term capability evaluation for the acceptance of metal-cutting machine tools in machining processes be primarily carried out on workpiece-dependent special-purpose machines, e.g. working stations of transfer lines, with a process-determined cycle time of less than 10 min, so that at least 50 workpieces are manufactured in one shift as the statistical uncertainty increases strongly for a smaller number. In principle, short-term capability evaluation can also be performed on universal machine tools, such as machining centres used for large batch production if they meet the above-mentioned statistical requirements.

NOTE 2 The term “short-term capability”, which is a widely used term in machine tool industry, corresponds to the term “process performance index” specified in ISO 3534-2:2006 for normal distribution.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements 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.

ISO 4288, *Geometrical Product Specifications (GPS) — Surface texture: Profile method — Rules and procedures for the assessment of surface texture*

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

— ISO Online browsing platform: available at https://www.iso.org/obp

— IEC Electropedia: available at http://www.electropedia.org/

3.1
short-term capability
ability of a manufacturing unit to produce a given part within specified tolerances at a specified confidence level, a concept mainly applied to batch production

Note 1 to entry: A manufacturing unit may be a single machine tool, one spindle of a multi-spindle machine tool, one station of a transfer line, etc.

Note 2 to entry: In this document, short-term capability indices, C_s and C_sk, are estimated under the assumption of normal distribution of the characteristic value considered. If this assumption is not fulfilled, *short-term range values*, $R_\mathrm{V,s}$, (3.4) and *critical short-term range value*, $R_\mathrm{V,sk}$, (3.5) are evaluated instead of capability indices.

Note 3 to entry: This document adapts to and conforms to the specifications established in ISO 22514 (all parts). However, the term "process performance index" specified in ISO 3534-2:2006 and used in ISO 22514-3 corresponds for normal distribution to the term "short-term capability" in this document. The term "short-term capability" is widely used in the machine tool industry; therefore, ISO/TC 39/SC 2 decided to maintain this term.

3.2
short-term capability index
C_s
ratio of the specified tolerance itself to the standard deviation of the measured values quantifying the scatter

Note 1 to entry: See Formula (14).

Note 2 to entry: Measured values are also known as characteristic values.

3.3
critical short-term capability index
C_sk
ratio of the specified tolerance itself to the standard deviation of the measured values quantifying the scatter under consideration of the location of the mean value

Note 1 to entry: If the mean value of the measured values is in the centre of the tolerance zone, this is called a centred distribution; if the mean value is not in the centre of the tolerance zone, this is called a shifted distribution. For the relationship between centred and shifted distributions, see A.1.

Note 2 to entry: Measured values are also known as characteristic values.

3.4
short-term range value
$R_\mathrm{V,s}$
ratio of the range of the measured values to the specified tolerance itself

3.5
critical short-term range value
$R_\mathrm{V,sk}$
ratio of the range of the measured values to the specified tolerance itself under consideration of the location of the mean value

3.6
control chart
chart on which some statistical measure of a series of samples is plotted in a particular order to steer the process with respect to that measure and to control and reduce variation

Note 1 to entry: The particular order is usually based on time or sample number order.

[SOURCE: ISO 3534-2:2006, 2.3.1, modified — Note 2 to entry has been deleted.]

3.7
control chart for individuals
individuals control chart
variables *control chart* (3.6) for evaluating the process level in terms of the individual observations in the sample

[SOURCE: ISO 3534-2:2006, 2.3.15, modified — The preferred term has been added and the notes to entry have been deleted.]

3.8
control limit
line on a *control chart* (3.6) used for judging the stability of a process

[SOURCE: ISO 3534-2:2006, 2.4.2, modified — The notes to entry have been deleted.]

3.9
lower specification limit
LSL
L_{SL}
specification limit that defines the lowest value a quality characteristic might have and still be considered conforming

[SOURCE: ISO 22514-1:2014, 3.1.13, modified — The symbol has been changed from *L* and Note 1 to entry has been deleted.]

3.10
upper specification limit
USL
U_{SL}
specification limit that defines the highest value a quality characteristic can have and still be considered conforming

[SOURCE: ISO 22514-1:2014, 3.1.12, modified — The symbol has been changed from *U* and Note 1 to entry has been deleted.]

3.11
upper control limit
UCL
U_{CL}
control limit (3.9) that defines the upper control boundary

[SOURCE: ISO 3534-2:2006, 2.4.8]

3.12
lower control limit
LCL
L_{CL}
control limit (3.9) that defines the lower control boundary

[SOURCE: ISO 3534-2:2006, 2.4.9]

4 Symbols

4.1 Uppercase letters

C	capability index
C_k	critical capability index
C_s	short-term capability index (corresponds to process performance index P_P in ISO 3534-2:2006 for normal distribution);
$C_{s,nom}$	nominal short-term capability index
C_{sk}	critical short-term capability index
$C_{sk,nom}$	nominal critical short-term capability index
C_{act}	actual capability index
K_i	i^{th} class (histogram)
U	uncertainty (of measurement or capability index)
U_{CL,s_i}	upper control limit for the standard deviation s_i
$U_{CL,\bar{x}j}$	upper control limit for the average values $\bar{x}_j$
U_{SL}	upper specification limit
R	range
$R_{V,s}$	short-term range value
$R_{V,s,nom}$	nominal short-term range value
$R_{V,sk}$	short-term critical range value
$R_{V,sk,nom}$	nominal short-term critical range value
T	tolerance
T_{min}	minimum usable tolerance for capability evaluation
$L_{CL,sj}$	lower control limit for the standard deviation s_j
$L_{CL,\bar{x}j}$	lower control limit for the average values $\bar{x}_j$
L_{SL}	lower specification limit

4.2 Lowercase letters

e	shift of the average value
f	feed in mm/min or in mm/rev
i	running index for measurements
j	running index for groups of measurements
k	running index for measurements within one group
m	number of groups of parts for control charts
n	sample size (number of evaluated parts)
n_{mp}	number of manufactured parts
n_{K}	number of classes (histogram)
n_{min}	minimum value of necessary parts
r	resolution of the measuring device
s	estimator of the standard deviation
$\overline{s}$	average standard deviation of the samples (groups)
s_{act}	actual standard deviation of process
s_{g}	standard deviation of the measurement (gauging) system
s_j	standard deviation of the j^{th} sample (group)
t	time
t_{m}	manufacturing time
t_{tot}	total manufacturing time
$\overline{x}$	mean value of population (of 50 measurements)
$\overline{x}'$	mean value of population with shifted distribution
$\overline{\overline{x}}$	mean value of group means $\overline{x}_j$
x_i	i^{th} measurement value
$x_{i,\mathrm{T}}$	i^{th} measurement value (trend corrected)
$x_{\mathrm{u},k}$	upper class limit of the k^{th} class (histogram)
$\overline{x}_j$	mean of the j^{th} sample (group)
x_{max}	maximum value
x_{min}	minimum value

4.3 Greek letters

$\delta X_{\mathrm{tot,T}}$	total trend (in relation to all values)
$\delta X_{\mathrm{tot,w}}$	total trend per workpiece
δX_{td}	trend due to thermal distortion

$\delta X_{td,w}$	trend due to thermal distortion per workpiece
$\delta X_{td,perm}$	permissible trend due to thermal distortion per workpiece in X-direction
δX_{a}	trend due to tool wear
$\delta X_{a,exp}$	expected trend due to tool wear
Δd_{u}	distance between the maximum value and the upper tolerance limit
Δd_{l}	distance between the minimum value and the lower tolerance limit
Δd_{c}	critical distance between the extreme values and the tolerance limits
ΔX_{k}	class width (histogram)
$\Delta X_{K,k}$	border line of class (histogram)
ΔX_{c}	critical distance of the average value to the tolerance limits
ΔX_{u}	distance between the average value and the upper tolerance limit
ΔX_{l}	distance between the average value and the lower tolerance limit
$\Delta x(t)$	thermal displacement as a function of time t
Δx_{max}	maximum displacement
$\Delta \upsilon_{amb}$	ambient temperature gradient
$\Delta \upsilon_{amb,max}$	maximum ambient temperature gradient
ϑ	temperature
$\vartheta_{amb,0}$	ambient temperature at beginning of test
ϑ_{max}	maximum temperature
ϑ_{min}	minimum temperature
$\delta Y_{td,perm}$	permissible trend due to thermal distortion per workpiece in Y-direction
$\delta Z_{td,perm}$	permissible trend due to thermal distortion per workpiece in Z-direction
$\hat{\sigma}$	estimation of the standard deviation of the population
τ	thermal time constant
Ψ	shift ratio for shifted distribution

5 Preliminary remarks

Short-term capability evaluation belongs to the class of indirect testing methods and, hence, is a different approach to machine tool acceptance testing in comparison to the direct testing defined in several series of International Standards, e.g. ISO 230 (all parts).

The measured feature shall be machined on one machining unit only. If the same feature is machined on different, but similar, machining units, the statistical analysis shall be carried out separately for each machining unit.

6 Procedure for short-term capability evaluation

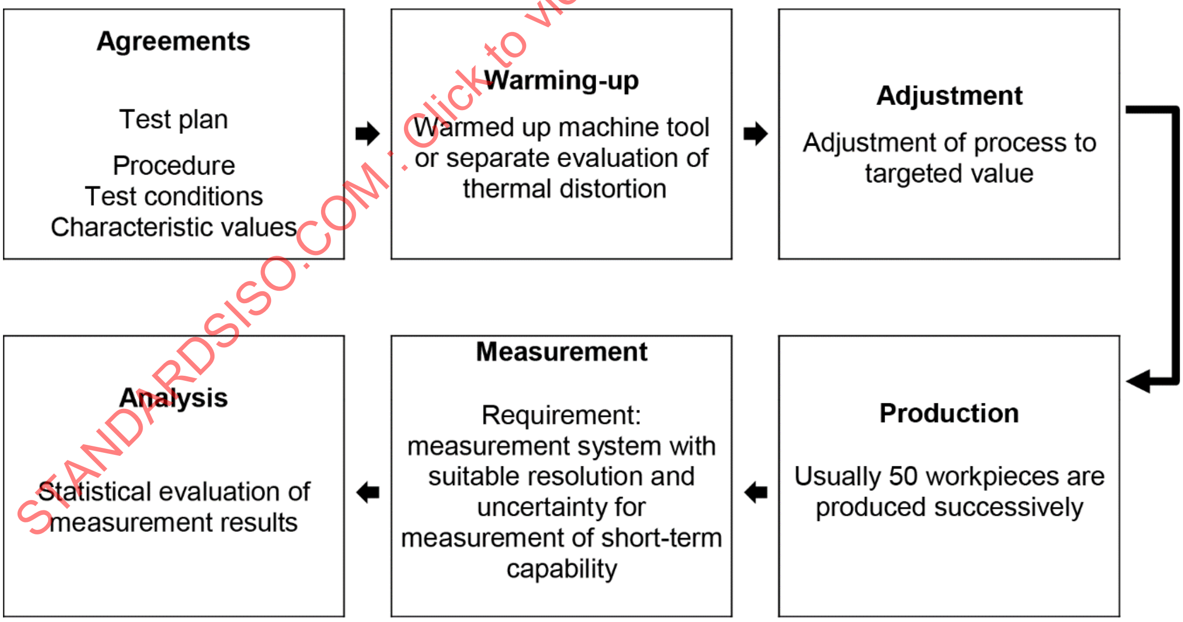
6.1 General

The basic procedure during a short-term capability evaluation is shown in Figure 1. Acceptance according to a short-term capability evaluation is only recommended for machine tools used in large batch production with a process cycle time of less than 10 min. In addition, the adequate short-term capability (see 6.6) of the measuring process is a necessary requirement for measuring the workpieces.

NOTE In some cases, preparatory studies are performed in order to demonstrate that the operator can successfully interact with the machining process and that the subsequent process capability study will be successful (see ASME B89.7.3.1).

Before initiating the test and evaluation process, the supplier/manufacturer and the user shall reach necessary agreements concerning the test plan, including the workpiece features to be measured and analysed, the procedure, the test conditions and the characteristic values. Hereinafter, all agreements which are referred to are between the supplier/manufacturer and the user. The evaluations process is started by warming-up the machine tool. The subsequent adjustment is for the setting of the manufacturing process to the required tolerances (e.g. the middle of the tolerance zone in the case of characteristic with two-sided tolerances or zero for a zero-limited characteristic). The 50 workpieces are then manufactured in series and measured with a suitable measuring device. The measurements attained are then statistically evaluated in the final step.

If the short-term capability indices or the short-term range values and, if applicable, thermal distortion are beyond specified tolerances, the reasons shall be investigated. These can be, for example, faults which can be recognized as outlier values in the outlier management (see 6.7.3). If improvements are possible, these shall be carried out and the tests shall be repeated in part or whole.



NOTE This is recommended only for large batch production machine tools with cycle time <10 min.

Figure 1 — Basic procedure for short-term capability evaluation

6.2 Agreements

Before the actual acceptance test is carried out, agreements between the manufacturer/supplier and the user are necessary in order to ensure that:

a) the machine tool and the applied machining process are evaluated with as few interfering influences as possible;

b) requirements, which cannot be fulfilled due to the various influencing factors and the narrowing of the tolerance caused by the statistical analysis, are not set;

c) contractual agreements between the manufacturer/supplier and the user can be formulated, defining the scope, procedure and evaluation factors for the acceptance;

d) tolerances that are subject to a short-term capability evaluation are identified considering the associated costs.

The relevant agreements are listed in the forms provided in Annex B; Annex D provides an example. The test conditions under which the machine tool is evaluated shall be negotiated between the manufacturer/supplier and the user. These include, among others, the ambient temperature and its allowable variation during the test period. The limits depend on the manufacturing task, as does the location where the machine tool is installed in the machine shop or in an air-conditioned room. The following limits shall be used as default values for normal manufacturing tasks: ambient temperature, i.e. temperature change within ±3 °C during time of test; temperature gradient, i.e. within a maximum of +2 °C/h or −2 °C/h.

Since the aim of the acceptance test is to prove the short-term capability and not the long-term capability, which is influenced by additional factors, a defined and uniform quality of the oversized blanks shall be ensured. The composition and characteristics of the material shall not be influenced by a change of batch. An oversize tolerance shall be agreed upon by the manufacturer/supplier and the user in order to limit the differences in static deformation due to back forces (component of the total cutting force perpendicular to the working plane) for varying oversizes.

Machining of blanks can have a direct influence (e.g. differences in machined dimension) and an indirect influence (e.g. differences in flatness of machined clamping faces) on the scattering of the measured features resulting from the process. Therefore, tolerances for machining of blanks shall be compatible with the required process short-term capability. In addition, it can be necessary to further limit the tolerances of the blanks depending on the machining process and sequence.

Fifty workpieces shall be manufactured in series. The total manufacturing time shall not exceed 8 h, resulting in a permissible manufacturing time of 10 min per workpiece. In special circumstances of longer manufacturing times per workpiece, a lower number of workpieces may be agreed upon by the manufacturer/supplier and the user; but in any case, the number of workpieces shall not be less than 30. If workpieces with small cycle times are being manufactured, a total manufacturing period of 6 h to 8 h and the production of more than 50 workpieces with the taking of samples from the larger set, which results in a total of 50 measurements (sample size of group multiplied by number of samples) may be negotiated.

Furthermore, the manufacturing technology and an adequate warm-up procedure shall be agreed upon by the manufacturer/supplier and the user before starting the acceptance test, in order to ensure that the machine tool is in thermal equilibrium (see 6.3 and 7.2).

The resolution and measuring uncertainty of the measuring device shall be taken into account. The short-term capability of the measuring device shall be verified. Generally, one needs a measurement equipment investigation, including the influence of the operator, at the time of evaluating the short-term capability (see 6.6).

As an alternative to the short-term capability indices, C_s or C_{sk}, the evaluation of the short-term range values, $R_{V,s}$ or $R_{V,sk}$, may be agreed upon by the manufacturer/supplier and the user. Additional information on the relationship between standard deviation and short-term range values is given in A.2. The short-term range values only take account of the greatest and least values and are very susceptible to outliers in the set. Therefore, they do not provide enough information about the process behaviour within the extreme values. Consequently, if short-term range values are used, the evaluation of the process using the control chart for individuals, the $\bar{x}-s$ control chart and a histogram is of special importance (see 6.7).

NOTE The definition of the short-term capability indices or short-term range values is of great economic importance. On the one hand, conformity to stringent requirements can guarantee reliable production. On the other hand, this does not necessarily mean that the manufacturing costs can be reduced. Generally, much higher expenditure is needed for achieving greater short-term capability indices or lesser short-term range values. Such costs result from supplementing or equipping the machine tool with additional components (e.g. direct measuring systems, probing devices) and additional control circuits (e.g. measurement control, thermal compensation) or changing to a more expensive manufacturing method (e.g. from turning to grinding).

The required values shall be specified with considerations of the technical possibility and economical feasibility. In this sense, it is not suitable to set uniform boundaries for all processes. The direct relationship between the short-term capability indices and the required tolerances shall be taken into special consideration. As proof of short-term capability naturally guarantees a statistical confidence regarding the manufacturing process, current tolerances set by the designer for safety reasons should be re-thought. According to current short-term capability indices, the thresholds given in Table 1 are recommended for evaluating short-term capability. In individual cases, it can be of advantage to make other agreements.

The basis for the recommendation of the limits is the fact that, for long-term capability with increased influencing factors, a C_s value of at least 1,33 should be attained (see reference [10]). The calculation of the characteristic values is described in 6.7.

For certain processes or features, it can be appropriate for manufacturer/supplier and the user to disregard the C_{sk} value and only agree on a C_s value. For example, this can be the case if the setting of the process is very complicated, but principally unproblematic (see 6.4) or if features which depend largely on the cutting tools are investigated, e.g. the diameter during drilling, countersinking and reaming.

Table 1 — Recommended values for short-term process capability parameters

Process/feature	C_s	C_{sk}	$R_{V,s}$	$R_{V,sk}$	**Notes**
Normal processes or features	≥1,67	≥1,67	—	—	For example diameter or length in uncontrolled processes
In-process measurement control	—	—	≤100 %	≤100 %	The full tolerance may be used.
Roughness values	—	—	if necessary ≤ 80 %	≤80 %	In many cases, there is only an upper limit; therefore, only $R_{V,sk}$ is specified.
One-sided limited tolerance	—	≥1,67	—	≤60 %	The manufacturer/supplier and the user shall agree on which of the two characteristic values is used for acceptance.
Other special processes or features (e.g. meas. control)	≥1,67	≥1,67	≤60 %	≤60 %	The manufacturer/supplier and the user shall agree which values, i.e. C_s and C_{sk} or $R_{V,s}$ and $R_{V,sk}$ are relevant for acceptance.

Whenever applying an in-process measurement control, agreed action limits for the control algorithm shall be defined. These have, for instance, a safety margin of 10 % to 20 % towards the tolerance limits. In this case, short-term capability is proven if all values are within the tolerance limits.

Roughness values are usually not very scattered. Therefore, they result in a high confidence against exceeding a limit. In such cases, it is sufficient to keep a safety margin of 10 % of the tolerance towards the tolerance limit. Due to the strong influence of the position of the measuring area on the surface of the workpiece on the roughness value, it is advisable to perform repetitive measurements in different areas on some workpieces and, if necessary, calculate the average of the measured values.

Features with one-sided tolerance shall be evaluated only by their critical parameters. The question of whether C_{sk} or $R_{V,sk}$ are relevant for acceptance shall be agreed between the manufacturer/supplier and the user.

For other special processes or features, the question of relevance of the characteristic values shall be agreed upon by the manufacturer/supplier and the user for each individual case. For example, in the case of multi-spindle machines which manufacture several workpieces simultaneously, or if using several identical clamping units, it is useful to use a C_s value that is calculated using the standard deviation estimation value $\hat{\sigma}$ [see Formula (6)]. The number of values per spindle or device shall be an integer multiple of the number of values per group in order to avoid mixing the results of the individual spindles or clamping units. This procedure is similar to separately evaluating workpieces of each spindle or clamping unit. Additionally, the short-term range value, $R_{V,s}$, calculated from all workpieces, shall be within limits in order to ensure that all parts are within the tolerance. If these two conditions are not met, each spindle or clamping unit shall be investigated individually for the respective causes and reasons. Depending on the number of clamping units investigated and the work load for the production of a workpiece, it can be useful to carry out an adjustment run with two to three workpieces per clamping unit in order to determine the scattering and setting of the workpiece contact surface. The sample workpieces destined for evaluation can then be taken from one clamping unit.

The maximum permissible trend due to thermal distortion depends on the manufacturing method, the size of the machine tool and the production and ambient conditions. During the warm-up phase, a trend due to thermal distortion of up to 40 µm/h can be expected (see Reference [8]). As described in 6.3, this trend is often of lesser importance for machine tools undergoing short-term capability tests. It shall, therefore, only be agreed upon as relevant by the manufacturer/supplier and the user for acceptance in individual cases.

6.3 Warm-up procedure

A warm-up procedure should be planned for the short-term capability test to ensure that the machine tool is operating in thermal equilibrium. If, nevertheless, the trend due to thermal distortion is of special importance to the user or the warm-up period cannot be extended until the machine tool is in thermal equilibrium, a permissible trend shall be agreed between the manufacturer/supplier and the user before running the test and also be considered during the analysis.

For small batches, the thermoelastic deformation due to mixed or interrupted production is of greater importance for the thermal behaviour of the machine tool. This behaviour may be evaluated using other test methods, such as direct thermal tests (e.g. according to ISO 230-3) or a suitable machining test.

6.4 Adjustment

The adjustment run serves the purpose of adjusting the process to the target value (or preferred or reference value) of a characteristic. A target value can be equal to the middle of the tolerance zone for features with a two-sided tolerance or to zero for zero-limited features. A.3 shows the effects of the setting on the remaining tolerance. If the mean value is not in the middle of the tolerance zone, the remaining area which can be used by production is limited. This means, for instance, that for a displacement of the mean value by a quarter of the tolerance and a C_{sk} requirement of 1,67, the remaining $6s$ area (roughly the maximum permissible range) is only 30 % of the tolerance.

How exact the adjustment of the process should be in terms of the set value depends, among other factors, on how much work is involved and the importance of the mean value position varies for each individual case. For instance, one can expect that keeping the mean value in the middle of the tolerance zone is time-consuming, but in principle, possible without any problem. In such a case, it can be useful to set the process such that the mean value is only roughly in the middle of the tolerance zone, and only agree on the short-term capability index, C_s, or the short-term range value, $R_{V,s}$, as acceptance criteria.

The blanks shall be supplied with the required quality and shall have acquired the ambient workshop temperature. Uncoated cutting tools shall not be used in mint condition as they are subject to high initial wear. Besides the consequence on workpiece dimensions, such high initial wear increases the cutting force significantly. For this reason, if an uncoated tool in mint condition is being used, some cutting runs shall be performed before the adjustment runs.

If the trend due to thermal distortion is evaluated, the trend due to tool wear shall also be determined. This may be predetermined on the basis of previous experience in similar cutting conditions or may be measured with a microscope or contact stylus instrument. As a rule, the assumption of linear tool wear and measuring the tool before and after the acceptance test is sufficient, since the tool is not applied in mint condition. If it is known that the tool life is much larger than the manufacturing time using the applied manufacturing parameters during the acceptance test, the evaluation of the tool wear may be abandoned.

6.5 Production

The workpieces shall be manufactured in sequence and without interruption. Since any change in the method and the time period of manufacture affects the process and therefore distorts the actual process behaviour, manufacturing of workpieces shall be a continuous process. Disturbances during the manufacturing process, such as vibration of the foundation (floor), temperature variation and vibrations on the machine tool, may be recorded in order to facilitate the interpretation of the measurement data at a later date and, if necessary, to initiate a new test.

If measurement control or trend compensation is part of the machine tool, they shall be included in the short-term capability test, i.e. the machine tool shall not be tested without the control. During the evaluation, the changed distribution function of the features shall be taken into account in such a manner that short-term range values shall be calculated instead of the short-term capability indices.

6.6 Measurement

According to the feature tolerances, requirements shall be set for the measuring device, the measurement location (air-conditioned room for measuring, shop floor) and the measurement method. The measurements may only be performed by trained personnel. The temperature of the measuring device and the workpiece shall not differ from the ambient temperature of the measuring location.

Every time form tolerances are being checked, the surface quality of the tested pieces shall be considered, as there is a danger of false interpretation of roughness as form errors.

The measuring device shall have an adequately high resolution. Conformity to the following condition is recommended: resolution ≤0,03 T, where T is the tolerance of the feature under test, in order to have a small enough influence of the resolution to the standard deviation s_g of the measurement equipment.

The suitability of the measuring device applied for the short-term capability evaluation shall be proven by a measurement system short-term capability evaluation. This is carried out by measuring a measurement standard 50 times under constant conditions and subsequent calculation of the measurement equipment standard deviation s_g. The measurement standard may be a sample workpiece. If no suitably accurate sample workpiece is available, a workpiece from normal production may be used. The measurements for s_g shall be carried out under constant and repeatable conditions. The measuring device standard deviation s_g shall conform to the following requirement:

$$6 \cdot s_g \leq 0{,}15 \cdot T$$

or $s_g \leq 2{,}5\ \%$ of T, where T is the tolerance of the feature under test.

Conformity to this requirement means that the deterioration of the short-term capability index due to the standard deviation of the measuring device is sufficiently small (less than 1,1 % for $C_s = 1{,}00$ and less than 4,2 % for $C_s = 2{,}00$) and therefore may be neglected. If this requirement is not fulfilled, the measuring device may not be used for the short-term capability test as the results can be corrupted (see A.4). The reduction of the standard deviation associated with the process by the amount of the standard deviation associated with the measuring device is not a suitable method for correcting the result as it strongly increases the statistical uncertainty.

If critical values are evaluated, the measurement uncertainty, U (coverage factor equal 2) shall be less than or equal to 10 % of the tolerance.

6.7 Computation and analysis

6.7.1 General

The statistical analysis of a short-term capability evaluation shall not consist only of the calculation of the short-term capability indices, but shall analyse the process with regard to trend, outlier values, stability, special process situations and conformity to normal distribution (for C_s and C_{sk} values). Commercially available statistics software which offer graphical display possibilities [e.g. control charts for individuals (see ISO 7870-2), histograms and probability charts] and calculate the appropriate statistical parameters can be of great help. A possible calculation sequence for the analysis is provided in the forms given in Annex C. The procedure is demonstrated by an example in Annex D.

The main steps comprising analysis are shown in Figure 2. The verification of the short-term capability of the measuring system is the prerequisite for the useful evaluation of the short-term capability.

Based upon the knowledge of the process and by means of a control chart for individuals, a decision should be made as to whether a special process or feature is subject to evaluation. This covers, for instance, the inclusion of a measurement control, non-adjustable tools, multi-spindle machines or roughness values. If it is a special process or a special feature, the trend correction described in 6.7.2 is not carried out.

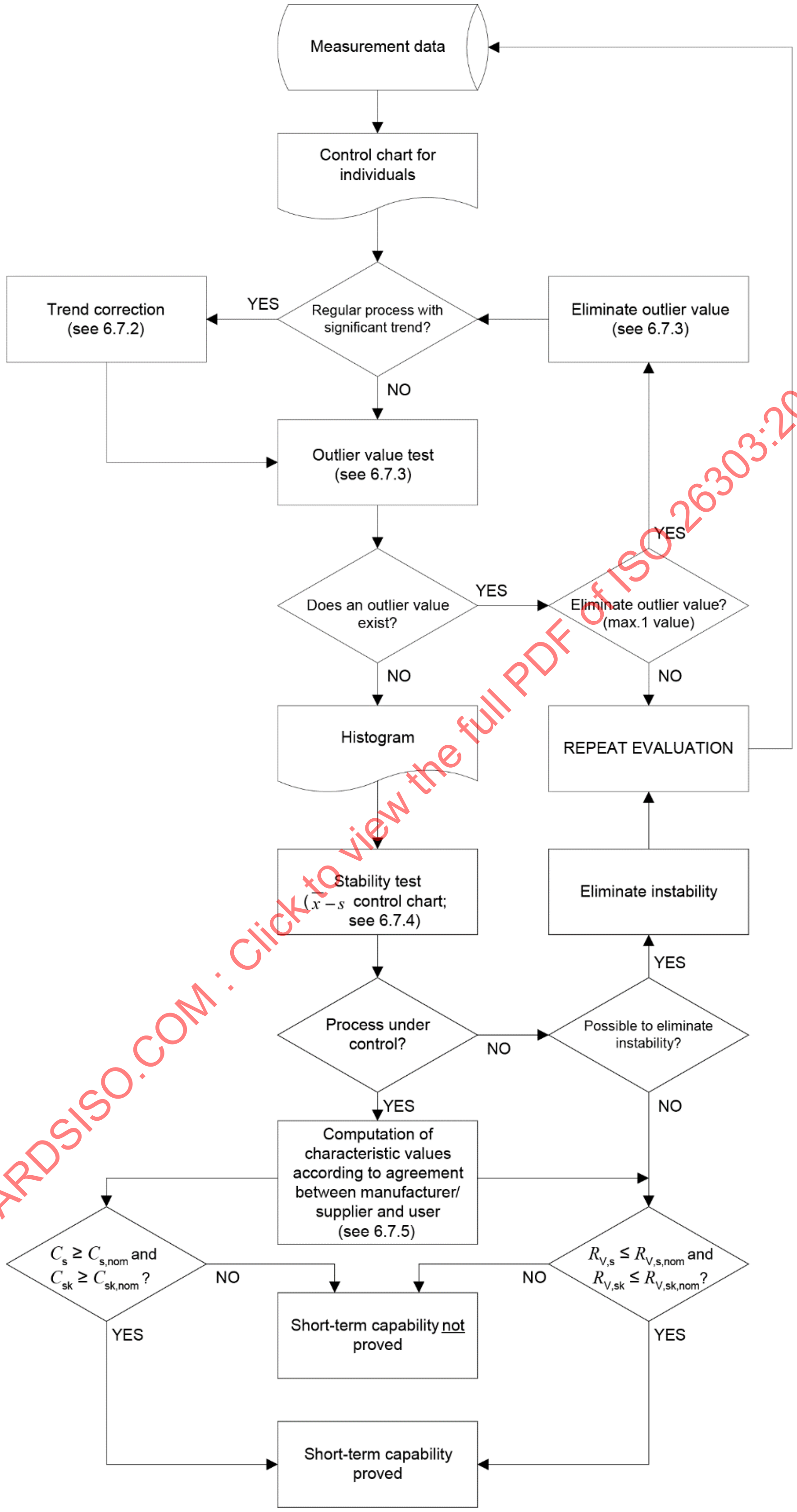


Figure 2 — Evaluation diagram

6.7.2 Trend correction

A control chart for individuals is used to evaluate the total trend, $\delta X_{tot,T}$ of the measurement data. Applying the knowledge of the trend due to tool wear, δX_a (known or measured in similar processes), the trend due to thermal distortion, δX_{td}, may be calculated as given by Formula (1), if no special influences are apparent:

$$\delta X_{td} = \delta X_{tot,T} - \delta X_a \tag{1}$$

Since the short-term capability indices are always calculated using an estimation of the standard deviation, $\hat{\sigma}$ [see Formulae (14) and (15)], a small trend due to group formation during the calculation of the standard deviation shall be eliminated. Nevertheless, one cannot rule out that, due to the trend, the mean value can exceed the permissible control limit, so in the case of doubt, a trend correction may be carried out. If a strong trend is present, a trend correction may be carried out to evaluate the trend and the scattering of measured features associated with the process separately. The measurement data are corrected using Formulae (2) and (3):

$$x_{i,T} = x_i - (i-1) \cdot \delta X_{tot,w} \tag{2}$$

where

$$\delta X_{tot,w} = \frac{1}{n-1} \delta X_{tot,T} \tag{3}$$

$x_{i,T}$ is the *i*th trend-corrected measurement;

x_i is the *i*th measurement (not trend-corrected);

$\delta X_{tot,w}$ is the total trend per workpiece.

If a trend correction is carried out, the subsequent calculations shall be carried out using the trend-corrected data. The range, *R*, the mean value, $\bar{\bar{x}}$, and an estimation value for the standard deviation, $\hat{\sigma}$, (via fivefold measurement grouping) shall be calculated as given by Formulae (4) to (7):

range:

$$R = x_{max} - x_{min} \tag{4}$$

mean value:

$$\bar{\bar{x}} = \frac{1}{m} \cdot \sum_{j=1}^{m} \bar{x}_j \tag{5}$$

estimated standard deviation:

$$\hat{\sigma} = \frac{\bar{s}}{0,94} \tag{6}$$

where

$$\bar{s} = \frac{1}{m} \cdot \sum_{j=1}^{m} s_j \tag{7}$$

and s_j according to Formula (A.3), where *n* is replaced by the sample size of the j^{th} group.

NOTE Constant in Formula (6) 0,94 is for group sample size of five; constant in Formula (6) becomes 0,89 for group sample size of three.

6.7.3 Outlier management

The existence of outliers among the measurements of the 50 workpieces shall be tested.

The outlier value test described in ISO 5725-2 and other references is based, among other things, on the assumption of Gaussian normal distribution; thus, it can only be applied for normally distributed measured values associated with processes or features (see ISO 5725-2, ISO 14253-2 and Reference [9]). If Formulae (8) and (9) are fulfilled, x_{max} and/or x_{min} shall be the outlier values (significance level: 1 %; sample size: 50):

$$x_{\max} > \overline{\overline{x}} + 3{,}34 \cdot \hat{\sigma} \tag{8}$$

$$x_{\min} < \overline{\overline{x}} - 3{,}34 \cdot \hat{\sigma} \tag{9}$$

If an outlier value is present, a new outlier test shall be carried out without this value. In the case of two or more outlier values, the reason shall be sought and the short-term capability test shall be repeated as the process is obviously not under control. If only one outlier value is found, a decision may be made on whether to proceed with the calculations without this value or to repeat the entire short-term capability test.

6.7.4 Stability of the process

The stability of the process shall be checked as follows.

A histogram shall be drawn in order to have a visual representation of the distribution of the measurement values. For 50 values, classification into seven classes is recommended.

The stability of the process is evaluated using a $\overline{x} - s$ control chart. If the mean values and the standard deviations of the groups are within the control limits (U_{CL} and L_{CL}), i.e. the conditions described in Formulae (10) to (13) are fulfilled by all 10 groups (j = 1 to 10), the process shall be considered as stable (significance level α = 1 %; sample size of group n = 5):

$$\overline{x}_j \le U_{\mathrm{CL},\overline{x}j} = \overline{\overline{x}} + 1{,}15 \cdot \hat{\sigma} \tag{10}$$

$$\overline{x}_j \ge L_{\mathrm{CL},\overline{x}j} = \overline{\overline{x}} - 1{,}15 \cdot \hat{\sigma} \tag{11}$$

$$s_j \le U_{\mathrm{CL},sj} = 1{,}93 \cdot \hat{\sigma} \tag{12}$$

$$s_j \ge L_{\mathrm{CL},sj} = 0{,}23 \cdot \hat{\sigma} \tag{13}$$

where

$\overline{\overline{x}}$ is the mean value according to Formula (5);

$\hat{\sigma}$ is the standard deviation according to Formula (6).

Once again, if the control limits are exceeded, the reasons shall be investigated and the test shall be repeated. If the instability cannot be remedied, the calculation of the short-term capability indices shall not be permitted. In this case, upon agreement between the manufacturer/supplier and the user, only the short-term range values may be used as the acceptance criteria.

6.7.5 Calculation of indices

6.7.5.1 General

The characteristic values that are agreed upon by the manufacturer/supplier and the user before the acceptance test shall be calculated. Recommendations are given in Table 1 (see 6.2) and in the agreement sheets/forms (see Annex B). These are as given by Formulae (14) to (18):

short-term capability index:

$$C_s = \frac{T}{6 \cdot \hat{\sigma}} \tag{14}$$

critical short-term capability index:

$$C_{sk} = \frac{\left\{U_{SL} - \bar{\bar{x}}\,;\, \bar{\bar{x}} - L_{SL}\right\}_{min}}{3 \cdot \hat{\sigma}} \tag{15}$$

short-term range value:

$$R_{V,s} = \frac{R}{T} \tag{16}$$

or

$$R_{V,s} = \frac{R}{T} \cdot 100$$

in per cent;

critical short-term range value:

$$R_{V,sk} = \left\{\frac{x_{max} - \bar{x}}{U_{SL} - \bar{\bar{x}}}\,;\, \frac{\bar{x} - x_{min}}{\bar{\bar{x}} - L_{SL}}\right\}_{max} \tag{17}$$

or

$$R_{V,sk} = \left\{\frac{x_{max} - \bar{x}}{U_{SL} - \bar{\bar{x}}}\,;\, \frac{\bar{x} - x_{min}}{\bar{\bar{x}} - L_{SL}}\right\}_{max} \cdot 100$$

in per cent;

(if agreed upon) trend due to thermal distortion:

$$\delta X_{td} = \delta X_{tot,T} - \delta X_a \tag{18}$$

where

T	is the tolerance of the feature under test;
$\hat{\sigma}$	is the standard deviation according to Formula (6);
$\bar{x} = \frac{1}{n}\sum_{i=1}^{n} x_i$	is the mean value of population and n is the number of measurements, generally n = 50;
U_{SL}	is the upper specification limit;

L_{SL} is the lower specification limit;

δX_{td} is the trend due to thermal distortion according to 6.7.2;

$\delta X_{tot,T}$ is the total trend of the measurement data (in relation to all values) according to 6.7.2;

δX_{a} is the trend due to tool wear according to 6.7.2.

6.7.5.2 One-sided limited features

For one-sided limited features, short-term capability indices and short-term range values are calculated by considering mean values and the lower or upper tolerance limits. The calculation of critical values is similar to the procedure applied in the case of two-sided limited features. The cases given in Formulae (19) to (22) shall be differentiated:

a) limited towards upper limit:

$$C_{sk} = \frac{U_{SL} - \overline{x}}{3 \cdot \hat{\sigma}} \tag{19}$$

$$R_{V,sk} = \frac{x_{max} - \overline{x}}{U_{SL} - \overline{x}} \tag{20}$$

b) limited towards lower limit:

$$C_{sk} = \frac{\overline{x} - L_{SL}}{3 \cdot \hat{\sigma}} \tag{21}$$

$$R_{V,sk} = \frac{\overline{x} - x_{min}}{\overline{x} - L_{SL}} \tag{22}$$

6.7.5.3 Surface roughness values

For surface roughness values, where the 16 % rule in accordance with ISO 4288 applies, at least two roughness measurements per workpiece shall be carried out. If any values are out of upper or lower tolerance, up to 16 % of the measurements (i.e. 8 measurements for a population of 50) may be disregarded; the evaluation of the short-term range value (or short-term capability index) shall be evaluated with the remaining roughness values.

For roughness values, the short-term range value is recommended.

7 Factors influencing short-term capability evaluation

7.1 General

The dominant problems for the short-term capability evaluation of a machining process on a metal-cutting machine tool are the various external influencing factors which increase manufacturing uncertainty without allowing the machine tool manufacturer any form of direct influence, even though the robustness of the machine behaviour under various influences can be understood as a quality criterion. Table 2 provides a list of the most relevant factors, which are described in more detail in 7.2 to 7.4.

Apart from the ambient influences, such as workshop temperature variation, the process parameters and tool wear directly influence the working accuracy. Additional measurement deviations can be expected due to the deflection caused by increasing cutting forces due to tool wear. Variations in the dimensions of the blanks and unsuitable clamping of the blanks also have negative influence on the working accuracy.

Table 2 — Factors influencing short-term capability evaluation

Factors affecting the accuracy of the workpiece				
Process:	**Machine tool:**	**Operator:**	**Environment:**	**Workpiece material:**
feature/tolerance process parameters cutting forces lubricated/dry machining tool wear built-up edge geometric accuracy of the tool tool offset after tool change, etc.	static and dynamic compliance thermal distortion accuracy performance of axes positioning system bearing clearance histeresis and backlash maintenance mounting/foundation transfer function of feed drives, etc.	qualification training motivation working and environmental conditions information flow, etc.	vibration caused by nearby machines temperature variation ambient temperature ≠ 20 °C external heat sources or heat sinks, etc.	composition heat treatment residual stresses dimension and surface of blanks pre-machining change of batch static and dynamic stiffness of workpiece clamping face, etc.

Factors affecting measurement	**Factors affecting analysis**
Influences/issues:	**Influences/issues:**
measurement resolution and uncertainty measurement method operator maintenance environment temperature of workpiece, measurement device and surrounding surface roughness, etc.	manually or computer-aided analysis method statistical uncertainty methods for non-normal distributions computational accuracy, etc.

7.2 Thermal influences

The working accuracy of a machine tool is dependent upon its geometric, static, dynamic and thermal characteristics. The machine short-term capability shall always be seen in connection with the process loads which are defined by the process parameters, and the requirements regarding tolerance and process time.

Internal and external heat sources and process heat in the cutting zone lead to thermo-elastic deformation at the work point. The magnitude of these deformations depends on the process parameters, the process conditions (dry or lubricated) and the thermal condition of the machine tool (warm-up phase or operating phase in thermal equilibrium).

The thermal displacement as a function of time, *t*, in the warm-up phase can be approximated by an exponential function expressed in Formula (23):

$$\Delta x(t)=\Delta x_{max}\left(1-e^{-\frac{t}{\tau}}\right) \tag{23}$$

where

τ is the thermal time constant.

According to the type and size, the thermal time constants for cutting machine tools are in the range of 20 min to 6 h, for maximum displacements Δx_{max} of a few micrometres up to 100 µm. If the acceptance test is carried out in the thermal equilibrium phase, depending on the machine tool, warming-up periods of 40 min up to 12 h shall be expected in order to ensure that the displacement of the machine tool has reached 85 % of the maximum displacement. Otherwise, a trend of between 5 µm/h and 40 µm/h is expected due to thermal distortion during the warm-up phase.

Machine tools subject to this document are usually applied to large batch production. In the case of three-shift operation, the machine tools are in thermal equilibrium and the thermal distortion in the warm-up phase is only apparent as an increased adjustment frequency at the beginning of the week, which can be controlled by using statistical process control methods. In this respect, thermal distortion in the warm-up phase is of less importance for a short-term capability study.

NOTE Systematic investigations regarding the influence of ambient thermal conditions on the working accuracy of cutting machine tools show displacements at the cutting point of between 0,5 µm/°C and 8 µm/°C due to ambient temperature variation. Delay times, i.e. times between temperature change and resulting displacement, of 0,5 h to 5 h are expected.

7.3 Influences due to measuring uncertainty

The measuring uncertainty lowers the short-term capability indices as these are calculated using the standard deviation of the measured features, which in turn depends on the standard deviation of the measuring device, e.g. a gauge. In A.4, one can see that for a standard deviation of measuring device, s_g, of 60 % of the actual process standard deviation, s_{act}, the actual capability index of C_{act} = 2,00 is reduced by the measurement scattering to C_S = 1,71. This example demonstrates the importance of the measurement short-term capability as a prerequisite for the application of such equipment (see 6.6).

Clause A.4 also includes information on the reasons for the requirement on the measurement equipment standard deviation s_g, i.e. $6 \cdot s_g \leq 0{,}15 \cdot T$, T being the tolerance of the feature under test.

7.4 Influences arising from statistical analysis

7.4.1 Confidence level and sample size

The type and methodology of the statistical evaluation also influence the result of a short-term capability investigation. The projection of the accuracy of manufacturing 50 workpieces onto large batch production is associated with uncertainties. It is stressed that the short-term capability index determined during the evaluation of the machining process on a metal-cutting machine tool is, therefore, only an estimation of the actual process capability. If, for instance, a short-term capability index of C_S = 1,71 is determined using 50 measurements, the actual capability index for the basic population is between 1,39 and 1,95 based upon a confidence level of 95 % (see A.5) and based upon the assumption of normal distribution of characteristic value. Hence the uncertainty, U, for the capability index, C_S (confidence level 95 %) is ±0,28.

The short-term capability index, in the case of acceptance tests normally determined using a small sample therefore generally differs from a long-term capability index for the same process, which is determined over a very large sample, e.g. several weeks of production. Nevertheless, this means that fulfilling the requirement of $C_S \geq 1{,}67$ not only entails a narrowing of the tolerance by 40 % (10 s range within the tolerances), but also aiming at much smaller ranges in order to successfully complete the acceptance test.

7.4.2 Type of distribution

The short-term capability indices shall be calculated by means of the determination of the standard deviation of the measurement data. An implicit assumption is that the process can be described using the normal distribution. This does not apply in full for all machining processes. Furthermore, the distribution of one-sided tolerances (for example many tolerances of form and location) are often asymmetric as they have a physical limit on one side. For this reason, other statistical programmes and distribution models as a supplement to the normal distribution have been developed. The respective mathematical algorithms allow the determination of a distribution function for the individual data set. Equivalent standard deviations are then calculated and used for comparison with a normal distribution curve. Nevertheless, treating the measurement data in a purely mathematical way without taking the technical and physical conditions into account leads to a situation in which various distribution functions are calculated as approximations by the statistics programs, without being able to decide which of these describes the actual relationships in the best way. Together with the calculation of the equivalent standard deviations, this leads to the calculation of very different short-term capability indices depending on the chosen distribution model.

It is, therefore, not sensible to derive a distribution model based upon measurement data only. On the other hand, the choice of the distribution function cannot be purely formalistic, but has to take into account process knowledge and physical circumstances. Additional information is provided in A.6. This is, however, not always possible for acceptance tests based on the low number of 50 measurements.

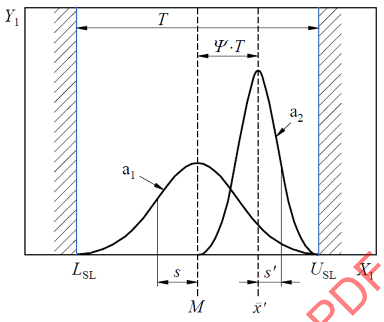
For this reason, it is recommended to carry out the process evaluation by means of control charts for individuals, $\bar{x}-s$ control charts and histograms, and to calculate the short-term capability indices with the help of an estimation of the standard deviation, derived by grouping the measurement data. In the case of a special process or characteristic, in which a Gaussian distribution does obviously not correspond with the empirical distribution, the range of the measured values is taken as the acceptance criterion (see 6.2). In individual cases, it can be reasonable to use other or additional criteria for the analysis of the process capability also in accordance with ISO 22514-3:2020, 7.5, and ISO 22514-4:2016.

Annex A
(informative)

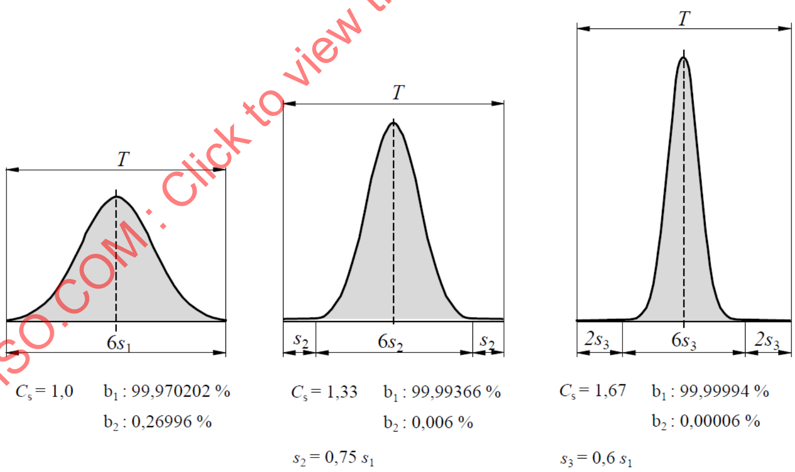
Additional information related to statistical evaluations

A.1 Relationship between centred and shifted distributions

The critical short-term capability index, C_{sk}, considers also the location of the mean [see Figure A.1 a)].



a) Centred and shifted distribution



b) Remaining area for 6·*s*

Key

X_1	characteristic value	C_s	short-term capability index
Y_1	frequency	L_{SL}	lower specification limit
a_1	centred distribution with $\overline{x}$ and s	M	mean of L_{SL} and U_{SL}
a_2	shifted distribution with $\overline{x}'$ and s'	T	tolerance
b_1	share of parts estimated as in conformity with specification	U_{SL}	upper specification limit
b_2	share of parts estimated as not in conformity with specification	Ψ	shift ration for shifted distribution (see Formula (A.4))

Figure A.1 — Short-term capability and shifted distribution

In this context, Formulae (A.1) and (A.2) apply with the assumption of normal distribution.

Short-term capability index (for the case of normal distribution):

$$C_s = \frac{T}{6 \cdot s} \tag{A.1}$$

where

C_s is the short-term capability index;

T is the tolerance;

s is the standard deviation [see Formula (A.3)] of characteristic value, evaluated from 50 workpieces.

Critical short-term capability index (for the case of normal distribution):

$$C_{sk} = \left[\frac{\bar{x} - L_{SL}}{3 \cdot s}, \frac{U_{SL} - \bar{x}}{3 \cdot s} \right] \text{min} \tag{A.2}$$

where

C_{sk} is the critical short-term capability index;

$\bar{x}$ is the mean value;

L_{SL} is the lower specification limit;

U_{SL} is the upper specification limit;

s is the standard deviation [see Formula (A.3)] of characteristic value, evaluated from 50 workpieces.

Sample standard deviation (sample size n):

$$s = \sqrt{\frac{\sum_{i=1}^{n} (x_i - \bar{x})^2}{n-1}} \tag{A.3}$$

It is noted that estimating the standard deviation according to formula (A.3) is used instead of formula (6). It means that the overall variability is evaluated instead of the variability within subgroups.

Shift ratio (see Figure A.1) for shifted distribution with $\bar{x}'$ and s':

$$\Psi = \frac{|\bar{x} - M|}{T} \tag{A.4}$$

where

$$M = \frac{U_{SL} + L_{SL}}{2}$$

Sample standard deviation of the shifted distribution [see Figure A.1 a)]

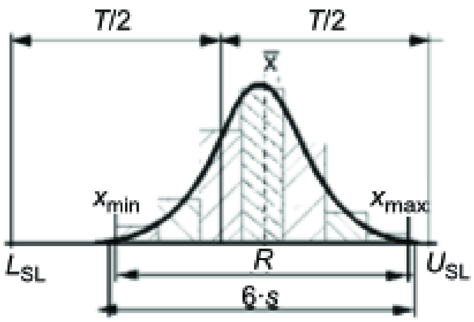
$$s' = (1 - 2 \cdot \Psi) \cdot s \tag{A.5}$$

Assuming normally distributed features, a short-term capability index of 1,0 indicates that 99,73 % of all characteristic values of the population are within the specified tolerance (see Figure A.1). For time and cost reasons, a short-term capability evaluation is usually carried out on the basis of a small number of machined parts (in the context of this document, it is 50). Therefore, the ascertained short-term capability index is only an estimation of the real short-term capability of the machining process. In order to compensate for this statistically given uncertainty with respect to a later large batch production, higher values for the short-term capability index are required, e.g. C_S > 1,33 or C_S > 1,67. As it can be seen in Figure A.1 b), this means that not only six times the standard deviation shall be within the specified tolerance but even eight or ten times.

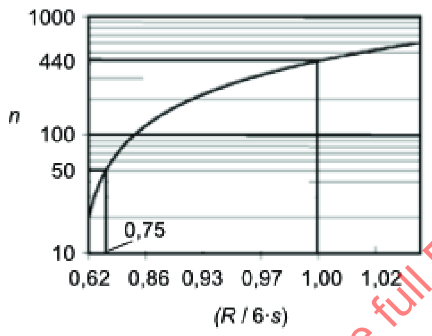
Figure A.3 exemplifies the effect of an increasing short-term capability index in terms of a reduction of the zone of conformity within the specified tolerance. A further reduction of C_{sk} occurs if the distribution is shifted away from the centre of the specified tolerance.

A.2 Correlation between short-term range values, $R_{V,S}$, and standard deviation

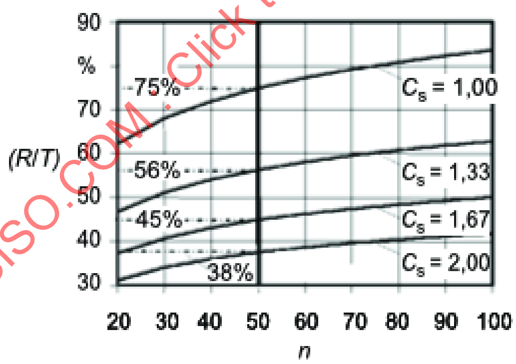
Figure A.2 shows the correlation between the standard deviation and the short-term range value depending upon the sample size. In the case of a Gaussian distribution for a confidence level of 99,73 % six times the standard deviation is 1,33 times greater than the range for a sample size of 50 workpieces. Conversely, it means that a short-term range value $R_{V,S}$ of 45 % equals a C_S of 1,67. This example can only demonstrate the magnitude of the ratio of the short-term capability indices to the short-term range values, as the short-term range values can only be recommended for non-normally distributed values.



a) Histogram and characteristic values for normal distribution



b) Number of samples *n* and ratio of range *R* to six times standard deviation *s* for normal distribution



c) Ratio of range *R* to tolerance *T* for different number of samples *n* and different short-term capability indices C_s for normal distribution

Key

C_s short-term capability index

L_{SL} lower specification limit

n sample size, default $n = 50$

R range of measurement values

s standard deviation of measured values

T tolerance

U_{SL} upper specification limit

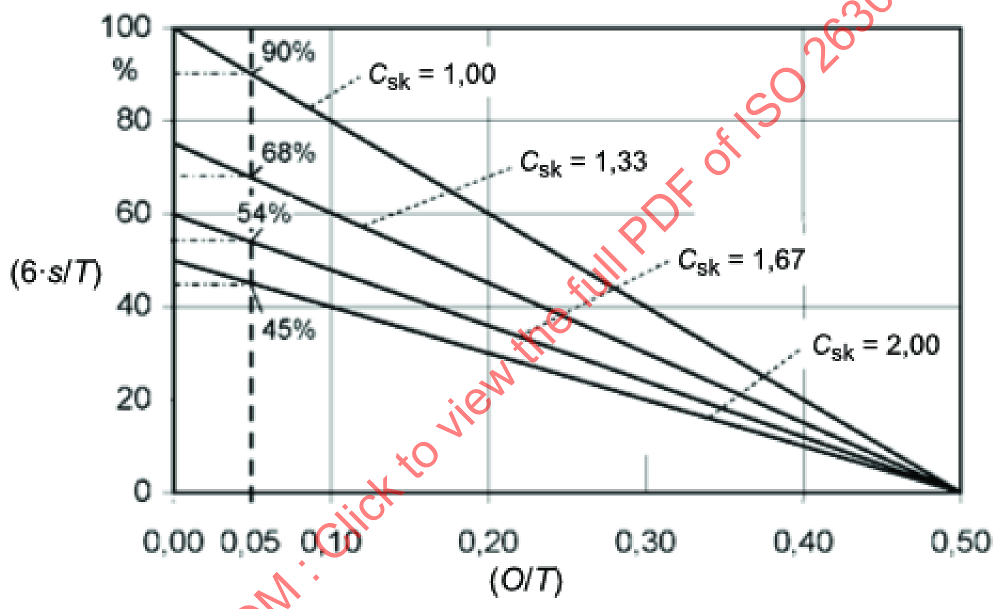
Figure A.2 — Comparison of characteristic values for normal distribution

A.3 Mean value not in the middle of the tolerance zone

As a rule, based on the production of five workpieces, the adjustment is supposed to test whether the critical distance of the mean value from the tolerance limits C_{sk} fulfils the following condition:

$$\Delta x_c \geq 0{,}45 \cdot T$$

This is equal to an offset of 5 % for values with two-sided tolerances. For a short-term capability index C_S of 1,67 (see Figure A.3), this results in a reduction of the 6*s* area related to the tolerance from 60 % to 54 %. If the mean value of the measurements for the adjustment is outside the area for Δx_C, the process shall be reset depending upon the ratio of the sixfold standard deviation and the tolerance, and the test shall be repeated. Otherwise, the manufactured workpieces may already be counted towards the acceptance workpieces as long as the manufacturing process was not interrupted for too long during the measurement of the adjustment products.



Key

O offset of mean value

T tolerance zone

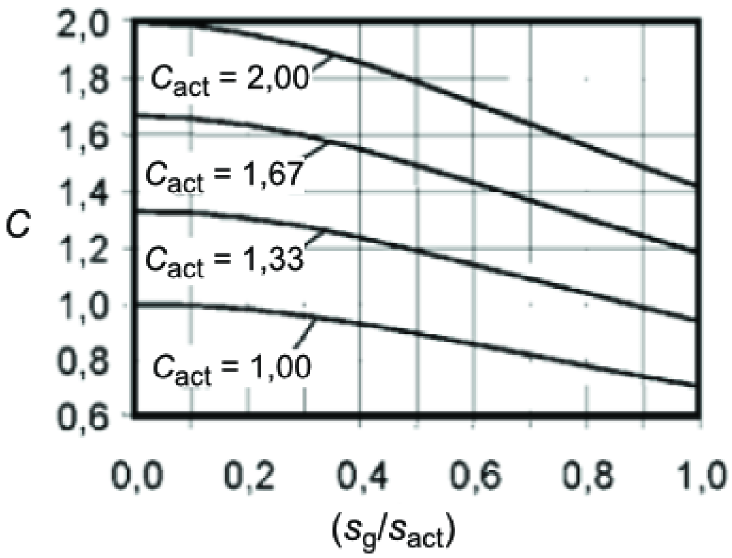
C_{sk} critical short-term capability index

s standard deviation of process

Figure A.3 — Effects if the mean value is not in the middle of the tolerance zone (offset of the mean value)

A.4 Measurement uncertainty and short-term capability index

Measurement uncertainty, expressed by the standard deviation of the measuring device, s_g, directly influences the short-term capability index as shown in Figure A.4.



Key

C evaluated capability index

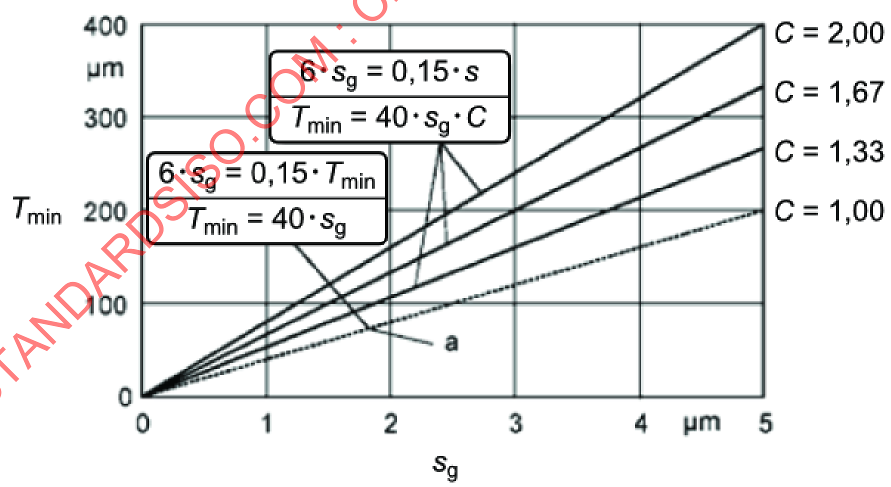
C_{act} actual capability index of process

s_{act} actual standard deviation of process

s_g standard deviation of measuring device

Figure A.4 — Change of capability index by standard deviation of measuring device

It is apparent that for continuous process improvement and lesser tolerances, the requirements on the measurement equipment with regard to the process standard deviation can no longer be fulfilled. This means that for short-term capability, only the reference to the tolerance of the workpieces is required. This correlates to the straight line "$6\,s_g = 0{,}15\,T_{min}$" in the diagram for the determination of the minimum measurable tolerance, T_{min}, for a given measurement device standard deviation, s_g; see Figure A.5.



Key

C capability index

s standard deviation of process

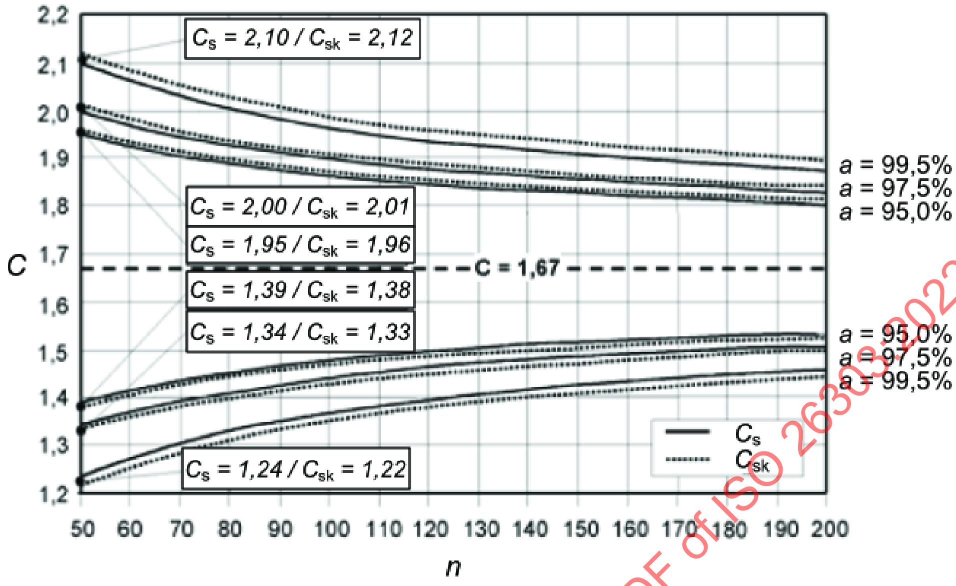
s_g standard deviation of measuring device

T_{min} minimum measurable tolerance for capability evaluation

Figure A.5 — Standard deviation of measuring device and minimum tolerance

A.5 Confidence level and sample size

Figure A.6 shows the confidence level of capability indices depending upon the sample size.



Key

a relevant confidence level

C Capability index

C_s short-term capability index

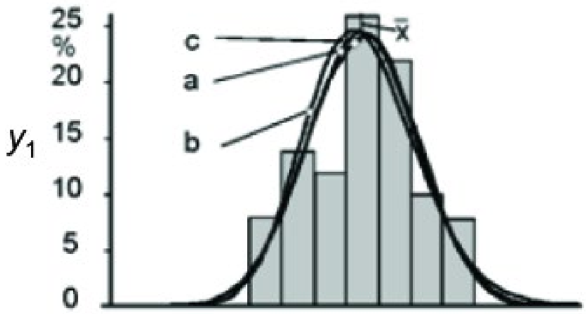
C_{sk} critical short-term capability index

n sample size

Figure A.6 — Confidence level and sample size, *n*, under the assumption of normal distribution of the characteristic values

A.6 Type of distribution and capability index evaluation

Figure A.7 exemplifies the problem of selecting a type of distribution using an example with 50 measurements. As the histogram with density function shows, all three distribution models (see normal distribution, logarithmic-normal distribution and Weibull distribution) are good approximations. This is confirmed by the small and similarly sized mean deviations of the measurement data from the calculated distribution function. Nevertheless, the short-term capability indices differ largely. While the C_S values lie between 1,51 and 1,88, C_{sk} values of 0,67 to 1,47 are calculated.



Distribution	Normal (a)	Log-normal (b)	Weibull (c)
Max. deviation	6,6 %	7,95 %	6,53 %
Mean value	0,39 %	0,41 %	0,41 %
s	5,88	6,63	5,33
C_s	1,70	1,51	1,88
C_{sk}	1,47	0,67	1,16

Key

y_1 density function, in per cent
C_s short-term capability index
C_{sk} critical short-term capability index
s standard deviation of process
$\overline{x}$ mean value
a normal distribution
b logarithmic-normal distribution
c Weibull distribution

Figure A.7 — Influence of selected type of distribution

Annex B
(informative)

Agreement forms

Agreement form 1 of 4	**Test plan**		
General information			
Machine tool description			
Machine serial no.			
Workpiece description			
Workpiece no.			
Material			
Quantity of workpieces/random test			
Machining time/workpiece, t_m			
Quantity of workpieces, n_{mp} $\left(\text{recom.:}n_{mp}=50\right)$			
Overall machining time, t_{tot}			
Quantity of workpieces for analysis, n (recom .: n=50)			
Random inspection (recommended sample size of group: 5)			
Schedule/logistic			
a) Preparation	**Manufacturer (M) Customer (C)**	**Place (M/C)**	**Date**
Blanks			
Tools			
Clamping devices			
Machine tool			
Operator for machine tool			
Measuring devices			
Operator for measuring			
b) Dates	**Start**	**End**	**Duration**
Preparation/set-up			
Warming-up phase			
Adjustment			
Production			
Measurement			
Analysis			

<table>
<tr><td colspan="2">Agreement form 2 of 4</td><td colspan="2">General information</td></tr>
<tr><td colspan="4">Blanks</td></tr>
<tr><td colspan="4">Material, Heat-treatment, Surface, Hardness, Strength, Tolerance of allowance, Tolerance of fixtures, etc.</td></tr>
<tr><td colspan="4"></td></tr>
<tr><td colspan="4">Test conditions</td></tr>
<tr><td colspan="2">Setting of fixture of machine tool</td><td colspan="2"></td></tr>
<tr><td colspan="2">Particular loads
(e.g. vibrations induced by surrounding production)</td><td colspan="2"></td></tr>
<tr><td colspan="2">Max. variation of ambient temperature during examination;
recommended limits: temperature change within ±3 °C during time of test</td><td colspan="2"></td></tr>
<tr><td colspan="2">Max. temperature gradient during evaluation;
recommended: within a maximum of +2 °C/h or −2 °C/h</td><td colspan="2"></td></tr>
<tr><td colspan="4">Features</td></tr>
<tr><td>No.</td><td>Description of feature</td><td>Nom. size</td><td>Dimension</td></tr>
<tr><td>1</td><td></td><td></td><td></td></tr>
<tr><td>2</td><td></td><td></td><td></td></tr>
<tr><td>3</td><td></td><td></td><td></td></tr>
<tr><td>4</td><td></td><td></td><td></td></tr>
<tr><td>5</td><td></td><td></td><td></td></tr>
<tr><td>6</td><td></td><td></td><td></td></tr>
<tr><td>7</td><td></td><td></td><td></td></tr>
<tr><td>8</td><td></td><td></td><td></td></tr>
<tr><td>9</td><td></td><td></td><td></td></tr>
</table>

Agreement form 3 of 4				**Feature dependent data I**			
Characteristic values							
Recommendations for characteristic values see at the end of this form				**Required short-term capability indices**		**Required short-term range values**	
No.	L_{SL} (lower limit)	U_{SL} (upper limit)	T tolerance	C_s	C_{sk}	$R_{V,s}$	$R_{V,sk}$
1							
2							
3							
4							
5							
6							
7							
8							
9							

Maximum permissible trend due to thermal distortion [µm/workpiece]		
$\delta X_{td,perm}$	$\delta Y_{td,perm}$	$\delta Z_{td,perm}$

Recommended characteristic values					
Process/feature	C_s	C_{sk}	$R_{V,s}$	$R_{V,sk}$	**Notes**
Normal processes or features	≥1,67	≥1,67	–	–	For example, diameter or length in uncontrolled processes.
In-process measurement control	–	–	≤100 %	≤100 %	The full tolerance may be used.
Roughness values	–	–	if necessary ≤80 %	≤80 %	In many cases there is only an upper limit; therefore, only $R_{V,sk}$ is specified.
One-sided limited tolerance	–	≥1,67	–	≤60 %	The manufacturer/supplier and the user shall negotiate which of the two characteristic values is used for acceptance.
Other special processes or features	≥1,67	≥1,67	≤60 %	≤60 %	The manufacturer/supplier and the user shall agree on whether C_s and C_{sk} or $R_{V,s}$ and $R_{V,sk}$ are relevant for acceptance.

Agreement form 4 of 4		**Feature dependent data II** (if necessary for each feature separately)	
Feature			
Technology			
Cutter material			
Cutter geometry			
Roughing conditions			
Finishing conditions			
Expected tool wear (e.g. flank wear)			
Expected trend due to tool wear $\delta X_{a,exp}$			
Measurement			
Location			
Device			
Device serial no.			
Resolution			
Standard deviation of measuring device, s_g			
0,03 T		≥ resolution ?	[ ] yes [ ] no: use another measuring device!
T/40		≥ s_g ?	[ ] yes [ ] no: use another measuring device!
Set-up of measuring device (e.g. filter, strategy; note special circumstances separately)			

Annex C
(informative)
Evaluation forms

Analysis form 1 of 4	**General information**		
Machine tool/workpiece			
Workpiece description			
Workpiece material			
Feature/nominal			
Lower specification limit (LSL)		Tolerance, $T = U_{SL} - L_{SL}$	
Upper specification limit (USL)			
Measuring device			
Device serial no.	Resolution	Standard deviation, s_g	
0,03 T =		≥ resolution? and	
T / 40 =		≥ s_g?	
[ ] yes	Analysis can be carried out		
[ ] no	No analysis allowed! Repeat measurement with a more precise measuring device!		
Trend	Tool wear		
Trend due to tool wear, δX_a			
Permissible trend due to thermal distortion for 50 workpieces (if criteria), $\delta X_{td,perm}$ ($\delta Y_{td,perm}$; $\delta Z_{td,perm}$, respectively)			
Ambient temperature	Within declared limits?	[ ] yes [ ] no	

$\vartheta_{amb,0}$		ϑ_{min}		ϑ_{max}		$\Delta\upsilon_{amb, max}$	

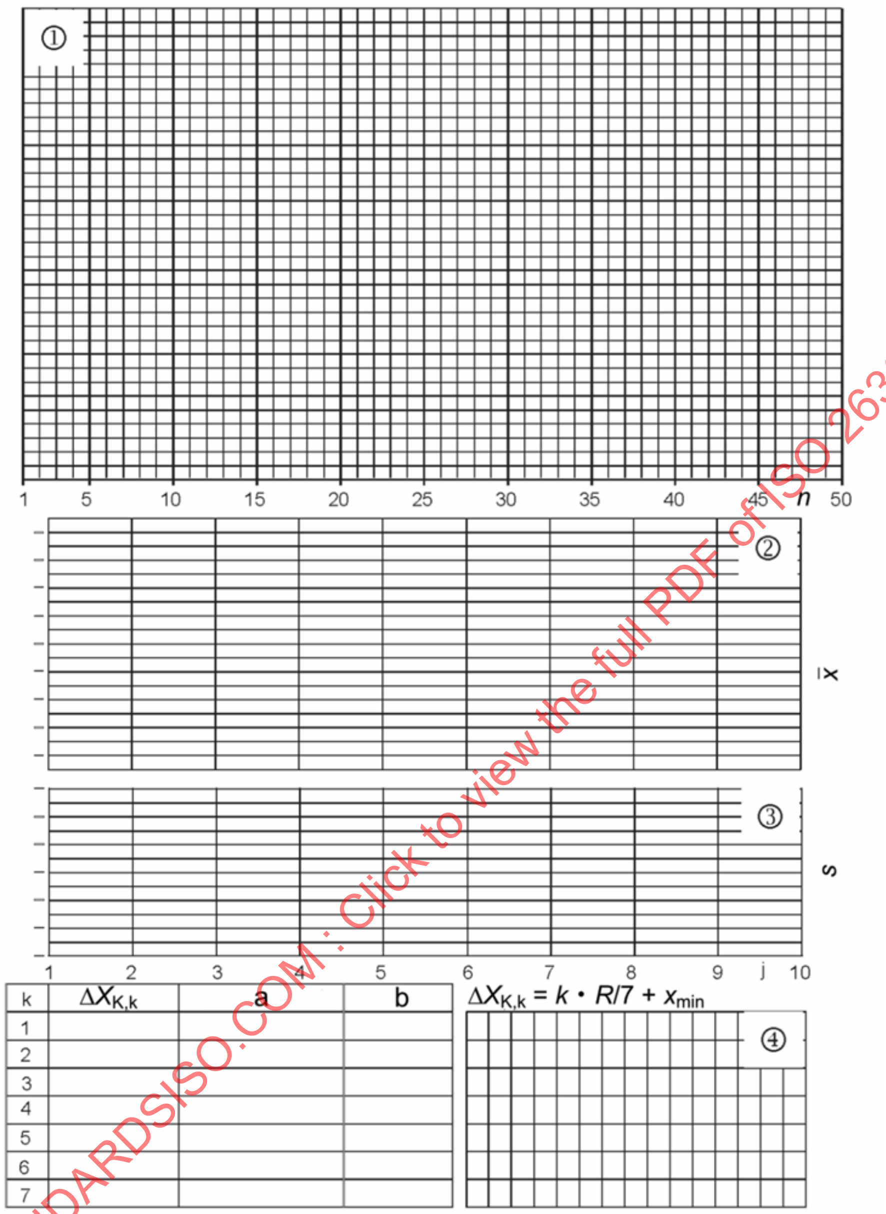
Measurement data, x_i (with trend) values in													as deviation from set point							
j →	1		2		3		4		5		6		7		8		9		10	
1	1		6		11		16		21		26		31		36		41		46	
2	2		7		12		17		22		27		32		37		42		47	
3	3		8		13		18		23		28		33		38		43		48	
4	4		9		14		19		24		29		34		39		44		49	
5	5		10		15		20		25		30		35		40		45		50	

Now, generate the control chart for individuals. For normal processes/features and a significant trend, first perform trend correction (sheet: 3 of 4) and carry out all other calculations with trend-corrected data.

$\bar{x}_j$										
s_j										

Formulae: $\bar{x}_j = \frac{1}{5}\cdot\sum_{k=1}^{5} x_k$ $\quad s_j = \sqrt{\frac{1}{4}\cdot\sum_{k=1}^{5}\left(\bar{x}_j - x_k\right)^2}$

Analysis form 2 of 4	Graphical representation



Key

a	count of measured values x_i in class ($x_i \leq \Delta X_{K,k}$)	1	control chart for individuals
b	number of measured values in a class	2,3	$\bar{x}-s$ control chart
k	class for histogram	4	histogram

Analysis form 3 of 4	**Correction of trend**	
Correction of trend		
Only for normal processes/features and significant trend (e.g. not for in-process control, not adjustable tool, etc.)		
Overall trend (single value chart)	$\delta X_{\text{tot, w}}$	
Overall trend per workpiece (ref. 50 values)	$\delta X_{\text{tot, w}} = \frac{\delta X_{\text{tot, T}}}{n-1} = \frac{\delta X_{\text{tot, T}}}{49}$	
Trend due to thermal distortion	$\delta X_{\text{td}} = \delta X_{\text{tot, T}} - \delta X_{\text{a}}$	
Trend due to thermal distortion per workpiece (ref. 50 values)	$\delta X_{\text{td,w}} = \frac{\delta X_{\text{td}}}{n-1} = \frac{\delta X_{\text{td}}}{49}$	

Trend-corrected measurement data $x_{i,T}$							$x_{i,\text{T}} = x_i - (i-1) \cdot \delta X_{\text{tot,w}}$			
k \ j	1	2	3	4	5	6	7	8	9	10
1	1	6	11	16	21	26	31	36	41	46
2	2	7	12	17	22	27	32	37	42	47
3	3	8	13	18	23	28	33	38	43	48
4	4	9	14	19	24	29	34	39	44	49
5	5	10	15	20	25	30	35	40	45	50
$\bar{x}_j$										
s_j										

Formulae: $\bar{x}_j = \frac{1}{5} \cdot \sum_{k=1}^{5} x_k \quad s_j = \sqrt{\frac{1}{4} \cdot \sum_{k=1}^{5} (\bar{x}_j - x_k)^2}$

If the trend was corrected, the following calculations shall be performed with the corrected data, $x_{i,\text{T}}$!

Maximum value, $x_{\max}$		Minimum value, $x_{\min}$	
Range, $R = x_{\max} - x_{\min}$		Total average value, $\bar{\bar{x}} = \frac{1}{10} \cdot \sum_{j=1}^{10} \bar{x}_j$	
$U_{\text{SL}} - \bar{\bar{x}}$		$\bar{\bar{x}} - L_{\text{SL}}$	
$\frac{x_{\max} - \bar{\bar{x}}}{U_{\text{SL}} - \bar{\bar{x}}}$		$\frac{\bar{\bar{x}} - x_{\min}}{\bar{\bar{x}} - L_{\text{SL}}}$	
Avg. standard dev.		Estimation of the standard deviation (factor for sample size of group 5), $\hat{\sigma} = \frac{\bar{s}}{0{,}94}$	

