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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 travaillant par enlèvement de métal

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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.

International Standards are drafted in accordance with the rules given in the ISO/IEC Directives, Part 2.

The main task of technical committees is to prepare International Standards. Draft International Standards adopted by the technical committees are circulated to the member bodies for voting. Publication as an International Standard requires approval by at least 75 % of the member bodies casting a vote.

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.

ISO 26303 was prepared by Technical Committee ISO/TC 39, *Machine tools*, Subcommittee SC 2, *Test conditions for metal cutting machine tools*.

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 International Standard 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 recognised 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 International Standard 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 under test, the machining process, tooling and clamping applied, as well as the workpiece properties, and

— the estimate of relevant machine capability indexes.

This International Standard adapts to and complies with the specifications established in ISO 22514 (all parts). However, the term “process performance” specified in ISO 22514-3 corresponds to the term “short-term capability” in this International Standard. 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 International Standard defines 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 International Standard 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 International Standard covers neither functional tests, which are generally carried out before testing the accuracy performance, nor the testing of the safety conditions of the machine.

Annex A gives additional information related to statistical evaluation, (normative) 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 properties, such as geometric or positioning accuracy. Short-term capability evaluation is meant to prove that a machine has the capability to fulfil a specific process task. It is, therefore, important to recognise 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 machines, 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” specified in ISO 22514-3.

2 Normative references

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

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

ISO 22514-3:2008, *Statistical methods in process management — Capability and performance — Part 3: Machine performance studies for measured data on discrete parts*

ISO/TR 22514-4:2007, *Statistical methods in process management — Capability and performance — Part 4: Process capability estimates and performance measures*

3 Terms and definitions

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

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 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 Process capability is defined in ISO/TR 22514-4:2007, 2.2.1, as: statistical estimate of the outcome of a characteristic from a process which has been demonstrated to be in a state of statistical control and which describes that process's ability to realize a characteristic that will fulfil the requirements for that characteristic.

NOTE 3 In this International Standard, 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, $R_{\text{V,s}}$ and $R_{\text{V,sk}}$, are evaluated instead of capability indices.

NOTE 4 This International Standard adapts to and complies with the specifications established in ISO 22514 (all parts). However, the term "process performance" specified in ISO 22514-3 corresponds to the term "short-term capability" in this International Standard. 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 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 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 Measured values are also known as characteristic values.

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

3.5
critical short-term range value
$R_{\text{V,sk}}$
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, with upper and lower control limits, on which values of some statistical measure for a series of samples, spiked samples and blanks, are plotted, usually in date or sample number order

[ISO 5667-14:1998, 3.10]

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

[ISO 3534-2:2006, 2.3.15]

3.8
control limit
line on a control chart used for judging the stability of a process

[ISO 3534-2:2006, 2.4.2]

3.9
lower specification limit
specification limit that defines the lowest value a quality characteristic may have and still be considered conforming

[ISO 22514-1:2009, 2.1.13]

3.10
upper specification limit
specification limit that defines the highest value a quality characteristic may have and still be considered conforming

[ISO 22514-1:2009, 2.1.12]

4 Symbols

4.1 Upper case letters

C	Capability index
C_{k}	Critical capability index
C_{s}	Short-term capability index (corresponds to machine performance index P_{m} in ISO 22514-3:2008);
$C_{\mathrm{s,nom}}$	nominal short-term capability index
C_{sk}	Critical short-term capability index
$C_{\mathrm{sk,nom}}$	Nominal critical short-term capability index
C_{act}	Actual capability index
K_i	i^{th} class (histogram)
U	Uncertainty (of measurement or capability index)
$U_{\mathrm{CL},si}$	Upper control limit for the standard deviation s_i
$U_{\mathrm{CL},\bar{x}j}$	Upper control limit for the average values $\bar{x}_j$
U_{SL}	Upper specification limit

R	Range
$R_{\mathrm{V,s}}$	Short-term range value
$R_{\mathrm{V,s,nom}}$	Nominal short-term range value
$R_{\mathrm{V,sk}}$	Short-term critical range value
$R_{\mathrm{V,sk,nom}}$	Nominal short-term critical range value
T	Tolerance
T_{min}	Minimum usable tolerance for capability evaluation
$L_{\mathrm{CL},sj}$	Lower control limit for the standard deviation s_j
$L_{\mathrm{CL},\bar{x}j}$	Lower control limit for the average values $\bar{x}_j$
L_{SL}	Lower specification limit

4.2 Lower case letters

e	Shift of the average value
f	Feed speed
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	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
$\bar{s}$	Average standard deviation of the samples (groups)
$\bar{s}'$	Sample standard deviation of shifted distribution
s_{g}	Standard deviation of the measurement (gauging) system
$s_{\mathrm{g,act}}$	Actual standard deviation of the measurement system
s_j	Standard deviation of the jth sample (group)
t_{m}	Manufacturing time
t_{tot}	Total manufacturing time
$\bar{x}$	Mean value of population (of 50 measurements)
$\bar{x}'$	Mean value of population with shifted distribution
$\bar{\bar{x}}$	Mean value of group means x_j
x_i	ith measurement value
$x_{i,\mathrm{T}}$	ith measurement value (trend corrected)
$x_{\mathrm{u},k}$	Upper class limit of the kth class (histogram)
$\bar{x}_j$	Mean of the jth sample (group)

x_{max}	Maximum value
x_{min}	Minimum value

4.3 Greek letters

$\delta X_{tot,T}$	Total trend (in relation to all values)
$\delta X_{tot,w}$	Total trend per workpiece
δX_{td}	Trend due to thermal drifting
$\delta X_{td,w}$	Trend due to thermal drifting per workpiece
$\delta X_{td,perm}$	Permissible trend due to thermal drift per workpiece
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
$\Delta \upsilon_{amb}$	Ambient temperature gradient
$\Delta \upsilon_{amb,max}$	Maximum ambient temperature gradient
μ_{P}	Mean value for population
ϑ	Temperature
$\vartheta_{amb,0}$	Ambient temperature at beginning of test
ϑ_{max}	Maximum temperature
ϑ_{min}	Minimum temperature
σ	Standard deviation of the population
$\hat{\sigma}$	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 acceptance testing in comparison to the direct testing defined in several series of International Standards, e.g. ISO 230.

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

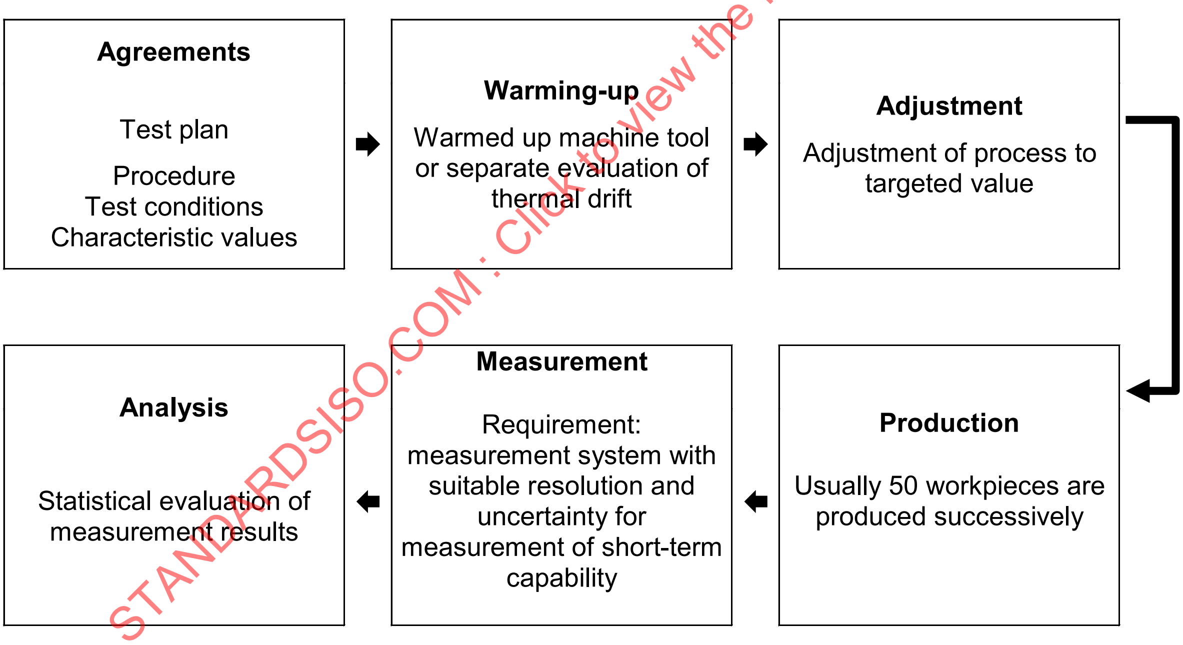
6.1 General

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 [31].

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. 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 range values and, if applicable, thermal drift are beyond specified tolerances, the reasons shall be investigated. These can be, for example, faults which can be recognised as outlier values in the control chart for individuals (see 6.7.3). If improvements are possible, these shall be carried out and the tests shall be repeated in part or whole.



This is recommended only for large batch production machine 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 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, and

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 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 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 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 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 range values, $R_{\mathrm{V,s}}$ or $R_{\mathrm{V,sk}}$, may be agreed upon by the manufacturer/supplier and the user. Additional information on the relationship between standard deviation and range values is given in A.2. The 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 range values are used, the evaluation of the process using the control chart for individuals, the control chart and a histogram is of special importance (see 6.7).

NOTE The definition of the short-term capability indices or range values is of great economic importance. On the one hand, the conformance 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 range values. Such costs result from supplementing or equipping the machine 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[41]. 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 Equation (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 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 drift depends on the manufacturing method, the size of the machine and the production and ambient conditions. During the warm-up phase, a trend due to thermal drift of up to 40 µm/h can be expected[36]. As described in 6.3, this trend is often of lesser importance for machines 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 is operating in thermal equilibrium. If, nevertheless, the trend due to thermal drift is of special importance to the user or the warm-up period cannot be extended until the machine 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. 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 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 drift 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 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 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. Conformance to the following condition is recommended: resolution $\leq 0{,}03\ T$, where T is the tolerance of the feature under test.

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 shall conform to the following requirement:

$$6 \cdot s_{\mathrm{g}} \leq 0{,}15 \cdot T$$

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

Conformance 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 $C_{\mathrm{s}} = 1{,}00$ and less than 4,2 % for $C_{\mathrm{s}} = 2{,}00$) 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 $k = 2$) shall be less than or equal to10 % 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 conformance 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 8258), histograms and probability charts] and calculate the appropriate statistical parameters can be of great help. The 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.

6.7.2 Trend correction

A control chart for individuals is used to evaluate the total trend, $\delta X_{\mathrm{tot,T}}$ 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 drift, δX_{td}, may be calculated as given by Equation (1), if no special influences are apparent:

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

Since the short-term capability indices are always calculated using an estimation of the standard deviation, $\hat{\sigma}$ [see Equations (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 Equations (2) and (3):

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

where

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

$x_{i,\mathrm{T}}$ is the ith trend corrected measurement;

x_i is the ith measurement (not trend-corrected);

$\delta X_{\mathrm{tot,w}}$ 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 five-fold measurement grouping) shall be calculated as given by Equations (4) to (7):

range:

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

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

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

NOTE Constant in Equation (6) 0,94 is for groups of five; constant in Equation (6) becomes 0,89 for groups of three.

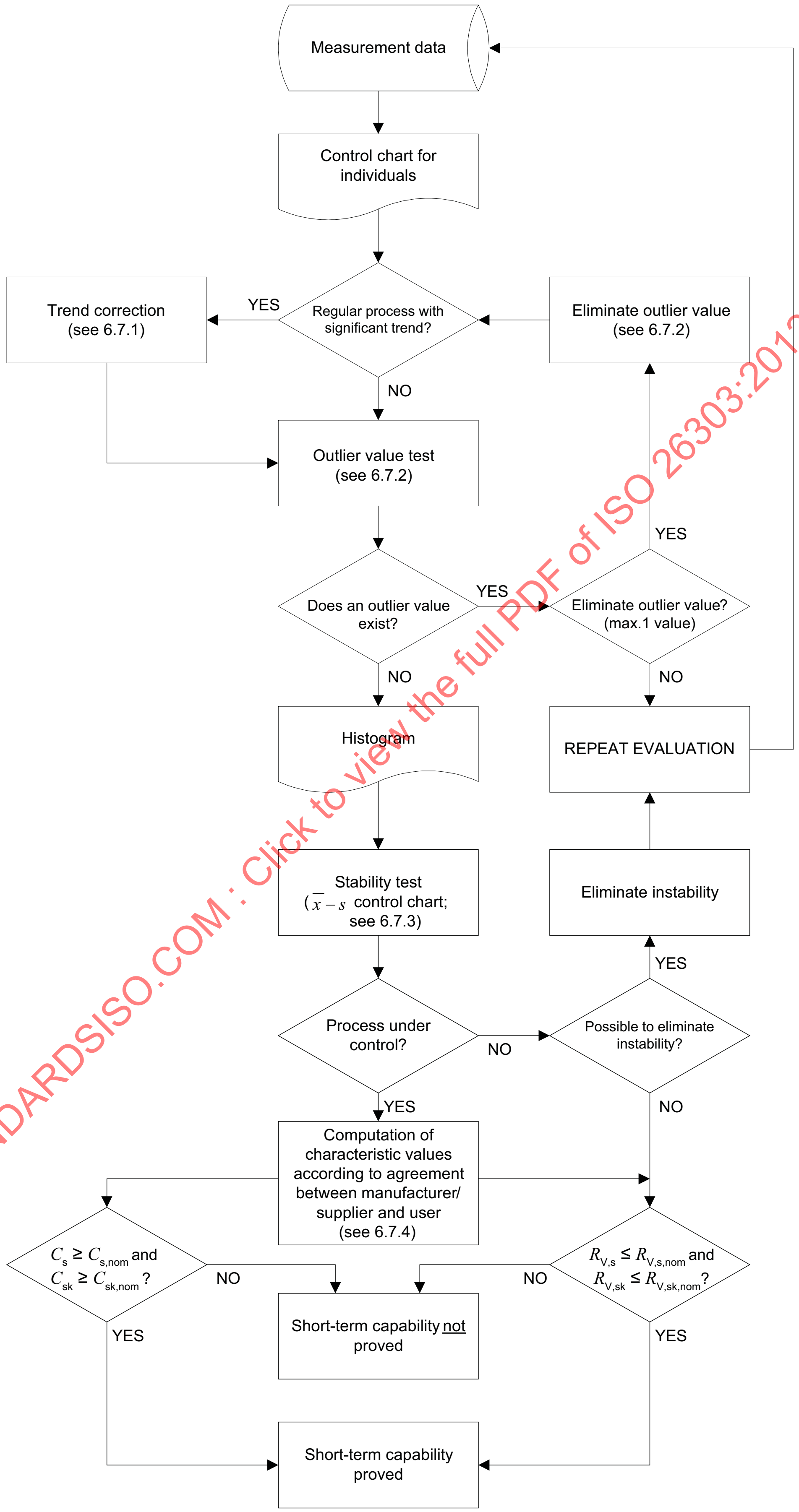


Figure 2 — Evaluation diagram

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, amongst others things, on the assumption of Gaussian normal distribution; thus, it can only be applied for normally distributed measured values associated with processes or features [20][24][38]. If Equations (8) and (9) are fulfilled, x_{max} and/or x_{min} shall be the outlier values (confidence level: 99 %; sample size: 50):

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

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

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 groups is recommended.

The stability of the process is evaluated using a $\bar{x} - s$ 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 Equations (10) to (13) are fulfilled by all 10 groups (j = 1 to 10), the process shall be considered as stable (confidence level: $1 - \alpha = 99$ %; sample size n = 5):

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

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

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

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

where

$\bar{\bar{x}}$ is the mean value according to Equation (5);

$\hat{\sigma}$ is the standard deviation according to Equation (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 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 agreements sheets/forms (see Annex B). These are as given by Equations (14) to(18):

short-term capability index:

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

critical short-term capability index:

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

range value:

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

or

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

in per cent;

critical range value:

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

or

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

in per cent;

(if agreed upon) trend due to thermal drift:

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

where

T	is the tolerance of the feature under test;
$\hat{\sigma}$	is the standard deviation according to Equation (6);
$\overline{x} = \frac{1}{n}\sum_{i=1}^{n} x_i$	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;
$\delta X_{tot,T}$	is the trend due to thermal drift 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 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 following cases shall be differentiated:

a) limited towards upper limit:

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

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

b) limited towards lower limit:

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

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

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.

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 (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 Equation (23):

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

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 $\Delta x_{\max}$ of a few micrometres up to 100 µm. If the acceptance test is carried out in the thermal equilibrium phase, depending on the machine, warming-up periods of 40 min up to 12 h shall be expected in order to ensure that the displacement of the machine has reached 85 % of the maximum displacement. Otherwise, a trend of between 5 µm/h and 40 µm/h is expected due to thermal drift during the warm-up phase.

Machine tools subject to this International Standard are usually applied to large batch production. In the case of three-shift operation, the machines are in thermal equilibrium and the thermal drift 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 drift 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.

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 drift — accuracy performance of axes positioning system — bearing clearance — histeresis and backlash — maintenance — mounting/ foundation — transfer function of feed drives, etc.	— qualification — training — motivation — mood — 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 — measurement resolution and uncertainty — measurement method — operator — maintenance — environment — temperature of workpiece, measurement device and surrounding — surface roughness, etc.	Influences/issues — manually or computer-aided analysis method — statistical uncertainty — methods for non-normal distributions — computational accuracy, etc.

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).

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 $C_s = 1{,}67$ 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 % ($10s$ 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.

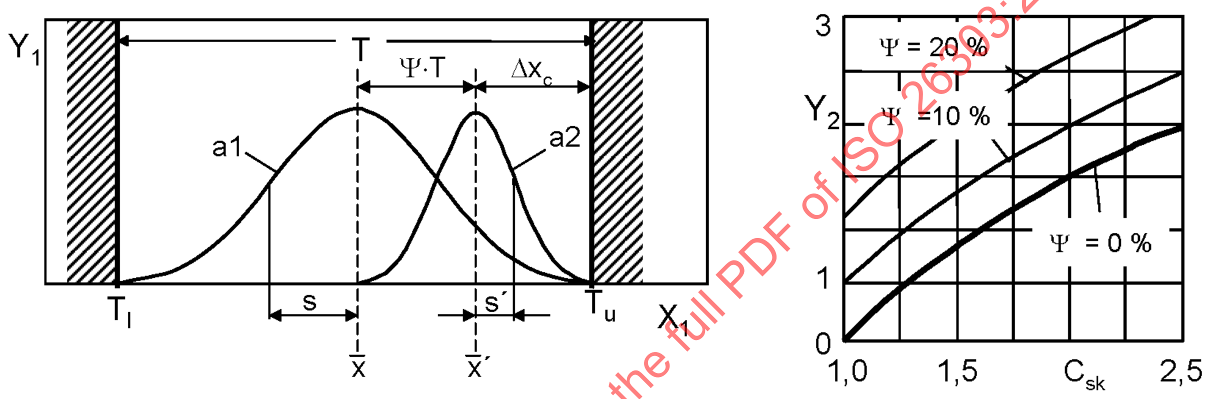
For this reason, it is recommended to carry out the process evaluation by means of control charts for individuals, control charts and histograms, and to calculate the short-term capability indices with the help of an estimation of the standard deviation, derived by grouping the measurement data. In the 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 5.1). 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 22514-3:2008, 5.6, and ISO/TR 22514-4:2007.

Annex A
(informative)

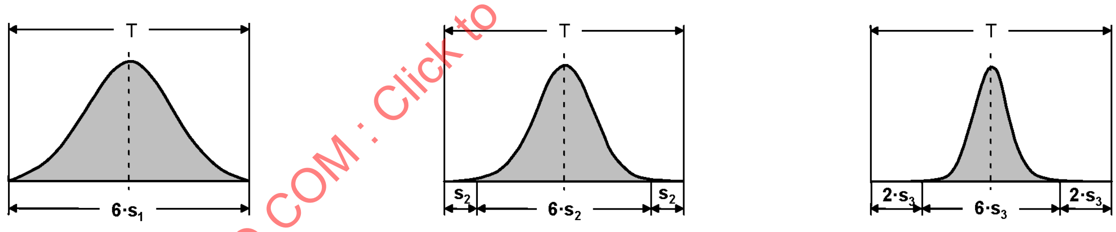
Additional information related to statistical evaluations

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) b)



C_s = 1,0 b1: 99,730 02 %
b2: 0,269 96 %

C_s = 1,33 b1: 99,993 66 %
b2: 0,006 %
s_2 = 0,75 s_1

C_s = 1,67 b1: 99,999 94 %
b2: 0,000 06 %
s_2 = 0,6 s_1

c)

Key

X_1 characteristic value
Y_1 frequency
Y_2 reduction of the zone of conformity within the specified tolerance [ISO tolerance unit]
a1 centred distribution
a2 shifted distribution with $\overline{x}'$ and s'
b1 share of parts estimated as in conformance with specification
b2 share of parts estimated as not in conformance with specification

Figure A.1 — Short-term capability definition for characteristic value with normal distribution

In this context, Equations (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 Equation (A.3)] of characteristic value, evaluated from 50 workpieces.

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

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

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 Equation (A.3)] of characteristic value, evaluated from 50 workpieces.

Sample standard deviation (sample size n):

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

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

$$\Psi = \frac{|\bar{x}' - \bar{x}|}{T} \tag{A.4}$$

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

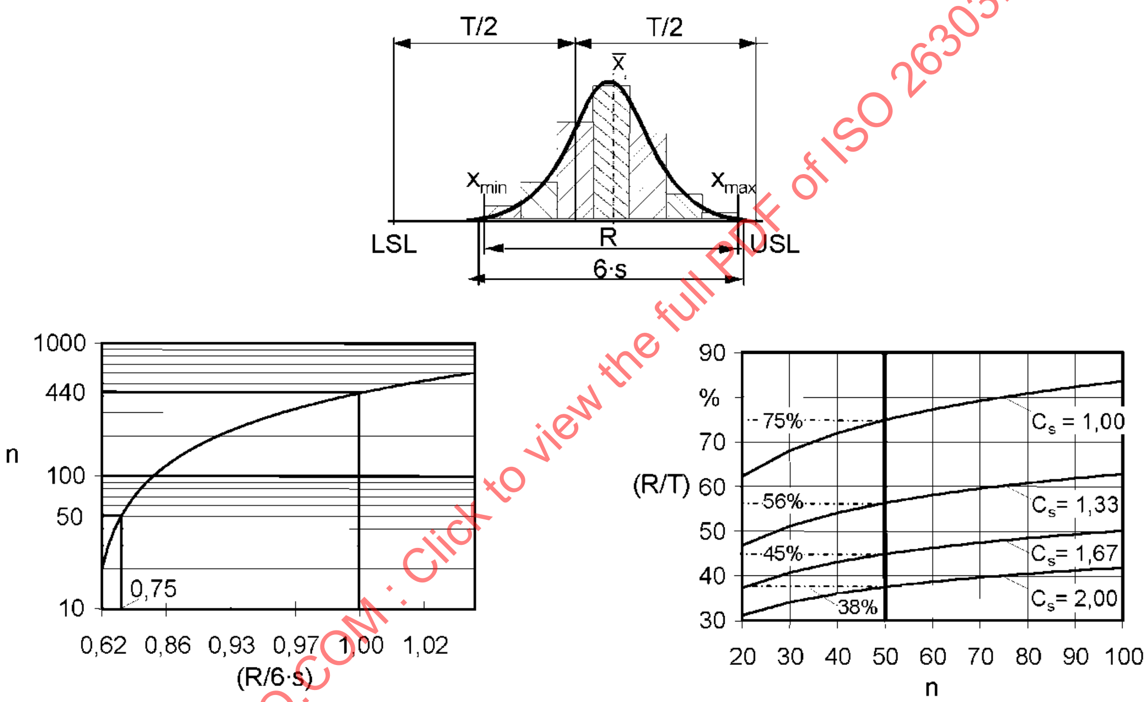
$$s' = (1 - 2 \cdot \Psi) \cdot s \tag{A.5}$$

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 International Standard, 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 c), this means that not only six times the standard deviation shall be within the specified tolerance but even eight or ten times.

Figure A.1 b) 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 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 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 range values, as the range values can only be recommended for non-normally distributed values.



Key

L_{SL} lower specification limit

n number of samples, default n = 50

R range of measurement values

s standard deviation of measured values

T tolerance

U_{SL} upper specification limit

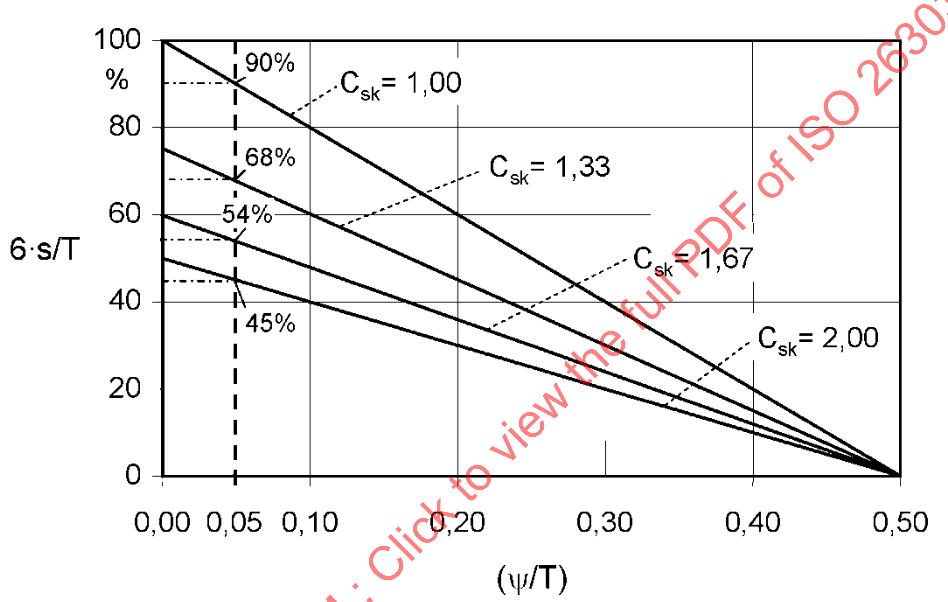
Figure A.2 — Comparison of characteristic values for normal distribution

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:

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

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 6s 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_k, the process shall be reset depending upon the ratio of the six-fold 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

Ψ offset of mean value

T tolerance zone

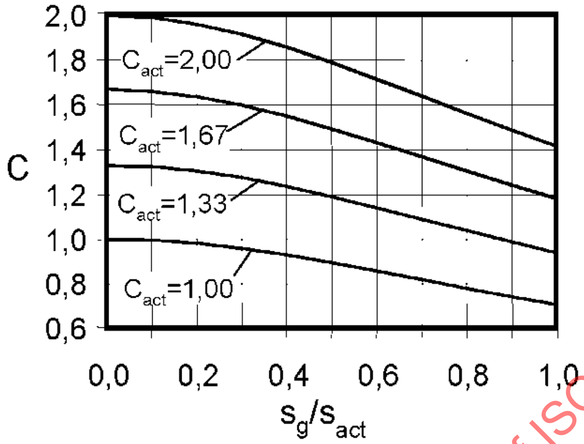
C_{sk} critical short-term capability index

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

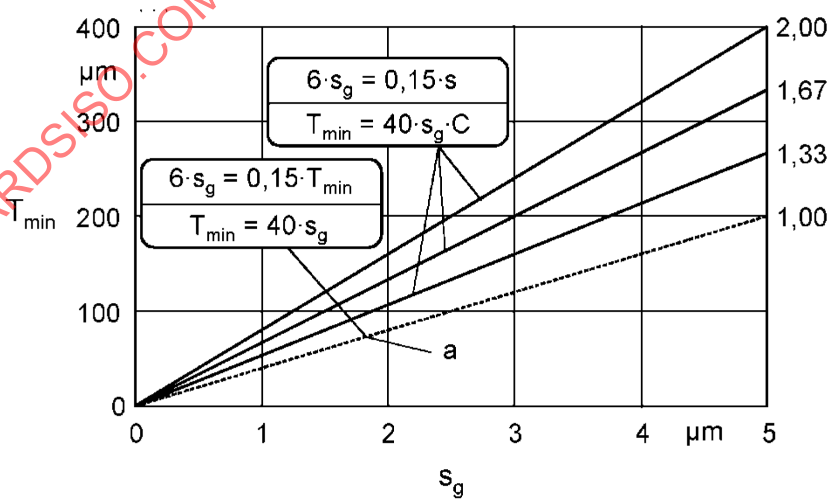
C_{act} actual capability index of process

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

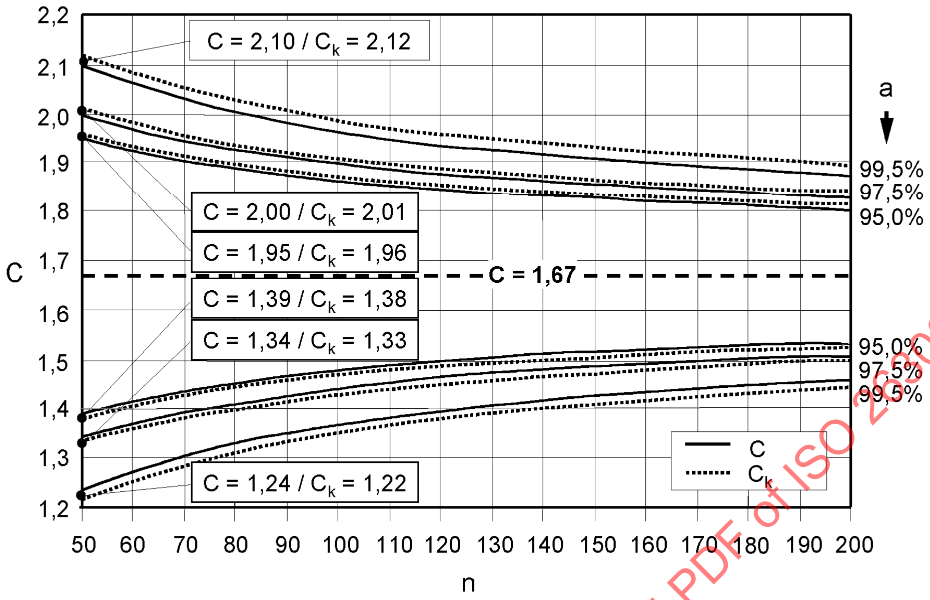
s_g standard deviation of measuring device

T_{min} minimum measurable tolerance

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 confidence level

C capability index

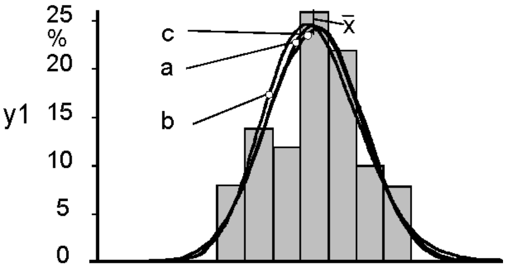
C_k critical capability index

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

y1 density function, in per cent

C capability index

C_k critical capability index

s standard deviation of process

$\bar{x}$ mean value

[a] Normal distribution.

[b] Logarithmic-normal distribution.

[c] Weibull distribution.

Figure A.7 — Influence of selected type of distribution

Annex B
(normative)

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} (recom.: $n_{mp} = 50$)			
Overall machining time $t_{tot} \approx n_{mp}(t_m + t_{np})$			
Quantity of workpieces for analysis n (recom.: $n = 50$)			
Random inspection (recommended sample size: 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			

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

Agreement Form 3 of 4	Feature dependent data I

CHARACTERISTIC VALUES

Recommendation s. b.				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 DRIFT [µm/workpiece]

$\delta X_{td,prm}$	$\delta Y_{td,prm}$	$\delta Z_{td,prm}$

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 $\delta x_{\mathrm{a,exp}}$			
MEASUREMENT			
Location			
Device			
Device serial no.			
Resolution			
Standard deviation of measuring device s_{g}			
0,03 T		$\geq$ resolution ?	[ ] yes [ ] **no: *use another measuring device!***
T/40		$\geq s_{\mathrm{g}}$?	[ ] yes [ ] **no: *use another measuring device!***
Set-up of measuring device (e.g. filter, strategy; note special circumstances separately)			

Annex C
(normative)

Evaluation forms

Analysis Form 1 of 4	**General information**		
MACHINE/WORKPIECE			
Workpiece description			
Workpiece material			
FEATURE/NOMINAL			
Lower specification limit L_{SL}		Tolerance $T = U_{SL} - L_{SL}$	
Upper specification limit U_{SL}			
MEASURING DEVICE			
Device serial no.	Resolution	standard deviation s_g	
$0{,}03 \cdot T =$		$\geq$ resolution? **and**	
$T / 40 =$		$\geq s_g$?	
[ ] 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 drift 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}		$\Delta\vartheta_{amb,max}$	

Measurement data x_i (with trend) values in ______ as deviation from set point

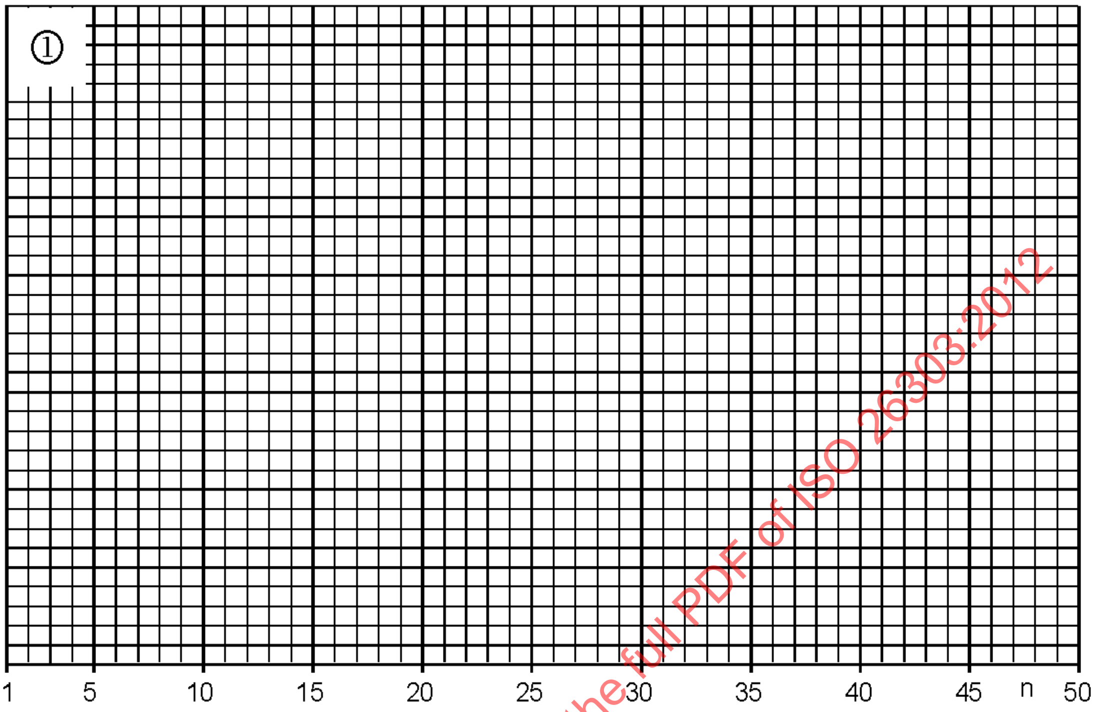
$j \rightarrow$	1	2	3	4	5	6	7	8	9	10
1	1	6	11	16	21	26	31	36	41	46
2	2	7	12	17	22	27	32	37	42	47
3	3	8	13	18	23	28	33	38	43	48
4	4	9	14	19	24	29	34	39	44	49
5	5	10	15	20	25	30	35	40	45	50

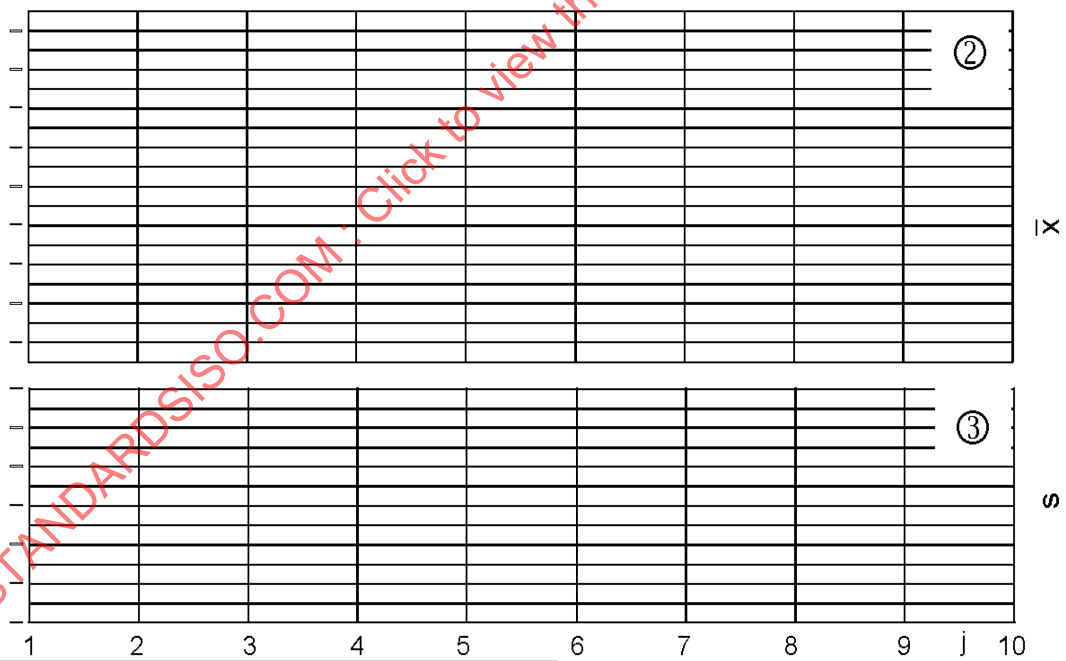
Now, generate the control chart for individuals. For normal processes/features and a significant trend, first perform trend correction (sheet: 3 of 4), and carry out all other calculations with trend corrected data.

$\bar{x}_j$										
s_j										

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

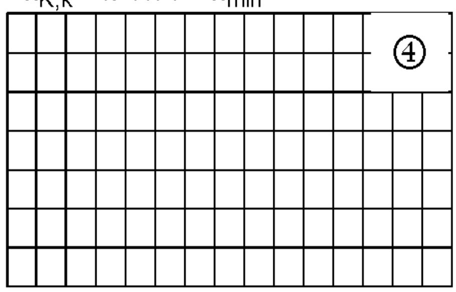
Analysis Form 2 of 4	Graphical representation





k	$\Delta x_{K,k}$	a $(x_i \leq x_{K,k})$	b
1			
2			
3			
4			
5			
6			
7			

$\Delta x_{K,k} = k \cdot R / 7 + x_{min}$



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,...)		
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 drift	$\delta X_{\text{td}} = \delta X_{\text{tot,T}} - \delta X_{\text{a}}$	
Trend due to thermal drift 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 $x_{i,\text{T}}$	$x_{i,\text{T}} = x_i - (i-1) \cdot \delta X_{\text{tot,w}}$

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										

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

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 5) $\hat{\sigma} = \frac{\bar{s}}{0{,}94}$	

Analysis Form 4 of 4	**Evaluation**		
OUTLIER VALUE TEST for normal processes/features (Grubbs: 50 values/confidence level 99%)			
$\overline{\overline{x}} + 3{,}34 \cdot \hat{\sigma}$		$< x_{\text{max}}$?	[ ] yes [ ] no
$\overline{\overline{x}} + 3{,}34 \cdot \hat{\sigma}$		$< x_{\text{min}}$?	[ ] yes [ ] no
yes: x_{max} and/or x_{min} are outlier values	**no**: x_{max} or/and x_{min} are not outlier values		
If an outlier value is present, a new outlier value test shall be carried out without this value. In the case of two or more outlier values, the reason shall be sought and the test should be repeated as the process is obviously not under control. If only one outlier value is found, a decision shall be made on whether to proceed with the calculations without this value or to repeat the entire test.			

STABILITY TEST (Factors based on sample size 5 with a confidence level of 99%)				
	Exceeding of the control limits?		yes	no
Upper control limit of $\overline{x}_j$	$U_{\text{CL},\overline{x}j} = \overline{\overline{x}} + 1{,}15 \cdot \hat{\sigma}$			
Lower control limit of $\overline{x}_j$	$L_{\text{CL},\overline{x}j} = \overline{\overline{x}} - 1{,}15 \cdot \hat{\sigma}$			
Upper control limit of s_j	$U_{\text{CL},sj} = 1{,}93 \cdot \hat{\sigma}$			
Lower control limit of s_j	$L_{\text{CL},sj} = 0.23 \cdot \hat{\sigma}$			
Process stable: Continue with the calculation of the declared characteristic values. **Process not stable**: If possible, redeem instability and repeat test.				

CHARACTERISTIC VALUES (as declared)		Requirements fulfilled?		yes	no
Short-term capability index	$C_{\text{s}} = \dfrac{T}{6 \cdot \hat{\sigma}}$		$C_{\text{s}} \geq C_{\text{s,nom}}$?		
Critical short-term capability index	$C_{\text{sk}} = \dfrac{\{U_{\text{SL}} - \overline{\overline{x}}\,;\, \overline{\overline{x}} - L_{\text{SL}}\}_{\text{min}}}{3 \cdot \hat{\sigma}}$		$C_{\text{sk}} \geq C_{\text{sk,nom}}$?		
Range value	$R_{\text{V,s}} = \dfrac{R}{T}$		$R_{\text{V,s}} \leq R_{\text{V,s,nom}}$?		
Critical range value	$R_{\text{V,sk}} = \left\{ \dfrac{x_{\text{max}} - \overline{\overline{x}}}{U_{\text{SL}} - \overline{\overline{x}}} \,;\, \dfrac{\overline{\overline{x}} - x_{\text{min}}}{\overline{\overline{x}} - L_{\text{SL}}} \right\}_{\text{max}}$		$R_{\text{V,sk}} \leq R_{\text{V,sk,nom}}$		

TREND DUE TO THERMAL DRIFT (carryover from sheet 3 of 4)			
δX_{td} : overall (50 workpieces)	$\delta X_{\text{td,w}}$: per workpiece		
Trend less than permissible trend? $\delta X_{\text{td}} \leq \delta X_{\text{td,perm}}$ (according to agreement by manufacturer/supplier and the user)		[ ] yes	[ ] no
SUMMARIZED EVALUATION			
Short-term capability proven, machine accepted		**[ ] yes**	**[ ] no**

Annex D
(informative)

Examples of capability agreements and analysis

Agreement Form 1 of 4	Test plan
GENERAL INFORMATION	
Machine tool description	lathe XYZ
Machine serial no.	D 08 15
Workpiece description	shaft
Workpiece no.	W 47 11
Material	Ck 45
QUANTITY OF WORKPIECES/RANDOM TEST	
Machining time/workpiece t_m	4,5 min
Quantity of workpieces n_{mp} (recom.: $n_{mp} = 50$)	50
Overall machining time $t_{tot} \approx n_{mp}(t_m + t_{np})$	approx. 5 h
Quantity of workpieces for analysis n (recom.: $n = 50$)	50
Random inspection (recommended sample size: 5)	---

SCHEDULE/LOGISTIC

a) Preparation	Manufacturer (M) Customer (C)	Place (M / C)	Date
Blanks	C	M	10. WEEK
Tools	C	M	10. WEEK
Clamping devices	M	M	10. WEEK
Machine tool	M	M	13. WEEK
Operator for machine tool	M	M	13. WEEK
measuring devices	M	M	13. WEEK
Operator for measuring	M	M	13. WEEK

b) Dates	Start	End	Duration
Preparation/set-up	11. WEEK	12. WEEK	2 weeks
Warming-up phase	28.3./16:00	29.3./8:00	16 h
Adjustment	29.3./8:00	29.3./10:00	2 h
Production	29.3./10:00	29.3./15:00	5 h
Measurement	30.3.	5.4.	1 week
Analysis	6.4.	8.4.	3 days

Agreement Form 2 of 4	General information

BLANKS

Material, heat-treatment, surface, hardness, strength, tolerance of allowance, tolerance of fixtures, etc.

Ck 45
Round bar steel
cut to length

TEST CONDITIONS

Setting of fixture of machine tool	Installation shoes
Particular loads (e.g. vibrations induced by surrounding production)	none
Max. variation of ambient temperature during examination; recommended limits: temperature change within ±3 °C during time of test	± 3° C
Max. temperature gradient during evaluation; recommended: within a maximum of +2 °C/h or –2 °C/h	± 2° C / h

FEATURES

No.	Description of feature	Nom. size	Dimension
1	Diameter D 1	56 +0,046/-0	mm
2	Length L 1	120	mm
3	Concentricity of diameter D 1	0,010	mm
4			
5			
6			
7			
8			
9			