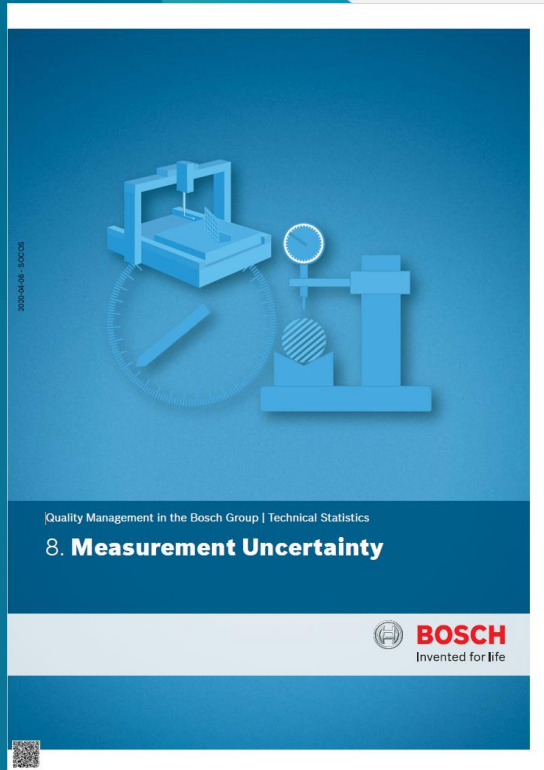


Notes:



TQ017 - Determining Measurement Uncertainty

Bosch Booklet 8 – Version 06.2015



Notes:

Agenda

Requirements of International Standards, Basics and Philosophy

Terminology and Approach according to GUM

Approach according to Booklet 8 and GUM

Approach according to Booklet 8 and ISO 22514-7 (and VDA Volume 5)

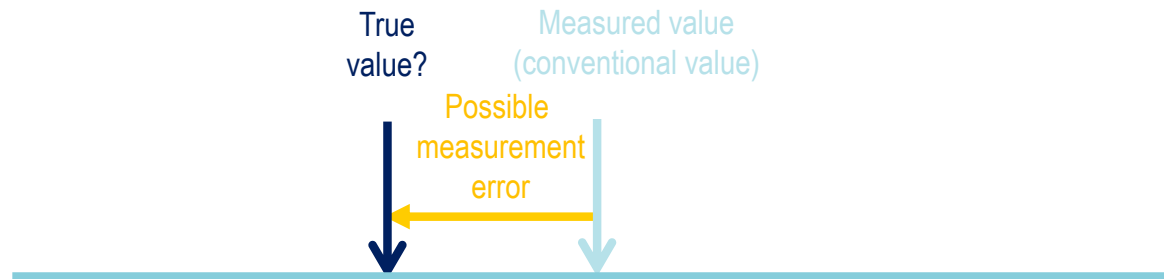
Brief Discussion about Capability Indices and Ratios C_{MS} , C_{MP} , Q_{MS} , Q_{MP}

Measurement Uncertainty according to Booklet 8 Based on Booklet 10 and ISO 22514-7

Notes:

Definition: Expanded Measurement Uncertainty U

- Definition of ISO/IEC Guide 99 (VIM)



True (quantity) value

Quantity value consistent with the definition of a quantity

NOTE 1 In the Error Approach to describing measurement, a true quantity value is considered unique and, in practice, unknowable...

Conventional (quantity) value

Quantity value attributed by agreement to a quantity for a given purpose

NOTE 1 The term "conventional true quantity value" is sometimes used for this concept, but its use is discouraged.

Notes:

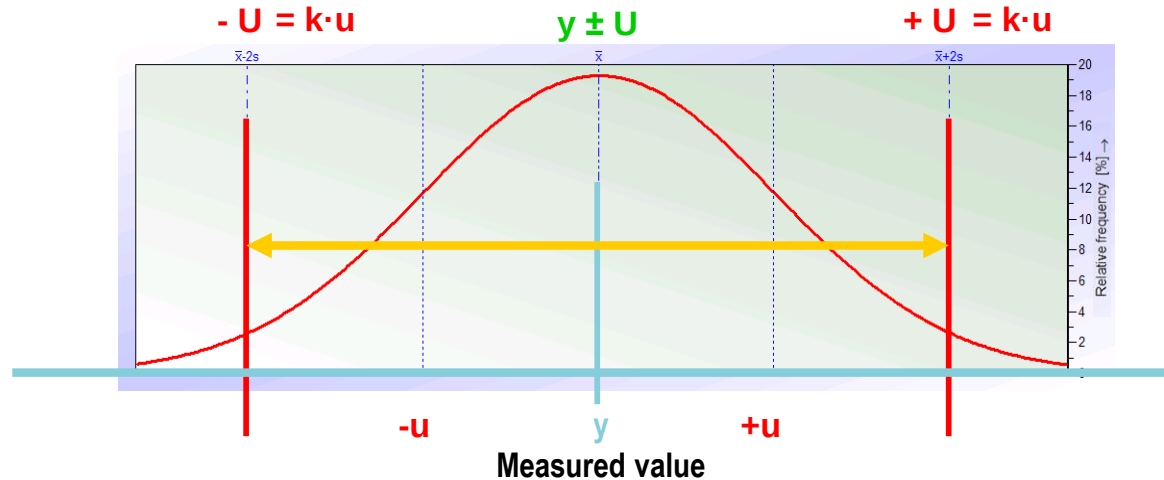
Definition of GUM: True / Conventional Value

- True value (of a quantity)
 - Value consistent with the definition of a given particular quantity.
 - This is a value that would be obtained by a perfect measurement.
 - True values are by nature indeterminate.
- Conventional value (of a quantity)
 - Value attributed to a particular quantity, sometimes by convention
 - Accepted as having an uncertainty
 - “Best estimate”, “assigned value”
 - Example:
 - May be realized by a reference standard
 - Recommended value for a fundamental constant

Notes:

Definition: Expanded Measurement Uncertainty U

- Definition



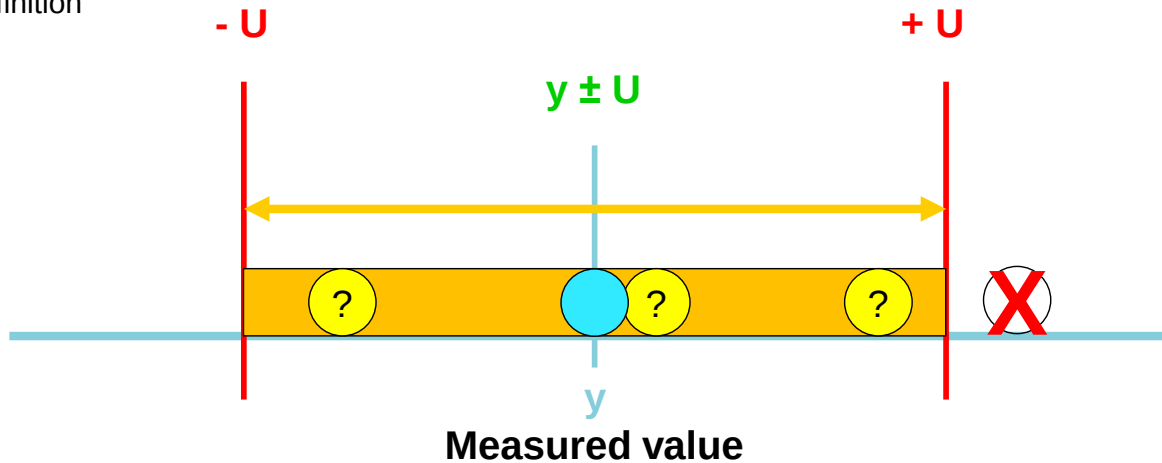
Measurement uncertainty – definitions given in various standards:

- ISO 3534-2: Parameter associated with the **measurement result or test result**, that characterizes the dispersion of the values that could reasonably be attributed to the particular quantity (...).
- ISO/IEC Guide 99 (VIM): Non-negative parameter characterizing the dispersion of the quantity values being attributed to a measurand, based on the information used.

Notes:

Term of Measurement Uncertainty

- Definition

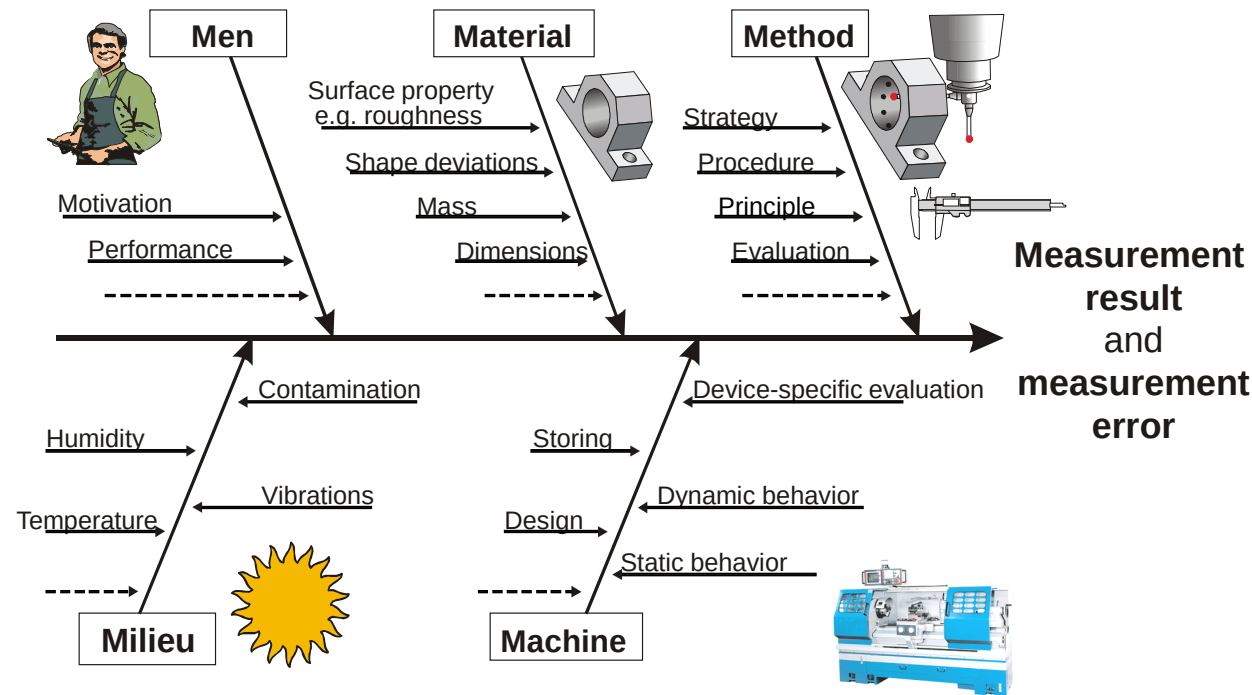


measurement uncertainty (according to DIN 1319-1):

Parameter obtained from measurements and which – together with the result of measurement – characterizes the range of values within which the true value of a measurand is estimated to lie.

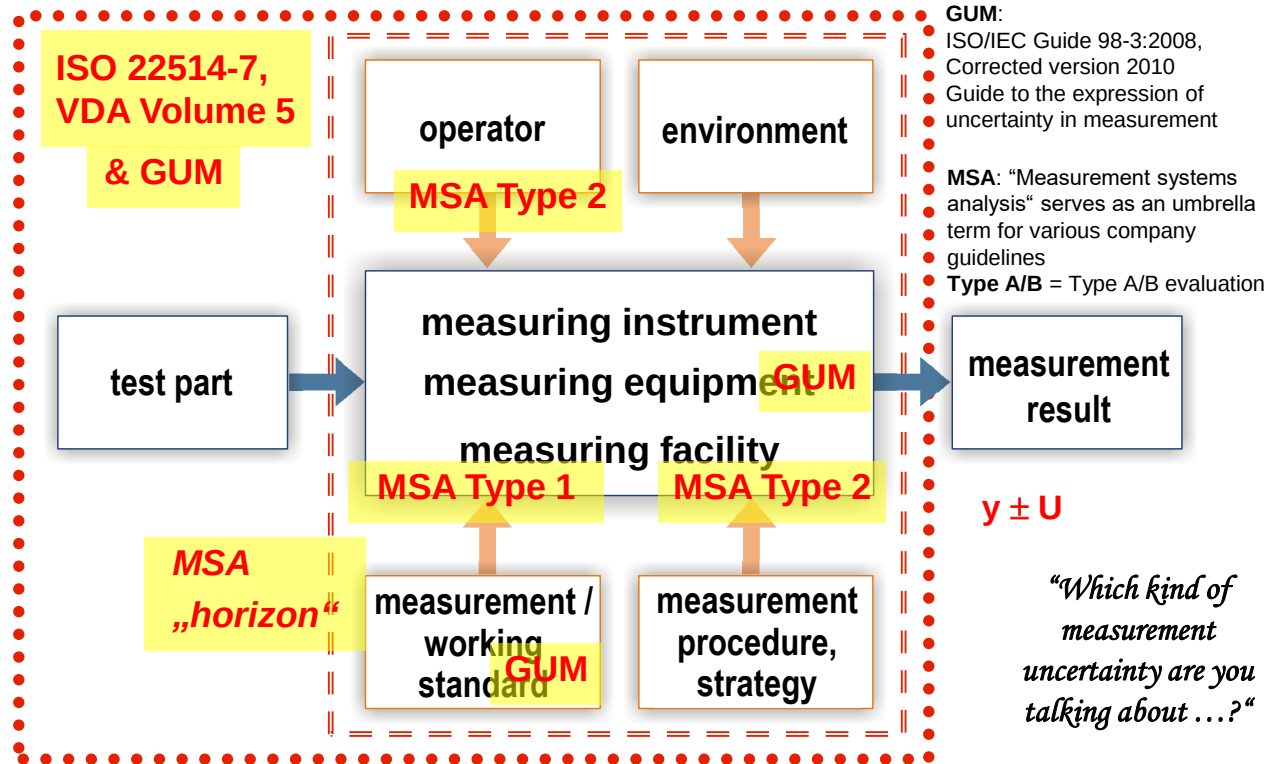
Notes:

Causes of Measurement Errors



Definition: Measuring System and Process

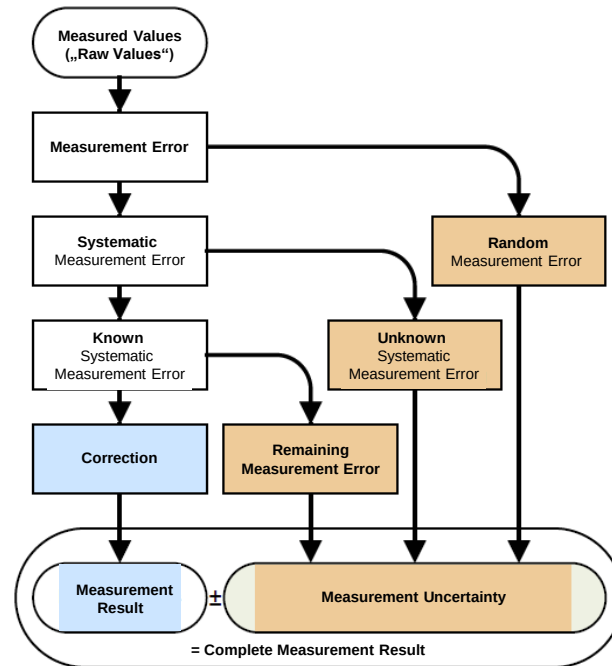
Notes:



Notes:

Systematic and Random Measurement Errors

- Systematic and random effects of measurement deviations



Notes:

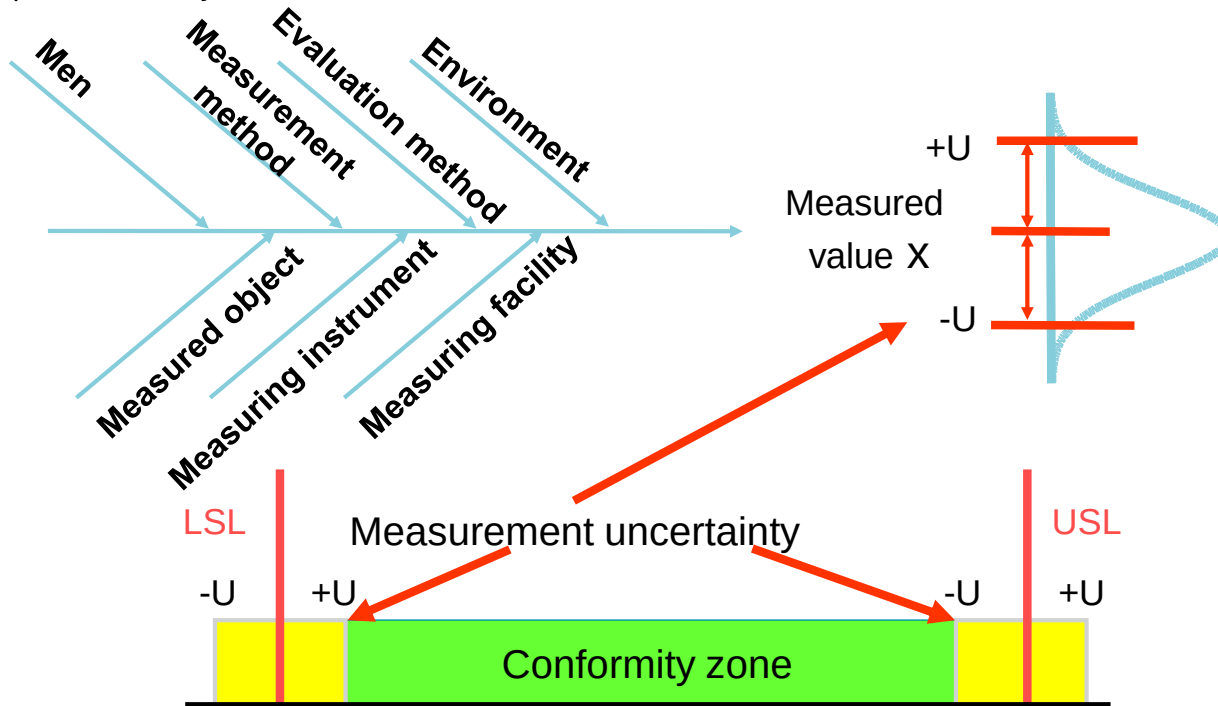
Terms as Defined in GUM: Measurement Error

- In general, a measurement has imperfections and gives rise to an **error** in the measurement result.
- Errors **cannot be known** exactly.
- Two components
 - Random error
 - Unpredictable
 - Can be reduced by increasing the number of observations
 - Expectation is zero
 - Systematic error
 - Correction can be applied to compensate an error arising from a recognized effect
 - After correction, the expectation is zero

Notes:

Measurement Uncertainty

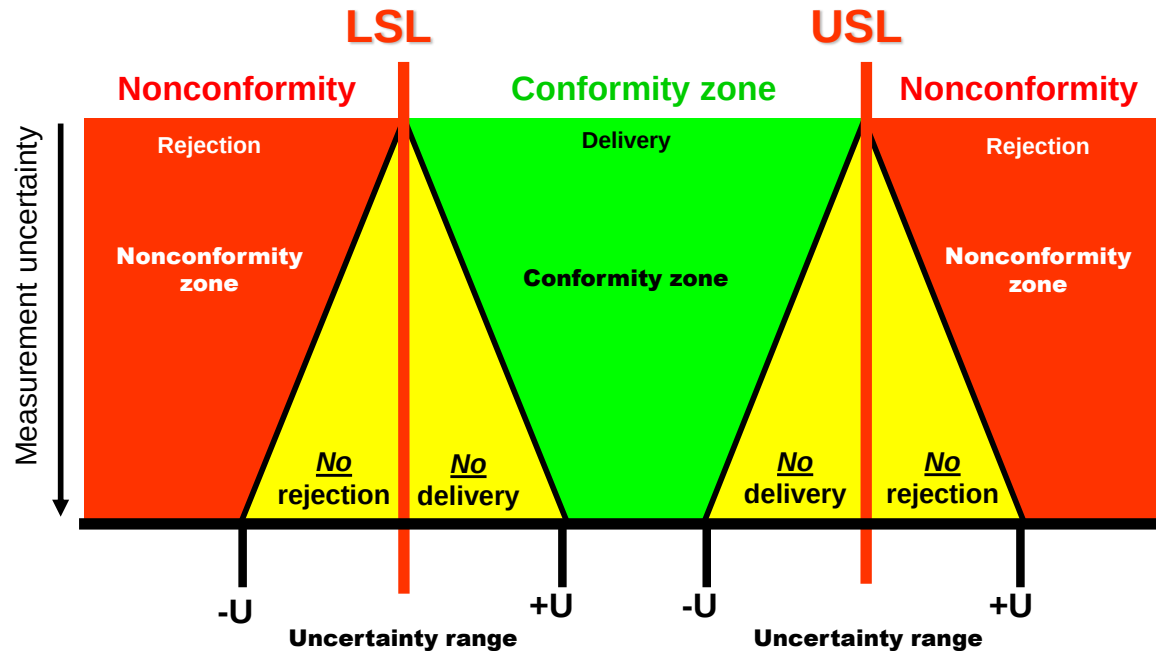
- Example: Conformity decision



Notes:

Measurement Uncertainty and Proof of Conformity

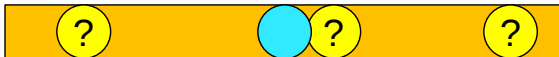
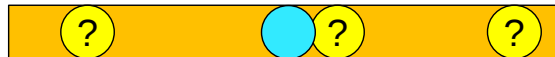
- ISO 14253-1



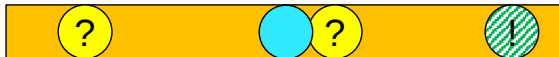
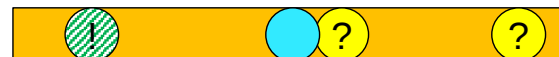
Notes:

Measurement Uncertainty and Product Development

- Example: Are two measurement results different?

1st measured value2nd measured value

Individual measured values differ at a high level of confidence

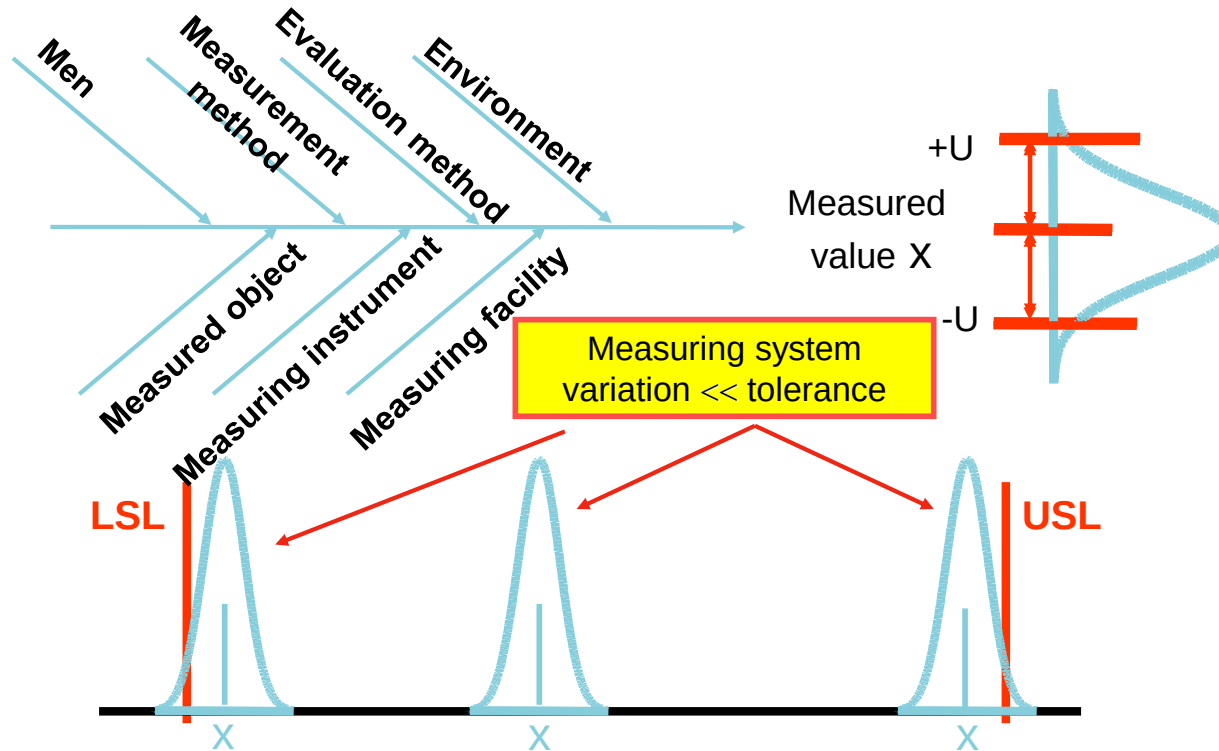
1st measured value2nd measured value

Hatched value could be true value - no clear difference

Notes:

Measurement Uncertainty and Production Monitoring

- Proof of Capability vs. Proof of Conformity



Notes:

Uncertainty vs. Measurement System Analysis

Associations

Jungi-Mal-Centy-Markt
D-69488 Weinheim

0815

1

Calibration uncertainty

5.30

1

Repeatability

3.20

3

Reproducibility of operators

9.80

1

Temperature

8.35

Total

26.65

Expanded uncertainty

53.30

Components

4

Cash

200

Change

93.40

4711

10:53 #003

Thank you for your measurement
process capability analysis

MSA Gage Airlines Ltd.

Process Capability Check

Date

01.7.2021

Time

10:53

Crew

TraiCon

Equipment

TQ017

Resolution

☒

Bias or Cg/Cgk

☒

Linearity

☒

GRR/R&R Type-2 or Type-3

☒

ndc

☒

Stability

☒

Decision: System Capable

☒

Signature



Notes:

Uncertainty vs. Measurement Systems Analysis

	measurement uncertainty	measurement process capability
<u>Application</u>	Conformity assessment (for products) in case of individual measurements if procedures of Booklet 10 cannot be applied, calibration	Release of machines and processes for serial test processes in series production (capability analyses, control charts, process analyses)
<u>Target</u>	Calculation of the expanded measurement uncertainty of measurement results	Calculation of statistics C_g , C_{gk} , B_i , %GRR, ...
<u>Specialist literature</u>	Booklet 8, ISO/IEC Guide 98 (GUM)	Booklet 10, company guidelines



Notes:

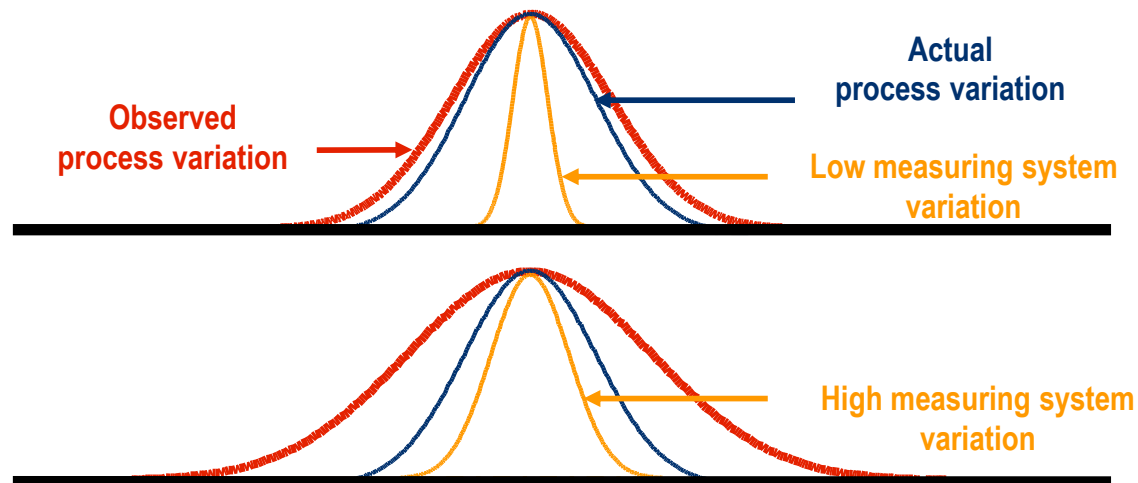
Impact of Measurement Process Variation

- How measurement uncertainty affects the observed process variation

$$\sigma^2_{\text{observed}} = \sigma^2_{\text{actual}} + \sigma^2_{\text{MSA}}$$

$$TV^2 = PV^2 + GRR^2$$

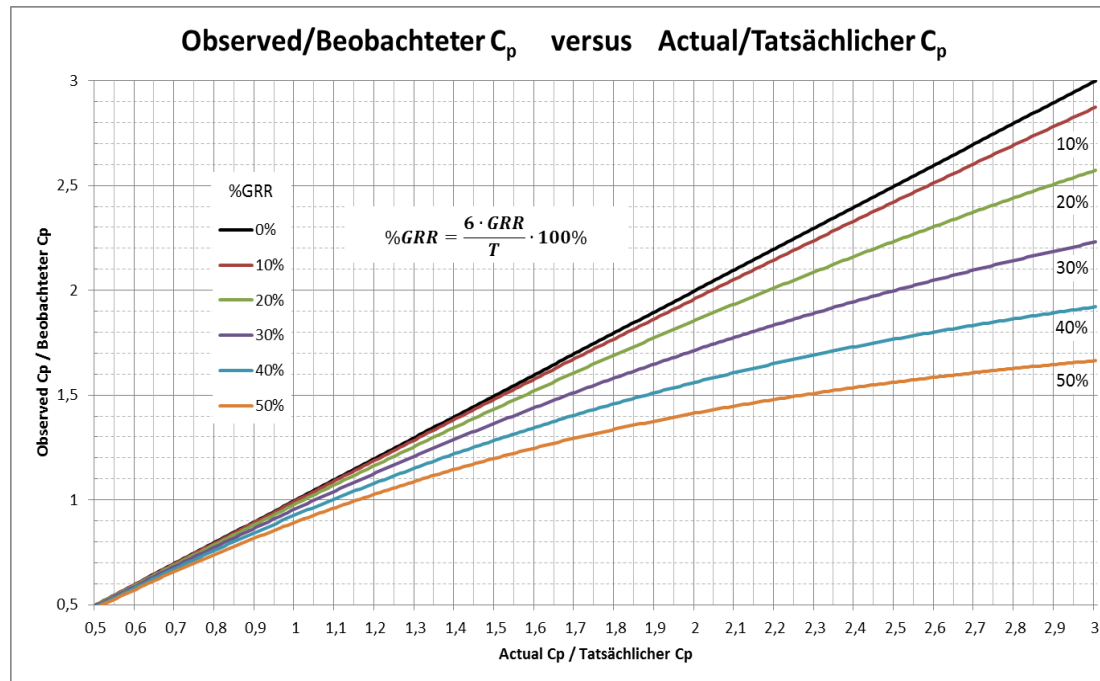
Notation according to
AIAG Core Tool MSA



Notes:

Impact of Measurement Process Variation

- Observed machine / process capability



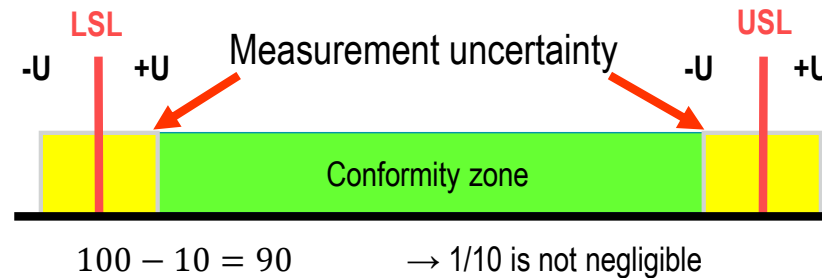
Notes:

Testing and Measuring - Summary

- Effects and consideration of measurement uncertainties

ISO 22514-7/ VDA Volume 5

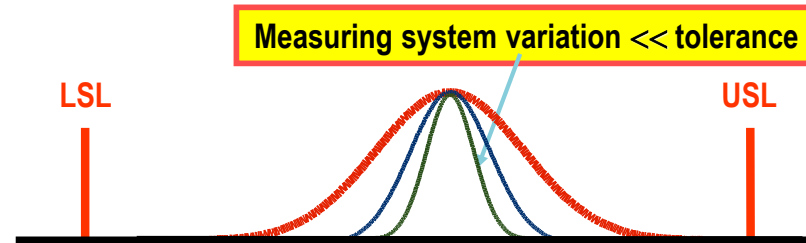
Testing



$$\sqrt{100^2 + 10^2} = 100,5 \rightarrow 1/10 \text{ is negligible}$$

Measuring

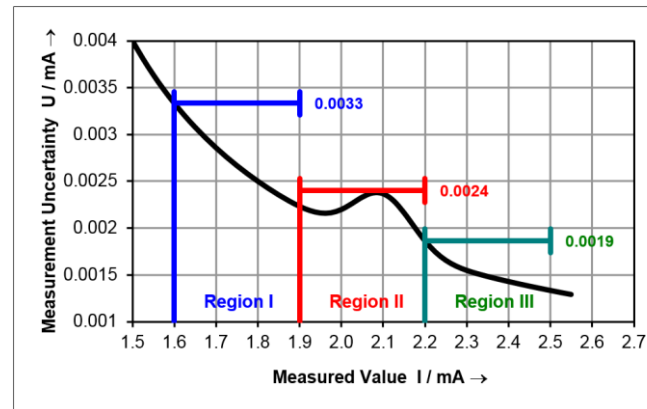
MSA
ISO 22514-7 / VDA Volume 5



Notes:

Range of Validity for Measurement Uncertainties

- GUM: It is necessary to characterize the quality of a result of a measurement in order to evaluate and express its uncertainty.
- This does not mean ...
 - that you have to determine the uncertainty of each measurement;
 - it rather means that you may even express measurement uncertainties sweepingly for certain (plausible) ranges.
- Example of measurement uncertainties associated with certain measurement ranges



Notes:

Agenda

Requirements of International Standards, Basics and Philosophy

Terminology and Approach according to GUM

Approach according to Booklet 8 and GUM

Approach according to Booklet 8 and ISO 22514-7 (and VDA Volume 5)

Brief Discussion about Capability Indices and Ratios C_{MS} , C_{MP} , Q_{MS} , Q_{MP}

Measurement Uncertainty according to Booklet 8 Based on Booklet 10 and ISO 22514-7

Notes:

Guide to the Expression of Uncertainty in Measurement

- Combination of
 - Bosch Booklet 8 and
 - GUM – Guide to the expression of uncertainty in measurement
- GUM is the international document establishing rules
 - for expressing measurement uncertainties in the fields of standardization, calibration, laboratory accreditation and metrology services.
- Booklet 8 is based on GUM and summarizes its contents. The following slides therefore start with the basic principles of this guide. Moreover, Booklet 8 illustrates different approaches to determine measurement uncertainty in line with GUM.

Notes:

Guide to the Expression of Uncertainty in Measurement

- Aim
 - Developing a guidance to the expression of uncertainty in measurement, establishing general rules for evaluating and expressing uncertainty in measurement that can be followed in the fields of standardization, calibration, laboratory accreditation and metrology services.
- Purpose of this guidance
 - Promoting full information on how uncertainty statements are arrived at.
 - Providing a basis for the international comparison of measurement results.

Notes:

Guide to the Expression of Uncertainty in Measurement

- The ideal method for evaluating and expressing the uncertainty of a result should be:
 - **Universal**
 - for all kinds of measurements
 - **Internally consistent**
 - directly derivable from components and independent of how they are grouped
 - **Transferable**
 - as a component of measurement uncertainty in evaluating the uncertainty of another measurement in which the first result is used

Notes:

Guide to the Expression of Uncertainty in Measurement

- Scope
 - “... from the shop floor to fundamental research ...”
 - Quality control and quality assurance
 - Complying with and enforcing laws and regulations
 - Basic research
 - Calibration of standards and measuring instruments
 - Tests throughout a national measuring system in order to achieve traceability to national standards
 - Development, maintenance and comparison of international and national physical reference standards
 - Even conceptual measurement results and uncertainties that are based entirely on hypothetical data

Notes:

Guide to the Expression of Uncertainty in Measurement

- This Guide does NOT ...
 - ... provide technology-specific instructions.
 - ... discuss how these uncertainties may be used for different purposes.
 - ... draw conclusions about the compatibility with other similar results.
 - ... establish tolerance limits in a manufacturing process.
 - ... decide if a certain course of action may be safely undertaken.

Notes:

Guide to the Expression of Uncertainty in Measurement

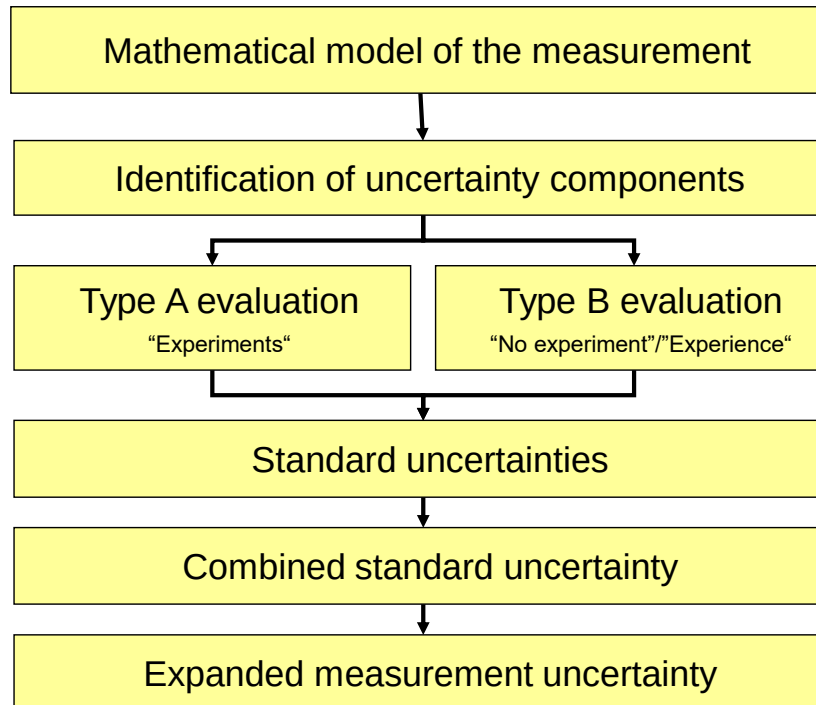
- Conclusion

- Chapter 1.4

“It may therefore be necessary to develop particular standards based on this Guide that deal with the problems peculiar to specific fields of measurement or with the various uses of quantitative expressions of uncertainty.”

Notes:

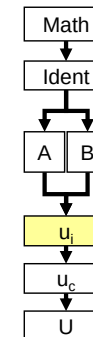
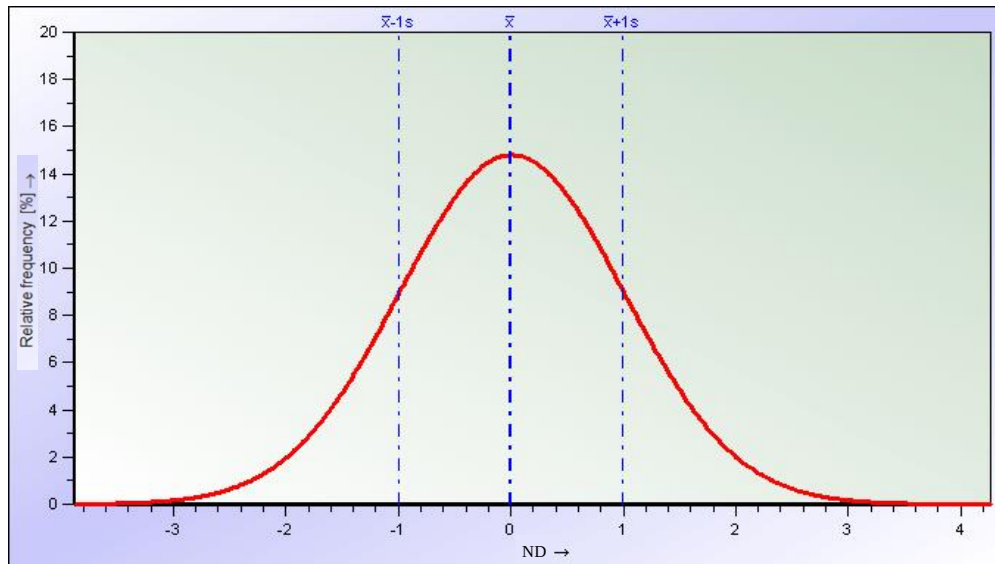
Approach according to GUM



Notes:

Term of Standard Uncertainty

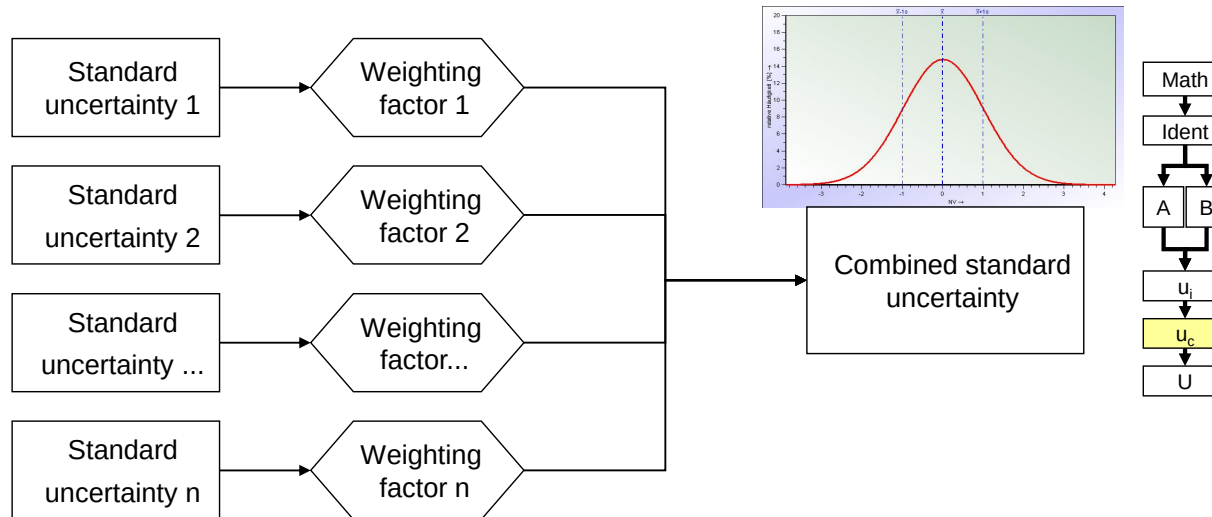
- The standard uncertainty is the uncertainty of the result of a measurement expressed as a standard deviation.



Notes:

Term of Combined Standard Uncertainty

- The combined standard uncertainty is the standard uncertainty of the result of a measurement in case this result is obtained from the values of a number of other quantities.

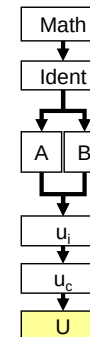
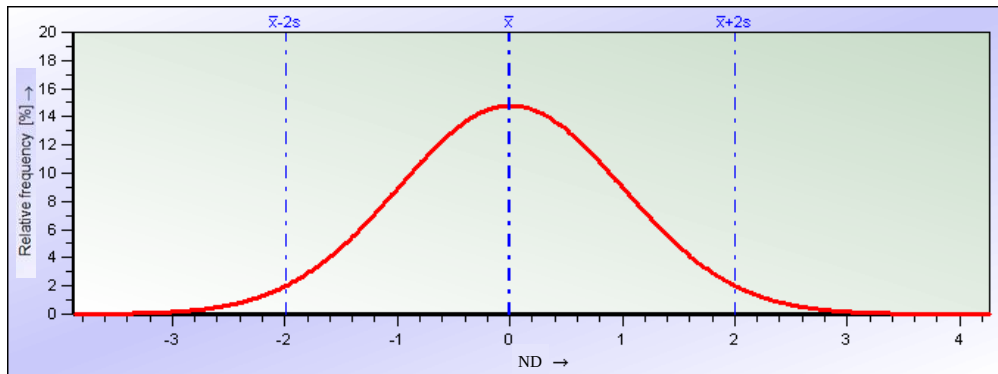


- The weighting factors are called sensitivity coefficients c .

Notes:

Term of Expanded Measurement Uncertainty

- Quantity defining an interval about the result of a measurement that may be expected to encompass a large fraction of the distribution of values.
 - “Coverage probability” or “level of confidence”
 - Requires assumptions regarding the probability distribution
 - Termed “overall uncertainty” in Recommendation INC-1 (1980)
 - To meet the needs of industrial and commercial applications



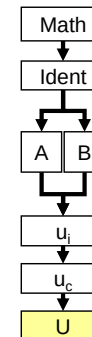
Notes:

Determining Expanded Uncertainty

- Expressing the combined standard uncertainty $u_c(y)$ would actually be sufficient.
- In some commercial, industrial, and regulatory applications, and when health and safety are concerned, it is necessary to define an interval encompassing a larger fraction of the distribution.

$$U = k \cdot u_c(y)$$

- Coverage factor k ...
 - ... corresponds to a particular level of confidence (90%, 95%, 99%, ...).
 - ... might have to consider the degrees of freedom.
- Note:
Booklet 8 refers to the coverage factor k as k_p in order to avoid confusions with other terms.



Notes:

Reporting Uncertainty – General Guidance

- Describe clearly the **methods** you use.
- List all **uncertainty components**.
- Document fully all **evaluations**.
- Each **step** of your data analysis can be **readily followed**.
- Give all **corrections** and **constants**.
- Basic principle:

“Have I provided enough information in a sufficiently clear manner that my result can be updated in the future if new information or data become available?”

Notes:

GUM Chapter 3.4: Practical Considerations

- Assumption: **Measurement can be modelled mathematically** to the degree imposed by the required accuracy of the measurement.
- Mathematical model can be incomplete. All relevant quantities should be varied to the fullest practical extent.
- Evaluation of uncertainty should be based as much as possible on **observed data**.
- “A **well-designed experiment** can greatly facilitate reliable evaluations of uncertainty and is an **important part** of the art of measurement.”
- All **corrections** are included.
- This Guide “ ... cannot **substitute for critical thinking, intellectual honesty and professional skill**.”

Notes:

Agenda

Requirements of International Standards, Basics and Philosophy

Terminology and Approach according to GUM

Approach according to Booklet 8 and GUM

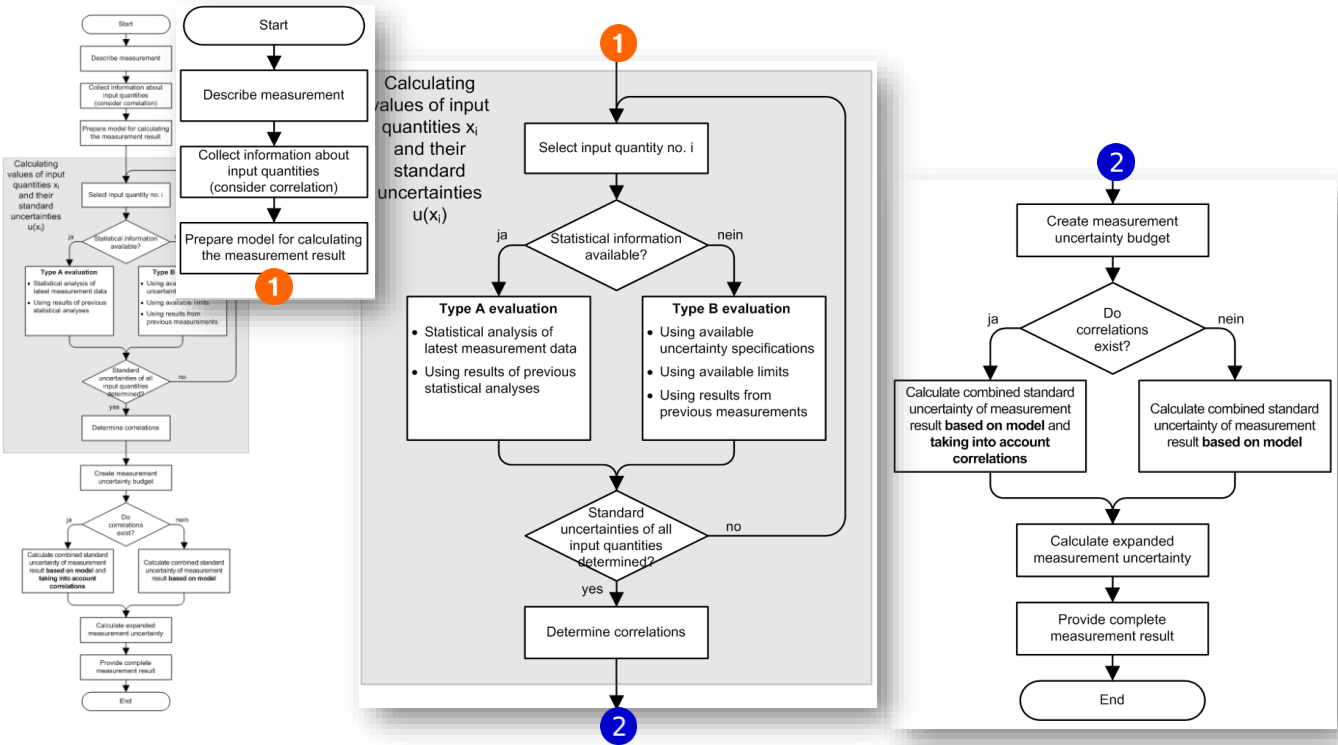
Approach according to Booklet 8 and ISO 22514-7 (and VDA Volume 5)

Brief Discussion about Capability Indices and Ratios C_{MS} , C_{MP} , Q_{MS} , Q_{MP}

Measurement Uncertainty according to Booklet 8 Based on Booklet 10 and ISO 22514-7

Notes:

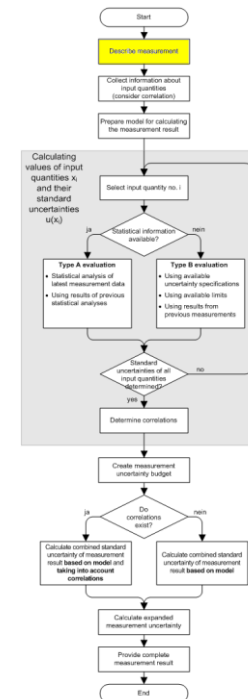
Flow Chart Based on Bosch Booklet 8



Describing the Measurement

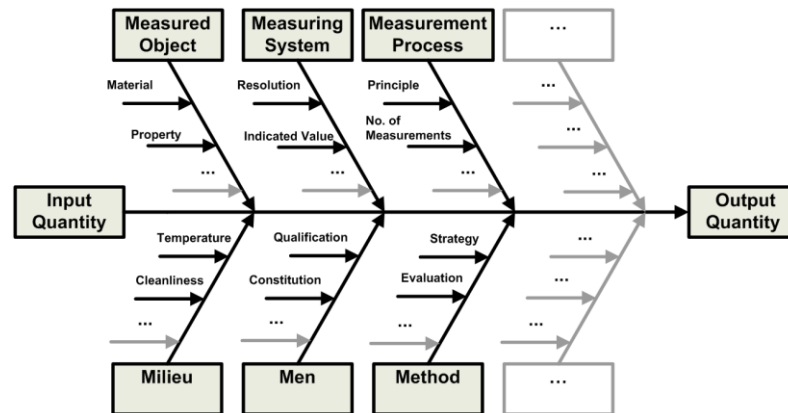
- Measurement task
- Measurand
- Measurement method
- Measurement procedure
- Measuring system (incl. preparation)
- Measured object (incl. state before/after the measurement)
- Measurement standard (identification number and data from calibration certificate)
- Environmental / boundary conditions
- Detailed information if these are necessary for understanding (physical laws, reactions / interactions between measuring system and measured object, measurand type)
- Information from any existing tool inspection plans

Notes:



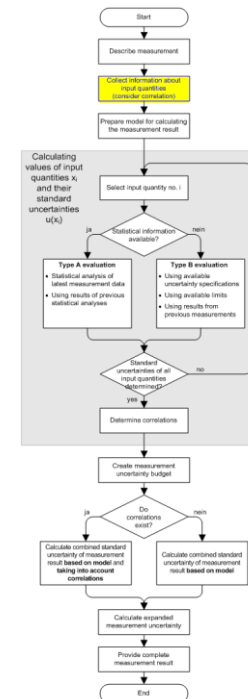
Collecting Information about Input Quantities

- Identify input quantities
 - Ishikawa / cause-and-effect diagram



- Different categories possible:
 - 5M: Measured object, measuring system, method, men, milieu
 - According to VDI/VDE 2618: measured object, procedure, device

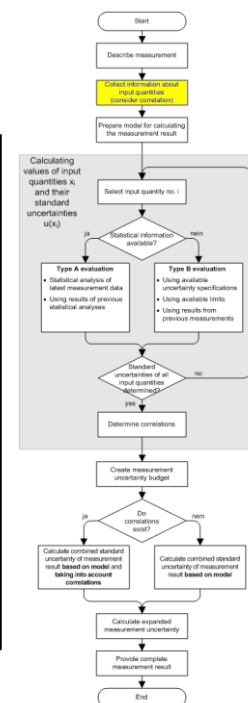
Notes:



Collecting Information about Input Quantities

- List input quantities in a table
 - Examples

Measuring task:		
Length measurement with a yardstick	Resistance measurement with a multimeter	pH value measurement with a pH meter
Typical input quantities:		
Reading of the length	Current	Difference of potential (ECPD)
Reading of the angle	Voltage	Temperature
Quality of the yardstick	Frequency	Probe material
Lighting conditions	Cable length	Concentration
Application set-up	Contact resistance	Liquid composition
Temperature	Internal resistance	Measurement principle (device type)
Reference value of the standard	Reference value of the standard	Reference value of the standard
Calibration uncertainty	Calibration uncertainty	Calibration uncertainty
...	...	...

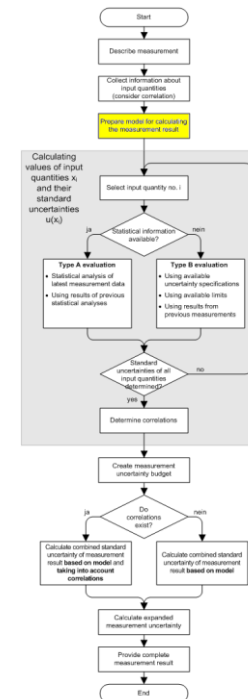


Notes:

Preparing the Model

- Quotations from GUM
 - The measurand Y is determined from N other quantities through a functional relationship f .
 - The input quantities X_i may themselves depend on other quantities.
 - The resulting functional relationship may...
 - be complicated.
 - be determined experimentally.
 - exist as an algorithm that must be evaluated numerically.
 - The function $y = f(x_1, x_2, \dots, x_N) \dots$ (contains) every quantity, including all corrections and correction factors, that can contribute a significant component of uncertainty to the measurement result.

Notes:



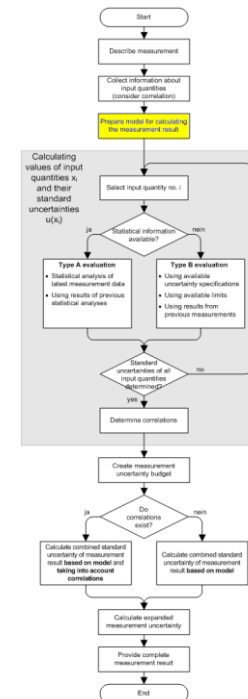
Preparing the Model – Simplified Models

- Additive model
 - Sum of several input quantities

$$y = x_1 + x_2 + \dots + x_n$$

- Attention:
 - All input quantities need to have the same measurement unit.
 - Input quantities are independent from one other.
- Write down some examples:

Notes:



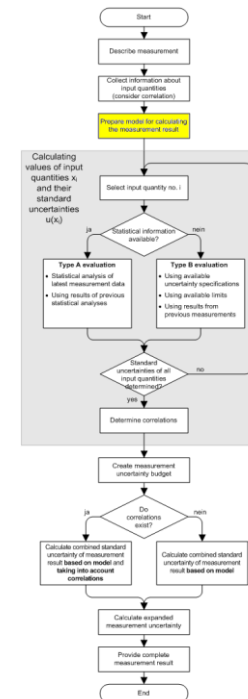
Preparing the Model – Simplified Models

- Additive model
- GUM also applies this model in case the correct model is too complex or cannot be defined completely

$$y = y_0 + \delta x_1 + \delta x_2 + \dots + \delta x_n$$

- where
 - y_0 conventional (maybe corrected) value
 - $\delta x_2 \dots \delta x_n$ deviations from the conventional value of the input quantities in the measurement unit of the measurement result with an expectation equal to zero

Notes:



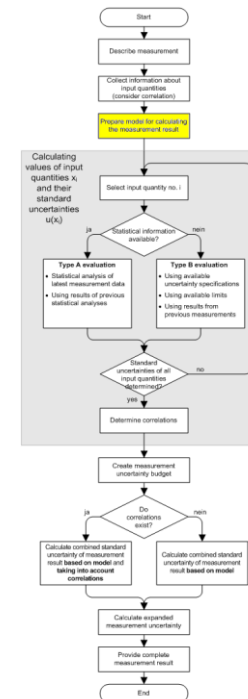
Preparing the Model – Simplified Models

- Multiplicative model
- Product and/or quotient of several input quantities

$$y = \frac{x_1 \cdot x_2 \cdot \dots}{\dots \cdot x_{n-1} \cdot x_n}$$

- Attention:
 - All input quantities have to be supplied using measurement units which are converted to the measurement unit of the output quantity when used with the model equation.
 - Relative units in % need to be converted into absolute values.
- Write down some examples.

Notes:



Preparing the Model – Simplified Models

- Linear model
 - Linear relation between several input quantities

$$y = (a_1 + b_1 \cdot x_1) + (a_2 + b_2 \cdot x_2) + \dots + (a_n + b_n \cdot x_n)$$

- Special case $n = 1$ represents a straight line
- Common application: Mathematical correction

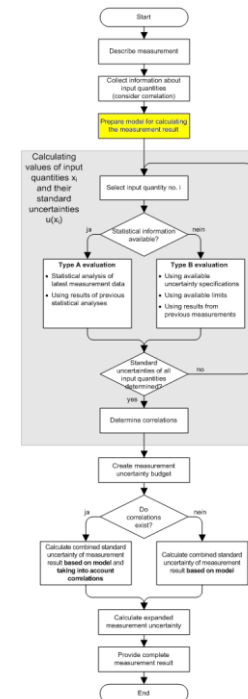
$$y = y' + \alpha_K + \beta_K \cdot y'$$

where

- y corrected measurement result
- α_K correction constant
- β_K correction factor
- y' uncorrected measurement result ("raw value")

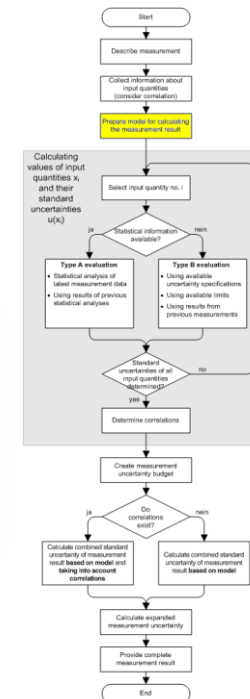
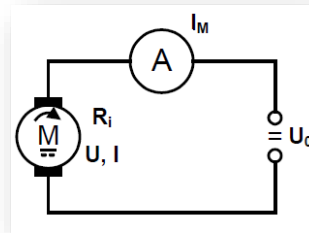
- Write down some examples.

Notes:



Preparing the Model – Simplified Models

- General model
 - Generally applicable approach is inherently incomplete and cannot be described in full.
- Example:
 - Needed:
Power consumption P of a motor
 - Known:
Internal resistance R_i of a motor
 - Measured:
Current I_M
 - “Fundamental physics”: $P = U \cdot I_M$ and $U = R_i \cdot I_M$
 - Leading to $P = R_i \cdot I_M \cdot I_M = R_i \cdot I_M^2$

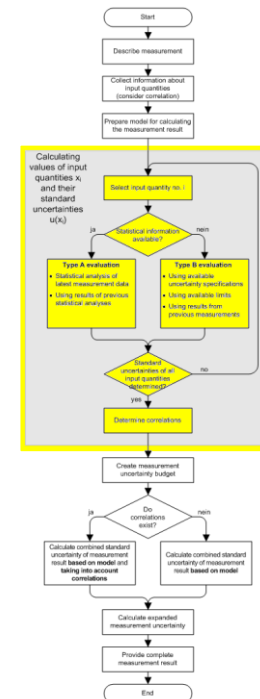


Notes:

Input Quantities

- GUM formally distinguishes between two methods for determining input quantities.
- Type A evaluation:
 - Values x_i and $u(x_i)$ are estimated from repeated observations and the results of their statistical analysis
 - Examples: Measured data recorded for a specific purpose; results of stability monitoring; data sets of previous observations
- Type B evaluation:
 - Values x_i and $u(x_i)$ are determined based on other sources and their preparation
 - Examples: Manufacturer's specifications; limits; parameters from previous investigations; literature values
- According to GUM, this makes it easier to discuss the topic

Notes:



Input Quantities: Type A Evaluation - Expectation

- This method tries to obtain the best available estimate of quantity value x_i from several measurements.
- Best estimate for quantity value x_i is the arithmetic mean of m individuals

$$\bar{x}_i = \frac{1}{m} \sum_{k=1}^m x_{ik}$$

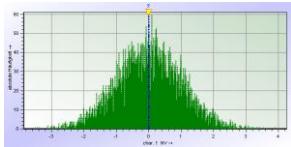
- Attention:
 - Measurements are taken under the same conditions of measurement.
 - A sufficient number of m individuals is required (confidence interval).
 - Assumption that a normal distribution describes the data sufficiently well.

Notes:



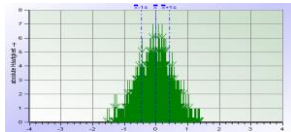
Input Quantities: Type A Evaluation - Uncertainty

- Uncertainty is calculated from the dispersion of individuals
- Best estimate for the dispersion of quantity value x_i is the standard deviation of m individuals



$$s(x_i) = \sqrt{\frac{1}{m-1} \sum_{k=1}^m (x_{ik} - \bar{x}_i)^2}$$

- The standard uncertainty of input quantity i is the dispersion of the mean value $\bar{x}_i$



$$u(\bar{x}_i) = \frac{s(x_i)}{\sqrt{m}}$$



Notes:



Input Quantities: Type A Evaluation - Uncertainty

- Attention please! Pitfall: What is m ?
- What is the purpose of your analysis?
- You want to know the “accuracy” of a measurement result.
Example: Calibration of a gage block
 - Take several measurements and calculate the mean.
 - You want to find out the “accuracy” of the mean.
 - This leads to m = number of (repeated) measurements.
- You want to analyse the repeatability of a measuring instrument in the series measurement process on site.
 - Take several (repeated) measurements.
 - However, you are only looking for the repeatability of subsequent individual measurements.
 - This leads to $m = 1$.



Notes:

Input Quantities: Type A Evaluation - Uncertainty

- Based on previous measurement results
 - Example: Several measurements were performed under identical conditions over a certain period of time.
- Uncertainty is calculated from the pooled standard deviation s_p

$$s_p(x_i) = \sqrt{\frac{\sum_{j=1}^{j_p} (m_j - 1) \cdot s_j^2(x_i)}{\sum_{j=1}^{j_p} (m_j - 1)}}$$

- Where
 - j_p no. of pooled data sets
 - m_j no. of measured values in data set no. j
 - $s_j(x_i)$ standard deviation of data set no. j

Notes:



Input Quantities: Type A Evaluation - Uncertainty

- Based on previous measurement results (continued)
- The standard uncertainty of input quantity i is calculated from the pooled standard deviation

$$u(\bar{x}_i) = \frac{s_p(x_i)}{\sqrt{m}}$$

- $m \geq 1$ refers to the actual number of measured values collected during the current measurement uncertainty study.

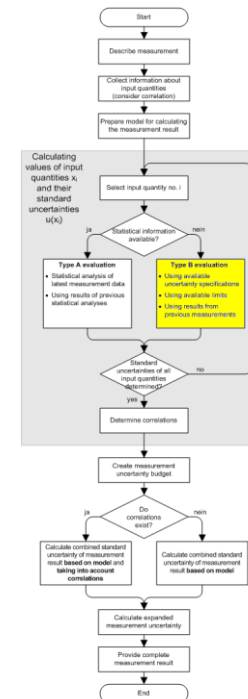
Notes:



Input Quantities: Type B Evaluation – Why?

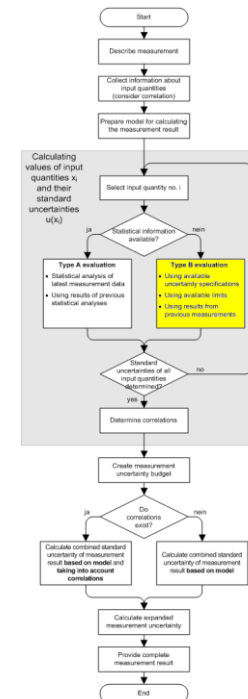
- Results of previous observations are used e.g. because...
 - it is not possible to take series of measurements (e.g. for technical or economic reasons).
 - measurements have already been performed but only the evaluation results are available now (e.g. dispersion, distribution, unless applied according to Type A evaluation).
 - input quantities cannot be recorded metrologically (e.g. in case of subjective influences).

Notes:



Input Quantities: Type B Evaluation – Wherefrom?

- Standard uncertainties can be obtained from...
 - evaluation results of previous measurements.
 - manufacturer's specifications, data sheets.
 - uncertainties assigned to reference data from handbooks.
 - data provided in calibration and other certificates.
 - experience with or general knowledge of the behavior and properties of relevant materials and instruments.

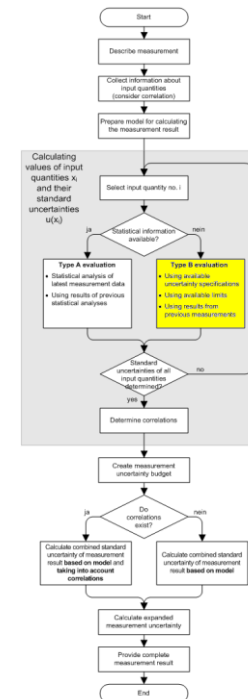


Notes:

Input Quantities: Type B Evaluation – How?

- Information may be available in the form of ...
- uncertainty specifications
 - Expanded measurement uncertainty with coverage factor
e.g. " $U(k_p = 2) = 3 \mu m$ "
 - Expanded measurement uncertainty with confidence level
e.g. " $U(95\%) = 0.2 mg$ "
 - Standard measurement uncertainty
e.g. " $u = 0.02 m^3/h$ "
- limits
 - e.g. "maximum permissible error $4 \mu m$ "

Notes:



Input Quantities: Type B Evaluation – Uncertainties

- Information may be available in the form of uncertainty specifications, namely...

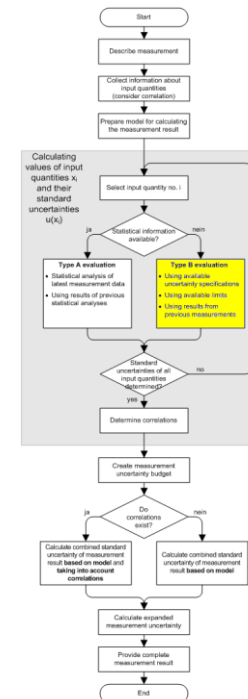
- expanded measurement uncertainty $U = k_p \cdot u$
 - Such as “ $U(k_p = 2) = 3\mu m$ ”: Known coverage factor
 - Such as “ $U(95\%) = 0.2 mg$ ”: Confidence level leads to coverage factor k_p (Booklet 8, annex D)

- Calculation of standard uncertainty

$$u = \frac{U}{k_p}$$

- Standard uncertainty
 - Such as “ $u = 0.02 m^3/h$ ”
- Known standard measurement uncertainty that you can apply directly.

Notes:

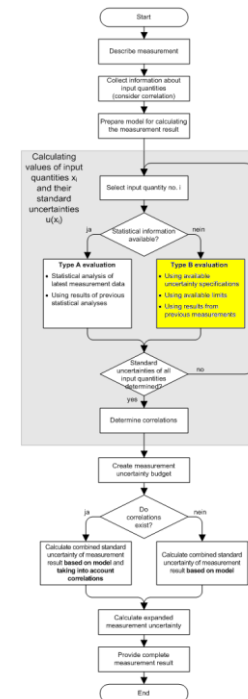


Input Quantities: Type B Evaluation – Limits

- Information are available in the form of limits.
- Limit a is often specified, i.e. the values lie between a_- and a_+
- The interval $\pm a$ is specified and the values lie within this interval with a certain probability.
- Assume an a priori distribution with distribution factor b .
- Calculate the standard uncertainty from

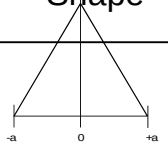
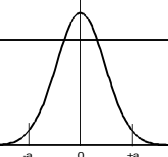
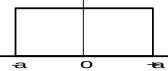
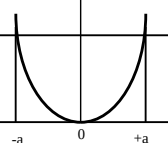
$$u = a \cdot b$$

Notes:

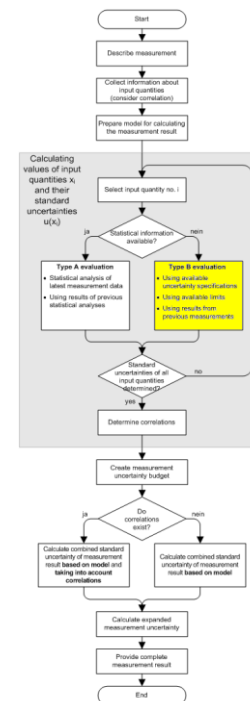


Input Quantities: Type B Evaluation – Limits

- Distribution factor b of a priori distributions

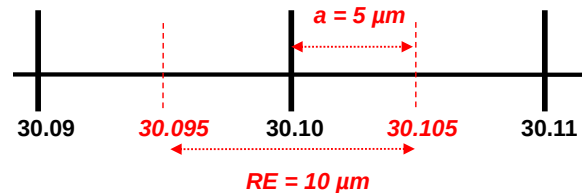
Distribution	Shape	Distribution factor b
Triangular distribution		$1/\sqrt{6} = 0.408$
Normal distribution		$1/\sqrt{4} = 0.5$
Rectangular distribution		$1/\sqrt{3} = 0.577$
U-shaped distribution		$1/\sqrt{2} = 0.707$

Notes:



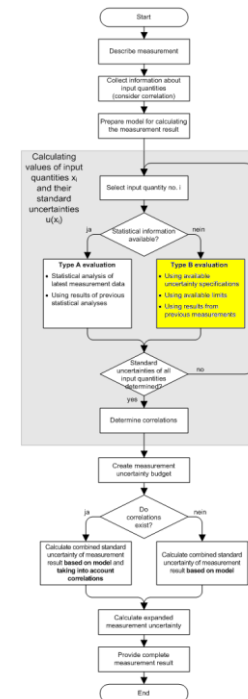
Input Quantities: Type B Evaluation – Limits

- Information are available in the form of limits.
- Example: Resolution of an indicating device



- Resolution $RE = 10\mu m$
- RE refers to interval $\pm a \Rightarrow 2 \cdot a = 10\mu m \Rightarrow a = 5\mu m$
- Distribution: Rectangular $\Rightarrow b = \frac{1}{\sqrt{3}} = 0.577 \approx 0.6$
- $\Rightarrow u = b \cdot a = 0.6 \cdot 5\mu m = 3\mu m$
- Standard measurement uncertainty $u_{RE} = 3\mu m$

Notes:

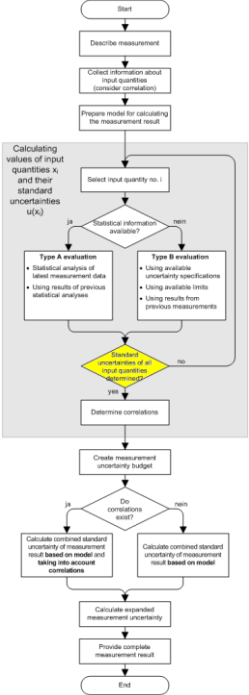


Notes:

Input Quantities: Determining All Components

- You evaluate all input quantities step by step according to Type A or Type B evaluation and determine the standard uncertainties

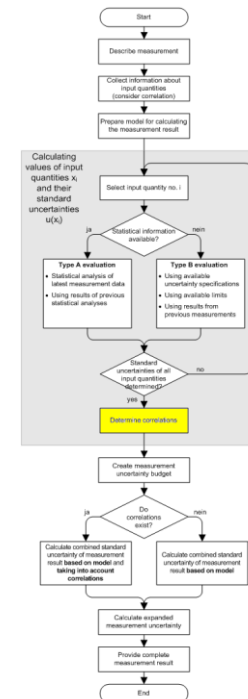
Information about input quantities							Standard uncertainties of input quantities				Contrib
No. Seq.	Description	Variable (symbol)	Measuring unit	Value of the variable	Value of the uncertainty data	Comments (z.B. references, explanatory notes, links to documents)	Evaluation type	Type A: Number of measured values; Type B: k_p (z(1), confidence level (%), distribution	Numerical factor for calculating the standard uncertainty	Standard uncertainty	Sensit. coeff.
i				x_i	Δx_i		A B	m_i k_p , %, name	1 or $\sqrt{m_i}$ k_p	$u(x_i) = \Delta x_i / k_p$	c_i
1											
2											
3											
4											
5											
Model equation:							Total result:				



Input Quantities: Determining Correlations

- Correlations are caused e.g. by...
 - interdependent physical quantities.
 - Example:
 - Relative mass fractions of a mixture of substances,
 - caused by chemical changes,
 - their sum is constant.
 - physical quantities that are not determined independently of one another.
 - Examples:
 - Determining two quantities in the same experiment (intercept and slope of a calibration curve)
 - Applying the same measurement standards
 - Effects of a common influence of any third-party parameters (temperature, humidity)

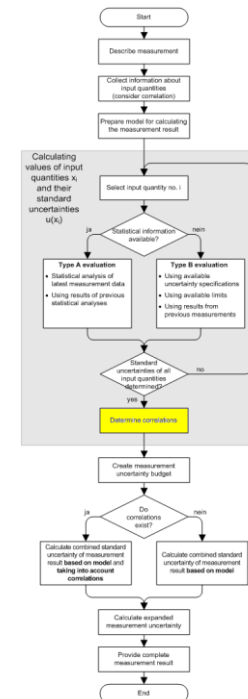
Notes:



Input Quantities: Determining Correlations

- Correlations are negligible if...
 - data sets originate from different analyses carried out at different times
 - the available input quantities are constant (no change -> no effect)
 - standard uncertainties of one of the two correlated input quantities are negligible

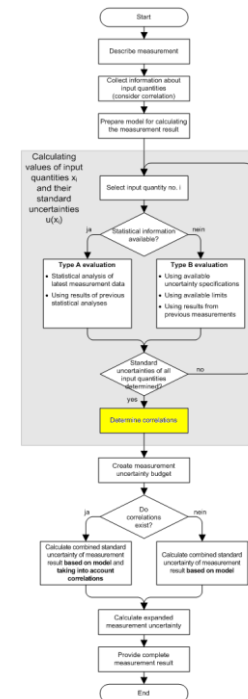
Notes:



Input Quantities: Determining Correlations

- You can avoid correlations ...
 - by considering parameters affecting several input quantities as additional input quantities in the model
 - by interpreting model equations in a way that correlations are negligible

Notes:

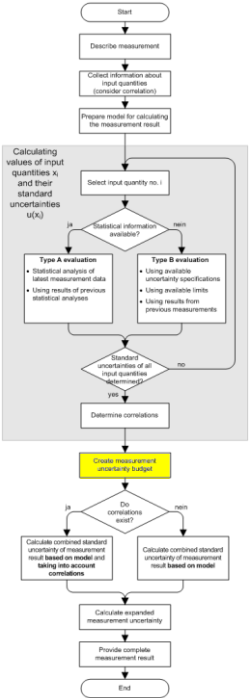


Notes:

Creating the Measurement Uncertainty Budget

- Example given in Booklet 8 annex I

Information about input quantities							Standard uncertainties of input quantities			Contributions to the measurement uncertainty of the measurand					Determining k_p for the measurand		
Size No.	Description	Variable (symbol)	Measuring unit	Value of the variable	Value of the uncertainty data	Comments (z.B. references, explanatory notes, links to documents)	Evaluation type	Type A: Number of measured values, Type B: k_p (≥ 1), confidence level (%), distribution	Numerical factor for calculating the standard uncertainty	Standard uncertainty	Sensitivity coefficient	Contribution to uncertainty	Contribution to uncertainty (squared)	Percentage contribution to MU budget (according to Pareto)	Estimated uncertainty of the uncertainty data	Degrees of freedom	Contribution to the denominator of the Welch-Satterthwaite formula
				x_i	Δx_i		A B	n_i k_p , % name	1 or $\sqrt{3}$ k_p	$u(x_i) = \Delta x_i / k_p$	c_i	$c_i \cdot u(x_i)$	$(c_i \cdot u(x_i))^2$	$\frac{(c_i \cdot u(x_i))^2}{\sum_{i=1}^N (c_i \cdot u(x_i))^2}$ [%]	$\Delta u(x_i) / u(x_i)$	ν_i	$\frac{(c_i \cdot u(x_i))^2}{\nu_i}$
1																	
1																	
2																	
3																	
4																	
5																	
Model equation:							Total result:					$u_c^2 =$					$\sum_{i=1}^N \frac{(c_i \cdot u(x_i))^2}{\nu_i} =$
												$u_c =$					$y_{\text{eff}} =$
												$k_p =$					$1 - \alpha =$
												$U =$					$k_p =$

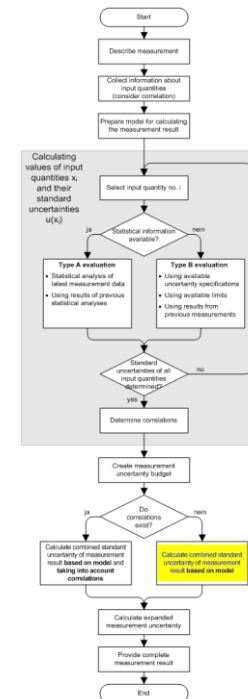


Combined Standard Uncertainty without Correlation

- Additive model
 - $y = x_1 + x_2 + \dots + x_n$
- Combined standard measurement uncertainty
 - $u_c(y) = \sqrt{u^2(x_1) + u^2(x_2) + \dots + u^2(x_n)}$

- Additive model (alternative)
 - $y = y_0 + \delta x_1 + \delta x_2 + \dots + \delta x_n$
- Combined standard measurement uncertainty
 - $u_c(y) = \sqrt{u^2(\delta x_1) + u^2(\delta x_2) + \dots + u^2(\delta x_n)}$

Notes:



Combined Standard Uncertainty without Correlation

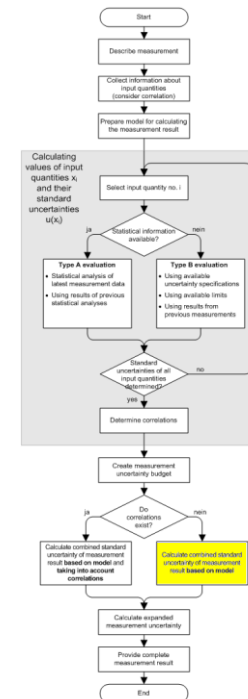
- Multiplicative model

$$y = \frac{x_1 \cdot x_2 \cdot \dots}{\dots \cdot x_{n-1} \cdot x_n}$$

- Combined standard measurement uncertainty

$$\frac{u_c(y)}{y} = \sqrt{\left(\frac{u(x_1)}{x_1}\right)^2 + \left(\frac{u(x_2)}{x_2}\right)^2 + \dots + \left(\frac{u(x_n)}{x_n}\right)^2}$$

Notes:



Combined Standard Uncertainty without Correlation

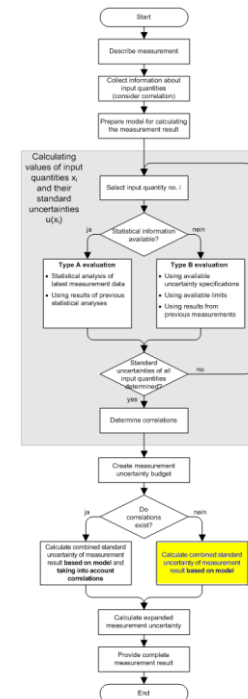
- Linear model

$$y = (a_1 + b_1 \cdot x_1) + (a_2 + b_2 \cdot x_2) + \dots + (a_n + b_n \cdot x_n)$$

- Combined standard measurement uncertainty

$$u_c(y) = \sqrt{u^2(a_1) + x_1^2 \cdot u^2(b_1) + b_1^2 \cdot u^2(x_1) \dots \dots + u^2(a_n) + x_n^2 \cdot u^2(b_n) + b_n^2 \cdot u^2(x_n)}$$

Notes:



Combined Standard Uncertainty without Correlation

- General model

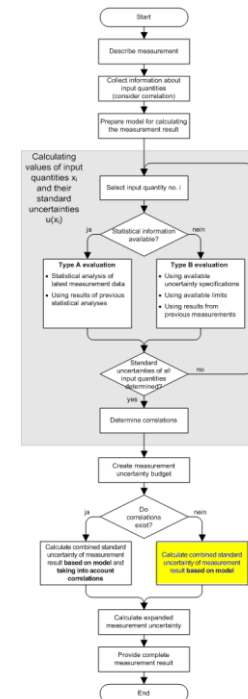
- $$y = f(x_1, x_2, \dots, x_n)$$

- Combined standard measurement uncertainty

- $$u_c(y) = \sqrt{c_1^2 \cdot u^2(x_1) + c_2^2 \cdot u^2(x_2) + \dots + c_n^2 \cdot u^2(x_n)}$$

- with sensitivity coefficients $c_i = \frac{\partial y}{\partial x_i}$ (partial derivative)

Notes:



Combined Standard Uncertainty without Correlation

- Example of a general model

- $$P = R_i \cdot I_M^2$$

- Sensitivity coefficients

- $$c_{R_i} = \frac{\partial P}{\partial R_i} = I_M^2$$

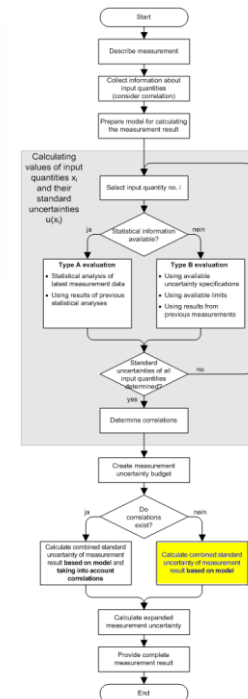
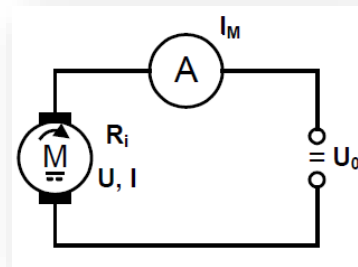
- $$c_{I_M} = \frac{\partial P}{\partial I_M} = 2 \cdot R_i \cdot I_M$$

- Combined standard measurement uncertainty

$$u(P) = \sqrt{c_{R_i}^2 \cdot u^2(R_i) + c_{I_M}^2 \cdot u^2(I_M)}$$

$$u(P) = \sqrt{I_M^4 \cdot u^2(R_i) + 4 \cdot R_i^2 \cdot I_M^2 \cdot u^2(I_M)}$$

$$u(P) = I_M \cdot \sqrt{I_M^2 \cdot u^2(R_i) + 4 \cdot R_i^2 \cdot u^2(I_M)}$$



Notes:

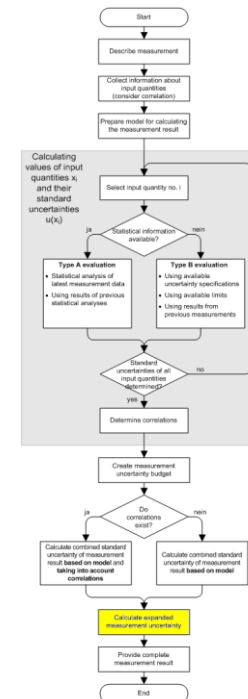
Calculating the Expanded Measurement Uncertainty

- The expanded measurement uncertainty U defines the range within which the true value is expected to lie with a defined probability

$$U = k_p \cdot u_c$$

- where k_p coverage factor based on a certain confidence level
 u_c combined standard uncertainty
- In metrology, $k_p = 2$ is common practice.
 - It refers to a level of confidence of 95.45%.
 - It requires $m \geq 20$ measured values.
 - To simplify this approach, $k_p = 2$ is often applied with a confidence level of 95%.

Notes:



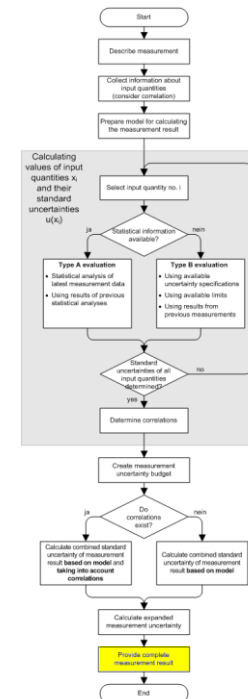
Providing the Complete Measurement Result

- There are different notations available to express measurement uncertainty.
 - $y \pm U$
 - y, U
 - y, U_{rel} with a relative uncertainty $U_{rel} = U/|y|$
 - $y \cdot (1 \pm U_{rel})$
 - $y (U)$ (not recommended since mistakable)
 - .
- Recommended notation for Bosch

$$y \pm U$$

- Example: Mass measurement standard having a nominal value of 100g
 - $m_s = (100.02147 \pm 0.00079) \text{ g}$

Notes:



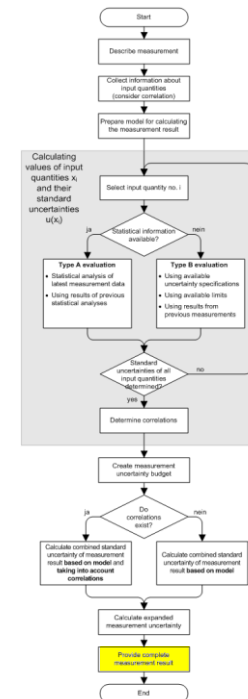
Providing the Complete Measurement Result

- Rounding rules
 - Measurement uncertainties are specified with two significant decimal places
 - Measurement results and the expanded measurement uncertainty need to have one more decimal place than the resolution of the measuring system
 - Always round up uncertainty specifications:

$$U = 0.422\mu m \cong 0.43\mu m$$

(“... and allow reason to prevail”: $U = 0.4205\mu m \cong 0.42\mu m$)
 - Specify three significant places of correlation coefficients when their values are close to 1

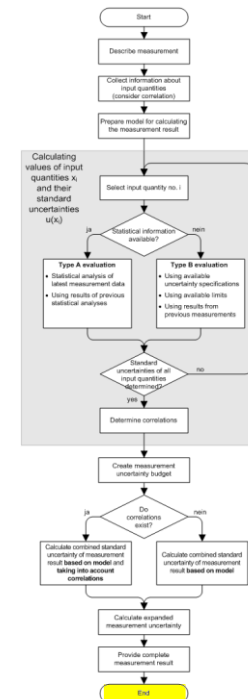
Notes:



Documentation

- No specific format required
- Recommendation: Measurement uncertainty budget (see Booklet 8 annex I)
- Minimum requirements:
 - Model equation
 - All input quantities (in the form of symbols)
 - (Estimated) value of each input quantity
 - Respective associated standard uncertainty
 - Information about correlations and, where applicable, covariances
 - Applied probability density function
 - Degrees of freedom (according to GUM 4.2.6, always required for Type A evaluations)
 - Type of measurement uncertainty evaluation (Type A or B)
 - Sensitivity coefficients
 - Uncertainty components affecting the output quantity
 - Value of the output quantity
 - Combined standard uncertainty of the output quantity
 - Coverage factor

Notes:



Notes:

Agenda

Requirements of International Standards, Basics and Philosophy

Terminology and Approach according to GUM

Approach according to Booklet 8 and GUM

Approach according to Booklet 8 and ISO 22514-7 (and VDA Volume 5)

Brief Discussion about Capability Indices and Ratios C_{MS} , C_{MP} , Q_{MS} , Q_{MP}

Measurement Uncertainty according to Booklet 8 Based on Booklet 10 and ISO 22514-7

Notes:

Approach according to ISO 22514-7

- Background
 - Measurement uncertainty is nothing but an objective statement about the uncertainty range.
 - Is required for conformity assessment (ISO 14253).
 - Usual procedure: Measurement uncertainty according to booklet 8
- BUT: Does not analyze process capability with respect to the tolerance of a characteristic.
- Measurement process capability analysis is often required for a certain application.
- Example: Release of a series measurement process
- Standard approach: Measurement process capability according to Booklet 10
- BUT: Measurement process capability does not provide any information about the measurement uncertainty.
- Which solution is recommended in which case?

Notes:

Approach according to ISO 22514-7

- Which one is the suitable approach?
 - Where measurement tasks change frequently (e.g. in developing and test departments), it is preferable to determine measurement uncertainties. 
 - Where a sufficiently large number of similar repeated measurements of a specific characteristic are taken (e.g. in manufacturing), it is preferable to determine measurement process capabilities. 
 - If conformity has to be evaluated according to ISO 14253, it is important to determine measurement uncertainties instead of or in addition to capabilities. 

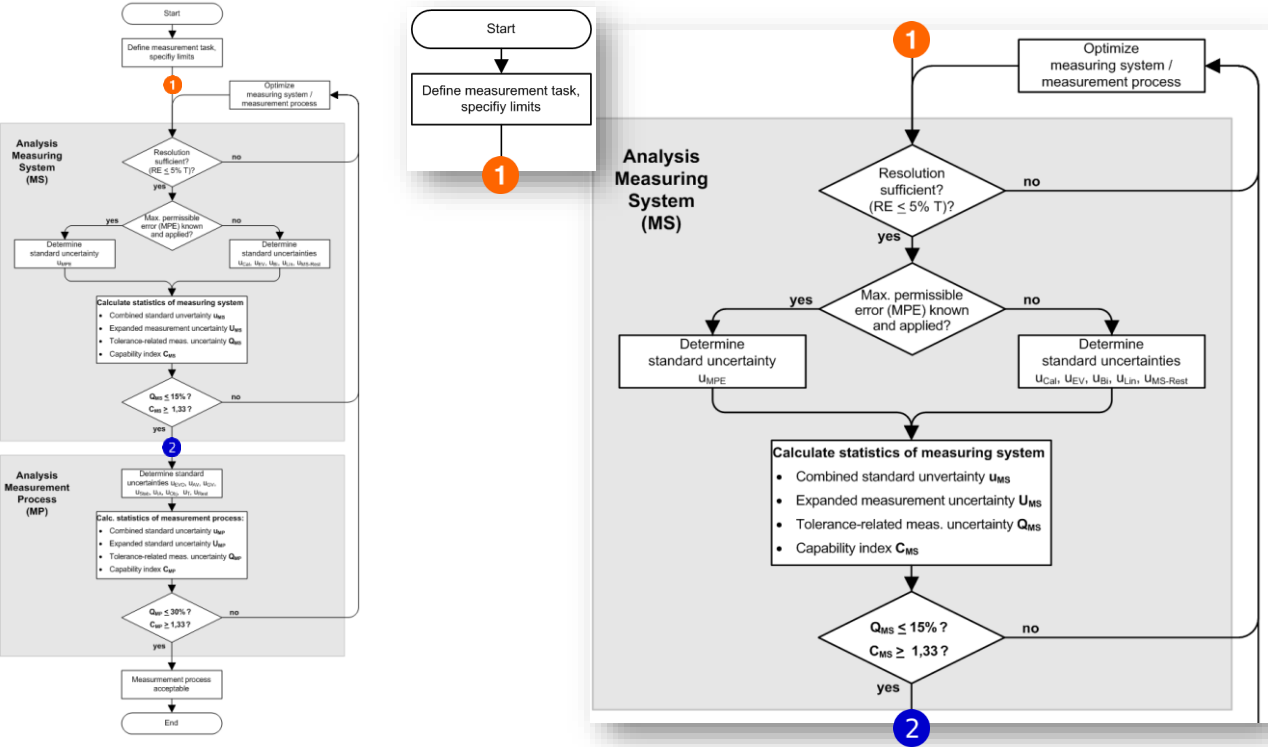
Notes:

Approach according to ISO 22514-7

- ISO 22514-7 provides a field-tested method to determine measurement uncertainties according to GUM and an approach to analyse the capability of measuring systems and measurement processes based on the single components of measurement uncertainty.
- 1st step
 - Capability of the measuring system (MS)
 - Capability ratio Q_{MS} and index C_{MS} including defined limits
- 2nd step
 - Capability of the measurement process (MP)
 - Capability ratio Q_{MP} and index C_{MP} including defined limits

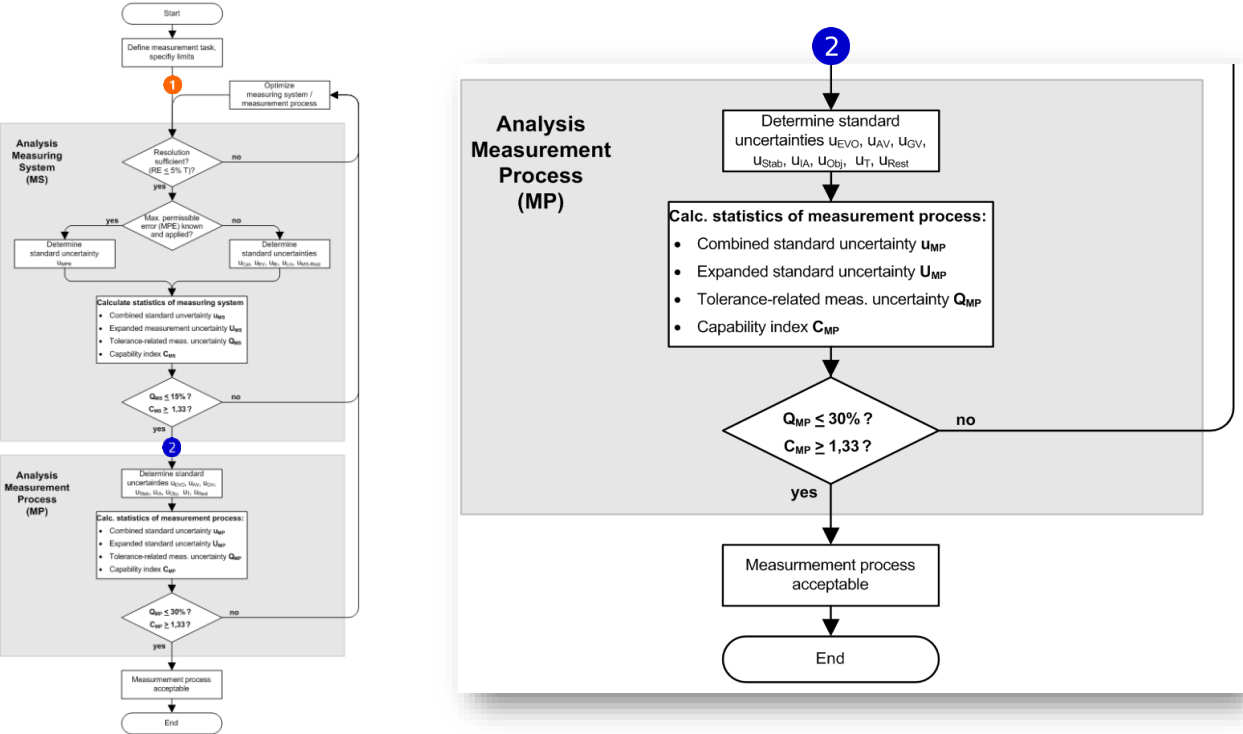
Notes:

Approach according to ISO 22514-7



Notes:

Approach according to ISO 22514-7

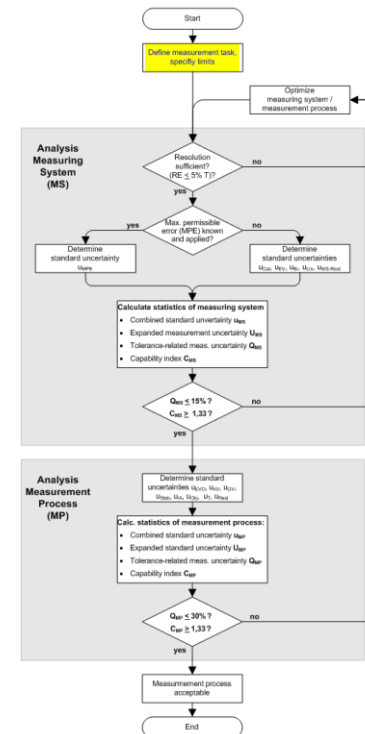
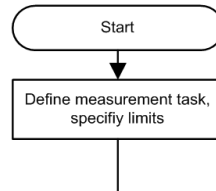


Approach according to ISO 22514-7

- Define the measurement process
- Specify limits
- Modelling
 - Simplified approach (ISO 22514-7): Additive model
 - Measuring system

$$y_{MS} = y' + \delta x_{CAL} + \delta x_{EV(MS)} + \delta x_{BI} + \delta x_{LIN} + \delta x_{REST(MS)}$$
 - Measurement process

$$y_{MP} = y_{MS} + (\delta x_{EV(MP)} - \delta x_{EV(MS)}) + \delta x_{AV} + \delta x_{IA} + \delta x_{OBJ} + \delta x_{GV} + \delta x_{STAB} + \delta x_{\vartheta} + \delta x_{REST(MP)}$$
 - Note 1: All expectations $\delta x_i = 0$ (no correction)
 - Note 2: $(\delta x_{EV(MP)} - \delta x_{EV(MS)}) \geq 0$ since $\delta x_{EV(MS)} \in \delta x_{EV(MP)}$



Notes:

Notes:

Approach according to ISO 22514-7 – MS Analysis

- Modelling the measuring system

$$y_{MS} = y' + \delta x_{CAL} + \delta x_{EV(MS)} + \delta x_{BI} + \delta x_{LIN} + \delta x_{REST(MS)}$$

- Combined standard uncertainty

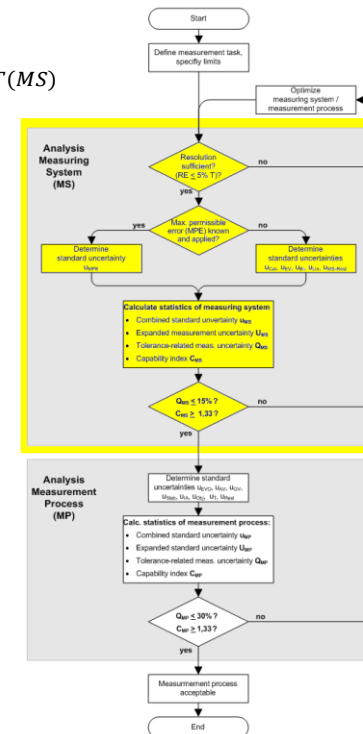
$$u_{MS} = \sqrt{u_{CAL}^2 + u_{EV(MS)}^2 + u_{BI}^2 + u_{LIN}^2 + u_{REST(MS)}^2}$$

$$u_{MS} = \sqrt{u_{CAL}^2 + \max(u_{EVR}^2, u_{RE}^2) + u_{BI}^2 + u_{LIN}^2 + u_{REST(MS)}^2}$$

- where

- $u_{EV(MS)}^2 = \max(u_{EVR}^2, u_{RE}^2)$
- u_{EVR}^2 uncertainty from repeatability on references/standards
- u_{RE}^2 uncertainty from the resolution of the measuring system

Notes:



Resolution and Repeatability – Correlation?

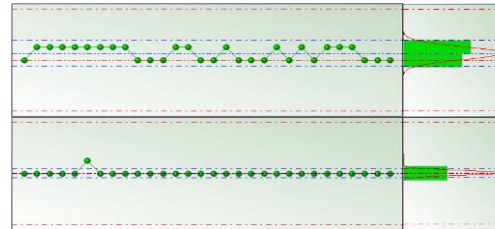
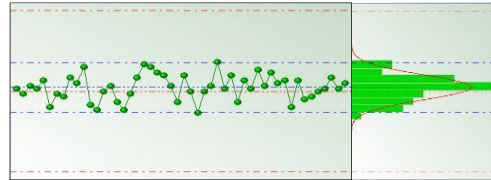
- Repeatability (or equipment variation) EV is already included in the resolution RE

- $$u_{MS} = \sqrt{u_{CAL}^2 + u_{EVR}^2 + \cancel{u_{RE}^2} + u_{BI}^2 + u_{LIN}^2 + u_{REST(MS)}^2}$$

- In case the resolution RE is relatively high, repeatability EV becomes quite small

- $$u_{MS} = \sqrt{u_{CAL}^2 + \cancel{u_{EVR}^2} + u_{RE}^2 + u_{BI}^2 + u_{LIN}^2 + u_{REST(MS)}^2}$$

- You alternatively evaluate u_{RE} or u_{EVR} - the greatest one of these two uncertainties is used



Notes:

Approach according to ISO 22514-7 – MS Analysis

- Determine calibration uncertainty u_{CAL}
 - Calibration certificate or manufacturer's specification

$$u_{cal} = \frac{U_{CAL}}{k_p}$$

- Example: Calibration certificate gauge block box

Measurement uncertainty

Deviation of the central length from nominal length
 $l = \text{nominal length}$ $U = 0,09 \mu\text{m} + 0,9 \cdot 10^{-6} \cdot l$
 Deviation f_o and f_u from central length
 (coverage factor $k = 2$) $U = 0,06 \mu\text{m}$

- 8 mm gage block:

$$U_{CAL} = 0,09 \mu\text{m} + 0,9 \cdot 10^{-6} \cdot 8000 \mu\text{m}$$

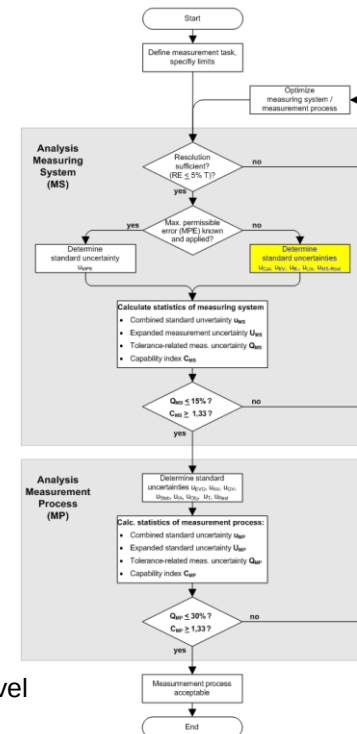
$$U_{CAL} = 0,0972 \mu\text{m}$$

$$u_{CAL} = \frac{U_{CAL}}{2}$$

$$k = 2$$

- Rules on the assumptions for k
 - $k=2$ in case of calibration certificate without specification of confidence level
 - $k=1$ in the case of unspecified general data

Notes:



Notes:

Approach according to ISO 22514-7 – MS Analysis

- u_{CAL} from the calibration of the standard

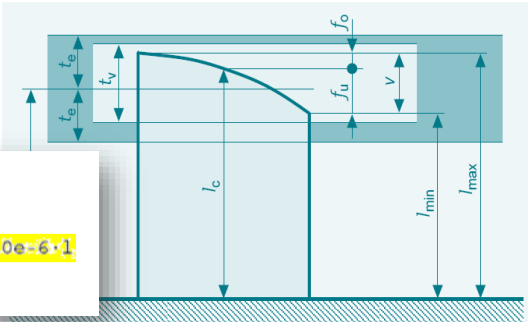
Incertitude de mesure (U95%)
Uncertainty of measurement (U95%) $\pm 0.77\mu m$
Messunsicherheit (U95%)

Measurement uncertainty

Deviation of the central length from nominal length
 l = nominal length
Deviation f_o and f_u from central length
(coverage factor $k = 2$)

$U = 0,09 \mu m + 0,9 \cdot 10^{-6} \cdot l$

$U = 0,06 \mu m$



Method	Type B	Measuring system documentation / calibration certificate
Known	U_{CAL} and k_p	$U_{CAL} = 0.77\mu m$ for $k_p = 2(95\%)$
Calculation	$u_{CAL} = U_{CAL}/k_p = 0.77 \mu m / 2 = 0.385 \mu m$	
Uncertainty	u_{CAL}	$u_{CAL} = 0.3853 \mu m$
Note	U_{CAL} can be specified in the form of an equation e.g. $U_{95\%} = 0.02\mu m + 0.2 \cdot l \cdot 10^{-6}$ (length l in μm)	

Notes:

Approach according to ISO 22514-7 – MS Analysis

- u_{CAL} from the calibration of the standard

Erreur Maximum
Maximale Abweichung
Maximum Error

2µm

Accuracy of DIATEST setting rings (company standard):

Max. deviation from nom. diameter 0.0009 mm
Max. concentricity error 0.0003 mm

Gage Block Sets - ident no. 152 and 154 154
32 pcs / grade 2

Limit deviations of the length l_v at any point and tolerances of variation in length l_v to EN ISO 3650:1998, former DIN 861

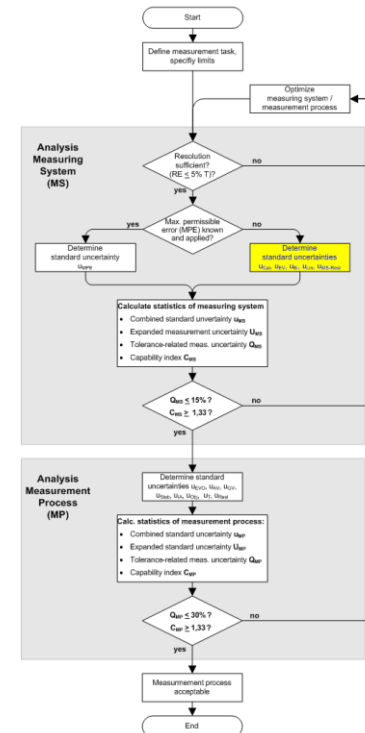
nominal length range mm	calibration grade K		grade 0		grade 1		grade 2	
	limit deviations of length at any point from nominal length $\pm l_e$ µm	tolerance for the variation in length l_v µm	limit deviations of length at any point from nominal length $\pm l_e$ µm	tolerance for the variation in length l_v µm	limit deviations of length at any point from nominal length $\pm l_e$ µm	tolerance for the variation in length l_v µm	limit deviations of length at any point from nominal length $\pm l_e$ µm	tolerance for the variation in length l_v µm
from 0,5 up to 10	0,2	0,05	0,12	0,1	0,2	0,16	0,45	0,3
over 10 up to 25	0,3	0,05	0,14	0,1	0,3	0,16	0,6	0,3
over 25 up to 50	0,4	0,06	0,2	0,1	0,4	0,18	0,8	0,3
over 50 up to 75	0,5	0,06	0,25	0,12	0,5	0,18	1	0,35
over 75 up to 100	0,6	0,07	0,3	0,12	0,6	0,2	1,2	0,35

Method	Type B	Measuring system documentation / calibration certificate
Known	t_e	$t_e = 0.45 \mu m$
Calculation	$u_{CAL} = b \cdot t_e = 0.577 \cdot 0.45 \mu m = 0.26 \mu m$	
Uncertainty	u_{CAL}	$u_{CAL} = 0.26 \mu m$
Note	The descriptions might differ: Limit deviation, accuracy, deviations from the central length, maximum deviation, ...	

Notes:

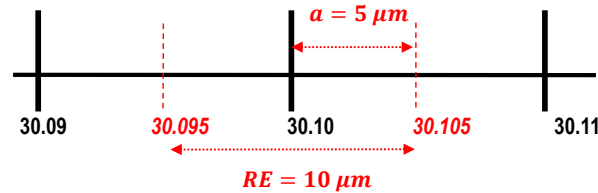
- Resolution is determined...
 - in the manufacturer's specification.
 - by reading the indicated value.
 - through estimation.

$$u_{RE} = \frac{1}{\sqrt{3}} \cdot \frac{RE}{2}$$



Notes:

Approach according to ISO 22514-7 – MS Analysis



- Resolution $RE = 10 \mu m$
- Limit of error $a \Rightarrow RE = 2 \cdot a = 10 \mu m \Rightarrow a = \frac{1}{2} RE = 5 \mu m$
- A priori distribution: Rectangle $\Rightarrow b = \frac{1}{\sqrt{3}} = 0.577 \approx 0.6$
- $u_{RE} = b \cdot a \approx 0.6 \cdot 5 \mu m = 3 \mu m$
- Standard measurement uncertainty $u_{RE} \approx 3 \mu m$

Notes:

Approach according to ISO 22514-7 – MS Analysis

- u_{RE} from resolution

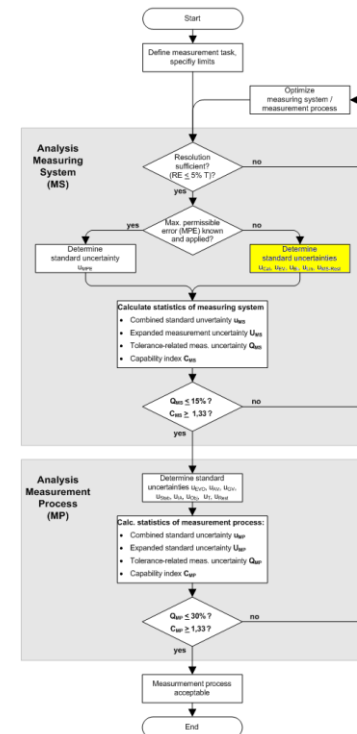


Method	Type B	Value indicated by the measuring instrument
Known	RE	$RE = 10\text{ }\mu m$
Calculation	$u_{RE} = b \cdot a = 0.577 \cdot \frac{1}{2}RE$	
Uncertainty	u_{RE}	$u_{RE} = 2.89\text{ }\mu m$
Note	In case of an analogue display, the resolution corresponds to the scale marking.	

Approach according to ISO 22514-7 – MS Analysis

- Calculate the uncertainty u_{EVR} from repeatability EV on the reference standard
- One single reference standard
 - Take $m \geq 30$ repeated measurements and
 - calculate s or u_{EVR} (analogously to Booklet 10, procedure 1)
- Several reference standards
 - Take $m \geq 30$ repeated measurements equally distributed and
 - calculate s or u_{EVR}
- Possible experiments and calculations
 - Multiple procedure 1
 - Take one V1 per normal and maximum u_{EVR}
- Linear regression analysis according to VDA Volume 5
 - calculate u_{EVR} from residual variation

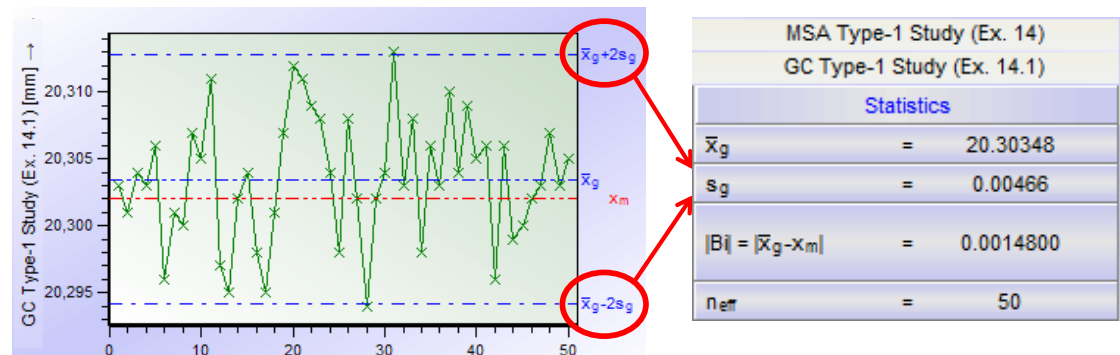
Notes:



Notes:

Approach according to ISO 22514-7 – MS Analysis

- u_{EVR} from procedure 1



Method	Type A	Procedure 1 C_g/C_{gk}
Known	s_g	$s_g = 4.66 \mu m$
Calculation	$u_{EVR} = s_g = 4.66 \mu m$	
Uncertainty	u_{EVR}	$u_{EVR} = 4.66 \mu m$
Note	When you measure the parts in the production process on site, you measure each part once ($n = 1$).	

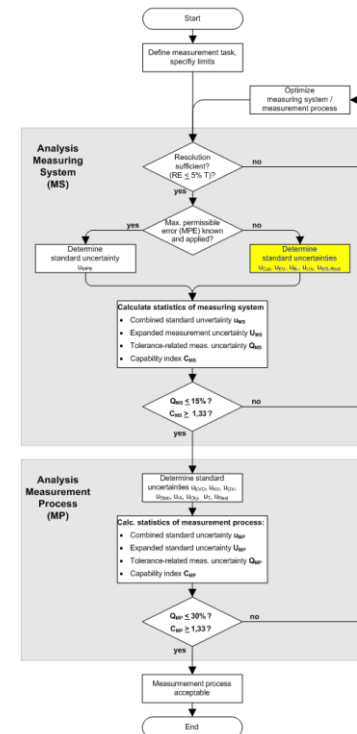
Approach according to ISO 22514-7 – MS Analysis

- Calculate the uncertainty u_{Bi} from the (not correctable) bias

$$u_{BI} = \frac{1}{\sqrt{3}} (\bar{x} - x_m)$$

- x_m = reference value of the reference part
- One single reference standard
 - Take $m \geq 30$ repeated measurements (analogously to Booklet 10, procedure 1) and
 - calculate Bi and u_{BI} .
- Several reference standards
 - Apply procedure 1 to each standard
 - select maximum standard uncertainty u_{BI}

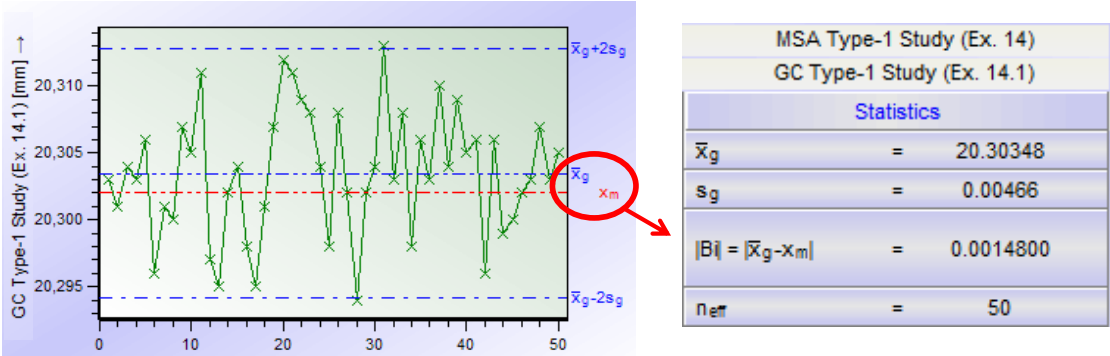
Notes:



Notes:

Approach according to ISO 22514-7 – MS Analysis

- u_{BI} from procedure 1

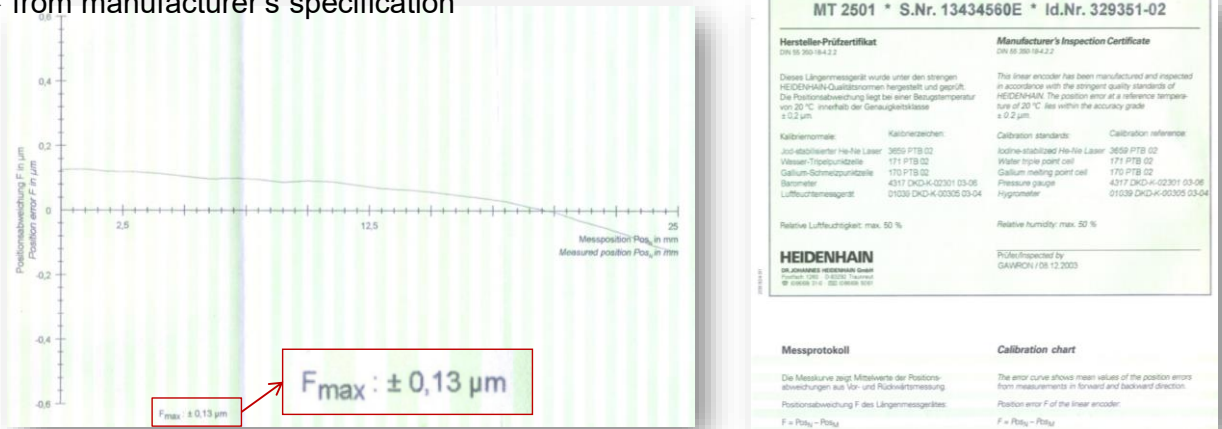


Method	Type A	Procedure 1 C_g/C_{gk}
Known	Bi	$Bi = 1.48\mu m$
Calculation	$u_{BI} = b \cdot a = 0.577 \cdot Bi$	$u_{BI} = 0.577 \cdot 1.48\mu m = 0.854\mu m$
Uncertainty	u_{BI}	$u_{BI} = 0.854\mu m$
Note	Other components (e.g. u_{LIN}) might already include u_{BI} .	

Notes:

Approach according to ISO 22514-7 – MS Analysis

- u_{BI} from manufacturer's specification



Method	Type B	Calibration certificate
Known	F_{max}	$F_{max} = 0.13\mu m$
Calculation	$u_{BI} = b \cdot a = 0.577 \cdot Fmax = 0.577 \cdot 0.13\mu m = 0.075\mu m$	
Uncertainty	u_{BI}	$u_{BI} = 0.075\mu m$
Note		



Approach according to ISO 22514-7 – MS Analysis

- Modelling the measuring system

$$y_{MS} = y' + \delta x_{CAL} + \delta x_{EV(MS)} + \delta x_{BI} + \delta x_{LIN} + \delta x_{REST(MS)}$$

- Combined standard uncertainty

$$u_{MS} = \sqrt{u_{CAL}^2 + \max(u_{EVR}^2, u_{RE}^2) + u_{BI}^2 + u_{LIN}^2 + u_{REST(MS)}^2}$$

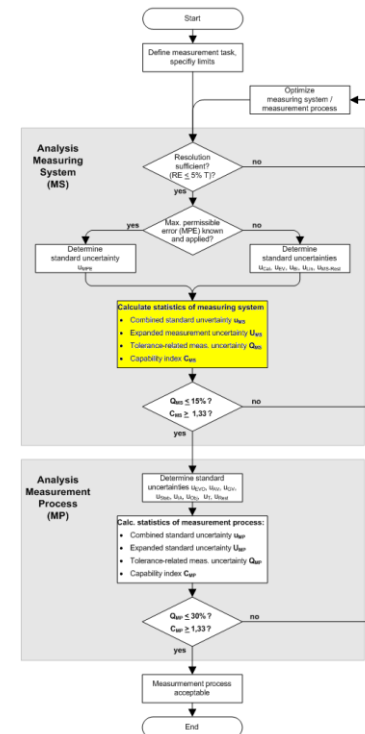
- Expanded measurement uncertainty

$$U_{MS} = k_p \cdot u_{MS} \quad \text{where } k_p = 2$$

- Evaluation of the measuring system

$$Q_{MS} = \frac{2 \cdot U_{MS}}{T}$$

Notes:



Approach according to ISO 22514-7 – MS Analysis

- Expanded measurement uncertainty

$$U_{MS} = k_p \cdot u_{MS} \quad \text{where } k_p = 2$$

- Evaluation of the measuring system

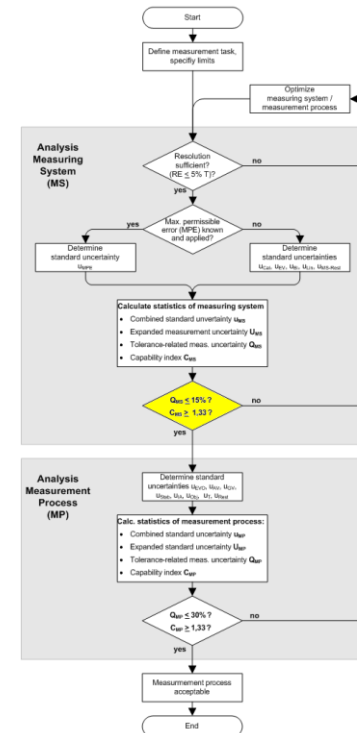
- Capability ratio

$$Q_{MS} = \frac{2 \cdot U_{MS}}{T} \cdot 100\% \leq 15\%$$

- Capability index

$$C_{MS} = \frac{0,3 \cdot T}{6 \cdot u_{MS}} \geq 1,33$$

Notes:



Approach according to ISO 22514-7 – MP Analysis

- Modelling the measurement process:

$$y_{MP} = y_{MS} + (\delta x_{EV(MP)} - \delta x_{EV(MS)}) + \delta x_{AV} + \delta x_{IA} + \delta x_{OBJ} + \delta x_{GV} + \delta x_{STAB} + \delta x_{\vartheta} + \delta x_{REST(MP)}$$

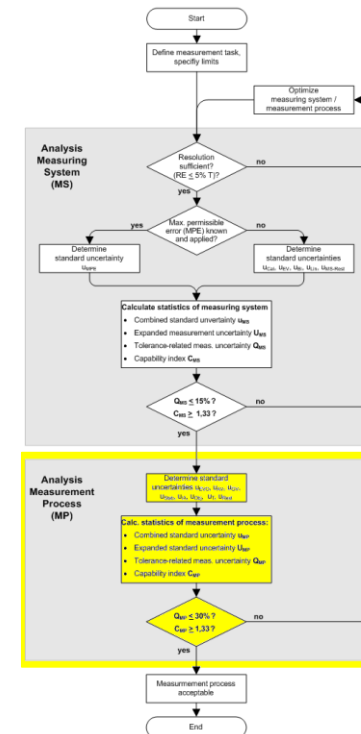
- Combined standard uncertainty:

$$u_{MP} = \sqrt{u_{MS}^2 + (u_{EV(MP)}^2 - u_{EV(MS)}^2) + u_{AV}^2 + u_{OBJ}^2 + u_{IA}^2 + u_{STAB}^2 + u_{\vartheta}^2 + u_{GV}^2 + u_{REST(MP)}^2}$$

- Where $u_{EV(MP)}^2 = \max(u_{EVO}^2, u_{EVR}^2, u_{RE}^2)$

- u_{EVO}^2 from repeatability on test parts
- u_{EVR}^2 from repeatability on reference standards
- u_{RE}^2 from the resolution of the indicating device

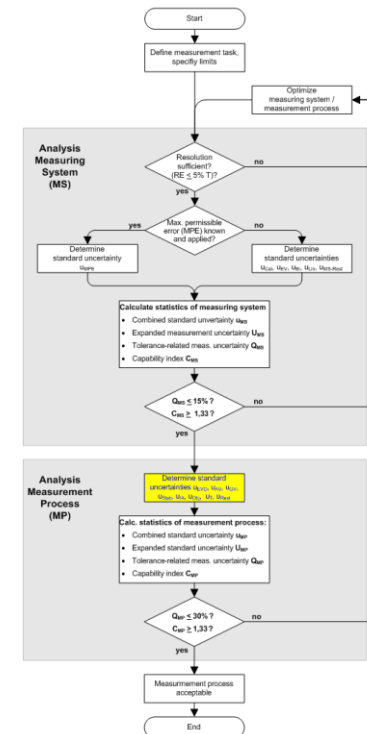
Notes:



Approach according to ISO 22514-7 – MP Analysis

- Determine the uncertainty u_{EVO} from repeatability EV on test parts
- Plan the experiment
 - Total of ≥ 30 measurements
 - ≥ 2 repeated measurements
 - ≥ 5 test parts (≥ 3 according to VDA Vol. 5)
 - ≥ 2 operators (if relevant)
 - ≥ 2 measuring systems (if relevant)

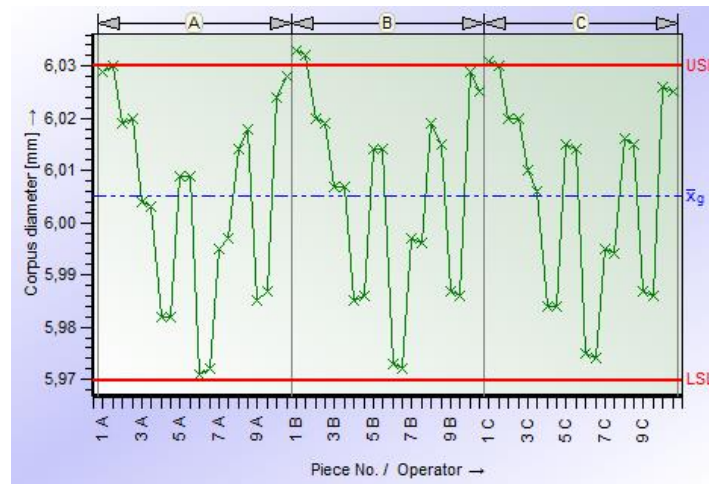
Notes:



Notes:

Excursus: Procedure 2 - %GRR

- Several operators (typically 3)
measure several test parts (typically 10)
several times (typically twice) under repeatability conditions.
- In general, the measured values ...
 - of each operator are evenly spread around a mean value
→ repeatability *EV*
 - of each operator vary around their mean value
→ reproducibility *AV*
 - of each operator and for each part vary around their mean value
→ interaction *IA*



Notes:

Approach according to ISO 22514-7 – MP Analysis

- u_{EVO} , u_{AV} and u_{IA} from procedures 2 and 3

	Variance	Standard dev.			
Repeatability	0.0012817	0.035940	EV	=0,028720 ± 0,035940 ± 0,048040	%EV = 53.91%
Reproducibility	0.00091204	0.030200	AV	= 0.00000 ± 0,030200 ± 0,21689	%AV = 45.30%
Uncertainty from interaction	0.0022338	0.047263	IA	=0,025368 ± 0,047263 ± 0,079959	%IA = 79.89%
Repeatability & Reproducibi	0.0044375	0.066615	GRR	= 0.059689 ± 0,066615 ± 0,22502	%GRR = 99.92%
Process Variation		0.0970873	%PV	= 289.17%	
Tolerance	= T =	0.40	TV	= 0.20	
Confidence interval			1-α	= 95.000%	
required Cp value	= req. Cp =				
Resolution	%RE	=			
Repeatability & Reproducibility	%GRR	=	99.92%		
Part Variation	%PV	=	289.17%		
number of distinct categories	ndc	=	4		
Test system resolution not given!					
BOSCH 2012 - MSA: Type 2					
T _{min} (%GRR)	=	3.997	T _{min} (%GRR)	=	1.332

Standard uncertainties/deviations
(with confidence interval)

EV	=0,028720 ≤ 0,035940 ≤ 0,048040
AV	= 0,00000 ≤ 0,030200 ≤ 0,21689
IA	=0,025368 ≤ 0,047263 ≤ 0,079959
GRR	=0,059689 ≤ 0,066615 ≤ 0,22502

NOTE:
Former calculation methods often provide statistics
EV, AV and IA as a multiple of s,
e.g. EV = 5.15 · s_{EV}.

Method	Type A	n operators measure k parts r times
Known	$s_{EVO} (s_{AV}, s_{IA})$	$s_{EVO} = 0.0359$
Calculation	$u_{EVO} = s_{EVO} = 0.0359 \mu m$	
Uncertainty	$u_{EVO} (u_{AV}, u_{IA})$	$u_{EVO} = 0.0359 \mu m$
Note	Same approach for $s_{AV}, s_{IA} \rightarrow u_{AV}, u_{IA}$	

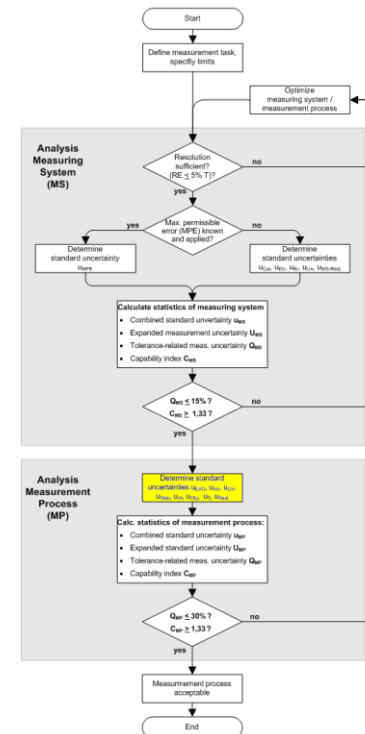
Approach according to ISO 22514-7 – MP Analysis

- Determine uncertainties based on the modified procedure 2
 - 1 operator at 3 different times:
AV becomes *STAB* (stability)
 - 1 operator uses 3 measuring systems:
AV becomes *GV* (gauge variation)
 - 1 operators takes measurements from 3 different points on the part: *AV* becomes *OBJ* (influence from test part)
- Proposal according to VDA Volume 5:

Analysis based on a D-optimum experimental design

 - Problem: Randomization of the experiment

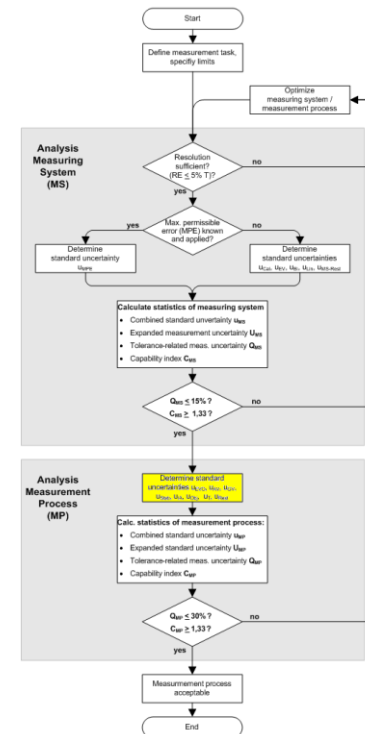
Notes:



Approach according to ISO 22514-7 – MP Analysis

- Calculate the uncertainty u_{GV} from the reproducibility of different measuring systems
- e.g. while using different (identically constructed) measuring systems at the same time.
- Determine standard uncertainties from
 - an experiment DOE – D-optimum experimental design
 - an experiment analogously to procedure 1
 - Observing min./max. values of the individuals and mean values you measured for each reference part

Notes:



Approach according to ISO 22514-7 – MP Analysis

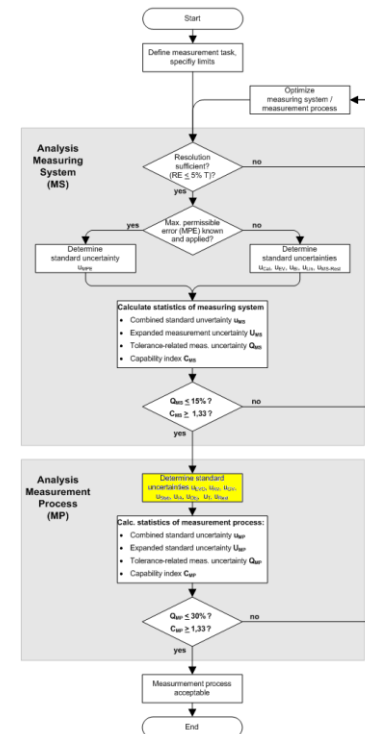
- Determine uncertainty u_{OBJ} from

test part inhomogeneity or the form deviation of the part

$$u_{OBJ} = \frac{1}{\sqrt{3}} \cdot a_{OBJ}$$

- Determine limit a_{OBJ} for test part influence from
 - drawing (maximum permissible error)
 - control chart (actual deviation)
 - experiment (procedure 2, D-optimum DOE)
 - Data sheet, manufacturer's specification (estimation)

Notes:



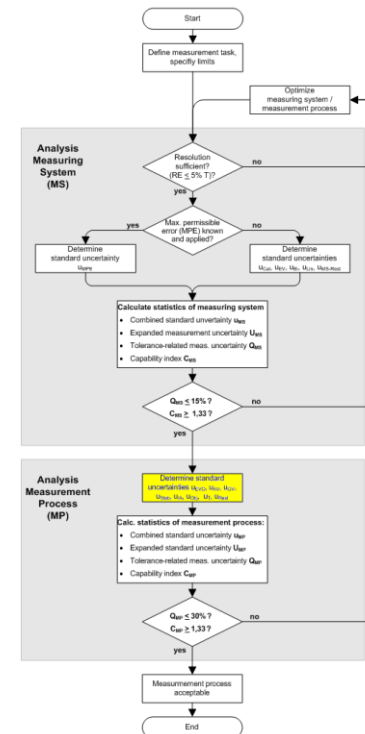
Approach according to ISO 22514-7 – MP Analysis

- Calculate the uncertainty u_{ϑ} from temperature difference

$$u_{\vartheta} = \sqrt{u_{TD}^2 + u_{TA}^2}$$

- Included components:
 - Uncertainty u_{TD} from temperature difference between test part and reference (value)
 - Uncertainty u_{TA} from expansion coefficients
 - Uncertainty $u_{\delta\vartheta}$ from temperature measurement (not considered in this seminar)

Notes:



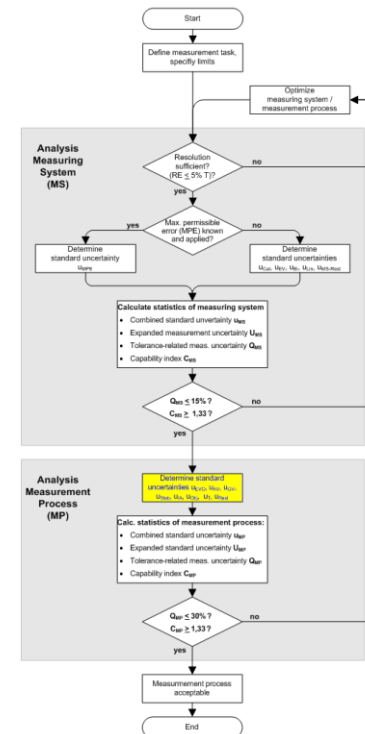
Approach according to ISO 22514-7 – MP Analysis

- Calculate uncertainty u_{TD} from temperature differences (ISO/TR 14253-2)

$$u_{TD} = \frac{\Delta\vartheta \cdot \alpha \cdot l}{\sqrt{3}}$$

- where
 - $\Delta\vartheta$ temperature difference
 - α thermal expansion coefficient
 - l result of the length measurement

Notes:



Approach according to ISO 22514-7 – MP Analysis

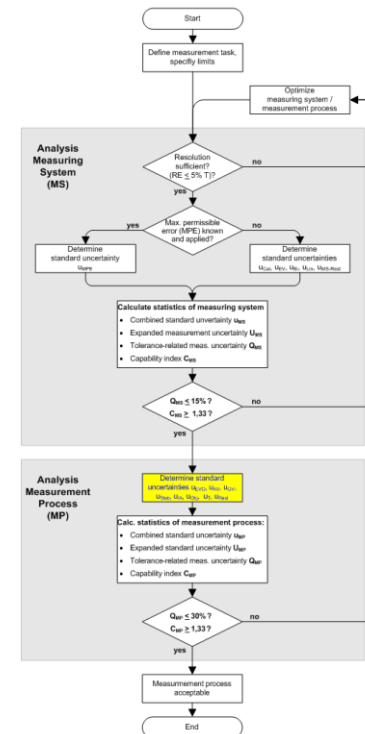
- Determine uncertainty u_{TA} from temperature differences (ISO 15530-3)

$$u_{TA} = |\vartheta - 20^{\circ}\text{C}| \cdot u_{\alpha} \cdot l$$

- where

- ϑ average temperature in $^{\circ}\text{C}$ during the measurement
- u_{α} standard uncertainty of the thermal expansion coefficient
- l result of the length measurement

Notes:



Approach according to ISO 22514-7 – MP Analysis

- Modelling the measurement process

$$y_{MP} = y_{MS} + (\delta x_{EV(MP)} - \delta x_{EV(MS)}) + \delta x_{AV} + \delta x_{IA} + \delta x_{OBJ} + \delta x_{GV} + \delta x_{STAB} + \delta x_{\theta} + \delta x_{REST(MP)}$$

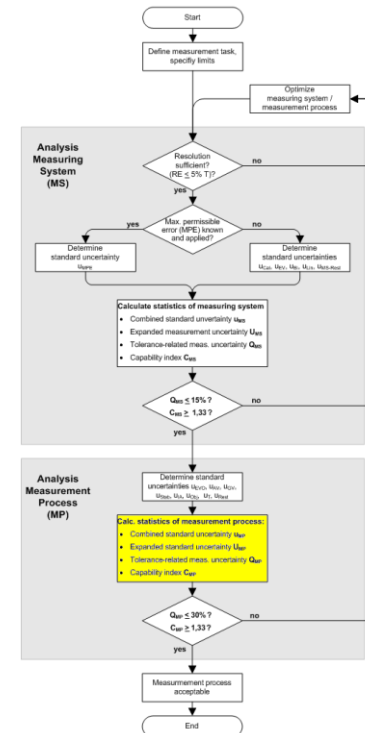
- Combined standard uncertainty

$$u_{MP} = \sqrt{u_{MS}^2 + \max(u_{EVO}^2, u_{EVR}^2, u_{RE}^2) - u_{EV(MS)}^2 + u_{AV}^2 + u_{OBJ}^2 + u_{IA}^2 + u_{STAB}^2 + u_{\theta}^2 + u_{GV}^2 + u_{REST(MP)}^2}$$

- Expanded measurement uncertainty

$$U_{MP} = k_p \cdot u_{MP} \quad (\text{where } k_p = 2)$$

Notes:



Approach according to ISO 22514-7 – MP Analysis

- Expanded measurement uncertainty

$$U_{MP} = k_p \cdot u_{MP} \quad \text{where } k_p = 2$$

- Evaluation of the measuring system

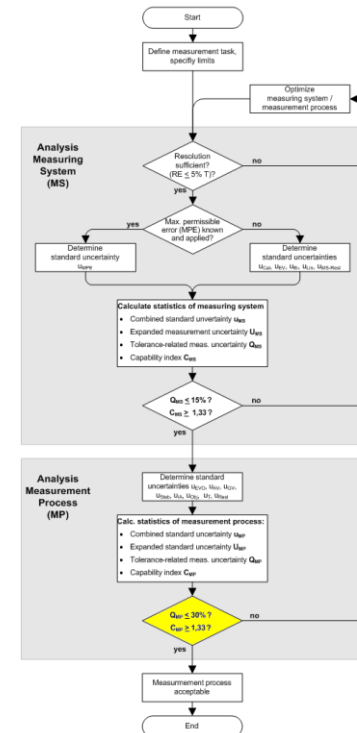
- Capability ratio

$$Q_{MP} = \frac{2 \cdot U_{MP}}{T} \cdot 100\% \leq 30\%$$

- Capability index

$$C_{MP} = \frac{0.3 \cdot T}{3 \cdot u_{MP}} \geq 1.33$$

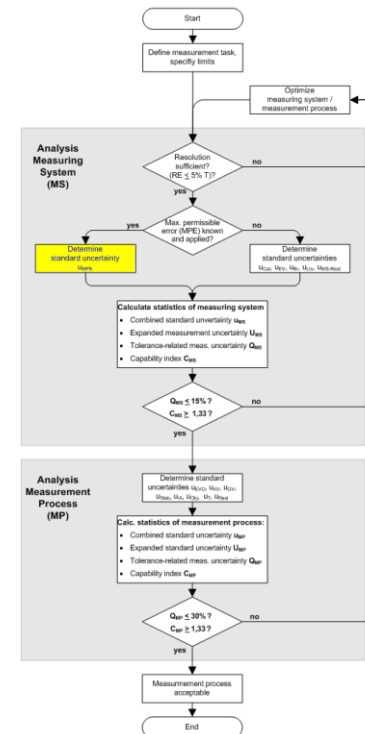
Notes:



Approach according to ISO 22514-7 – MPE

- Capability analysis based on known MPE
- Instead of calculating u_{MS} ,
you can apply the “maximum permissible error” MPE
- Advantage: Interchangeable for identical measuring systems
- Disadvantage: Often involves a higher uncertainty
- Attention: Specified MPE has to be suitable for the respective measurement task.
 - Example: The MPE_p of a CMM cannot be applied to calculate the measurement uncertainty of a measurement of flatness.

Notes:



Approach according to ISO 22514-7 – MPE

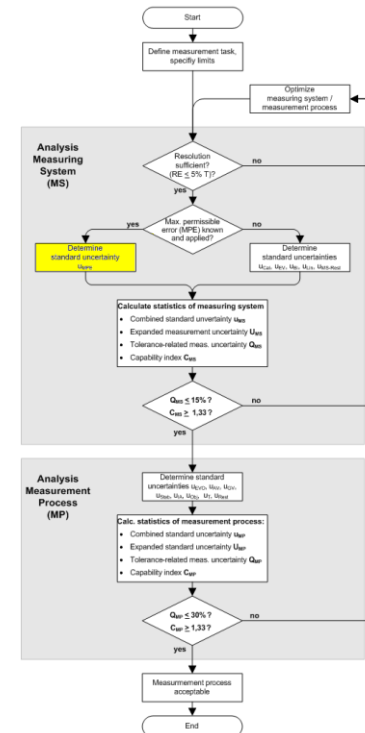
- Capability analysis based on known *MPE*
- Calculate uncertainty u_{MPE} from known *MPE*

$$u_{MPE} = \frac{1}{\sqrt{3}} \cdot MPE$$

- The following equation applies in case of several *MPE* values:

$$u_{MPE} = \frac{1}{\sqrt{3}} \cdot \sqrt{MPE_1^2 + MPE_2^2 + \dots + MPE_n^2}$$

Notes:



Approach according to ISO 22514-7 – MPE

- Modelling the measuring system / measurement process based on the MPE

$$y_{MS} = y' + \delta x_{MPE}$$

$$y_{MP} = y_{MS} + \delta x_{AV} + \delta x_{IA} + \delta x_{OBJ} + \delta x_{GV} + \delta x_{STAB} + \delta x_{\vartheta} + \delta x_{REST(MP)}$$

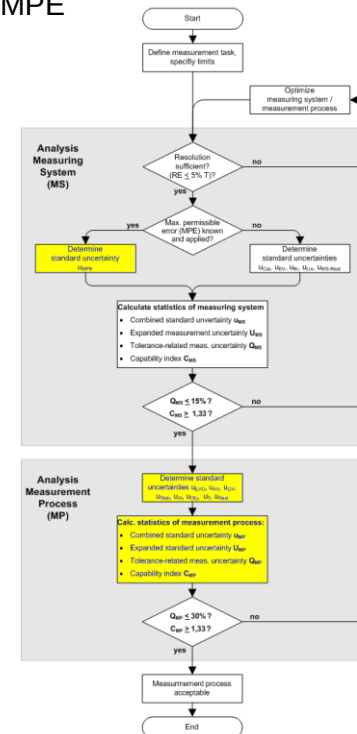
- Combined standard uncertainty MP

$$u_{MP} = \sqrt{u_{MPE}^2 + u_{AV}^2 + u_{OBJ}^2 + u_{IA}^2 + u_{STAB}^2 + u_{\vartheta}^2 + u_{GV}^2 + u_{REST(MP)}^2}$$

- Expanded measurement uncertainty

$$U_{MP} = k_p \cdot u_{MP} \quad (\text{where } k_p = 2)$$

Notes:



Approach according to ISO 22514-7 – MP Analysis

- Expanded measurement uncertainty

$$U_{MP} = k_p \cdot u_{MP} \quad \text{where } k_p = 2$$

- Evaluation of the measurement process

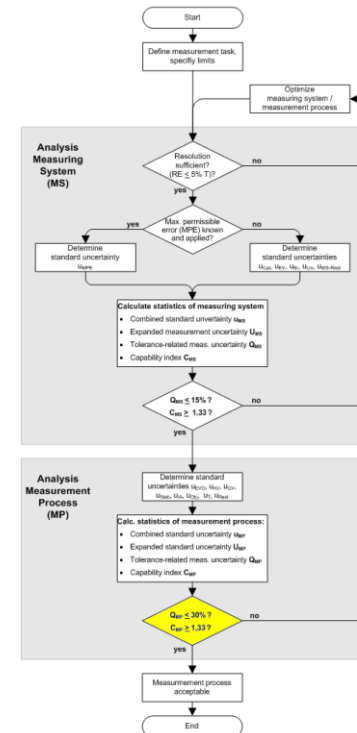
- Capability ratio

$$Q_{MP} = \frac{2 \cdot U_{MP}}{T} \cdot 100\% \leq 30\%$$

- Capability index

$$C_{MP} = \frac{0,3 \cdot T}{3 \cdot u_{MP}} \geq 1.33$$

Notes:



Notes:

Agenda

Requirements of International Standards, Basics and Philosophy

Terminology and Approach according to GUM

Approach according to Booklet 8 and GUM

Approach according to Booklet 8 and ISO 22514-7 (and VDA Volume 5)

Brief Discussion about Capability Indices and Ratios C_{MS} , C_{MP} , Q_{MS} , Q_{MP}

Measurement Uncertainty according to Booklet 8 Based on Booklet 10 and ISO 22514-7

Notes:

Comparing Capability Ratio Q with Index C

- Decision on the capability is the same for Q and C when $k_p = 2$
 - When $k_p > 2$, the required Q exceeds C.
 - When $k_p < 2$, the required C exceeds Q.
- How capability ratio Q and index C relate to each other:
 - $Q_{MS} = \frac{0.1}{C_{MS}} \cdot k_p$
 - $Q_{MP} = \frac{0.2}{C_{MP}} \cdot k_p$

Notes:

Comparing C_{MS}/C_{MP} and C_g/C_{gk}

- Be careful when you compare C_{MS} or C_{MP} to C_g
 - The following changes seem to suggest themselves:
 - $0.3T$ instead of $0.2T$ and
 - $3s/6s$ instead of $4s$
 - But: You simply rewrite the formula when $k_p = 2$
 - “ C_{MS} / C_{MP} is based on 95.45% whereas C_g is based on 99.73%.”
- C_{gk} considers the bias but not in a way that is compliant with GUM
 - $$C_{gk} = \frac{0.1 \cdot T - |Bi|}{3s}$$
- C_{MS}/C_{MP} values according to ISO 22514-7 and C_g/C_{gk} based on procedure 1...
 - are formally not comparable
 - do not provide a statement about the same type of information

Notes:

For Interested Parties only: From Q to C

- $Q_{MP} = \frac{2 \cdot U_{MP}}{T} \cdot 100\% \leq 30\%$
- $\frac{2 \cdot U_{MP}}{T} \leq 0.3$
- $\frac{4 \cdot u_{MP}}{T} \leq 0.3$ for $k_p = 2$
- $\frac{4 \cdot u_{MP}}{0.3 \cdot T} \leq 1$
- $\frac{0.3 \cdot T}{4 \cdot u_{MP}} \geq 1$
- $\frac{0.3 \cdot T}{4 \cdot u_{MP}} \cdot \frac{4}{3} \geq \frac{4}{3} = 1.33$
- $C_{MP} = \frac{0.3 \cdot T}{3 \cdot u_{MP}} \geq 1.33$
- $Q_{MS} = \frac{2 \cdot U_{MS}}{T} \cdot 100\% \leq 15\%$
- $\frac{2 \cdot U_{MS}}{T} \leq 0.15$
- $\frac{4 \cdot u_{MS}}{T} \leq 0.15$ for $k_p = 2$
- $\frac{4 \cdot u_{MS}}{0.15 \cdot T} \leq 1$
- $\frac{0.15 \cdot T}{4 \cdot u_{MS}} \geq 1$
- $\frac{0.15 \cdot T}{4 \cdot u_{MS}} \cdot \frac{4}{3} \geq \frac{4}{3} = 1.33$
- $\frac{0.15 \cdot T}{3 \cdot u_{MS}} \geq 1.33$
- $\frac{0.3 \cdot T}{6 \cdot u_{MS}} \geq 1.33$
- $C_{MS} = \frac{0.3 \cdot T}{6 \cdot u_{MS}} \geq 1.33$

Notes:

Comparing Q_{MP} and %GRR

- It is formally possible to convert Q_{MP} to %GRR
 - When $k_p = 3$, both statistics lead to the same decision
 - When $k_p = 2$, $Q_{MP-max} = 1.5 \cdot \%GRR_{max}$
- But:
- Q_{MP} according to ISO 22514-7 and %GRR based on procedures 2 and 3 do not provide a statement about the same type of information.
 - Q_{MP} includes all relevant influences of the measuring system and measurement process; it is based on a 95.45% confidence level.
 - %GRR only includes the components EV , AV and IA and is based on a 99.73% confidence level.

Notes:

Agenda

Requirements of International Standards, Basics and Philosophy

Terminology and Approach according to GUM

Approach according to Booklet 8 and GUM

Approach according to Booklet 8 and ISO 22514-7 (and VDA Volume 5)

Brief Discussion about Capability Indices and Ratios C_{MS} , C_{MP} , Q_{MS} , Q_{MP}

Measurement Uncertainty according to Booklet 8 Based on Booklet 10 and ISO 22514-7

Notes:

Uncertainty Based on Booklet 10 & ISO 22514-7

- Capability analyses according to Booklet 10 determine different variance components.
- These components are often associated with more than a single influence quantity.
- The specification of variance components according to Booklet 10 does often not comply with GUM.
- The variance components include measurement uncertainty components.
- Target: You determine the expanded measurement uncertainty from the variance components as given in Booklet 10, procedures 1-5.

Notes:

Uncertainty Based on Booklet 10 & ISO 22514-7

- Where can you find the required uncertainty components?
- Measuring system
 - u_{cal} calibration certificate of the applied measurement standard
 - $u_{EV(MS)}$ procedure 1: Measuring system variation (minor influences)
procedure 5: Measuring system variation (many influences)
 - u_{Bi} procedure 1: Bias (minor influences)
procedure 5: Mean deviation of measured values using a calibrated standard or reference part (many influences)
 - $u_{REST(MS)}$ procedure 5: Any other influences not caused by serial parts
- It does not include
 - u_{LIN} deviations from linearity (procedure 4 does not evaluate the kind of linearity deviation we are referring to in this case!)

Notes:

Uncertainty Based on Booklet 10 & ISO 22514-7

- Where can you find the required uncertainty components?
- Measurement process
 - $u_{EV(MP)}$ procedures 1 and 2/3: Influence from serial parts
 - u_{AV} procedure 2: Operator influence (minor influences)
procedure 5: Different operators (many influences)
 - u_{IA} procedure 2: Interactions between serial parts
procedure 5: Interactions caused by influences other than serial parts
 - u_{STAB} procedure 5: Long-term stability
 - u_{ϑ} procedure 5: Changes in temperature and settings
- It does not include:
 - u_{OBJ} deviations caused by test part inhomogeneity
 - u_{GV} : deviations caused by comparable measuring systems
 - $u_{REST(MP)}$ deviations caused by other measurement process influences

Notes:

Uncertainty Based on Booklet 10 & ISO 22514-7

- Modelling the measurement process

$$y_{MP} = y' + \delta x_{CAL} + \delta x_{BI} + \delta x_{PRO} + \delta x_{PAR} + \delta x_{EXT}$$

- Including the following influences:
 - δx_{CAL} influence from the calibration of the standard or reference part
 - δx_{BI} influence from uncorrected bias
 - δx_{PRO} influences from measurement procedure
 - δx_{PAR} influences from serial parts
 - δx_{EXT} further influences, if relevant (extra)

Notes:

Uncertainty Based on Booklet 10 & ISO 22514-7

- Standard uncertainties:
 - u_{CAL}, u_{BI} as known from previous slides
 - (Combined) standard uncertainty from the measurement procedure

$$u_{PRO} = \sqrt{u_{EV(MS)}^2 + u_{REST(MS)}^2 + u_{AV}^2 + u_{IA(1)}^2 + u_{STAB}^2 + u_{\theta}^2}$$

- (Combined) standard uncertainty from serial parts

$$u_{PAR} = \sqrt{u_{EV(MP)}^2 - u_{EV(MS)}^2} \approx \sqrt{EV^2 - S^2}$$

- (Combined) standard uncertainty from other influences

$$u_{EXT} = \sqrt{u_{LIN}^2 + u_{OBJ}^2 + u_{IA(2)}^2 + u_{GV}^2 + u_{REST(MP)}^2}$$

Notes:

Uncertainty Based on Booklet 10 & ISO 22514-7

- Standard uncertainty from calibration:
 - As known from previous slides
 - $u_{CAL} = \frac{U_{CAL}}{k_p}$
 - with U_{CAL} and k_p given in calibration certificate
- Standard uncertainty from bias
 - Unmodified(!) difference between the correct value and mean value of the stability chart
 - $u_{BI} = x_m - \bar{x}$

Notes:

Uncertainty Based on Booklet 10 & ISO 22514-7

- (Combined) standard uncertainty from the measurement procedure
 - Stability chart includes all influences.
 - Uncertainty refers to the dispersion of individuals as given in procedure 5

$$u_{PRO} = \sqrt{\frac{1}{m-1} \cdot \sum_{k=1}^m (x_k - \bar{x})^2}$$

- At least $m = 25$ measured values have to be available.

Notes:

Uncertainty Based on Booklet 10 & ISO 22514-7

- (Combined) standard uncertainty from serial parts
 - Obtained by comparing procedure 1 to procedures 2/3.
 - Procedure 1: Variation s without influence from serial parts
 - Procedure 2: Variation EV including influence from serial parts
 - F-test: Variation is significant when $EV^2 > 2s^2$
 - Note: Test applies to a confidence level of 95% and 20-30 measurements.
 - u_{PAR} is only considered if the F-test is significant

$$u_{PAR} = \sqrt{EV^2 - s^2}$$

Notes:

Uncertainty Based on Booklet 10 & ISO 22514-7

- (Combined) standard uncertainty from other influence components
 - These influences cannot be determined according to Booklet 10, procedures 1-5
 - You have to calculate them – if required – based on the methods described in ISO 22514-7

$$u_{EXT} = \sqrt{u_{LIN}^2 + u_{OBJ}^2 + u_{IA(2)}^2 + u_{GV}^2 + u_{REST(MP)}^2}$$

Notes:

Uncertainty Based on Booklet 10 & ISO 22514-7

- Modelling the measurement process

$$y_{MP} = y' + \delta_{CAL} + \delta_{BI} + \delta x_{PRO} + \delta x_{PAR} + \delta_{EXT}$$

- Combined standard measurement uncertainty u_c

$$u_c = \sqrt{u_{CAL}^2 + u_{BI}^2 + u_{PRO}^2 + u_{PAR}^2 + u_{EXT}^2}$$

- Expanded measurement uncertainty

$$U = k_p \cdot u_c$$

- where $k_p = 2$ for a 95.45% level of confidence
- Complete measurement result

$$y = y' \pm U$$

es:



Notes:

**Thank you for
your attention**

