
**Guidelines for implementation of
statistical process control (SPC) —**

**Part 4:
Reference data sets for measurement
process analysis software validation**

*Lignes directrices pour la mise en œuvre de la maîtrise statistique des
processus (MSP) —*

*Partie 4: Jeu de données pour la validation des logiciels d'analyse de
processus de mesure*

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Foreword

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A list of all parts in the ISO 11462 series can be found on the ISO website.

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 test examples were developed for the assessment of systems performing a measurement system analysis (MSA). They allow MSA software developers to evaluate their systems. Thus, the end user of those systems can be sure that the data sets are evaluated correctly with a high level of reliability. In order to cover as wide a spectrum as possible, suitable data sets were prepared individually for various constellations. The evaluation results of those data sets are documented and commented on the following pages.

The results were verified multiple times using different computer programs. This turns the data sets and the results into references for validation of the software. The data sets are listed in the related clauses of this document or can be accessed via <https://standards.iso.org/iso/tr/11462-4/ed-1/en>.

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Guidelines for implementation of statistical process control (SPC) —

Part 4: Reference data sets for measurement process analysis software validation

1 Scope

This document describes examples for software validation for software implementing the standards of ISO 22514-7 on the capability of measurement processes. In detail, the following standards are covered:

— ISO 22514-7.

It provides data sets and test results for testing the implementation of the evaluation methods described in these standards. This includes:

- a) the calculation of standard uncertainties from other sources (other than experiments – type B – ISO/IEC Guide 98-3);
- b) the estimation of uncertainty components using repeated measurements on reference parts;
- c) the estimation of uncertainty components using repeated measurements on multiple parts with different operators and their evaluation using the ANOVA method;
- d) the combination of uncertainty components using the Gaussian law of uncertainty propagation;
- e) the calculation of measurement process capability indices;
- f) the influence of operators on attributive measurements;
- g) the uncertainty range and capability indices for attributive measurements.

The test examples are intended to cover the calculation of the measuring system capability and measurement process capability according to ISO 22514-7.

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 22514-2, *Statistical methods in process management — Capability and performance — Part 2: Process capability and performance of time-dependent process models*

3 Terms and definitions, and symbols and abbreviated terms

3.1 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 22514-2 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 <https://www.electropedia.org/>

3.2 Symbols and abbreviated terms

Symbols used in this standard are identical to symbols used in ISO 22514-7.

a	half width of a distribution of possible values of input quantity
a_{OBJ}	maximal form deviation
α	significance level
B_i	bias
C_{attr}	capability index for attributive measurement
C_{MP}	measurement process capability index
C_{MS}	measuring system capability index
d	average interval
d_{LR}	interval from the last reference value, for which all operators have assessed the result as unsatisfied to the first reference value, for which all operators have the result as approved
d_{UR}	interval from the last reference value, for which all operators have assessed the result as approved to the first reference value, for which all operators have the result as unsatisfied
e_{nj}	residuals
K	number of repeatability measurements
k	coverage factor
k_{CAL}	coverage factor from the calibration certificate
L	lower specification limit
l	measured length
M	the number of subgroups
M_{PE}	maximum permissible error (of the measuring system) (MPE-value)
m_{ij}	frequencies in Bowker-test
N	number of standards
n	sample size of each subgroup
Q_{attr}	attributive measurement process capability ratio
Q_{MP}	measurement process capability ratio
Q_{MS}	measuring system capability ratio
$Q_{\text{MS}_{\text{max}}}$	capability ratio limit for measuring system

Q_{MP_max}	capability ratio limit for measurement process
R_E	resolution of measuring system
$\hat{\sigma}$	sample standard deviation
T	temperature
U	upper specification limit
U_{CAL}	uncertainty on the calibration of standards
u_α	standard uncertainty on the coefficient of expansion
u_{AV}	standard uncertainty from the operator's repeatability
u_{BI}	standard uncertainty from the measurement bias
u_{CAL}	calibration standard uncertainty on a standard
u_{EV}	standard uncertainty from maximum value of repeatability or resolution
u_{EVR}	standard uncertainty from repeatability on standards
u_{EVO}	standard uncertainty from repeatability on test parts
u_{GV}	standard uncertainty from reproducibility of the measuring system
u_{IAi}	standard uncertainty from interactions
u_{LIN}	standard uncertainty from linearity of the measuring system
u_{MPE}	standard uncertainty calculated based on maximum permissible error
$u_{MS-REST}$	combined standard uncertainty from other influence components not included in the analysis of the measuring system
u_{OBJ}	standard uncertainty from test part inhomogeneity
u_{RE}	standard uncertainty from resolution of measuring system
u_{REST}	standard uncertainty from other influence components not included in the analysis of the measurement process
u_{STAB}	standard uncertainty from the stability of measuring system
u_T	standard uncertainty from temperature
u_{TA}	standard uncertainty from temperature expansion coefficients
u_{TD}	standard uncertainty from temperature difference between workpiece and measuring system
U_{attr}	expanded measurement uncertainty on an attributive measurement
u_{attr}	combined standard uncertainty of attributive measuring
U_{MS}	expanded measurement uncertainty of the measuring system
u_{MS}	combined standard uncertainty on measuring system
U_{MP}	expanded measurement uncertainty of the measurement process

- u_{MP} combined standard uncertainty on measurement process
- u_{MX} standard uncertainty from effect of spindle clamping
- u_{RA} standard uncertainty from resolution
- u_{RE} standard uncertainty from repeatability
- x_i i^{th} reference quantity value
- x_{mU} reference quantity value of the standard (master) at the upper specification limit
- x_{mm} reference quantity value of the standard (master) in the centre of the specification
- x_{mL} reference quantity value of the standard (master) at the lower specification limit
- \bar{x} arithmetic mean of the conventional true values
- y_j j^{th} measurement value
- \bar{y} arithmetic mean of the measured values

3.3 Abbreviated terms

- ANOVA analysis of variance
- MSA measurement systems analysis
- MPE maximum permissible error

4 Overview of the test examples

4.1 Overview

For an overview of the test examples see [Table 1](#).

Table 1 — List of the test data sets

Test data set number	Sub-clause	Characteristics type	Decimal points	Description of data set	Source/ Reference
1	5.1	Variable	2	All uncertainty components mentioned in the 22514-7 are covered. Combination of type A and type B evaluation, including Linearity and GRR studies	ISO 22514-7 + additions
2	5.2	Attributive	---	Test on influence of operators based on experimental data	ISO 22514-7
3	5.3	Attributive	--- (6)	Calculation of uncertainty range and capability of the attributive measurement process based on experimental data	ISO 22514-7
4	5.4	Variable	4	Measurement process capability with three reference standards Linearity study, GRR with ANOVA Multiple uncertainty components: resolution, calibration, repeatability, linearity, bias, operators, part-interaction	VDA 5

Table 1 (continued)

Test data set number	Sub-clause	Characteristics type	Decimal points	Description of data set	Source/ Reference
5	5.5	Variable	4	Measurement process capability of a CMM Repeatability and bias with one standard Multiple uncertainty components: resolution, calibration, repeatability, linearity, bias, temperature	VDA 5 and ISO 15530-3
6	5.6	Variable	4	Measurement process capability of automated test device Multiple measurements on one standards and 10 parts Multiple uncertainty components: resolution, calibration, repeatability, linearity, bias, MPE(gauge)	VDA 5
7	5.7	Variable	4	Measurement process capability of a multiple-point measuring instrument GRR with ANOVA Multiple uncertainty components: resolution, calibration, repeatability, linearity, bias, MPE (sensor), reproducibility, part-interaction, temperature, error of temperature compensation	VDA 5

4.2 Notes

4.2.1 Notes on the accuracy of the test examples and results

Capability indices are always given with two digits (rounded).

4.2.2 Note on outlier detection

Each test data set was tested for outliers using Grubbs' test for outliers (according to ISO 5725-2) with a level of significance of 1 % and no outliers were detected.

4.2.3 Note on capability indices

There are various different capability indices given in the relevant different standards and guidelines. All are based on the ratio of the specification interval and the measurement uncertainty. Only the expansion factors and limit values vary. In this standard only the capability indices according to ISO 22514-7 are used.

4.2.4 Note on the model of the measurement and correlations

Although ISO/IEC Guide 98-3 provides the possibility of including non-linear models and correlations between input quantities, correlations and non-linearities are not covered by the ISO 22514-7. Therefore, only a linear model with sensitivity coefficients of one for every input quantity as well as no correlations are considered in this standard and its examples.

4.2.5 Note on other reference data sets

ISO/TR 12888 provides multiple examples especially for the case of GRR studies^[1].

4.2.6 Note on systematic errors

According to ISO/IEC Guide 98-3 any systematic error is compensated and the uncertainty of the systematic error is included into the measurement budget and is part of the combined uncertainty.

5 Reference data sets description and evaluation

5.1 Test data set 1 – example of linearity study with at least three standards

5.1.1 Test data set 1 – information

Test data set for ISO 22514-7 capability of measurement processes with a linearity and ANOVA study.

This example has been taken from ISO 22514-7:2021, Annex A (the data originally come from ISO 11095). The uncertainties arising from the object and the temperature were added.

5.1.2 Test data set 1 – data, calculations and results

5.1.2.1 Calculation of the measuring system capability

5.1.2.1.1 Components of type B which are not taken into account by experiments

Resolution

The uncertainty component caused by resolution is $u_{RE} = 0,00144 \mu\text{m}$.

The uncertainty component u_{RE} is much smaller than u_{EVR} , see behind [Table 4](#). Therefore, the component u_{RE} is not used.

Object

The maximum expected error due to the clamping of the part during the measurement is $a_{OBJ} = 0,0015 \mu\text{m}$.

The uncertainty component is therefore:

$$u_{OBJ} = \frac{a_{OBJ}}{\sqrt{3}} = 0,000866 \mu\text{m}$$

Calibration

It is assumed according to the calibration certificate that the calibration uncertainty u_{CAL} is $0,005 \mu\text{m}$.

5.1.2.1.2 Components of Type A which are derived from a linearity study with at least 3 standards

An experiment is carried out on an imaging system (an optical microscope with a measuring device). The data listed in [Table 2](#) are measured values and true values of intervals in the range of $0,5 \mu\text{m}$ to $12 \mu\text{m}$.

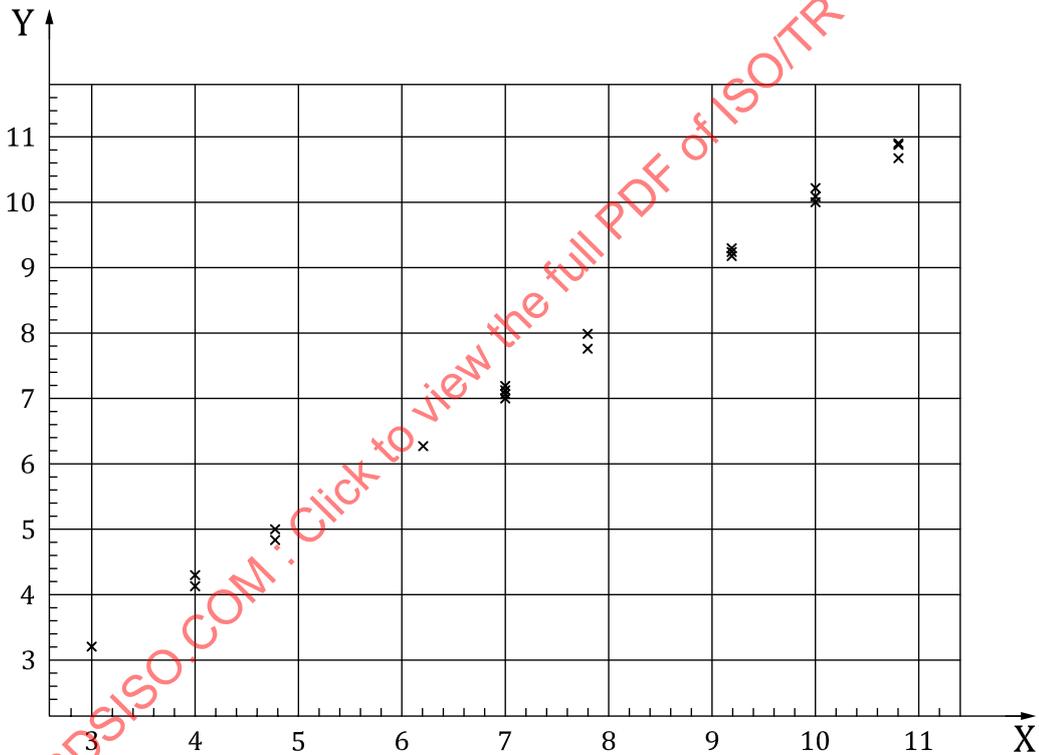
Table 2 — Values from repeated measurements on reference materials

Conventional true values x_n of the 10 reference materials	Values y_{nj} from $K = 4$ repeatability measurements on $N = 10$ reference materials			
	y_{n1}	y_{n2}	y_{n3}	y_{n4}
6,19	6,31	6,27	6,31	6,28
9,17	9,27	9,21	9,34	9,23

Table 2 (continued)

Conventional true values x_n of the 10 reference materials	Values y_{nj} from $K = 4$ repeatability measurements on $N = 10$ reference materials			
	y_{n1}	y_{n2}	y_{n3}	y_{n4}
1,99	2,21	2,19	2,22	2,20
7,77	8,00	7,81	7,95	7,84
4,00	4,27	4,15	4,15	4,15
10,77	10,93	10,73	10,92	10,89
4,78	4,95	4,87	5,00	5,00
2,99	3,24	3,17	3,21	3,21
6,98	7,14	7,07	7,18	7,20
9,98	10,23	10,02	10,07	10,17

Data in Table 2 are plotted in Figure 1.

**Key**

X reference value (μm)

Y measured value (μm)

Figure 1 — Plot of measured and true values

5.1.2.1.3 Calculation of means and residuals

For each reference material the mean value \bar{y}_n , the bias $B_{i,n}$ and the residuals e_{n1} to e_{n4} are calculated.

See Table 3 for the calculated values.

Table 3 — Calculation of means and residuals

Conventional true values x_n of the 10 reference materials	Mean values \bar{y}_n	$B_{i,n}$	Residuals			
			e_{n1}	e_{n2}	e_{n3}	e_{n4}
6,19	6,292 5	0,102 5	0,017 5	-0,022 5	0,017 5	-0,012 5
9,17	9,262 5	0,092 5	0,007 5	-0,052 5	0,077 5	-0,032 5
1,99	2,205 0	0,215 0	0,005 0	-0,015 0	0,015 0	-0,005 0
7,77	7,900 0	0,130 0	0,100 0	-0,090 0	0,050 0	-0,060 0
4,00	4,180 0	0,180 0	0,090 0	-0,030 0	-0,030 0	-0,030 0
10,77	10,867 5	0,097 5	0,062 5	-0,137 5	0,052 5	0,022 5
4,78	4,955 0	0,175 0	-0,005 0	-0,085 0	0,045 0	0,045 0
2,99	3,207 5	0,217 5	0,032 5	-0,037 5	0,002 5	0,002 5
6,98	7,147 5	0,167 5	-0,007 5	-0,077 5	0,032 5	0,052 5
9,98	10,122 5	0,142 5	0,107 5	-0,102 5	-0,052 5	0,047 5

Data in Table 3 are plotted in Figure 2.

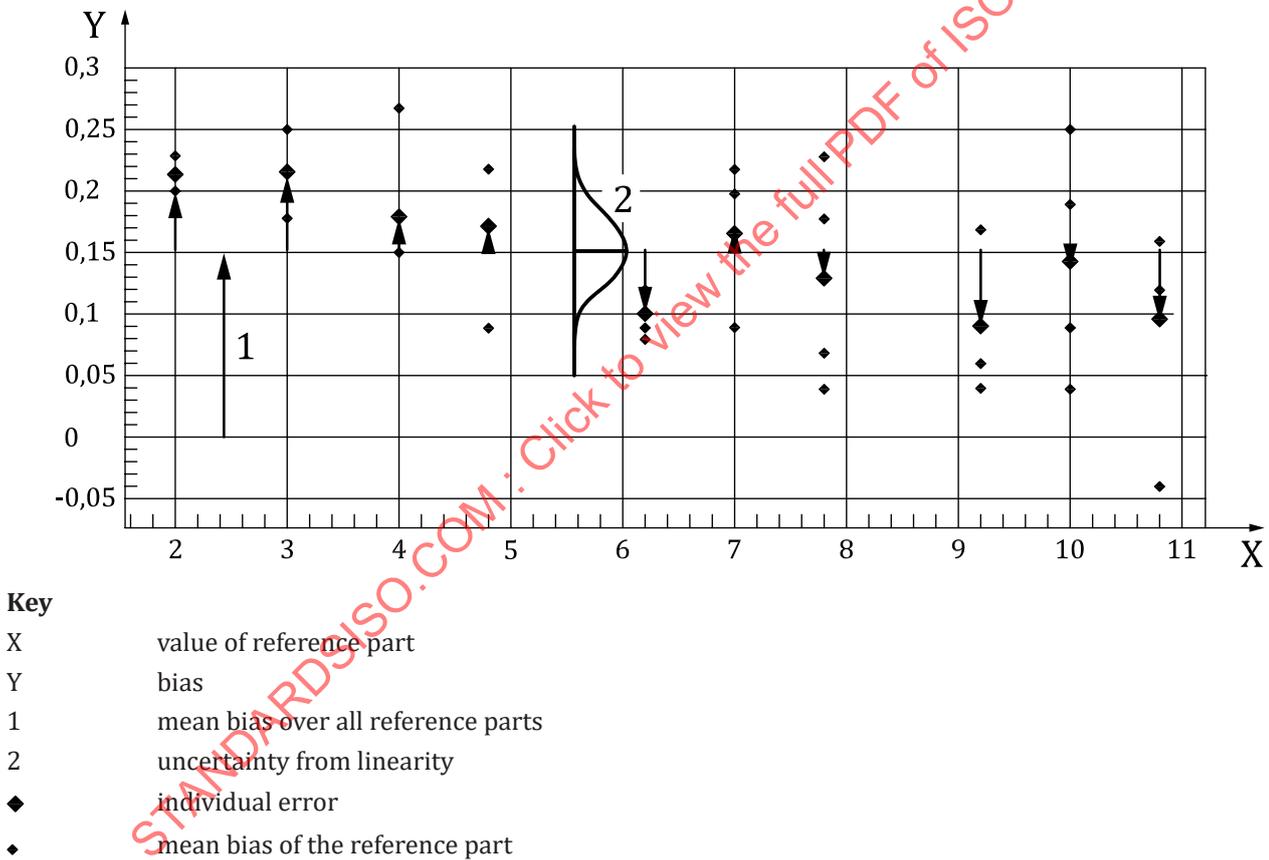


Figure 2 — Plot of deviations and conventional true values

5.1.2.1.4 ANOVA table

Given values:

- $N = 10$ Number of standards (Factor A)
- $K = 4$ Number of repeatability measurements

Calculated values:

$$\overline{B}_i = 0,152 \quad \text{Arithmetic mean of all biases.}$$

The components are calculated by an ANOVA, see [Table 4](#).

Table 4 — ANOVA table

Source	Sum of squares <i>SS</i>	Degrees of freedom <i>v</i>	Mean squares <i>MS</i>	Estimated variance <i>S</i> ²	Test statistic <i>F</i>	Critical value <i>F</i> ₀	Estimator <i>σ</i>
Factor A	0,077 39	9	0,008 599	0,001 121	2,089 6	2,210 7	0,033 480 9
Residual error	0,123 45	30	0,004 115	0,004 115			0,064 148 3
Total	0,200 84	39	--				

5.1.2.1.5 Estimation of uncertainty components

Estimated uncertainties from [Table 4](#) and mean bias:

$$\begin{aligned} \text{uncertainty due to bias} & \quad u_{\text{BI}} = \frac{\overline{B}_i}{\sqrt{3}} = 0,087 76 \\ \text{uncertainty due to linearity} & \quad u_{\text{LIN}} = \hat{\sigma}_A = 0,033 48 \\ \text{uncertainty due to repeatability on references} & \quad u_{\text{EVR}} = \hat{\sigma}_{\text{RES}} = 0,064 15 \end{aligned}$$

5.1.2.1.6 Determination of the combined and expanded uncertainty

The uncertainty components of the measuring system are listed in [Table 5](#) where the standard uncertainty of the measuring system is calculated as the Euclidian distance of the following components:

$$u_{\text{MS}} = \sqrt{u_{\text{CAL}}^2 + u_{\text{EVR}}^2 + u_{\text{LIN}}^2 + u_{\text{BI}}^2}$$

Because $u_{\text{RE}} \ll u_{\text{EVR}}$ the standard uncertainty of the resolution u_{RE} is excluded from the calculation of u_{MS} .

Table 5 — Uncertainty budget of the measuring system

Uncertainty component	Symbol	Type	<i>u</i> μm	Remark	Rank
Resolution of the measuring system	u_{RE}	B	(0,001 44)	$\ll u_{\text{EVR}}$	5
Calibration uncertainty	u_{CAL}	B	0,005 00		4
Repeatability on reference standard	u_{EVR}	A	0,064 15		2
Uncertainty from linearity	u_{LIN}	A	0,033 48		3
Uncertainty from Bias	u_{BI}	A	0,087 76		1
Measuring system	u_{MS}		0,113 85		

The combined uncertainty of the measuring system: $u_{\text{MS}} = 0,114 \mu\text{m}$

and the expanded uncertainty: $U_{\text{MS}} = 0,228 \mu\text{m}$.

5.1.2.2 Experimental determination of the measurement process uncertainty

In addition to the estimated uncertainty components from the measuring system found in Table 4, it can be useful to determine some additional uncertainty components (u_{EVO}, u_{AV}, u_{IAi}) from the measurement process by the evaluation of the results from this process under the real conditions. In this example (estimation of uncertainty components from different operators, repeatability and interaction between operators) the following data are collected, see Table 6.

Table 6 — ANOVA test data set in μm

Part no.	Operator 1			Operator 2			Operator 3		
	Measurement 1	Measurement 2	Measurement 3	Measurement 1	Measurement 2	Measurement 3	Measurement 1	Measurement 2	Measurement 3
1	8,120	8,435	8,480	8,200	8,290	8,245	8,525	8,435	8,345
2	7,445	6,815	7,490	7,300	7,120	7,075	7,535	7,355	7,085
3	9,965	10,010	9,560	9,660	9,340	9,250	9,830	9,695	9,515
4	6,140	5,960	6,365	6,095	6,185	6,185	6,140	6,140	6,050
5	5,690	5,600	5,780	5,080	5,340	5,440	5,780	5,735	5,555
6	2,855	2,450	2,585	2,315	2,585	2,315	2,630	2,360	2,585
7	10,685	10,595	10,775	10,450	10,840	11,050	10,865	11,000	11,180
8	6,725	6,275	6,545	6,240	6,120	6,300	6,590	6,500	6,725
9	4,970	5,105	5,510	5,015	5,285	5,150	5,060	5,195	5,105
10	9,875	10,100	9,875	10,080	9,800	9,970	10,190	9,785	9,965

From the measurements in Table 6 the following analysis of variance table can be calculated, see Table 7.

Table 7 — ANOVA table

Uncertainty component	Degrees of freedom ν	Sum of squares SS	Mean Square MS	Estimated variance $\hat{\sigma}_i^2$	Uncertainty $u_i = +\sqrt{\hat{\sigma}_i^2}$	Test statistic F	Critical value F_0 $\alpha = 5\%$
Operator	2	0,519 1	0,259 5	0,007 38	0,085 91	6,810	3,150
Part to part	9	526,877 5	58,541 9	6,500 43	n/a	1 536,234	2,040
Interaction between operator and part	18	0,685 9	0,038 1	0,002 05	0,045 29	1,193	1,778
Reproducibility	60	1,917 3	0,032 0	0,031 95	0,178 76	---	---

Since the interaction between operator and part is not significant ($F < F_0$) pooling is used. Then a modified variance table can be developed there, see Table 8

Table 8 — Modified ANOVA table

Uncertainty component	Degrees of freedom ν	Sum of squares SS	Mean Square MS	Estimated variance $\hat{\sigma}_i^2$	Uncertainty $u_i = +\sqrt{\hat{\sigma}_i^2}$	Test statistic F	Critical value F_0 $\alpha = 5\%$
Operator	2	0,519 06	0,259 53	0,007 54	0,086 82	7,776	3,114
Part to part	9	526,877 50	58,541 94	6,500 95	n/a	1 754,088	2,002
Reproducibility	78	2,603 22	0,033 37	0,033 37	0,182 69	---	---

The uncertainty components of the measurement process are then found:

$$u_{AV} = 0,086\,82\,\mu\text{m}$$

$$u_{EVO} = 0,182\,69\,\mu\text{m}$$

Temperature

The length of the object is $l = 10\,\mu\text{m}$.

The maximum temperature difference is $\delta_T = 0,1\,\text{K}$.

The average temperature during the measurement is $T = 21\,^\circ\text{C}$.

The expansion coefficient is $\alpha = 11,5 \cdot 10^{-6}\,\text{K}^{-1}$.

The uncertainty of α is $u_\alpha = 11,5 \cdot 10^{-7}\,\text{K}^{-1}$.

The uncertainty from temperature differences u_{TD} is $u_{TD} = \frac{\delta_T \cdot \alpha \cdot l}{\sqrt{3}} = 0,000\,006\,64\,\mu\text{m}$.

The uncertainty on expansion coefficients is $u_{TA} = \frac{|T - 20\,^\circ\text{C}| \cdot u_\alpha \cdot l}{\sqrt{3}} = 0,000\,006\,64\,\mu\text{m}$.

The influence from temperature is therefore $u_T = \sqrt{u_{TD}^2 + u_{TA}^2} = 0,000\,009\,39\,\mu\text{m}$.

Table 9 — Uncertainty budget of the measurement process

Uncertainty component	Symbol	Type	u μm	Remark	Rank
Resolution of the measuring system	u_{RE}	B	(0,001 4)	$\ll u_{EVO}$	7
Calibration uncertainty	u_{CAL}	B	0,005 0		6
Repeatability on reference standard	u_{EVR}	A	(0,064 1)	$\ll u_{EVO}$	4
Uncertainty from linearity	u_{LIN}	A	0,033 5		5
Uncertainty from Bias	u_{BI}	A	0,087 8		2
Reproducibility of operators	u_{AV}	A	0,086 8		3
Repeatability on test parts	u_{EVO}	A	0,182 7		1
Uncertainty from interactions	u_{IAI}	A		pooling	--
Inhomogeneity of measurand	u_{OBJ}	B	0,000 9		8
Temperature	u_T	B	0,000 0		9
Measurement process	u_{MP}		0,223 1		

The components u_{STAB} and u_{REST} are both set to 0.

The uncertainty components of the measurement process are given in [Table 9](#) where the standard uncertainty of the measurement process is calculated as the Euclidian distance of the following components:

$$u_{MP} = \sqrt{u_{CAL}^2 + u_{LIN}^2 + u_{BI}^2 + u_{AV}^2 + u_{EVO}^2 + u_{OBJ}^2 + u_T^2}$$

The combined uncertainty of the measurement process: $u_{MP} = 0,223\,\mu\text{m}$

and the expanded uncertainty: $U_{MP} = 0,446\,\mu\text{m}$.

5.1.2.2.1 Assessing the capability of measuring system and the measurement process

With the specification interval: $U - L = (11 - 2) \mu\text{m} = 9 \mu\text{m}$.

The capability ratios are:

$$\%Q_{MS} = \frac{2 \cdot U_{MS}}{U - L} \cdot 100 \% = \frac{2 \cdot 0,22770 \mu\text{m}}{(11 - 2) \mu\text{m}} \cdot 100 \% = 5,1 \%$$

$$\%Q_{MP} = \frac{2 \cdot U_{MP}}{U - L} \cdot 100 \% = \frac{2 \cdot 0,44614 \mu\text{m}}{(11 - 2) \mu\text{m}} \cdot 100 \% = 9,9 \%$$

The capability indices are:

$$C_{MS} = \frac{0,2 \cdot (U - L)}{2 \cdot k \cdot u_{MS}} = \frac{0,2 \cdot (11 - 2) \mu\text{m}}{2 \cdot 2 \cdot 0,11385 \mu\text{m}} = 3,95$$

$$C_{MP} = \frac{0,4 \cdot (U - L)}{2 \cdot k \cdot u_{MP}} = \frac{0,4 \cdot (11 - 2) \mu\text{m}}{2 \cdot 2 \cdot 0,22307 \mu\text{m}} = 4,03$$

The calculated statistics are listed in [Table 10](#).

Table 10 — Uncertainty and capability for test data set 1

	Measuring system		Measurement process	
	$U - L$	$9,00 \mu\text{m}$	$U - L$	$9,00 \mu\text{m}$
Specification interval	$U - L$	$9,00 \mu\text{m}$	$U - L$	$9,00 \mu\text{m}$
Combined standard uncertainty	u_{MS}	$0,114 \mu\text{m}$	u_{MP}	$0,228 \mu\text{m}$
Expanded measurement uncertainty	U_{MS}	$0,223 \mu\text{m}$	U_{MP}	$0,446 \mu\text{m}$
Capability ratio	$\%Q_{MS}$	$5,1 \%$	$\%Q_{MP}$	$9,9 \%$
Capability index	C_{MS}	$3,95$	C_{MP}	$4,03$

5.2 Test data set 2 - attribute measurement process - operator influence (ISO 22514-7)

5.2.1 Test data set 2 - information

Test data set for attributive measurement processes without reference values. Only the influence of different operators is determined. The example was taken from ISO 22514-7:2021, 12.2.

5.2.2 Test data set 2 - data, calculations and results

Typically at least 40 different test parts are tested 3 times by 2 different operators, called A and B.

Each of the 120 different measurement results on the 40 parts, which the operator A or operator B has achieved, is assigned to one of the following three classes.

- Class 1: all three test results on the same part gave the result “good”;
- Class 2: the three test results on the same part gave different results;
- Class 3: all three test results on the same part gave the result “bad”.

The test results are given in [Table 11](#).

Table 11 — Test result from an attribute measurement process

Frequency n_{ij}		Operator B		
		Class 1 Result '+++'	Class 2 Different results	Class 3 Result '- - -'
Operator A	Class 1 Result '+++'	7	3	1
	Class 2 Different results	10	4	7
	Class 3 Result '- - -'	2	1	5

The two operators in [Table 11](#) are tested using a Bowker-Test of symmetry. If there are no significant differences between operators, the resulting frequencies in [Table 10](#) are sufficiently symmetrical with respect to main diagonal. The hypothesis $H_0 : m_{ij} = m_{ji}$ ($i, j = 1, \dots, 3$ with $i \neq j$) says that the frequencies m_{ij} and m_{ji} which lies symmetrical with respect to the main diagonal are identical.

Test statistic

$$\chi^2 = \sum_{i>j} \frac{(n_{ij} - n_{ji})^2}{n_{ij} + n_{ji}} = \frac{(10-3)^2}{10+3} + \frac{(2-1)^2}{2+1} + \frac{(1-7)^2}{1+7} = 8,603$$

is compared to $(1-\alpha)$ fractile in the χ^2 distribution with 3 degrees of freedom. The null hypothesis test states that changes from one category to another are random in nature. The hypothesis on symmetry is rejected on the level if the test value is greater than the $(1-\alpha)$ fractile in the χ^2 distribution with 3 degrees of freedom. In this case, the hypothesis is rejected because the calculated value 8,603 is greater than the value 7,815 which is the 95 % fractile of the $\chi^2(3)$ distribution.

5.3 Test data set 3 – attributive measurements – capability calculations using reference values – calculation of the uncertainty range (ISO 22514-7)

5.3.1 Test data set 3 – information

Test data set for attributive measurement processes. Capability calculations using reference values including the calculation of the uncertainty range.

5.3.2 Test data set 3 – data, calculations and results

This method is based on signal detections and therefore requires workpieces with known reference values. When about 25 % of the workpieces is at or close to the lower specification limit and 25 % of the workpieces is at or close to the upper specification limit, the area of risk around the specification limits can be addressed. The purpose of this method is to determine the uncertainty range, in which an operator is unable to make an unambiguous decision. [Figure 2](#) illustrates the test results of an attribute measurement process obtained from a set of reference values.

Part No. Char. No.	Ref. 1	1			Part Descr. Char. Descr.			MSA Third Edition Attribute Study			
		XA1	XA2	XA3	XB1	XB2	XB3	XC1	XC2	XC3	
25	0,599581	-	-	-	-	-	-	-	-	-	☺
48	0,587893	-	-	-	-	-	-	-	-	-	☺
3	0,576459	-	-	-	-	-	-	-	-	-	☺
5	0,570360	-	-	-	-	-	-	-	-	-	☺
42	0,566575	-	-	-	-	-	-	-	-	-	☺
4	0,566152	-	-	-	-	-	-	-	-	-	☺
30	0,561457	-	-	-	-	-	+	-	-	-	☺
12	0,559918	-	-	-	-	-	-	-	+	-	☺
26	0,547204	-	+	-	-	-	-	-	-	+	☺
22	0,545604	-	-	+	-	+	-	+	+	-	☺
6	0,544951	+	+	-	-	+	-	+	-	-	☺
36	0,543077	+	+	-	+	+	+	+	-	+	☺
13	0,542704	+	+	+	+	+	+	+	+	+	☺
18	0,531939	+	+	+	+	+	+	+	+	+	☺
23	0,529065	+	+	+	+	+	+	+	+	+	☺
29	0,523754	+	+	+	+	+	+	+	+	+	☺
28	0,521642	+	+	+	+	+	+	+	+	+	☺
19	0,520469	+	+	+	+	+	+	+	+	+	☺
17	0,519694	+	+	+	+	+	+	+	+	+	☺
15	0,517377	+	+	+	+	+	+	+	+	+	☺
10	0,515573	+	+	+	+	+	+	+	+	+	☺
24	0,514192	+	+	+	+	+	+	+	+	+	☺
41	0,513779	+	+	+	+	+	+	+	+	+	☺
2	0,509015	+	+	+	+	+	+	+	+	+	☺
32	0,505850	+	+	+	+	+	+	+	+	+	☺
31	0,503091	+	+	+	+	+	+	+	+	+	☺
27	0,502436	+	+	+	+	+	+	+	+	+	☺
8	0,502295	+	+	+	+	+	+	+	+	+	☺
40	0,501132	+	+	+	+	+	+	+	+	+	☺
35	0,496696	+	+	+	+	+	+	+	+	+	☺
46	0,493441	+	+	+	+	+	+	+	+	+	☺
11	0,483803	+	+	+	+	+	+	+	+	+	☺
38	0,488184	+	+	+	+	+	+	+	+	+	☺
33	0,487613	+	+	+	+	+	+	+	+	+	☺
47	0,486379	+	+	+	+	+	+	+	+	+	☺
18	0,484167	+	+	+	+	+	+	+	+	+	☺
49	0,483803	+	+	+	+	+	+	+	+	+	☺
20	0,477236	+	+	+	+	+	+	+	+	+	☺
1	0,476901	+	+	+	+	+	+	+	+	+	☺
44	0,470832	+	+	+	+	+	+	+	+	+	☺
7	0,465454	+	+	+	+	+	+	+	+	+	☺
43	0,462410	+	-	+	+	+	+	+	+	-	☺
14	0,454518	+	-	-	+	+	+	+	-	-	☺
21	0,452310	+	+	-	+	+	+	+	+	-	☺
34	0,449696	-	-	+	-	-	+	-	+	+	☺
50	0,446697	-	-	-	-	-	-	-	-	-	☺
9	0,437817	-	-	-	-	-	-	-	-	-	☺
39	0,427687	-	-	-	-	-	-	-	-	-	☺
45	0,412453	-	-	-	-	-	-	-	-	-	☺
37	0,409238	-	-	-	-	-	-	-	-	-	☺

Figure 3 — Test data set

Symbols

In [Figure 3](#), the reference measurement values are introduced in the form of a code. A green plus sign means that the operator has indicated the result from the test piece as approved. A grey minus sign means that the operator has indicated the result from the test piece as not approved. A green smiley means that all three operators have indicated the result from the test piece as approved or rejected in all three tests, and that this assessment is consistent with the reference value. A red smiley indicates a case where at least one of the operators has come to a test result, which is not consistent with the reference value.

Steps for the calculation of the capability index:

Step 1:

Sort the table according to the measured reference size. In [Figure 2](#), a sorting in descending order is made – from the highest reference value descending to the lowest reference value.

Step 2:

Select the last reference value for which all operators have assessed all the results as being unsatisfactory (not approved). This is the transition from symbol “-” to symbol “X”.

0,566 152 mm	-
0,561 457 mm	X

Step 3:

Select the first reference value for which all operators the first time assessed all results being approved. This is the transition from symbol “X” to the symbol “+”.

0,543 077 mm	X
0,542 704 mm	+

Step 4:

Select the last reference value for which all operators last time assessed all the results as being approved. This is the transition from the “+” symbol to the symbol “X”.

0,470 832 mm	+
0,465 454 mm	X

Step 5:

Select the first reference value for which every operator has again first assessed all the results as unsatisfactory (not approved). This is the transition from symbol “X” to the symbol “-”.

0,449 696 mm	X
0,446 697 mm	-

Step 6:

Calculate the d_{UR} interval from the last reference value, for which all operators have assessed the result as unsatisfied (not approved) to the first reference value, for which all operators have the result as approved.

$$d_{UR} = (0,566 152 - 0,542 704) \text{ mm} = 0,023 448 \text{ mm}$$

Step 7:

Calculate the d_{LR} interval from the last reference value, for which all operators have assessed the result as approved to the first reference value, and for which all operators have the result as unsatisfied (not approved).

$$d_{LR} = (0,470 832 - 0,446 697) \text{ mm} = 0,024 135 \text{ mm}$$

Step 8:

Calculate the average “ d ” of the two intervals:

$$d = \frac{d_{UR} + d_{LR}}{2} = \frac{(0,023 448 + 0,024 135) \text{ mm}}{2} = 0,023 791 5 \text{ mm}$$

Step 9:

Calculate the uncertainty range and capability ratio/ index:

$$U_{\text{attr}} = \frac{d}{2} = 0,011\,90\text{ mm} \hat{=} 11,90\ \mu\text{m}$$

$$u_{\text{attr}} = \frac{U_{\text{attr}}}{2} = 0,005\,95\text{ mm} \hat{=} 5,95\ \mu\text{m}$$

$$\%Q_{\text{attr}} = \frac{2 \cdot U_{\text{attr}}}{U-L} \cdot 100\% = \frac{0,023\,791\,5\text{ mm}}{0,1\text{ mm}} \cdot 100\% = 23,79\%$$

where $U-L=0,1\text{ mm}$

$$C_{\text{attr}} = \frac{0,2 \cdot (U-L)}{2 \cdot k \cdot u_{\text{attr}}} = \frac{0,2 \cdot 0,1\text{ mm}}{2 \cdot 2 \cdot 0,005\,95\text{ mm}} = 1,68$$

Table 12 shows the uncertainty and capability statistics.

Table 12 — Uncertainty and capability for test data set 3

Specification interval	$U-L$	100,00 μm
Measurement uncertainty	u_{attr}	5,95 μm
Expanded measurement uncertainty	U_{attr}	11,90 μm
Capability ratio	$\%Q_{\text{attr}}$	23,79 %
Capability index	C_{attr}	1,68

5.4 Test data set 4 - measurement process capability with three reference standards (VDA 5)

5.4.1 Test data set 4 - information

Test data set for the Measurement Process Capability using 3 reference standards. The example was taken from the VDA 5, 2nd edition and the data are listed in Table 13.

5.4.2 Test data set 4 - data, calculations and results

An instrument measuring bothholes requires that the capability of the measurement process for inside diameters is evaluated and documented. Uncertainties from test part or the temperature are regarded as negligible and are not considered in the evaluation.

Table 13 — Information about measuring system and measurement process

Information about measuring system and measurement process	
Nominal dimension	30,000 mm
Upper specification limit U	30,008 mm
Lower specification limit L	30,003 mm
Resolution of the measuring system R_E (1 digit = 0,000 1 mm)	0,1 μm
Calibration uncertainty U_{CAL}	0,026 μm
Coverage factor k_{CAL}	2
Linearity	0
Reference quantity value of the standard at the upper specification limit x_{mu}	30,007 6 mm
Reference quantity value of the standard in the centre of the specification x_{mm}	30,005 0 mm

Table 13 (continued)

Information about measuring system and measurement process	
Reference quantity value of the standard at the lower specification limit x_{ml}	30,002 5 mm
Capability ratio limit measuring system Q_{MS_max}	15 %
Capability ratio limit measurement process Q_{MP_max}	30 %

5.4.2.1 Test data set 4 – evaluating the capability of measuring system

In order to determine the standard uncertainties from repeatability on standards and from measurement bias, an experiment was conducted performing 10 repeated measurements on each of three reference standards. The reference values and measuring results are listed in [Table 14](#).

Table 14 — Reference value and measurement values

Dimensions in millimetres

	Standard 1	Standard 2	Standard 3
Reference value	30,007 6	30,005 0	30,002 5
Measurement value 1	30,007 5	30,005 0	30,002 5
Measurement value 2	30,007 5	30,005 1	30,002 4
Measurement value 3	30,007 7	30,005 1	30,002 4
Measurement value 4	30,007 5	30,005 0	30,002 3
Measurement value 5	30,007 6	30,005 2	30,002 5
Measurement value 6	30,007 6	30,005 1	30,002 4
Measurement value 7	30,007 6	30,005 0	30,002 3
Measurement value 8	30,007 5	30,005 1	30,002 3
Measurement value 9	30,007 6	30,005 1	30,002 4
Measurement value 10	30,007 6	30,005 2	30,002 4

The information about the measuring system and the measured quantity values gained in the experiment leads to the following uncertainty budget and overview of results, see [Table 15](#).

Table 15 — Uncertainty budget of the measuring system

Uncertainty component	Symbol	Type	u μm	Remark	Rank
Resolution of the measuring system	u_{RE}	B	(0,03)	$\ll u_{EVR}$	3
Calibration uncertainty	u_{CAL}	B	0,01		4
Repeatability on reference standard	u_{EVR}	A	0,07		1
Uncertainty from linearity	u_{LIN}	B			--
Uncertainty from Bias	u_{BI}	A	0,06		2
Measuring system	u_{MS}		0,10		

where

$$u_{MS} = \sqrt{u_{CAL}^2 + u_{EVR}^2 + u_{BI}^2}$$

The calculated uncertainty and capability statistics are given in [Table 16](#).

Table 16 — Results of the measuring system

Specification interval	$U - L$	5,00 μm
Combined standard uncertainty	u_{MS}	0,10 μm
Expanded measurement uncertainty	U_{MS}	0,20 μm
Capability ratio	$\%Q_{\text{MS}}$	7,86 %
Capability index	C_{MS}	2,55

Due to a percentage resolution $\%R_E$ of 2,00 % and a capability ratio $\%Q_{\text{MS}}$ of 7,86 %, the capability of the measuring system of the instrument measuring boltholes is confirmed. After the capability of the measuring system is confirmed, the measurement process is analysed.

5.4.2.2 Test data set 4 - analysing the measurement process

The operator influence, the repeatability on test parts and their interactions are determined experimentally under operational conditions. In this experiment, 2 repeated measurements are performed on each of 10 test parts by 3 operators. For the measured values, see [Table 17](#).

Table 17 — Measurement values

Dimensions in millimetres

	Operator A		Operator B		Operator C	
	Trial 1	Trial 2	Trial 1	Trial 2	Trial 1	Trial 2
1	30,005 4	30,005 5	30,005 7	30,005 8	30,005 8	30,005 7
2	30,005 6	30,005 8	30,005 9	30,005 4	30,005 7	30,005 8
3	30,005 3	30,005 4	30,005 5	30,005 5	30,005 6	30,005 9
4	30,004 1	30,004 2	30,004 3	30,004 4	30,004 5	30,004 2
5	30,005 1	30,005 3	30,005 5	30,004 9	30,005 2	30,004 9
6	30,005 0	30,005 2	30,005 4	30,005 5	30,005 5	30,005 3
7	30,004 9	30,005 0	30,004 9	30,005 2	30,005 1	30,005 1
8	30,005 6	30,005 6	30,005 7	30,005 9	30,005 8	30,005 7
9	30,005 4	30,005 5	30,005 6	30,005 7	30,005 4	30,005 6
10	30,005 8	30,005 8	30,005 9	30,006 1	30,005 7	30,006 1

Based on the recorded measured quantity values, the individual standard uncertainties can be determined and allocated by using the method of ANOVA, see [Table 18](#).

Table 18 — ANOVA table (without the non-significant interaction term)

Uncertainty component	Degrees of freedom ν	Sum of squares SS	Mean Square MS	Estimated variance $\hat{\sigma}_i^2$	Uncertainty $u_i = +\sqrt{\hat{\sigma}_i^2}$	Test statistic F	Critical value F_0 $\alpha = 5 \%$
Operator	2	$3,423 \cdot 10^{-7}$	$1,712 \cdot 10^{-7}$	$7,420 \cdot 10^{-8}$	$8,614 \cdot 10^{-5}$	7,519	3,191
Part to part	9	$1,191 \cdot 10^{-5}$	$1,324 \cdot 10^{-6}$	$2,169 \cdot 10^{-7}$	n/a	58,157	2,082
Reproducibility	48	$1,093 \cdot 10^{-6}$	$2,276 \cdot 10^{-8}$	$2,276 \cdot 10^{-8}$	$1,509 \cdot 10^{-4}$	---	---

This leads to the following uncertainty budget and overview of results for the measurement process, see [Table 19](#). The standard uncertainty of the measurement process is $u_{\text{MP}} = \sqrt{u_{\text{CAL}}^2 + u_{\text{BI}}^2 + u_{\text{AV}}^2 + u_{\text{EVO}}^2}$.

Table 19 — Uncertainty budget of the measurement process

Uncertainty component	Symbol	Type	u μm	Remark	Rank
Resolution of the measuring system	u_{RE}	B	(0,03)	$\ll u_{EVO}$	5
Calibration uncertainty	u_{CAL}	B	0,01		6
Repeatability on reference standard	u_{EVR}	A	(0,07)	$\ll u_{EVO}$	3
Uncertainty from linearity	u_{LIN}	B			
Uncertainty from Bias	u_{BI}	A	0,06		4
Reproducibility of operators	u_{AV}		0,09		2
Repeatability on test parts	u_{EVO}		0,15		1
Uncertainty from interactions	u_{IAI}			pooling	
Measurement Process	u_{MP}		0,19		

Table 20 — Results (measurement process)

Combined standard uncertainty	u_{MP}	0,19 μm
Expanded measurement uncertainty	U_{MP}	0,37 μm
Capability ratio	$\%Q_{MP}$	14,83 %
Capability index	C_{MP}	2,70

Due to a capability ratio Q_{MP} of 14,83 % in case of a process capability ratio limit $Q_{MP,max}$ of 30 %, the capability of the measurement process of the instrument measuring boltholes is confirmed. For uncertainty and capability statistics see [Table 20](#).

The combined list of the uncertainty and capability statistics for measuring system and measuring process is given in [Table 21](#).

Table 21 — Uncertainty and capability for test data set 4

	Measuring system		Measurement Process	
	$U-L$		$U-L$	
Specification interval	$U-L$	5,00 μm	$U-L$	5,00 μm
Combined standard uncertainty	u_{MS}	0,10 μm	u_{MP}	0,19 μm
Expanded measurement uncertainty	U_{MS}	0,20 μm	U_{MP}	0,37 μm
Capability ratio	$\%Q_{MS}$	7,86 %	$\%Q_{MP}$	14,83 %
Capability index	C_{MS}	2,55	C_{MP}	2,70

5.5 Test data set 5 – Measurement Process Capability of a CMM (VDA 5 and ISO 15530-3)

5.5.1 Test data set 5 – information

The test data set is taken from the ISO 15530-3:2011, Annex A. The test data set is for the evaluation of the measurement process capability of a CMM including an uncertainty budget.

5.5.2 Test data set 5 – data, calculations and results

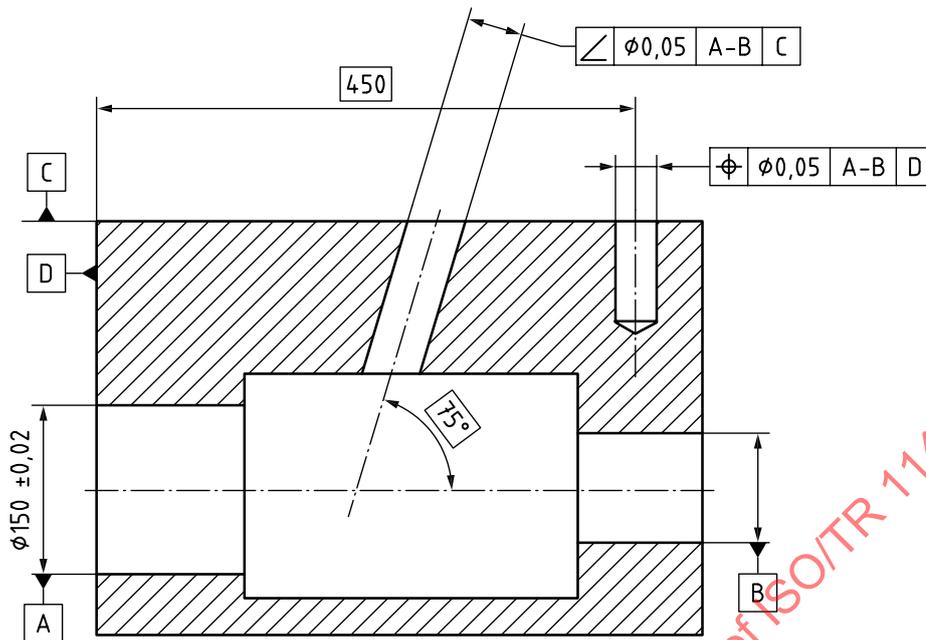


Figure 4 — Technical drawing of a pump housing (simplified)

Measuring the inside diameter of a pump housing (see Figure 4) on a reference standard by using a coordinate measuring machine requires that the capability of the measurement process is evaluated and documented. The basic data for this test example are given in Table 22.

Table 22 — Information about measuring system and measurement process

Information about measuring system and measurement process	
Nominal dimension	150,00 mm
Upper specification limit U	150,02 mm
Lower specification limit L	149,98 mm
Resolution of the measuring system R_E (1 digit = 0,000 1 mm)	0,1 μ m
Reference quantity value of the standard I_{Ref}	150,001 5 mm
Calibration uncertainty U_{CAL}	2 μ m
Coverage factor k_{CAL}	2
Linearity	0
Capability ratio limit measuring system Q_{MS_max}	15 %
Standard uncertainty from expansion coefficients of the test part $u_{\alpha(OB)}$	$1 \cdot 10^{-6}/K$
Mean temperature of the measurement process \bar{T}_{MP}	22 °C
Value displayed by measuring system I_{MS}	150,00 mm
Capability ratio limit measurement process Q_{MP_max}	30 %

5.5.2.1 Test data set 5 – evaluating the capability of measuring system

In order to determine the standard uncertainties from repeatability on standards and from measurement bias, 20 repeated measurements were performed on a reference standard. Since the linearity deviation is zero, the linearity can be neglected. For measured values see Table 23.

Table 23 — Measurements

Dimensions in millimetres

	Value		Value
1	150,003 7	11	150,002 1
2	150,004 3	12	150,002 4
3	150,003 0	13	150,002 4
4	150,002 1	14	150,003 0
5	150,003 3	15	150,003 1
6	150,003 9	16	150,003 4
7	150,003 2	17	150,002 2
8	150,002 7	18	150,002 0
9	150,002 5	19	150,001 8
10	150,003 2	20	150,003 0

The arithmetic mean of the measurements is $\bar{x} = 150,002\,865$ mm

The absolute value of the bias is:

$$|\bar{x} - l_{\text{Ref}}| = |150,002\,865 \text{ mm} - 150,001\,5 \text{ mm}| = 0,001\,365 \text{ mm}$$

The standard uncertainty due to bias is:

$$u_{\text{BI}} = \frac{|\bar{x} - l_{\text{Ref}}|}{\sqrt{3}} = \frac{0,001\,365 \text{ mm}}{\sqrt{3}} = 0,000\,788 \text{ mm} \hat{=} 0,79 \mu\text{m}$$

The standard uncertainty of repeatability on reference standard is:

$$u_{\text{EVR}} = s = 0,000\,677\,67 \text{ mm} \hat{=} 0,68 \mu\text{m}$$

The information about the measuring system and the measured quantity values gained in the experiment lead to the following uncertainty budget and overview of results, see [Table 24](#).

Table 24 — Uncertainty components of the measuring system

Uncertainty component	Symbol	Type	u μm	Remark	Rank
Resolution of the measuring system	u_{RE}	B	(0,03)	$\ll u_{\text{EVR}}$	4
Calibration uncertainty	u_{CAL}	B	1,00		1
Repeatability on reference standard	u_{EVR}	A	0,68		3
Uncertainty from linearity	u_{LIN}	B	—		—
Uncertainty from Bias	u_{BI}	A	0,79		2
Measuring system	u_{MS}		1,44		

The calculated statistics are listed in [Table 25](#).

Table 25 — Results for the measuring system

Specification interval	$U - L$	40,00 μm
Combined standard uncertainty	u_{MS}	1,44 μm
Expanded measurement uncertainty	U_{MS}	2,88 μm

Table 25 (continued)

Capability ratio	$\%Q_{MS}$	14,42 %
Capability index	C_{MS}	1,39

Due to a percentage resolution $\%R_E$ of 0,25 % and a capability ratio $\%Q_{MS}$ of 14,42 %, the capability of the measuring system of the CMM is confirmed.

5.5.2.2 Test data set 5 - analysing the measurement process

Since the measurement process capability only refers to one reference standard and a CMM does not involve a classical operator influence, the uncertainty from temperature is considered for this measurement process as described in ISO 15530-3.

$$u_T = |\bar{T}_{MP} - 20| \times u_{\alpha OBI} \times l_{MS}$$

$$u_T = |22\text{ °C} - 20\text{ °C}| \times 1 \cdot 10^{-6} \text{ 1 / K} \times 150 \text{ mm} = 0,000300 \text{ mm} \hat{=} 0,30 \mu\text{m}$$

This leads to the following uncertainty budget and overview of results for the measurement process, see [Table 26](#).

Table 26 — Uncertainty budget of the measurement process

Uncertainty component	Symbol	Type	u μm	Remark	Rank
Resolution of the measuring system	u_{RE}	B	(0,03)	$\ll u_{EVR}$	5
Calibration uncertainty	u_{CAL}	B	1,00		1
Repeatability on reference standard	u_{EVR}	A	0,68		3
Uncertainty from linearity	u_{LIN}	B	--		--
Uncertainty from Bias	u_{BI}	A	0,79		2
Uncertainty from temperature	u_T		0,30		4
Measurement Process	u_{MP}		1,47		

The statistics derived from that components are shown in [Table 27](#).

Table 27 — Results (measurement process)

Combined standard uncertainty	u_{MP}	1,47 μm
Expanded measurement uncertainty	U_{MP}	2,95 μm
Capability ratio	$\%Q_{MP}$	14,73 %
Capability index	C_{MP}	2,72

Due to a capability ratio $\%Q_{MP}$ of 14,73 % in case of a process capability ratio limit $\%Q_{MP,max}$ of 30 %, the measurement process capability of the CMM for measuring the inside diameter on a reference standard is confirmed.

The combined list of the uncertainty and capability statistics for measuring system and measuring process is given in [Table 28](#).

Table 28 — Uncertainty and capability for test data set 5

	Measuring system		Measurement process	
Specification interval	$U - L$	40,00 μm	$U - L$	40,00 μm

Table 28 (continued)

	Measuring system		Measurement process	
	Combined standard uncertainty	u_{MS}	1,44 μm	u_{MP}
Expanded measurement uncertainty	U_{MS}	2,88 μm	U_{MP}	2,95 μm
Capability ratio	$\%Q_{MS}$	14,42 %	$\%Q_{MP}$	14,73 %
Capability index	C_{MS}	1,39	C_{MP}	2,72

5.6 Test data set 6 – measurement process capability of automated test device

5.6.1 Test data set 6 – information

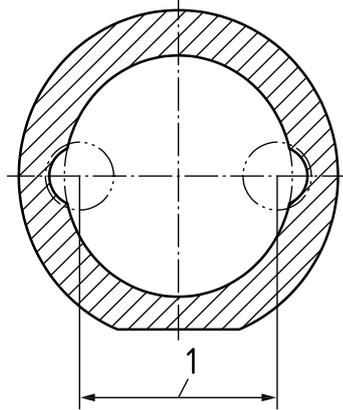
Test data set is for the evaluation of the measurement process capability of an automated test based on a complete uncertainty budget without the influence of an operator.

5.6.2 Test data set 6 – data, calculations and results

The measurement process capability of automated test device must be evaluated and documented. The basic data of this example are given in [Table 29](#).

Table 29 — Information about measuring system and measurement process

Information about measuring system and measurement process	
Nominal dimension	53,01 mm
Upper specification limit U	53,03 mm
Lower specification limit L	52,99 mm
Resolution of the measuring system R_E (1 digit = 0,000 1 mm)	0,5 μm
Calibration uncertainty U_{CAL}	1,6 μm
Coverage factor k_{CAL}	2
Linearity u_{LIN} (from preliminary investigation)	0
f_{max} of dial gauge (MPE)	1,2 μm
Reference quantity value of standard	53,010 5 mm
Capability ratio limit of measuring system Q_{MS_max}	15 %
Uncertainty from temperature without correction	0,000 519 mm
Uncertainty due to temperature during set-up	0,001 759 mm
Delta temperature of working standard at 20 °C	10 °C
Capability ratio limit measurement process Q_{MP_max}	30 %



Key

1 distance – measured at system level

Figure 5 — Measuring system level

5.6.2.1 Test data set 6 - evaluating the capability of measuring system

In order to determine the standard uncertainties from repeatability on standards and from measurement bias, 25 repeated measurements were performed on the reference standard, using the measuring system shown in Figure 5. For the measurement results see Table 30. A preliminary investigation did not detect any linearity deviations, so linearity is not necessary to be considered.

Table 30 — Measurement values

Dimensions in millimetres

	Value		Value		Value
1	53,011 0	11	53,010 5	21	53,011 0
2	53,011 0	12	53,012 0	22	53,011 0
3	53,011 5	13	53,011 0	23	53,011 0
4	53,011 0	14	53,011 0	24	53,011 5
5	53,010 5	15	53,011 0	25	53,011 0
6	53,010 5	16	53,010 5	26	53,011 0
7	53,011 0	17	53,011 5		
8	53,011 0	18	53,011 0		
9	53,011 0	19	53,010 5		
10	53,011 0	20	53,010 5		

The arithmetic mean of the measurements is:

$$\bar{x} = 53,010\,980\,77 \text{ mm}$$

The absolute value of the bias is:

$$|\bar{x} - l_{\text{Ref}}| = |53,010\,980\,77 \text{ mm} - 53,010\,5 \text{ mm}| = 0,000\,481 \text{ mm}$$

The standard uncertainty due to bias is:

$$u_{\text{BI}} = \frac{|\bar{x} - l_{\text{Ref}}|}{\sqrt{3}} = \frac{0,000\,481 \text{ mm}}{\sqrt{3}} = 0,000\,28 \text{ mm} \hat{=} 0,28 \mu\text{m}$$

The standard uncertainty of Repeatability on reference standard is:

$$u_{\text{EVR}} = s = 0,000\,360\,021 \text{ mm} \hat{=} 0,36 \mu\text{m}$$

The standard uncertainty due to the resolution is:

$$u_{\text{RE}} = \frac{R_{\text{E}}}{2 \cdot \sqrt{3}} = \frac{0,000\,5 \text{ mm}}{2 \cdot \sqrt{3}} = 0,000\,14 \text{ mm} \hat{=} 0,14 \mu\text{m}$$

The standard uncertainty due to f_{max} of the dial gauge is:

$$u_{\text{REST}} = \frac{f_{\text{max}}}{\sqrt{3}} = \frac{0,001\,2 \text{ mm}}{\sqrt{3}} = 0,000\,692 \text{ mm} \hat{=} 0,69 \mu\text{m}$$

The information about the measuring system and the measured quantity values gained in the experiment lead to the following uncertainty budget and overview of results, see [Table 31](#).

Table 31 — Uncertainty budget of the measuring system

Uncertainty component	Symbol	Type	u μm	Remark	Rank
Resolution of the measuring system	u_{RE}	B	(0,14)	$\ll u_{\text{EVR}}$	5
Calibration uncertainty	u_{CAL}	B	0,80		1
Repeatability on reference standard	u_{EVR}	A	0,36		3
Uncertainty from linearity	u_{LIN}	B	--		
Uncertainty from Bias	u_{BI}	A	0,28		4
f_{max} of dial gauge (MPE)	u_{REST1}	B	0,69		2
Measuring system	u_{MS}		1,15		

The uncertainty and capability statistics for this example are listed in [Table 32](#).

Table 32 — Results of the measuring system

Specification interval	$U - L$	40,00 μm
Combined standard uncertainty	u_{MS}	1,15 μm
Expanded measurement uncertainty	U_{MS}	2,30 μm
Capability ratio	$\%C_{\text{MS}}$	11,52 %
Capability index	C_{MS}	1,74

Due to a percentage resolution % R_E of 1,25 % and a capability ratio % Q_{MS} of 11,52 %, the measuring system capability of the automated measuring equipment is confirmed.

5.6.2.2 Test data set 6 - analysing the measurement process

After observing the measuring system, the measurement process of the automated test device is analysed. In an experiment, 2 repeated measurements are performed on each of 10 test parts, for measured values see [Table 33](#).

Table 33 — Measurements

Dimensions in millimetres

	1	2	3	4	5	6	7	8	9	10
Trial 1	30,011 0	30,011 5	30,010 0	30,011 0	30,011 5	30,011 0	30,012 0	30,010 0	30,011 0	30,011 0
Trial 2	30,011 0	30,012 0	30,010 0	30,011 0	30,011 5	30,011 0	30,012 0	30,010 0	30,011 0	30,011 0

The square root of the arithmetic mean of the 10 sample variances leads to the uncertainty due to Repeatability on test parts:

$$u_{EVO} = \sqrt{\frac{\sum_{i=1}^{10} s_i^2}{10}} = 0,000\,111\,8\text{ mm} \hat{=} 0,11\text{ }\mu\text{m}$$

From a similar study the known values of the standard uncertainties from temperature without correction and from temperature during setup are used:

Standard uncertainty from temperature without correction $u_T = 0,000\,519\text{ mm} \hat{=} 0,52\text{ }\mu\text{m}$

Standard uncertainty from temperature during setup $u_T = 0,001\,759\text{ mm} \hat{=} 1,76\text{ }\mu\text{m}$

This leads to the following uncertainty budget and overview of results, see [Table 34](#).

Table 34 — Uncertainty budget (measurement process)

Uncertainty component	Symbol	Type	u μm	Remark	Rank
Resolution of the measuring system	u_{RE}	B	(0,14)	$\ll u_{EVR}$	7
Calibration uncertainty	u_{CAL}	B	0,80		2
Repeatability on reference standard	u_{EVR}	A	0,36		5
Uncertainty from linearity	u_{LIN}	B	--		--
Uncertainty from Bias	u_{BI}	A	0,28		6
f_{max} of dial gauge (MPE)	u_{REST1}	B	0,69		3
Repeatability on test parts	u_{EVO}	A	(0,11)	$\ll u_{EVR}$	8
Temperature without correction	u_T	B	0,52		4
Temperature uncertainty from set-up	u_T	B	1,79		1
Measurement process	u_{MP}		2,17		

The uncertainty and capability statistics for this example are listed in [Table 35](#).

Table 35 — Results (measurement process)

Combined standard uncertainty	u_{MP}	2,17 μm
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