Measurement System Analysis

Requirement and related topics

The basics of statistics and especially statistical distributions are advantageous for these descriptions. Further topics are:

www.weibull.de/COM/Measurement_System_Analysis_discrete.pdf

Introduction

Measurement System Analysis investigations are the basic requirement for carrying out Capability Studies. They are intended to ensure that the used measuring equipment is suitable.

Note: With destructive tests (e.g., tensile or bend tests), a "substitute normal" must be used that is not destroyed (such as a thicker part, etc.). If there is force measurement of destroying test specimens, the test specimen can, for example, be replaced by a spring whose characteristic is in the test specimen's force/stroke range.

Procedure

Overall, a differentiation is made between the following influences:

1. **Repeatability** on a "**reference**" = constant master part
   (former process 1), pure test equipment deviation.
2. **Repeatability** on different **parts** (former process 3)
   Consideration of the value range to be measured.
3. **Reproducibility** on different parts and different **appraisers** (former process 2)
   Consideration of different appraisers.

According to VDA Volume 5 or the ISO 22514-7, measuring uncertainties are observed by means of the corresponding standard deviations that are expressed by the symbol *u* (measuring uncertainty budgets). The calculation is performed using an analysis of variance (ANOVA).

The overview below shows the most important measuring uncertainties:

Proportion	Calculation	Description
Resolution of the display	$u_{RE} = RE/\sqrt{12}$	RE Resolution of the equipment
Systematic deviation	$u_{Bi} = \left\|\bar{x}_{g} - x_m\right\|/\sqrt{3}$	$\bar{x}_g$ Disp. average val. of normal x_m Reference value of normal

Repeatability on normal	$u_{EVR} = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(x_i - \bar{x}_g)^2}$	x_i Meas. val. of the repetition i n Number of repetitions

From this, the influence of the instrument (MS = measuring system) is formed as an intermediate result (simplified representation considering no linearity deviation):

$$u_{MS} = \sqrt{u_{Cal}^2 + u_{BI}^2 + max\{u_{RE}^2; u_{EVR}^2\}}$$

The calibration uncertainty of the normal u_{Cal} should be considerably less than the total measuring uncertainty (recommendation of $u_{cal} \leq 0.15\ u_{MS}$). Refer to the calibration certificate for the calibration uncertainty.

$$\%Q_{MS} = 100\% \cdot \frac{k \cdot 2 \cdot u_{MS}}{TOL}$$

k = 2 VDA Standard for confidence level 95.45 %
k = 3 for confidence level 99.73 %, if the application requires, or the specialist department has corresponding normative stipulations, e.g. threaded fastener technology.

Requirement: ***%Q_{MS}* ≤ 15%**

This corresponds to the older requirement:

$$C_g = \frac{0{,}2 \cdot TOL}{2\ k\ s_g} \quad ; \quad C_{gk} = \frac{0{,}1 \cdot TOL - |\bar{x}_g - x_m|}{k\ s_g}$$

$\bar{x}_g$: mean of the measurements
x_m : mean of reference standard
s_g : standard deviation

In addition to the measurement uncertainties of the pure measuring system, influences from the part variation and the appraiser are also added. Overall, the measurement uncertainty of the entire measuring process is determined by:

Measuring process = Measuring uncertainty of instrument +
Measuring uncertainty of equipment & appraiser

The effects are determined by ANOVA with a variance analysis (see also Chapter ANOVA). In this method the effects are a combination of parts-variation, the appraiser, and the interaction between these together. The biggest advantage of the ANOVA is the consideration of the interaction, which is why this method is preferable. To assess the effects separately, one divides the sum of the square-errors over all measurements in sub-totals and their variances. The classic representation in the Anglo-Saxon world is:

Degrees of Freedom number of Information → DF; Sum of Squares → SS; Mean Square Variance = SS/DF → MS; F-value → F

	DF	SS	MS	F
Part	9	1,181E-05	1,313E-06	71,7
Appraiser	2	3,640E-07	1,820E-07	9,9
Part*Appraiser (interact.)	18	3,293E-07	1,830E-08	0,7
Repeatability	30	7,700E-07	2,567E-08	
Total	59	1,328E-05		

s^2_{EV}

The table of the MSA is:

$6 \cdot \sqrt{s^2_{EV}}$

	Sym.		Sym.	
Repeatability	EV	9,080E-04	%EV	18,2
Appr.-influence	AV	5,351E-04	%AV	10,7
Interaction	IA	0,000E-01	%IA	0,0
Part-variation	PV	2,782E-03	%PV	30,0
Measurem. Equipm.	RR	1,054E-03	%R&R	21,1

$$RR = \sqrt{EV^2 + AV^2 + IA^2}$$

$$\%R\&R = \frac{RR}{T} \cdot 100\%$$

First of all, the sums of squares of the table data will be formed horizontally and vertically (Sum of Squares). With the help of the degrees of freedom DF the variance can be determined (Mean Square) and the standard-deviation of the set. The results are in each case multiplicated with the factor 6 the standard-deviations, which means that 99.73% of the parts are included. Via the F-value, which is the ratio of the sum of variances of the appraiser to the repetitions the significances can be determined (which results mostly in the p-value).

In the example one has to consider that the results are different by calculation with interaction compared.

The scope of the equipment and the appraiser is:

Portion	**Calculation**	**Description**
Repeatability of test object	$u_{EVO} = \sqrt{MS_{EV}}$	MS_{EV} Variance repeatability
Reproducibility of appraiser	$u_{AV} = \sqrt{MS_{AV}}$	MS_{AV} Variance of appraiser
Interaction	$u_{IA} = \sqrt{MS_{IA}}$	MS_{IA} Variance Interaction

Overall, the measuring process is determined by (simplified view):

$$u_{MP} = \sqrt{u_{Cal}^2 + u_{BI}^2 + max\{u_{RE}^2;\ u_{EVR}^2;\ u_{EVO}^2\} + u_{AV}^2 + u_{IA}^2}$$

In a similar way to the repetition and comparability precision $\%R\&R$ reference is made to the tolerance and it yields the key figure:

$$\%Q_{MP} = 100\% \cdot \frac{k \cdot 2 \cdot u_{MP}}{USL - LSL}$$

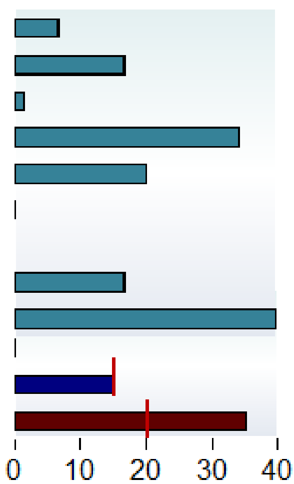
The requirement is, depending on the technology and importance of the application

$\%Q_{MP} \leq$ 20% (recommendation)

$\%Q_{MP} \leq$ 30% (standard)

Example:

VDA 5 / ISO 22514-7		values / 1000
Resolution of gauge	u_{RE}	0,0289
Repeatability Master	u_{EVR}	0,0738
Standard uncertainty (Bias)	u_{BI}	0,0058
Repeatability test-object	u_{EVO}	0,1513
Repeatability appraiser	u_{AV}	0,0892
Interaction	u_{IA}	0,0000
Uncertainty measurement	u_{MS}	0,0740
Uncertainty process	u_{MP}	0,1758
Measurement	$\%Q_{MS\ (95,45\%)}$	**14,8**
Process	$\%Q_{MP\ (95,45\%)}$	**35,2**



In this example, the requirement was met with $\%Q_{MS} \leq$ 15%, but the uncertainties from repeatability at different parts and appraiser are too high ⇨ $\%Q_{MP}$ = 35.2% > 20%. The reason can be in an incorrect measuring range, which cannot cover the variation of the parts. The appraisers should be re-instructed ("operational definition"), so that all proceed in the same way.

One-sided limited attributes and non-normally distributed data

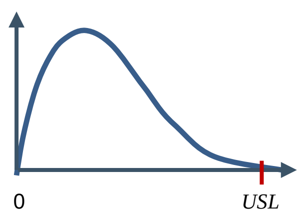
In some cases, there is only one-sided specification limit, e.g. an upper one for emission-relevant characteristics or a lower one for holding forces. Likewise, there are features that are generally not normally distributed, e.B. concentricity, perpendicularity, parallelism, imbalance.
The calculation of the capability indicator is based on the normal distribution. This also applies to non-normally distributed features, as the measurement scattering around a "constant" measuring point can be neglected in relation to the asymmetric distribution.

Case 1: Natural limit exists

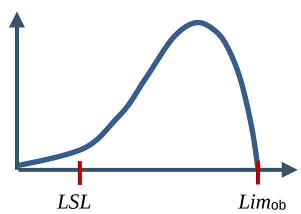
A natural 0 limit is, for example, roughness, roundness, flatness. The value 0 is also the desired target in these cases. Example: A maximum roughness should not be exceeded, or a roundness should not be worse than a maximum value. Here there is only the requirement of USL.

The same principle is given when there is a physical upper limit for a lower limit, e.g. a saturation at Lim upper = 100% in a liquid solution. Here there is only one requirement according to LSL. The relationships for both cases are then:

Natural lower limit at 0
One-sided upper specification limit



Natural upper limit
One-sided lower specification limit



$$\%Q_{MP} = 100\% \cdot \frac{k \cdot 2 \cdot u_{MP}}{USL}$$

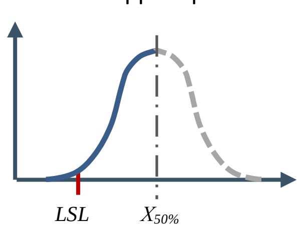
$$\%Q_{MP} = 100\% \cdot \frac{k \cdot 2 \cdot u_{MP}}{Lim_{up} - LSL}$$

with k=2 for confidence 95,45%, or k=3 for 99,73%

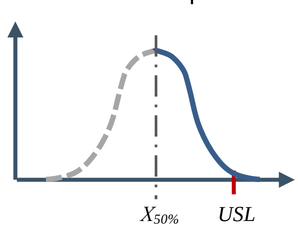
Case 2: Known application or defined nominal value.

If there are empirical values from process data and a corresponding median $X_{50\,\%}$, or a target value X_{nom}, the following applies:

Natural lower limit at 0
One-sided upper specification limit



Natural upper limit
One-sided lower specification limit



$$\%Q_{MP} = 100\% \cdot \frac{k \cdot u_{MP}}{X_{50\%} - LSL}$$

$$\%Q_{MP} = 100\% \cdot \frac{k \cdot u_{MP}}{USL - X_{50\%}}$$

$X_{50\,\%}$ Median, here from process experience

Case 3: Unknown application an not antural limit.

If there are no empirical values or target values and no natural limits are available, $\%Q_{MS}$ = 100 % (k · u_{MS}) / LSL results in an unfavorable value, especially if the process data is close to 0. On the other hand, $\%Q_{MS}$ = 100 % (k · u_{MS}) / USL gives too good a value, especially if the process data is far away from 0. In this case, the following procedure is recommended: First, a usable minimum measuring range $MRmin$ (smallest measurable tolerance) should be determined. This results from the conversion of the forms under case 2, if

MR_{min} ⇨ $X_{50\,\%} - LSL$ ⇨ $USL - X_{50\,\%}$

$$MR_{min} = 100\% \cdot \frac{k \cdot u_{MS}}{\%Q_{MS}}$$

The requirement $\%Q_{MS}$ = 15% result in:

$MR_{min,15\,\%} = 6{,}67 \cdot k \cdot u_{MS}$

In the specific application for the process range PR, the following situations may arise.

1.) $PB \geq MR_{min}$

The process range is equal to or greater than the minimum usable measuring range of the measuring system:

⇨ Measuring system suitable

2.) $PB < MR_{min}$

The process range is smaller than the minimum usable measuring range of the measuring system:

- A better measuring system should be used.
- If not representable, a correspondingly higher requirement for C_{mk} / C_{pk} applies

Similarly, the same designations apply to $\%Q_{MP}$, where a requirement

$\%Q_{MP}$ = 20 % applies:

$MR_{min,20\,\%} = 5 \cdot k \cdot u_{MS}$

Overview of the methods

The overview below is a comparison with the old methods mentioned above:

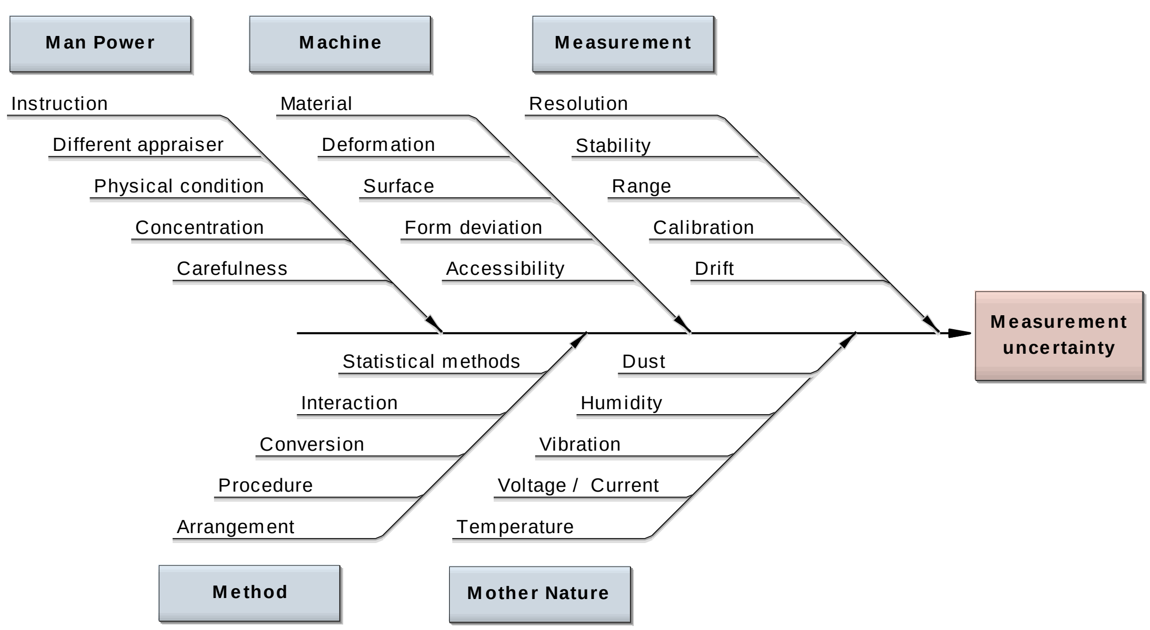
Influences →

	Repeatability		**Repeatability** Part to part	**Reproduceability** Part to part & Appraiser
	Testing with reference standard		Testing with various parts	Testing with various parts and various appraiser
VDA Volume 5 (ISO 22514-7)	u_{EVR}, u_{BI}	u_{RE}, u_{cal}, u_{lin}	u_{EVO}	u_{EVO}, u_{AV}, (u_{IA})
Requirement	$Q_{MS} \leq 15\,\%$		$Q_{MP} \leq 20\,\%$	$Q_{MP} \leq 20\,\%$
Former classic methods	Method 1 $C_g/C_{gk} \geq 1{,}33$		Method 3 range $\%R\&R \leq 20\,\%$	Method 2 range, mean value difference $\%R\&R \leq 20\,\%$

Other influences on measurement uncertainties

Along with the proportions of measurement uncertainties described above, there is a series of other possible influences such as stability and temperature.

$$u_{MP} = \sqrt{\ldots + u_{Lin}^2 + u_T^2 + \ldots}$$



Here too, as regards calculation further measurement uncertainties $u_{\text{influence}}$ are cumulative in accordance with the Gaussian law of error propagation.

$$u_{MP} = \sqrt{\dots + u_{E1}^2 + u_{E2}^2 + u_{E3}^2 \dots}$$

Especially measuring equipment holding devices and their possible deformation may have considerable influence on measurement uncertainties, see example mentioned in Ishikawa diagram. These should be quantified by tests as far as possible. If this is not possible, the percentage shares shall be considered e.g. by rigidity calculations. Furthermore, manufacturers' specifications shall be considered, e.g. in case of electronic measurement sensors.

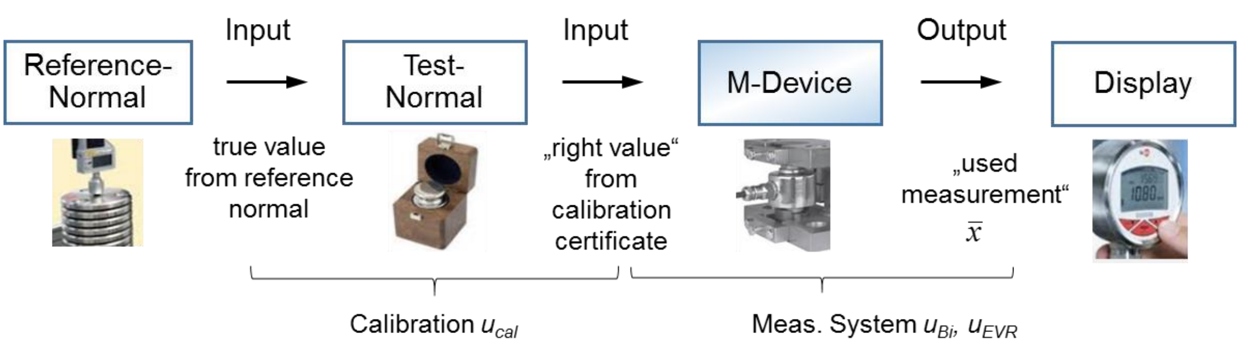
Reducing the measuring uncertainty by repetitions

In the event that the requirement is not met but no alternative measuring equipment is available, the possibility of repetitions exists. By multiple repeat measurements and averaging, it is possible to achieve a reduction in measuring uncertainty. It is possible to reduce random measuring uncertainties with m-repetitions by a factor $\sqrt{m}$. The proportion u_{EVO} then becomes

$$u_{EVO}^* = \frac{u_{EVO}}{\sqrt{m}}$$

If u_{EVO} is known from previous measurements, it is possible to determine the necessary number of repetitions to achieve the required measuring uncertainty.

Measurement chain

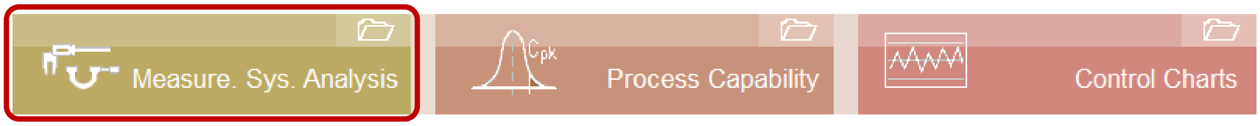


MSA for discrete characteristics

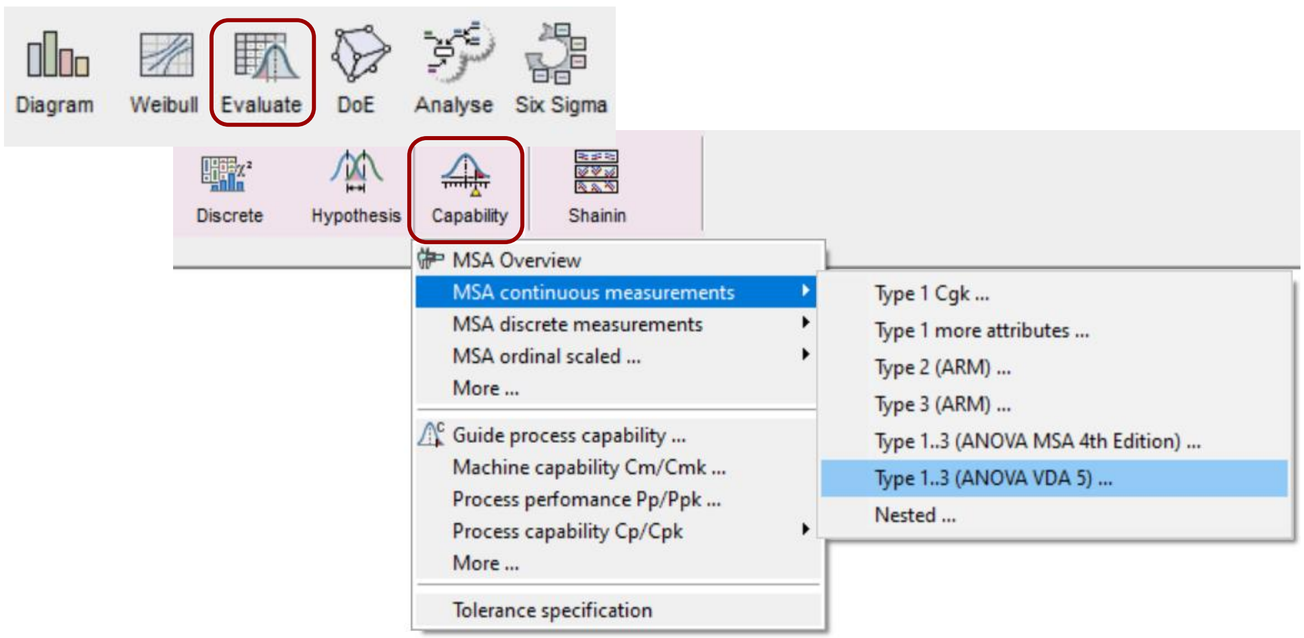
The methods for discrete attributes are described here:

www.weibull.de/COM/Measurement_System_Analysis_discrete.pdf

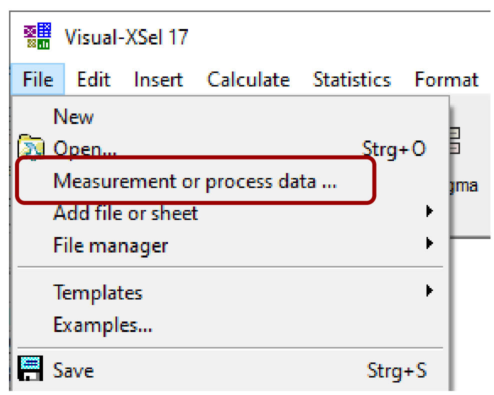
Using Visual-XSel 17.0



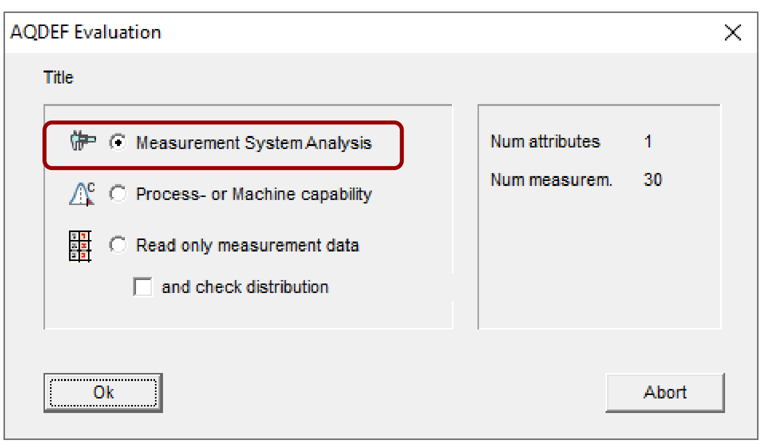
All procedures and analyses are carried out via templates. There are several possibilities to open them. The direct way is via the selection in the start guide, or via the icon *Evaluate/ Capability*.



In version 17.0 there is a new menu item to load directly measurement data in the AQDEF® format. www.q-das.com/en/service/data-format-aqdef



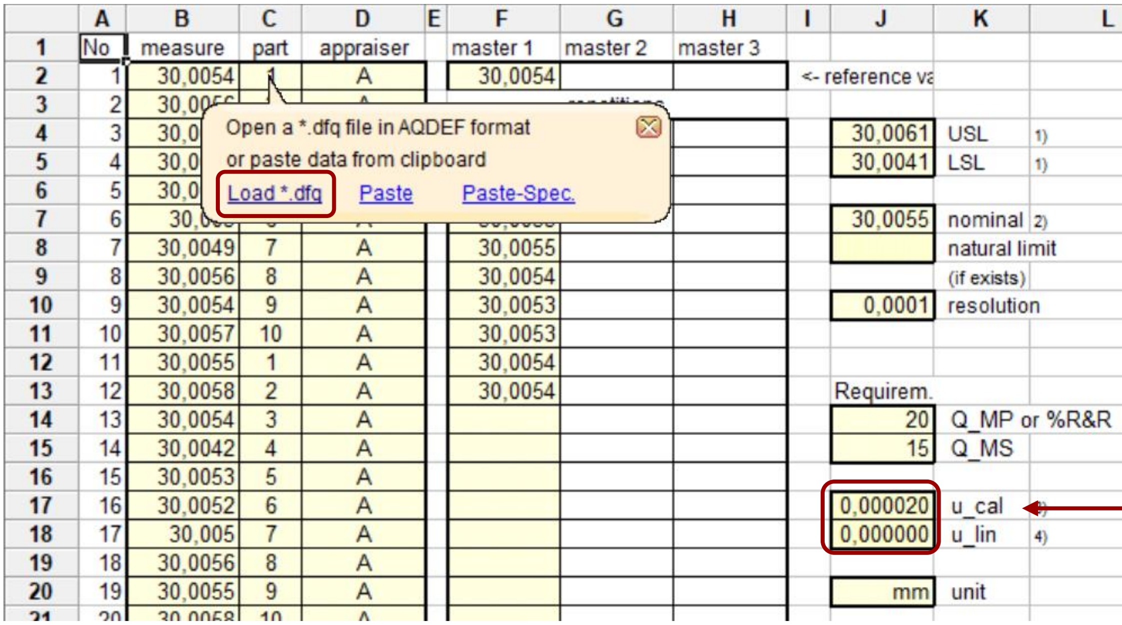
After loading one can select the analysis method.



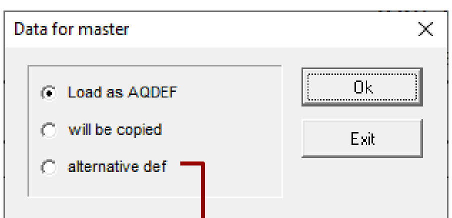
By using the first two options the relevant template will be loaded. Only templates with an under-score *_.vxg are shown here, as a sign for the AQDEF® format. However, manual data input via clipboard is still possible here.

Please note: Only one attribute can be used in the templates here!

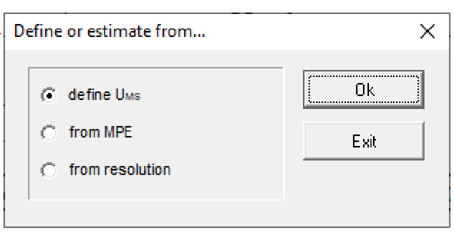
In case of the template *Meassurement_System_Analyse_ANOVA_VDA5_.vxg* it is possible to load data in the AQDEF® format. This option is available in all templates which ends with an underscore *_.vxg. Click to the first option:



What data are transferred depends on the source. For this template one shall load first the data for the measure with different parts and appraisers. In the second step the following options are possible:



- Load the master repetitions via *.qdf file. All other data in column J will be used from this file.
- Copy the data via clipboard in column F.
- If no data are available, the needed information for the master can be defined in a further dialog.



- Direct definition via the uncertainty of measurement system
- Estimation from Maximum Permissible Error MPE (documented by the supplier of the Measurem. Syst.)
- Estimation from the resolution RE of the system.

Some fields in column J have default values, like the requirements for Q_{MP} and Q_{MS}. May be also missing information about u_{cal} and u_{lin} should be defined manually.

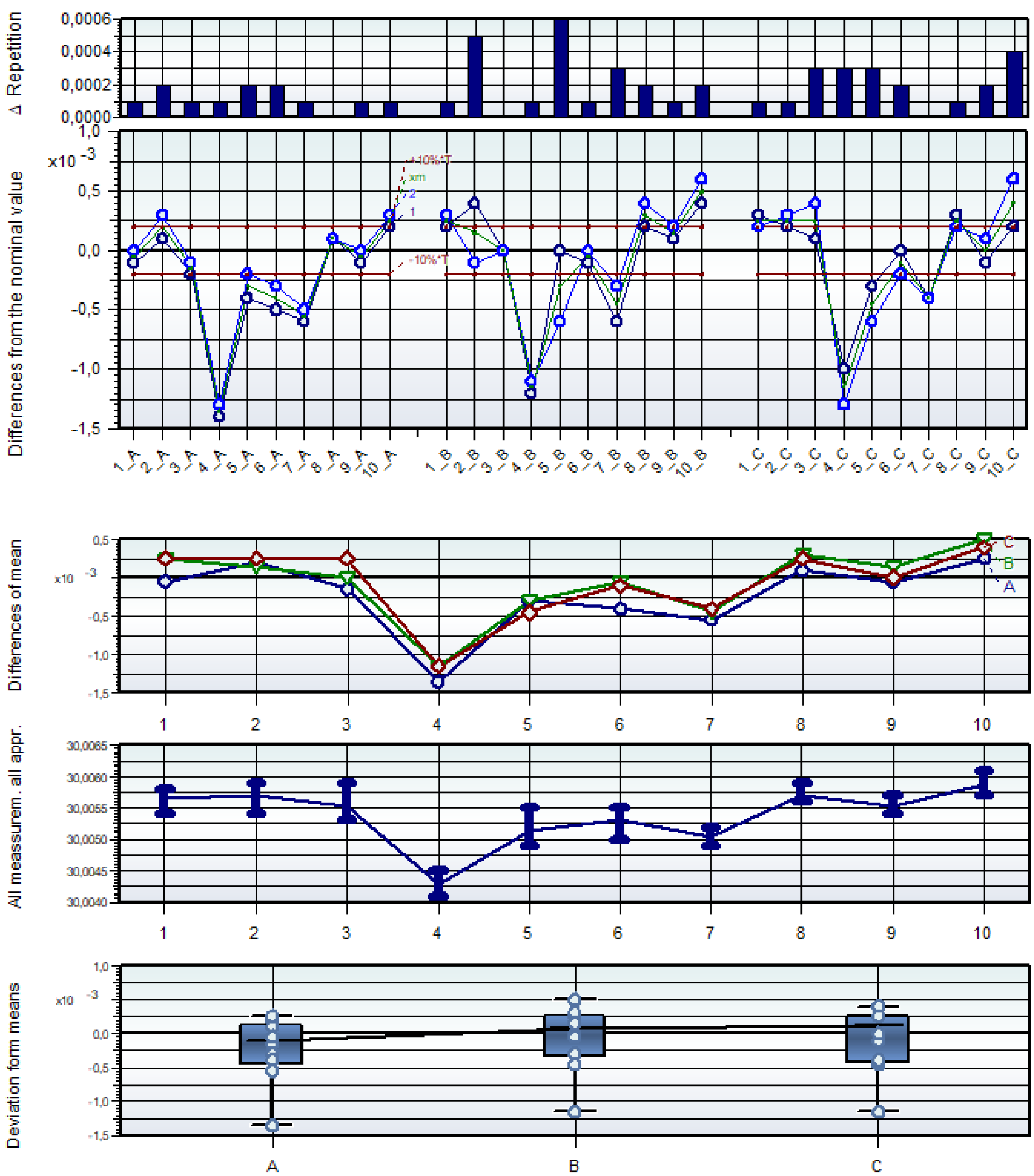
Optional the basis for RR can be defined on sheet T2. The default values are 4 standard deviations, which correspondents to a confidence level of 95,45%.

10	
11	RR/Q basis in s
12	4,000
13	4:95,45%; 5,152:99%; 6:99,73%
14	Cg basis s
15	4,000
16	4 : 95,45%; 6 : 99,73%

Number appraisers	
Number parts	
Number repetitions	

Only yellow marked cells should be defined. The number of appraisers, parts and repetitions were calculated through the data in sheet T1 by the macro.

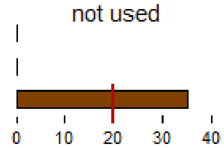
On the first page in the main-window the most important charts are shown. Here it is possible to regard the deviations between appraisers an parts.



The first results are on page 2 are equal to the standard ANOVA like in the MSA 4th Edition.

ANOVA with interactions

Reference : Tolerance	Tol	0,0020	resolution	0,0001	5,0%
					p-value
Repeatability	EV	6,053E-04	%EV	30,3	0,000
Appraiser	AV	3,568E-04	%AV	17,8	0,001
Interaction	IA	0,000E+00	%IA	0,0	not used
Part variation	PV	1,854E-03	%PV	92,7	
Total variation	TV	1,983E-03			
Meassurement-System	R&R	**7,026E-04**	%R&R (Tol)	**35,1**	
Number of distinct categories	ndc	3,7	required %R&R	20,0	



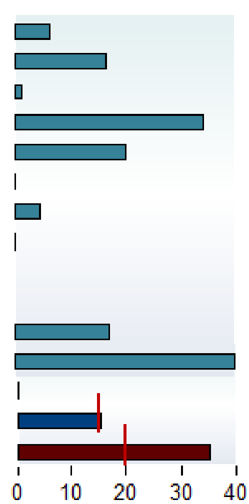
	DF	SS	MS	F	p-value
Part	9	1,181E-05	1,313E-06	71,742	0,000
Appraiser	2	3,640E-07	1,820E-07	9,948	0,001
Part*Appraiser	18	3,293E-07	1,829E-08	0,713	not used
Repeatability	30	7,700E-07	2,567E-08		
Total	59	1,328E-05			

ANOVA without interaction

	DF	SS	MS	F	p-value
Part	9	1,181E-05	1,313E-06	57,3100	0,000
Appraiser	2	3,640E-07	1,820E-07	7,9471	0,001
Repeatability	48	1,099E-06	2,290E-08		
Total	59	1,328E-05			

The next table shows the uncertainties of the VDA 5 / ISO 22514-7 definition, see introduction in the first section.

VDA 5 / ISO 22514-7		value / 1000
Resolution of gauge	u_{RE}	0,0289
Repeatability master	u_{EVR}	0,0738
Standard uncertainty (Bias)	u_{BI}	0,0058
Repeatability test-object	u_{EVO}	0,1513
Repeatability appraiser	u_{AV}	0,0892
Interaction	u_{IA}	0,0000
Calibration	u_{cal}	0,0200
Linearity	u_{lin}	0,0000
Uncertainty measurement	u_{MS}	0,0767
Uncertainty process	u_{MP}	0,1769
Measurement (reference to 4s, or 95,45%)	$\%Q_{MS\ (95,45\%)}$	**15,3**
	$\%Q_{MP\ (95,45\%)}$	**35,4**
Capability index (reference to 95,45%)	C_g	1,355
	C_{gk}	1,288



	value / 1000
Bi	0,0100

Vorg. 15
Vorg. 20

In templates without an underscore *_.vxg all data must be transferred via the clipboard, for example *Measurement_System_Analysis_GageR&R_Discrete.vxg*.

An overview of all methods can be found in *File/Templates/Measurement System Analysis.*