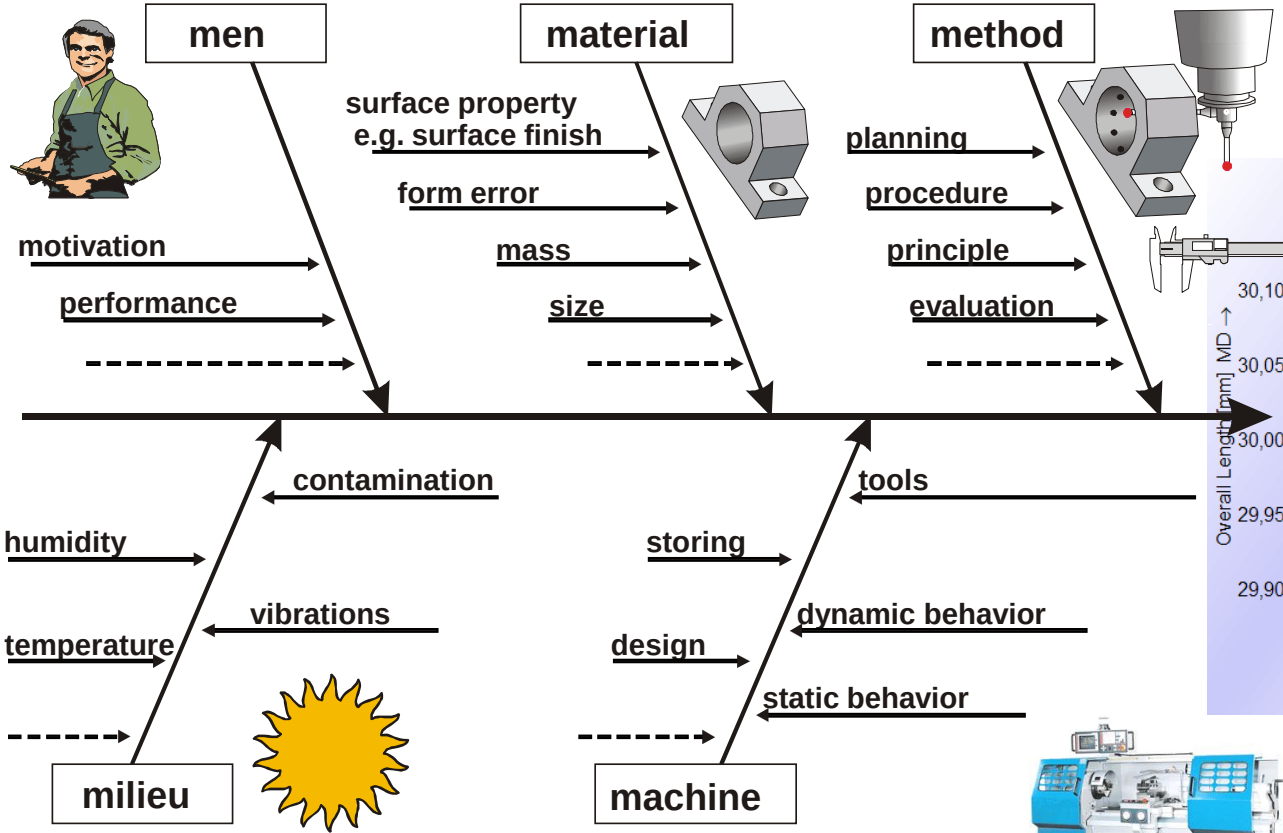
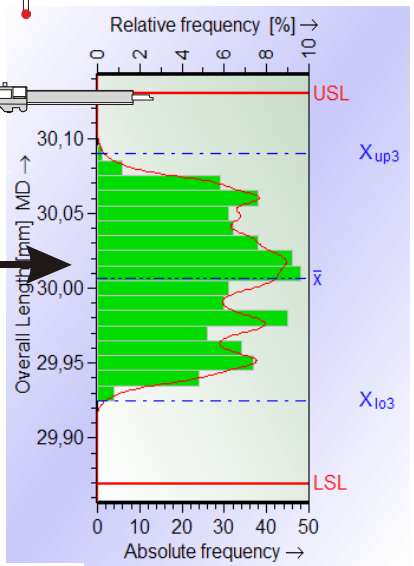
Machine and Process capability

Definition :

This document deals exclusively with production and assembly processes. A process is understood as a series of activities or procedures in which raw materials or pre-machined parts or components are further processed to generate a finished product.

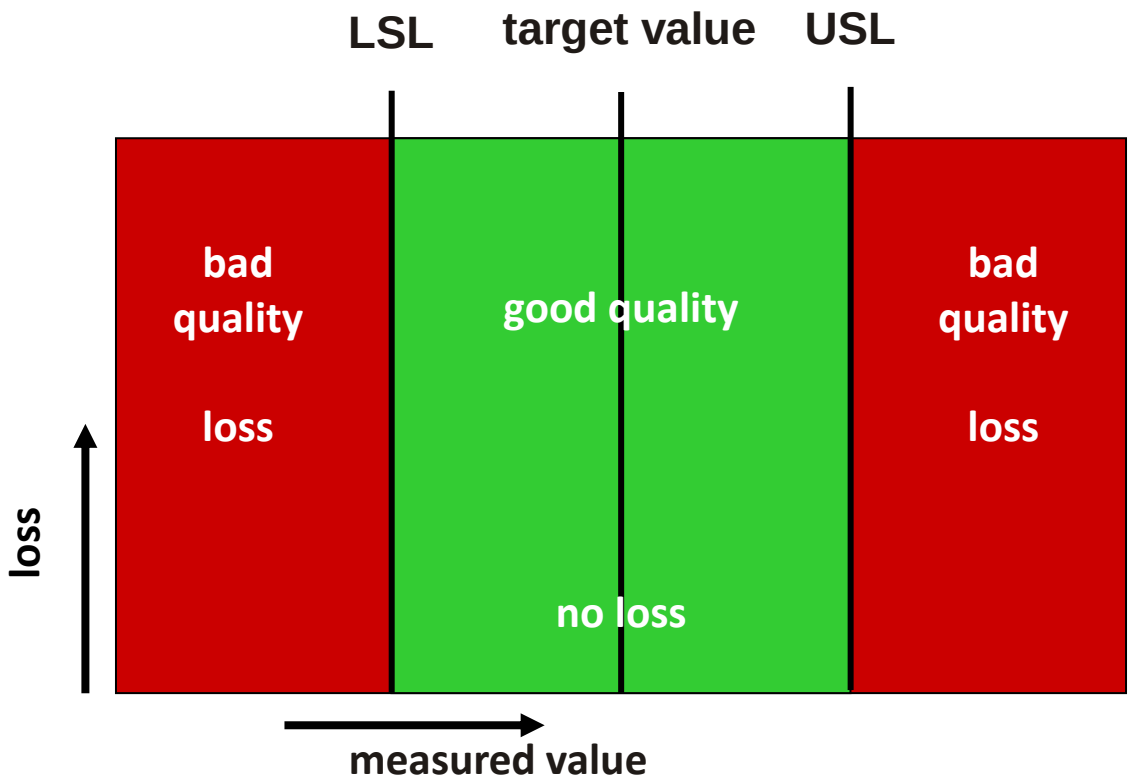
What Are the Reasons for Process Variation?





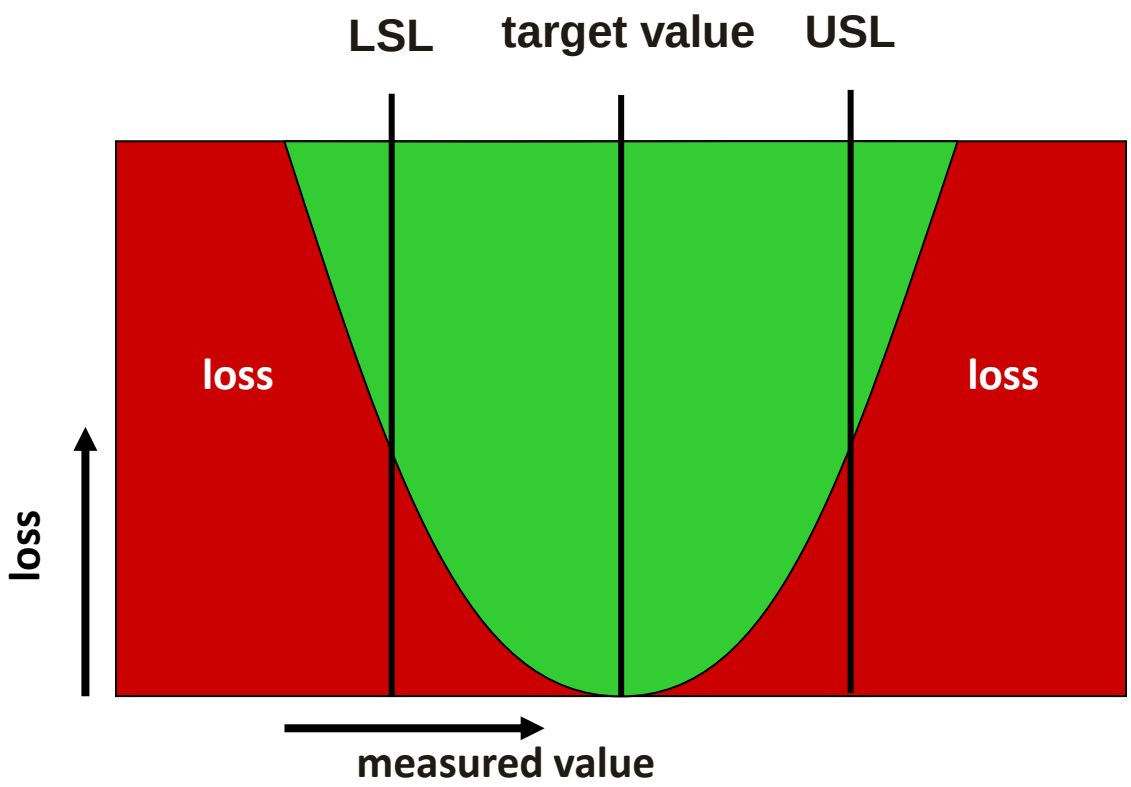
source: Pfeifer, T.: Fertigungsmeßtechnik, R. Oldenbourg Verlag, 1998

Process Evaluation Philosophies



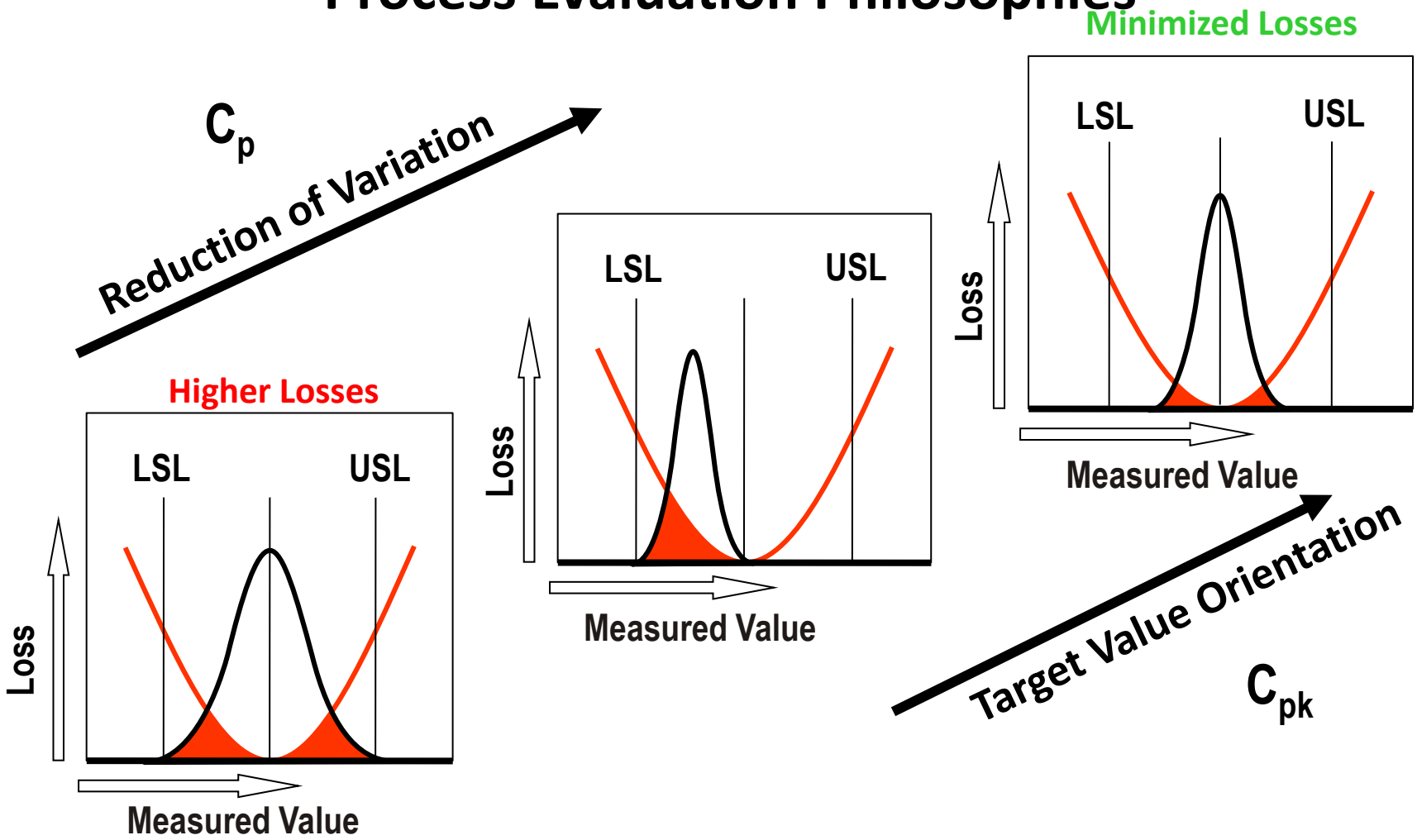
~~The tolerance belongs to the production!~~

Process Evaluation Philosophies

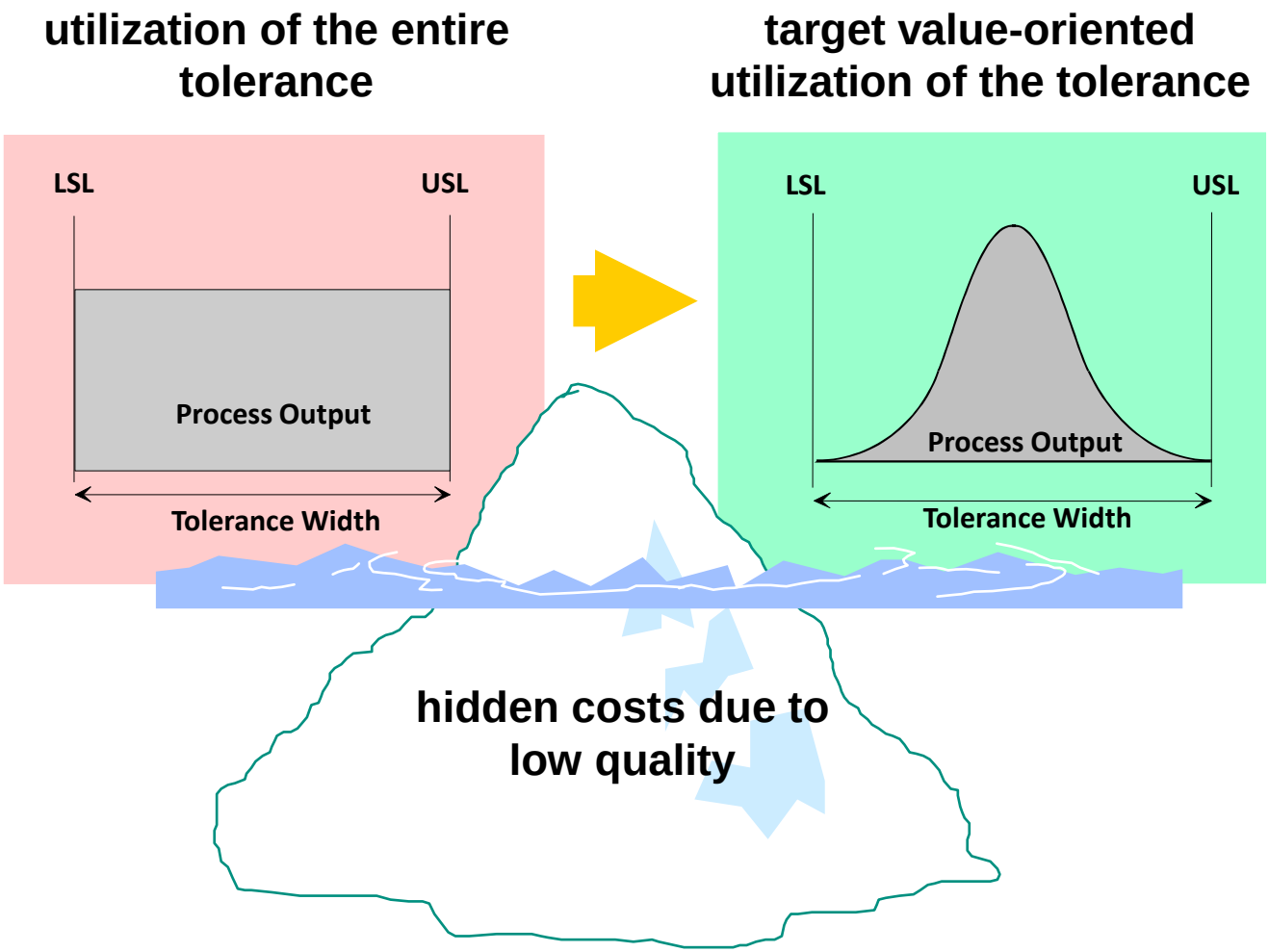


Taguchi loss function

Process Evaluation Philosophies



What follows from this?



- **Selection of Process and Characteristic**
  - Which product characteristics are important or relevant to the customer? Which ones are available for these specifications?
- **Measurability** of product characteristics
  - Are the measurement systems/measuring devices suitable to record the measurement values of the product characteristics with an appropriate degree of accuracy? (**measurement system analysis**)
- **Feasibility** of products
  - Are the machines/facilities suitable to produce products of appropriate quality? (**machine capability**)
- **Producibility** of products
  - Are we able to ensure the product quality over a longer period? (**process capability**)
- **Controllability** of processes
  - Do we know the process behavior sufficiently well in order to be able to react to changes in an appropriate way? (**quality control charts**)

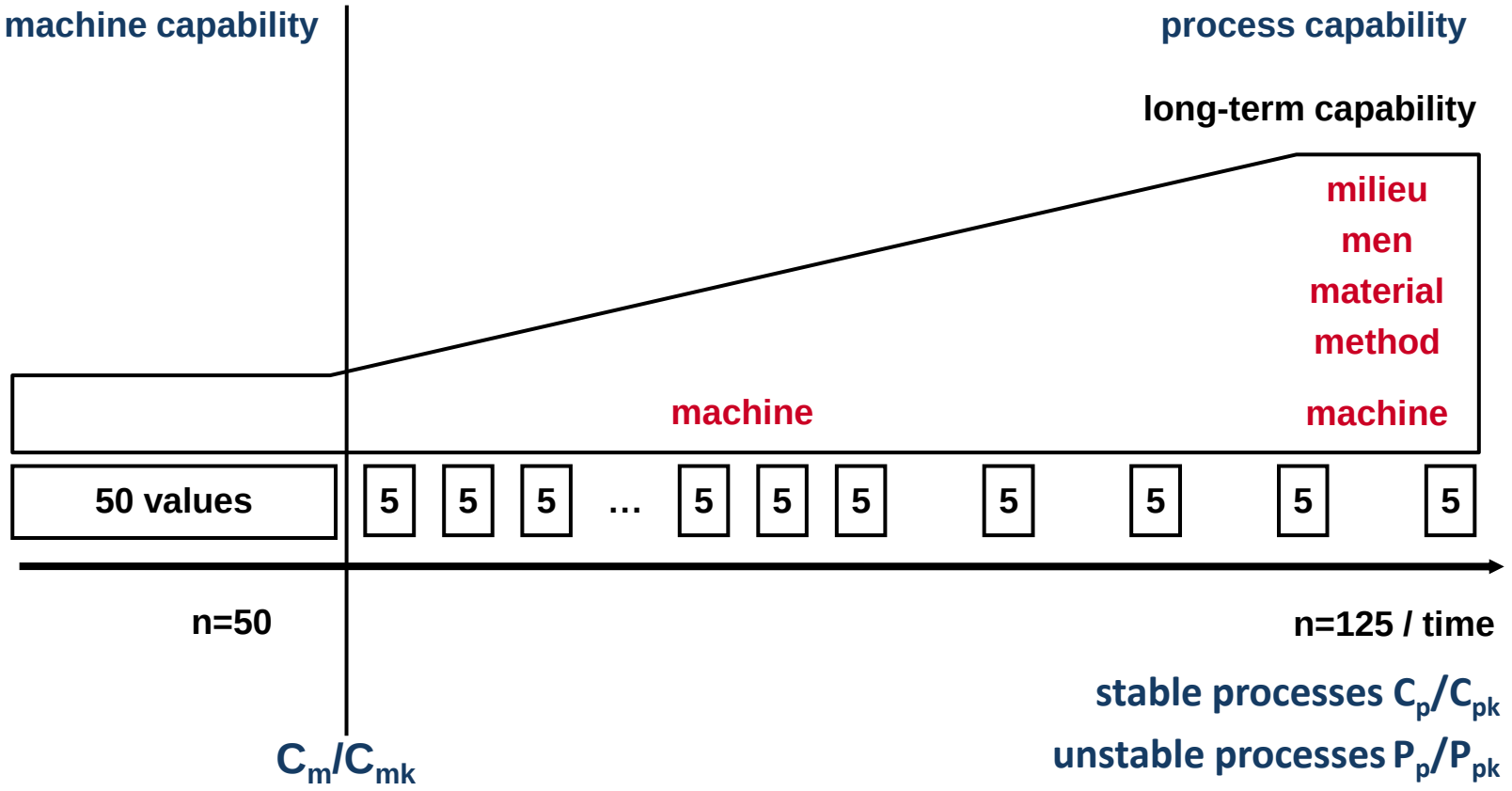
Capability indices according to Booklets

- **Measurement Process capability C_g/C_{gk}, %GRR**
  - procedure according to booklet 10 (training TQ038)

- **Machine capability C_m/C_{mk}**
  - procedure according to

- **Long-term capability/performance of a production process C_P/C_{PK} and P_P/P_{PK}**
  - procedure according to

Qualification Levels



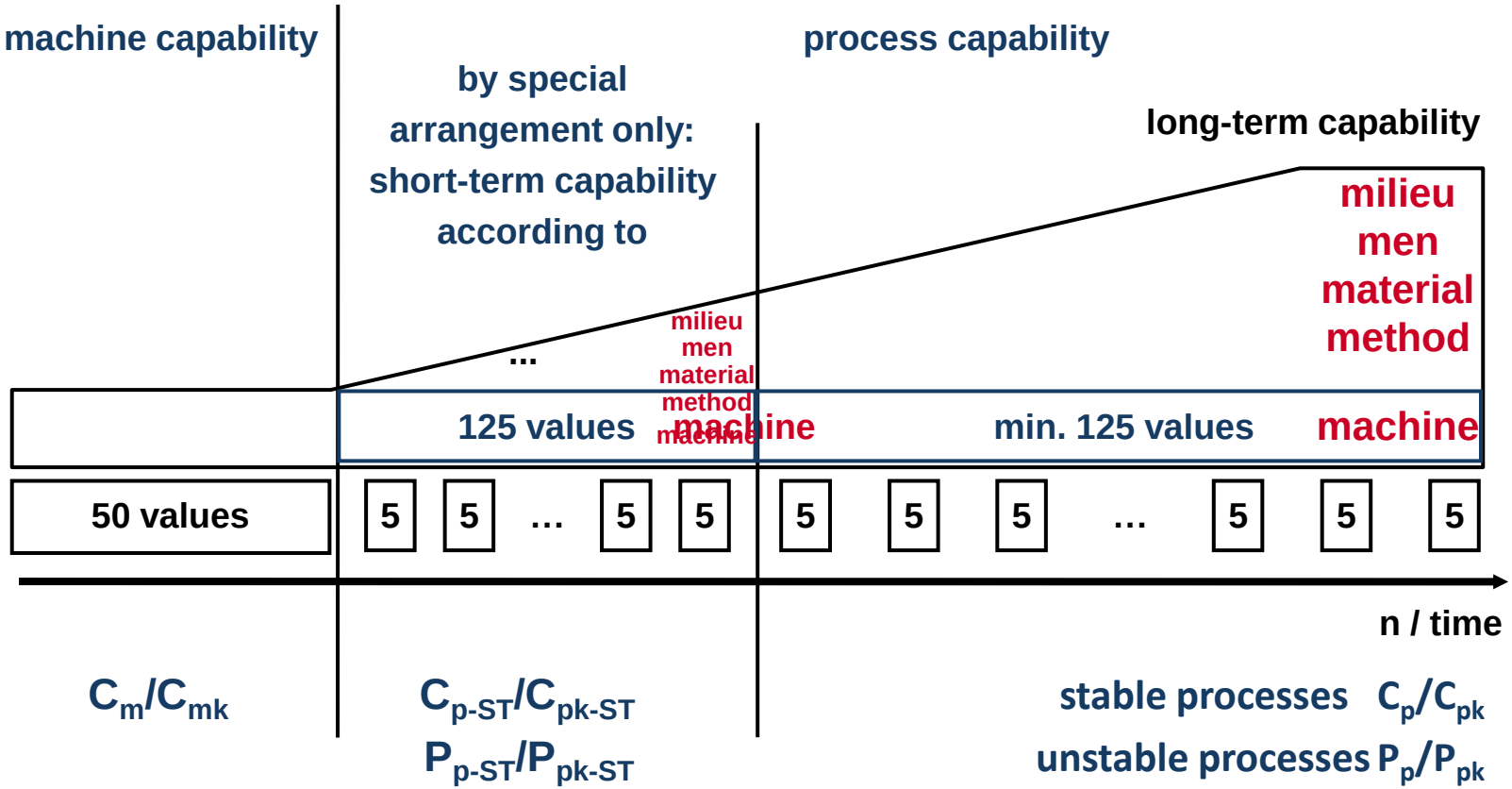
target values: 1.67 1.33

(2.0 in case of short acceptance)

Capability Indices

- **Measurement Process capability C_g/C_{gk}, %GRR**
- **Machine capability C_m/C_{mk}**
- **Short-term capability/performance of a production process $C_{p\text{-}ST}/C_{pk\text{-}ST}$ and $P_{p\text{-}ST}/P_{pk\text{-}ST}$ (not contained in , edition 2004)**
  - usually only conducted by particular arrangements (e.g. customer requirement)
  - preferably, parts should not be taken successively from the production process (all factors should affect the process)
  - however, contrary to long-term capability parts can be taken successively if too few parts are produced in total
  - products produced in the trial run are admissible upon agreement with customers or when no serial parts are available
  - calculation formulae as used for C_P/C_{pk} or P_P/P_{pk} according to
  - sample size n ≥ 125 and all statistical values $C_{xx\text{-}ST}/P_{xx\text{-}ST} \geq 1.67$
  - all reports must be marked as a result of a short term study
  - qs-STAT Module PCA Evaluation “ 2005 (Short Term / Kurzzeit)”
- **Long-term capability/performance of a production process C_P/C_{PK} and P_P/P_{PK}**

Qualification Levels



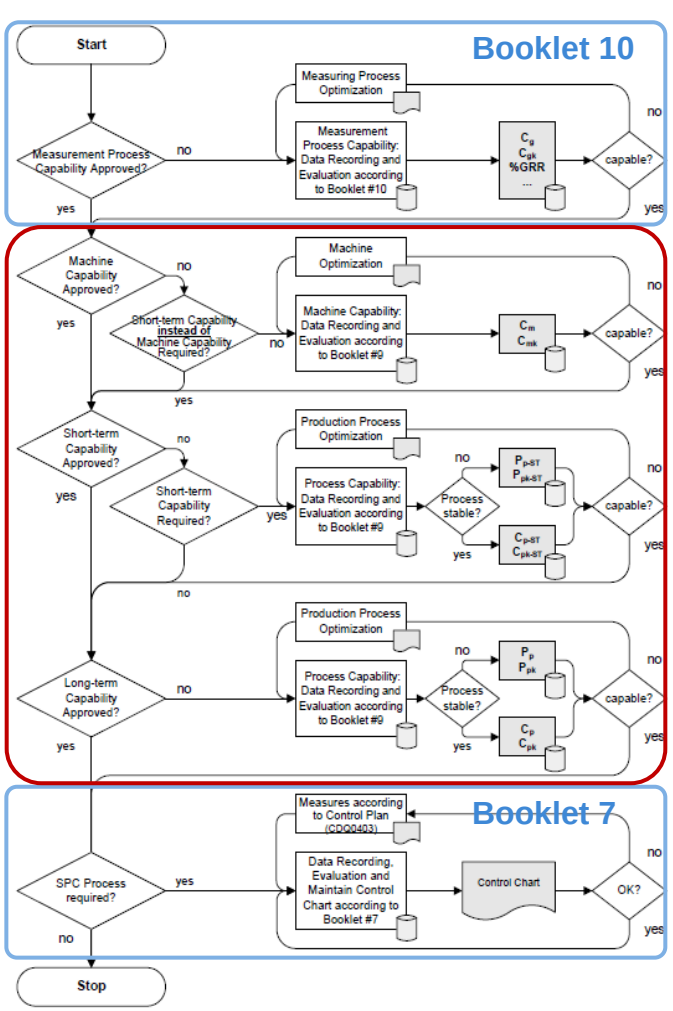
target values: 1.67 1.67 1.33

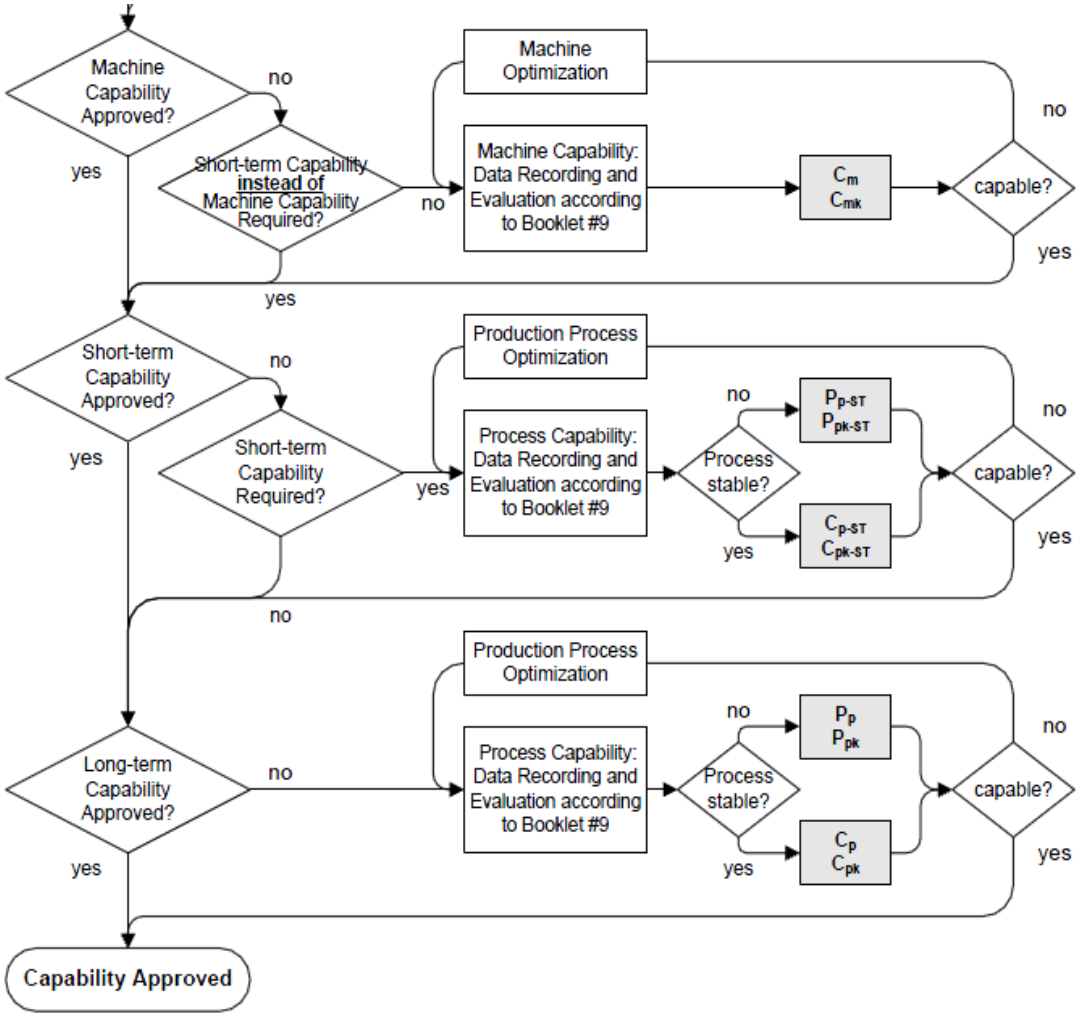
(2.0 in case of short acceptance)

Selection of Characteristics

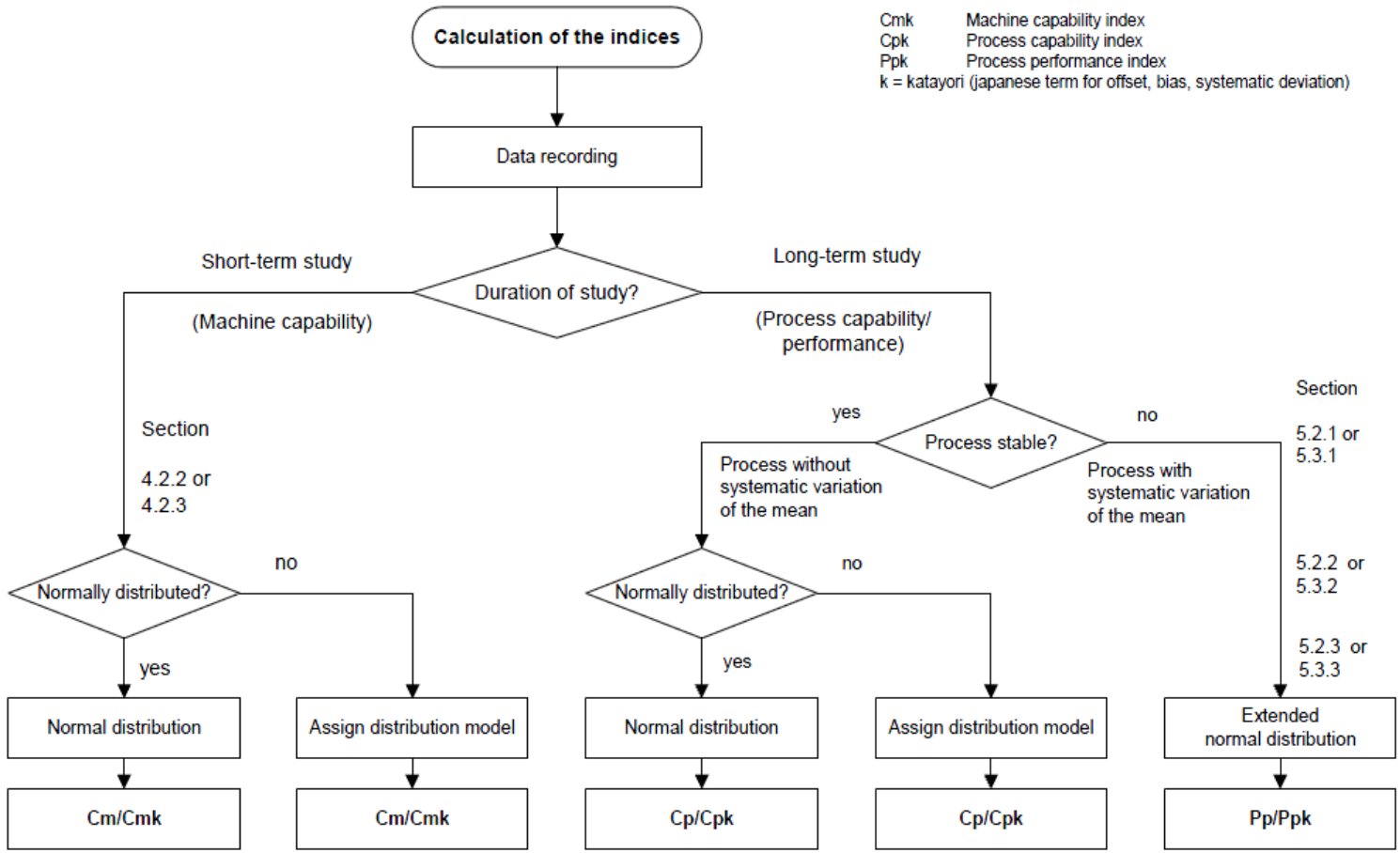
- SPC characteristics are mainly defined with regard to
  - customer preferences (customer requirements)
  - function (e.g. development requirements)
  - problems in the process (e.g. manufacturing engineering)
  - inspection (e.g. measurement technology)
  - safety (lawmaker)
- Quality characteristic (according to ISO 21747)
  - inherent characteristic of a product, process or system referring to a requirement
  - can be a product or process characteristic
- Determination
  - by an interdisciplinary team
    - e.g. simultaneous engineering, test planning team
  - e.g. from FMEA

Course of Investigation





3. Flow Chart for Machine and Process Capability Study



Schematic Illustration

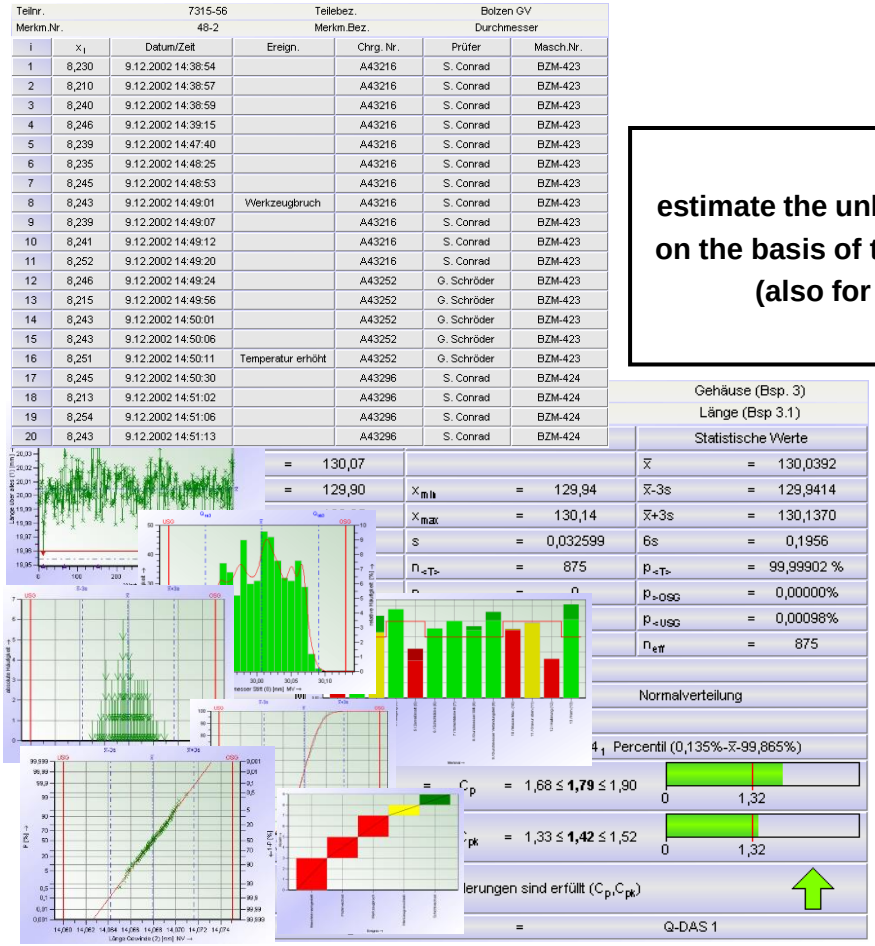
facts of ínterest

determine measurement data and additional information to be recorded

take random samples

record measurement data and additional information

data preparation in the form of tables graphics calculations



Teilnr.		7315-56	Teilebez.		Bolzen GV	
Merkm.Nr.		48-2	Merkm.Bez.		Durchmesser	
i	x_1	Datum/Zeit	Ereign.	Chrg. Nr.	Prüfer	Masch.Nr.
1	8,230	9.12.2002 14:38:54		A43216	S. Conrad	BZM-423
2	8,210	9.12.2002 14:38:57		A43216	S. Conrad	BZM-423
3	8,240	9.12.2002 14:38:59		A43216	S. Conrad	BZM-423
4	8,246	9.12.2002 14:39:15		A43216	S. Conrad	BZM-423
5	8,239	9.12.2002 14:47:40		A43216	S. Conrad	BZM-423
6	8,235	9.12.2002 14:48:25		A43216	S. Conrad	BZM-423
7	8,245	9.12.2002 14:48:53		A43216	S. Conrad	BZM-423
8	8,243	9.12.2002 14:49:01	Werkzeugbruch	A43216	S. Conrad	BZM-423
9	8,239	9.12.2002 14:49:07		A43216	S. Conrad	BZM-423
10	8,241	9.12.2002 14:49:12		A43216	S. Conrad	BZM-423
11	8,252	9.12.2002 14:49:20		A43216	S. Conrad	BZM-423
12	8,246	9.12.2002 14:49:24		A43252	G. Schröder	BZM-423
13	8,215	9.12.2002 14:49:56		A43252	G. Schröder	BZM-423
14	8,243	9.12.2002 14:50:01		A43252	G. Schröder	BZM-423
15	8,243	9.12.2002 14:50:06		A43252	G. Schröder	BZM-423
16	8,251	9.12.2002 14:50:11	Temperatur erhöht	A43252	G. Schröder	BZM-423
17	8,245	9.12.2002 14:50:30		A43296	S. Conrad	BZM-424
18	8,213	9.12.2002 14:51:02		A43296	S. Conrad	BZM-424
19	8,254	9.12.2002 14:51:06		A43296	S. Conrad	BZM-424
20	8,243	9.12.2002 14:51:13		A43296	S. Conrad	BZM-424

estimate the unknown population on the basis of the known sample (also for the future)

➔ **Definition :**

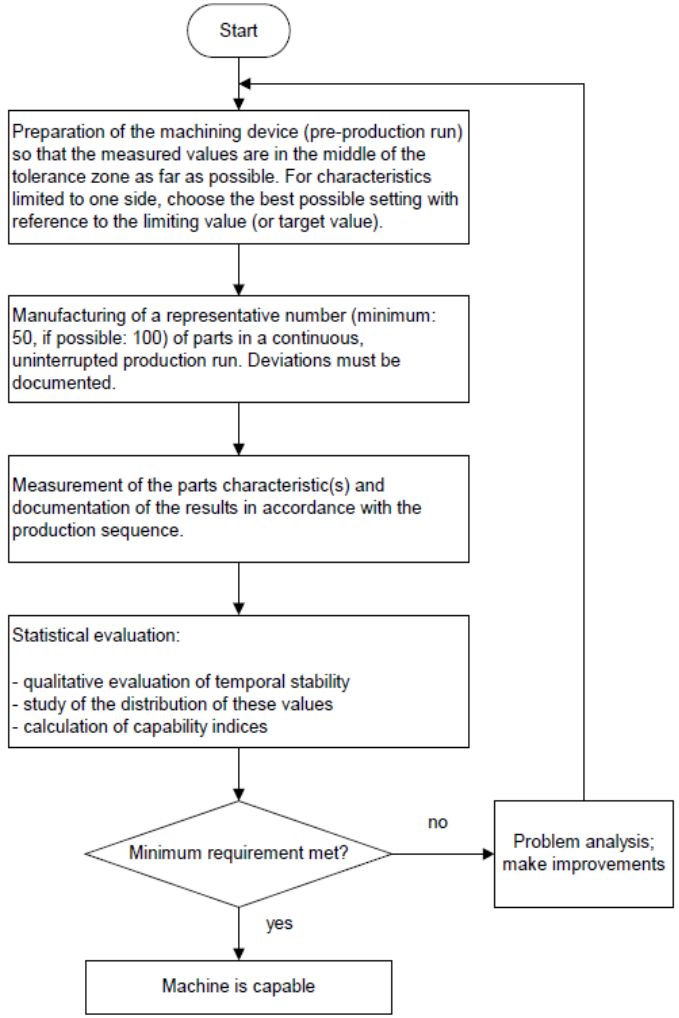
The machine capability study is a short-term study with the sole aim of discovering the machine-specific effects on the production process.

➔ **Application:**

- **at the manufacturer‘s in case of a new acquisition, purchase decision**
- **for acceptance after the installation at the destination**
- **when starting a production process that produces new products**

Machine Capability Study (MCS)

- Prepare machine
- Adjust tolerance center or target value (in case of unilateral characteristics)
- Produce representative number of parts
- Continuous and ongoing production flow
- Measurements according to the respective production sequence
- Statistical evaluation
  - qualitative evaluation of stability over time
  - inspection of the distribution
  - calculation of capability indices



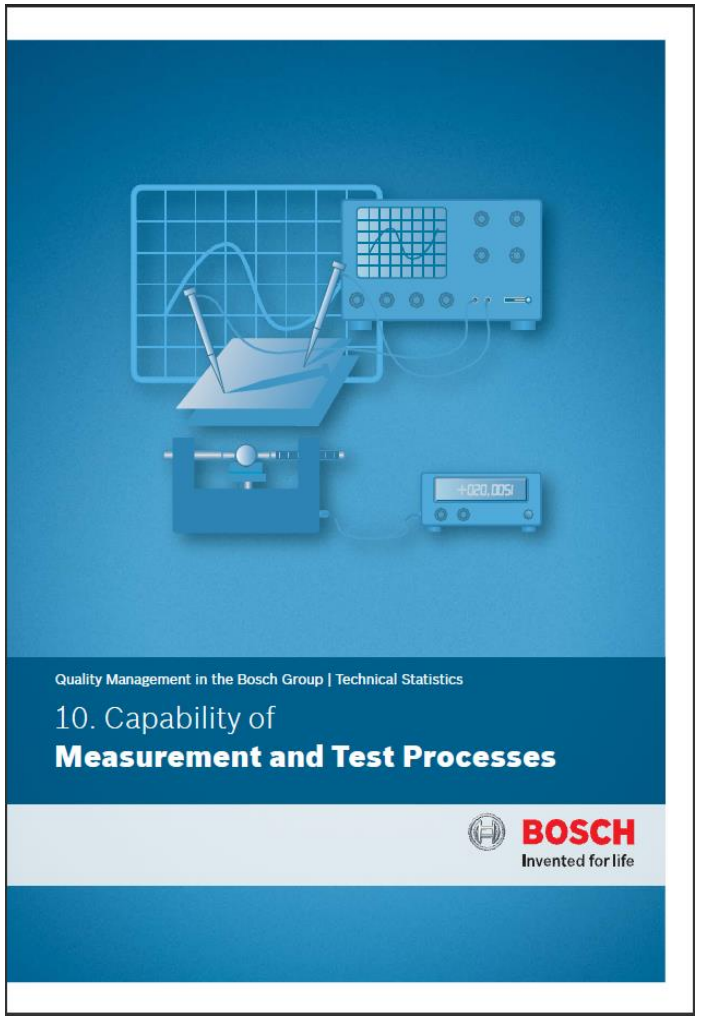
MCS – Acceptance Procedure

- Organizational preparations
  - inter-divisional acceptance team
    - quality
    - production
    - construction
    - metrology and test engineering
  - knowledge of statistical methods
  - determination of analysis methods and tools (guidelines und software)
    - guidelines and directives
    - software and evaluation strategy
    - particular formalities (process owner/project leader)
  - involvement of suppliers and subcontractors

MCS – Acceptance Procedure

- Planning of the machine acceptance
  - schedule, tasks and responsibilities
  - number of required parts
    - provision of parts by the customer
    - quality of raw materials/rough machining
  - confirmation of the test plan
    - determination of the types and classes of characteristics
  - special regulation
    - particular characteristics
    - special target values
  - verification of error prevention measures/process conditions
    - error proofing/process monitoring
    - fault simulation/rejection logic
  - determination of the sampling

- Capability of measurement and test processes
  - try to use the measuring and test equipment that will also be applied in the process
  - discuss alternate measuring devices with customers
  - capability study according to booklet 10 or
    - AIAG Quality Core Tool MSA
    - VDA Volume 5
    - customer guidelines



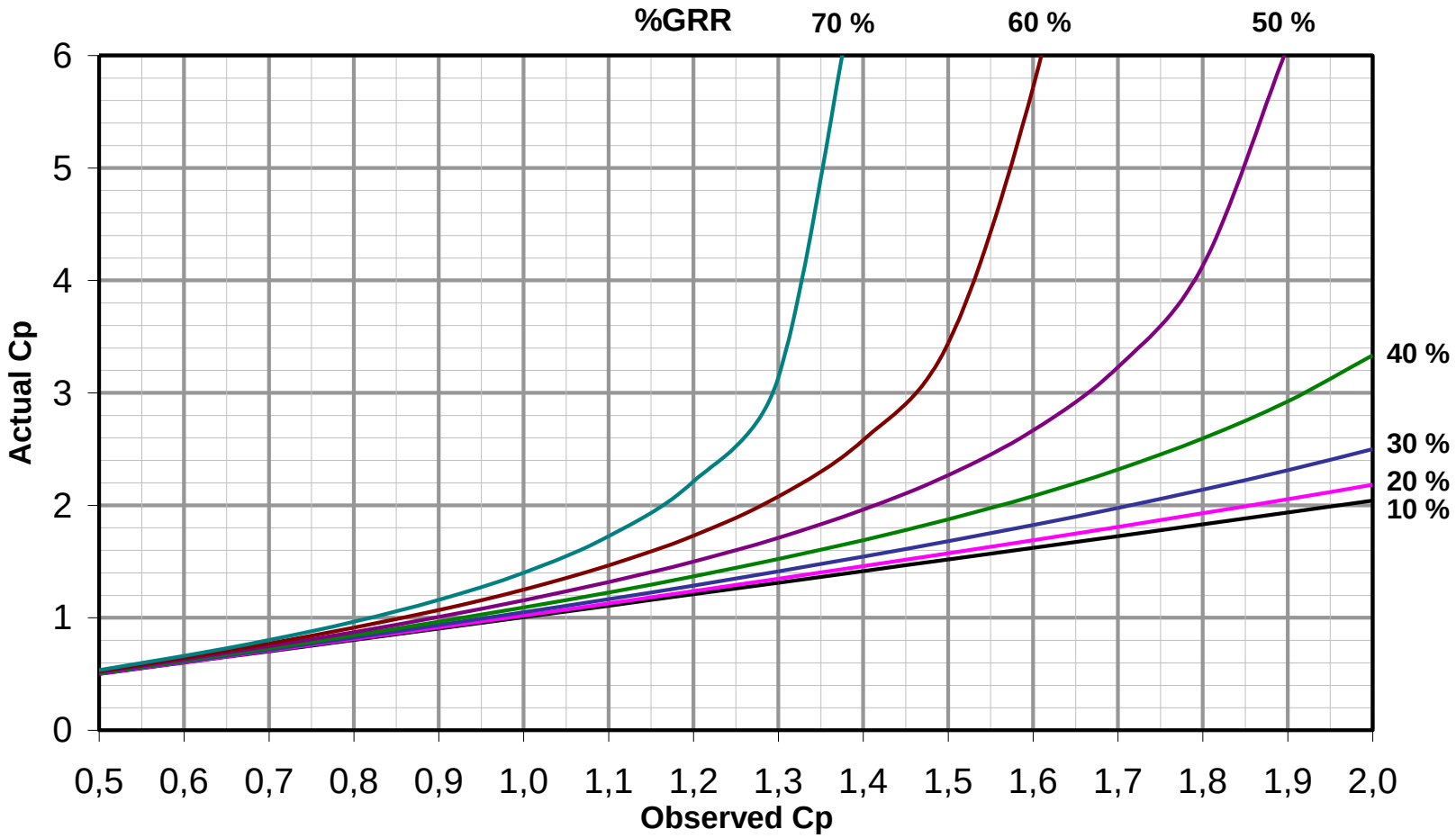
$$\sigma^2_{observed} = \sigma^2_{actual} + \sigma^2_{measuring\ system}$$

observed process variation

actual process variation

variation of the measuring system

Impacts on process capability!

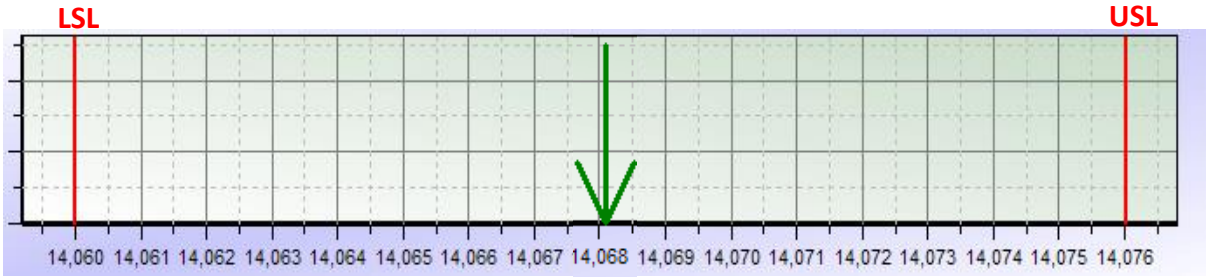

%GRR
70 %
60 %
50 %
40 %
30 %
20 %
10 %
Actual Cp
Observed Cp
0
1
2
3
4
5
6
0,5
0,6
0,7
0,8
0,9
1,0
1,1
1,2
1,3
1,4
1,5
1,6
1,7
1,8
1,9
2,0

- Machine preparation and adjustment
  - durability test
    - running time from 8 to 24 hours, same parameters as in production
    - reliability of mechanics and controls
    - error proofing, test error display and diagnostics procedure
    - provide documentation
  - handling of parts
    - take, transport, drop parts
    - highlight 5 parts, inspect alignment, locating and clamping points and transport supports
    - check for damages
  - cold start test
    - initial situation is the same as at the end of a shift
    - produce at least 5 parts in the cold start phase of the machine

- Machine preparation and adjustment (continued)
  - trial run test in order to adjust the machine
    - 1 part/ 5 parts test (exemplary)

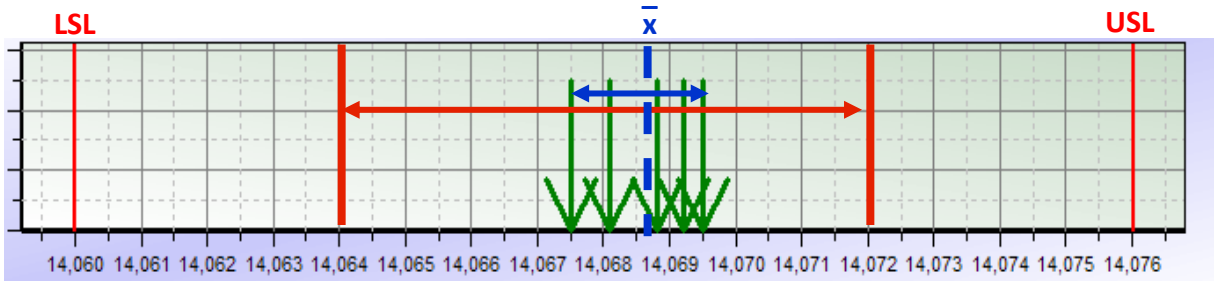
2005

Char.No.	Char.Descr.	LSL	USL	x	x-T_m	Require
1	Shaft Diameter #2	14.0600	14.0750	14,0681	0.000600	☺



value within 100% T

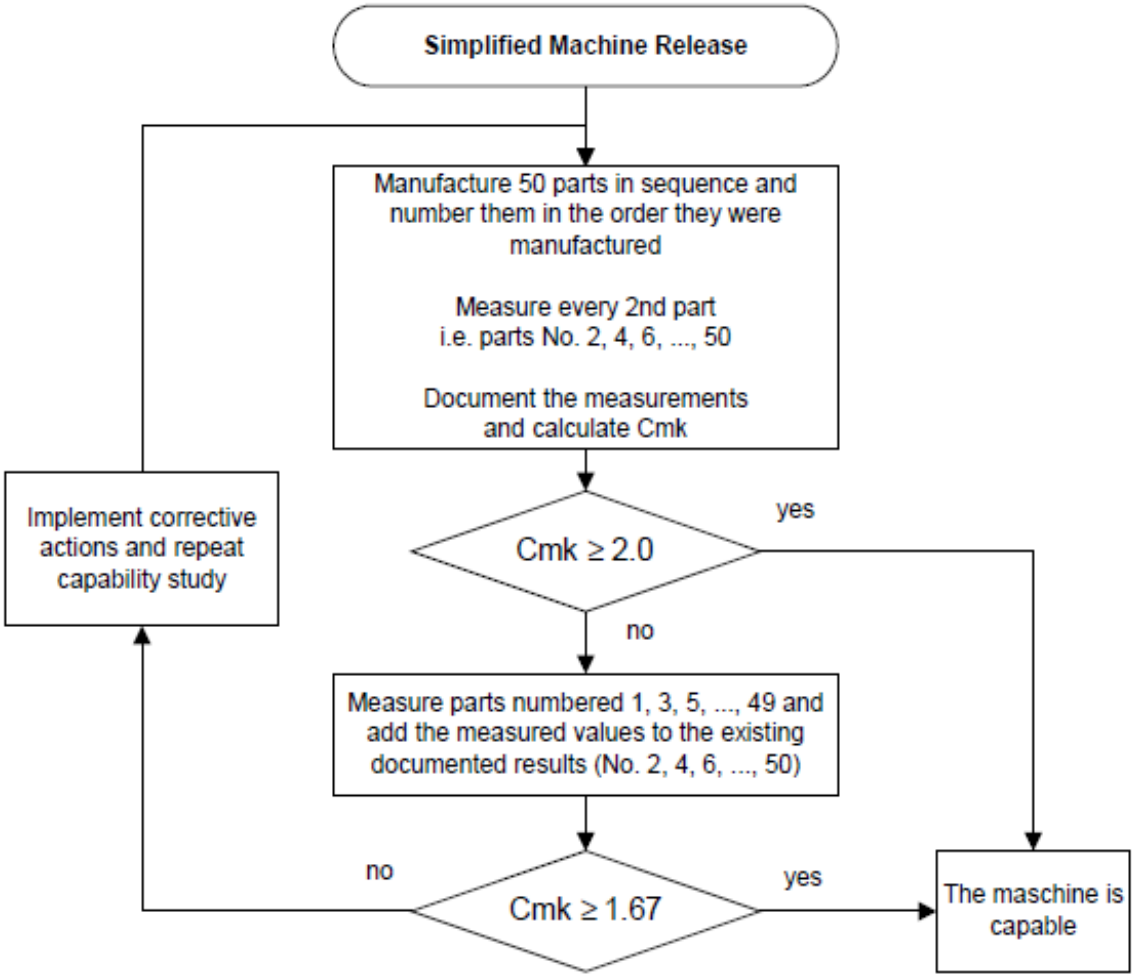
Char.No.	Char.Descr.	LSL	USL	$\bar{x}$	R/T	$\bar{x}$-T_m	Requirer
1	Shaft Diameter #2	14.0600	14.0750	14.06862(	13.33%	0.00112	☺



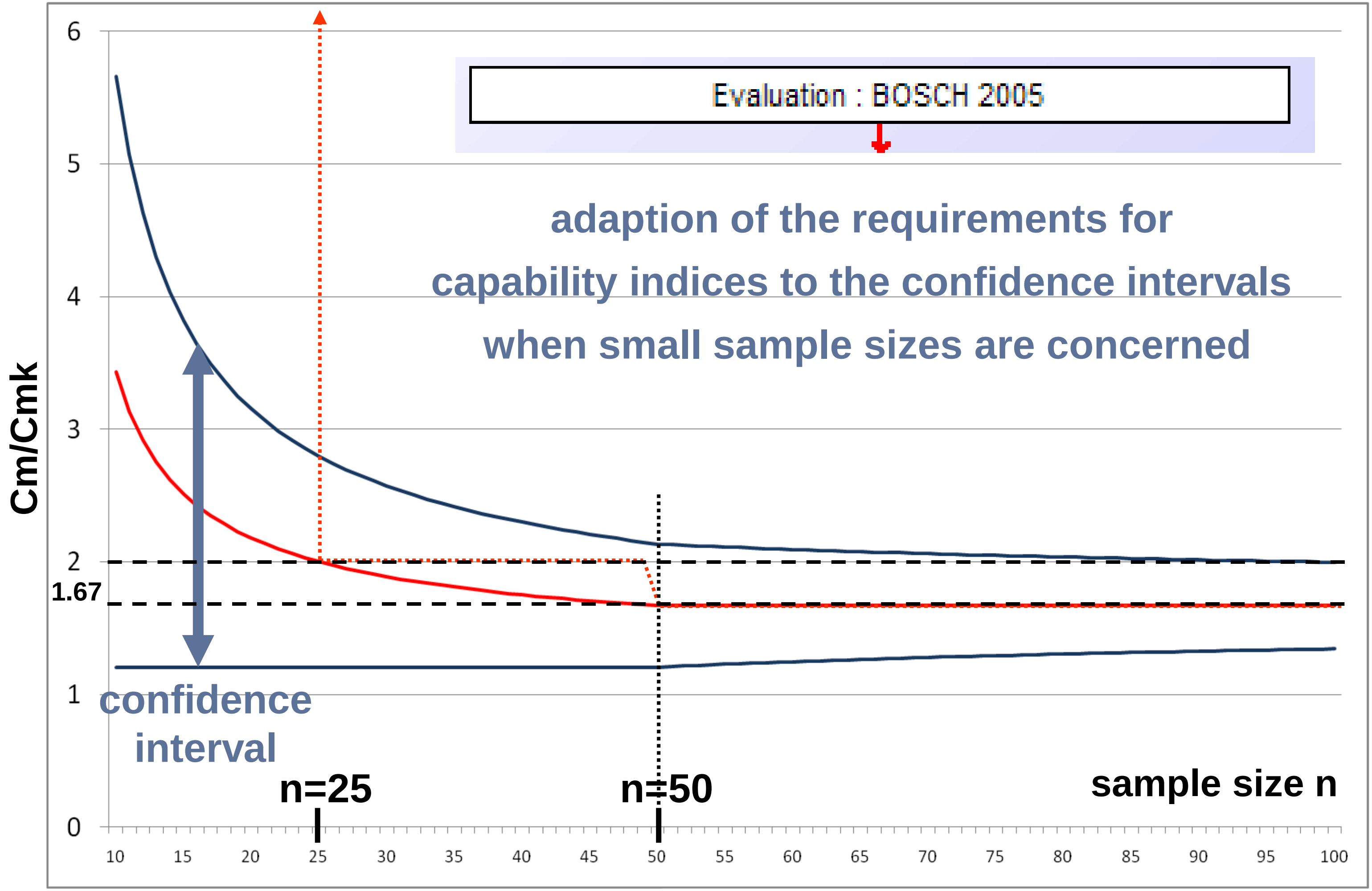
average within and range less than 50% T

- Machine at operating state temperature
- Set to working parameters
- Parts can clearly be identified and are recorded in machining sequence
- Continuous run
- Number of parts: typically 100, at least 50
- Transport of pallets
  - test all pallets for dimensions
  - selection of samples for machine acceptance
- Each station is treated like a separate machine
- Machining centers in combination with tool holders/pallets
  - optimization strategy (number of parts)

Machine Capability with Reduced Expense



Adaption of Capability Indices in MCS



- **Definition (, Page 14):**

The process capability study is a long-term study that is conducted over an extended operating time and includes sources of variation external to a machine.

These sources are typically summarized under the headings of Man, Machine, Material, Method and Environment (Milieu).

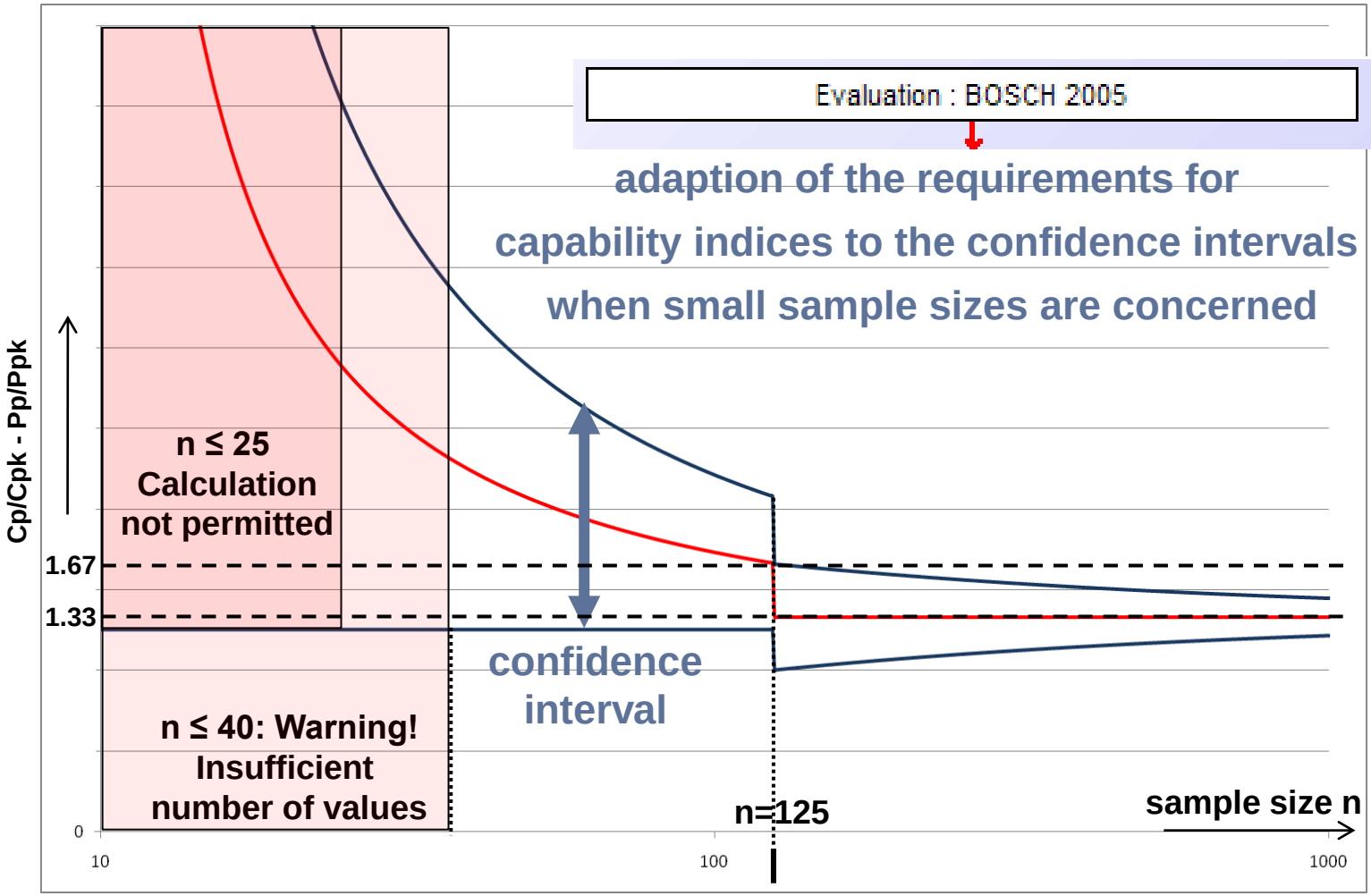
5.1 Procedure

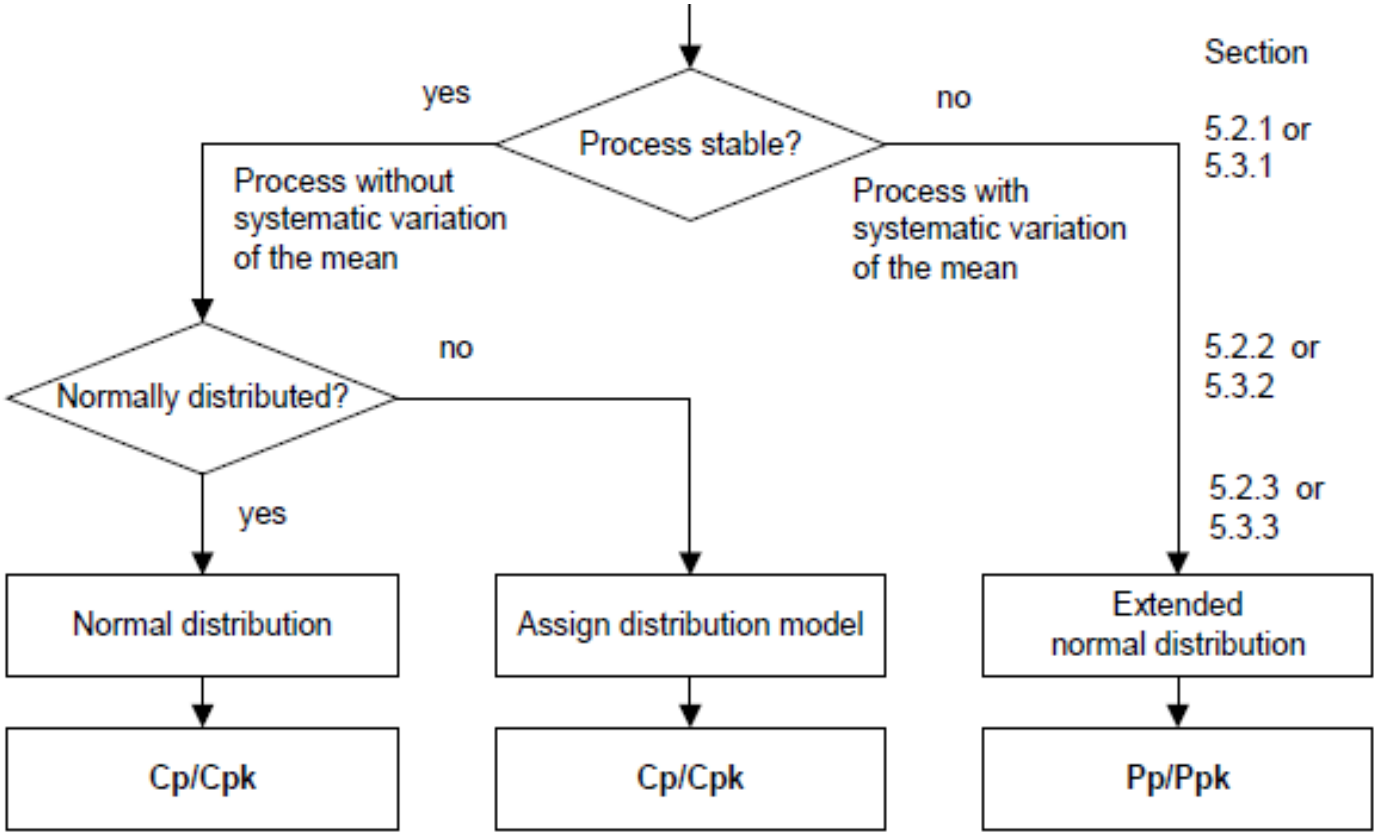
A process capability study includes the following steps:

- Select parts from series production in "rational" samples (not sorted); at least 25 subgroups should be evaluated. The preferred sample size is n = 5. Overall, at least 125 parts should be examinded.
- Measure part characteristics and record the results along with production sequence.
- Statistical evaluation of the data: Evaluate temporal stability and statistical distribution. Calculate capability indices.

Note: In special cases, use of fewer than 125 parts may be unavoidable due to time or cost of making the necessary measurements, or if the test is destructive. Smaller sample sizes lead to larger confidence intervals of the characteristic(s) being studied. In turn, this reduces the accuracy of the conclusions that may be drawn from the data. The quality assurance office must be consulted before the sample size is reduced.

Adaption of Capability Indices in PCS




Process stable?
yes
no
Process without systematic variation of the mean
Process with systematic variation of the mean
Section
5.2.1 or 5.3.1
Normally distributed?
no
yes
5.2.2 or 5.3.2
5.2.3 or 5.3.3
Normal distribution
Assign distribution model
Extended normal distribution
Cp/Cpk
Cp/Cpk
Pp/Ppk

variance-analytical

(Menu Numerics/Test procedures/ANOVA)

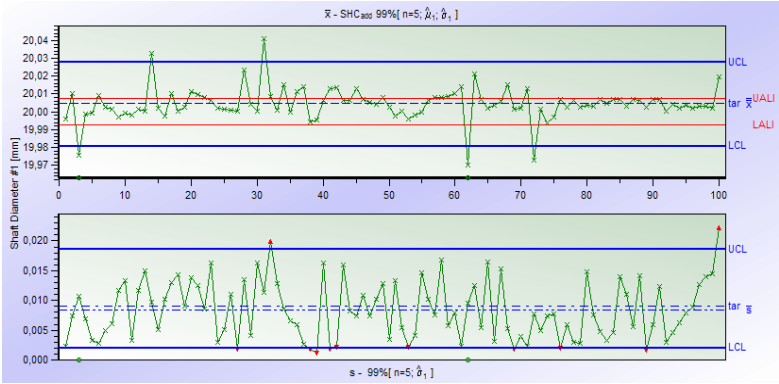
ANOVA			
Variation within subgroups	=	s_I^2	0.000093687
Additional variation between subgroups	=	s_A^2	0.000064438
Proportion of additional variation between subgroups	=	s_A^2/s_{tot}^2	0.41

H_0	Variation between subgroups is zero
H_1	Variance between subgroups is NOT zero

Test level	critical values lower	critical values upper	Test statistics
α = 5 %	---	1.28	4.43899***
α = 1 %	---	1.42	
α = 0.1 %	---	1.59	
Test results	Null hypothesis rejected at level $\alpha \leq 0{,}1\%$		

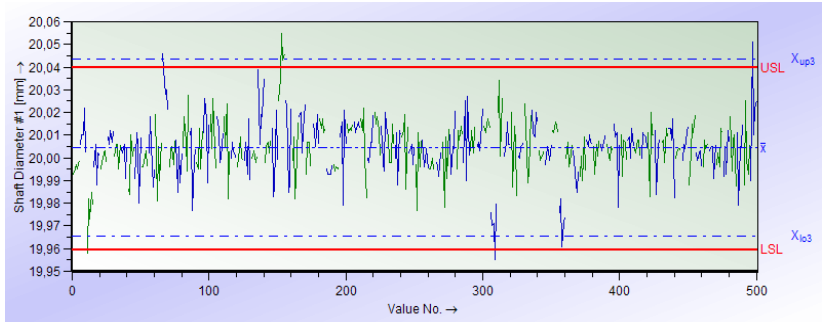
using quality control chart

(Menu QCC/ Analysis QCC or F8)



using individual value display

(Menu Individuals / Value chart or F2)




Get an
idea of your
data...

Value Chart

Part no.	1	Part descr.	Test 2
Char.No.	1	Char.Descr.	Shaft Diameter #2

i	x_i	Date/Time	i	x_i	Date/Time	i	x_i	Date/Time
1	14,0681	1992-05-07 13:43:08	11	14,0675	1992-05-07 13:44:10	21	14,0692	1992-05-07 13:45:30
2	14,0688	1992-05-07 13:43:28	12	14,0677	1992-05-07 13:44:12	22	14,0677	1992-05-07 13:45:32
3	14,0675	1992-05-07 13:43:32	13	14,0681	1992-05-07 13:44:14	23	14,0685	1992-05-07 13:45:36
4	14,0695	1992-05-07 13:43:36	14	14,0680	1992-05-07 13:44:14	24	14,0671	1992-05-07 13:45:38
5	14,0692	1992-05-07 13:43:38	15	14,0688	1992-05-07 13:44:16	25	14,0669	1992-05-07 13:45:40
6	14,							
7	14,							
8	14,							
9	14,							
10	14,							
i								
31	14,							
32	14,							
33	14,							
34	14,							
35	14,							
36	14,							
37	14,							
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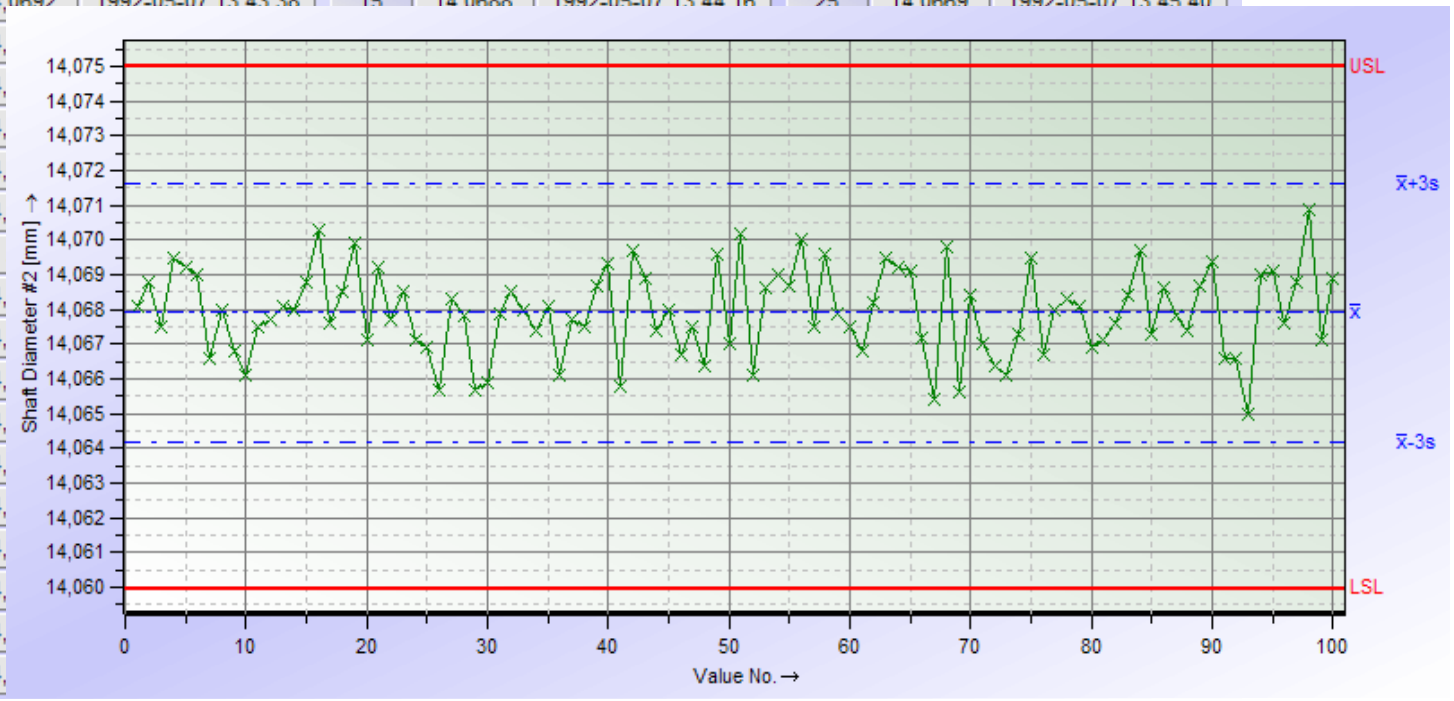
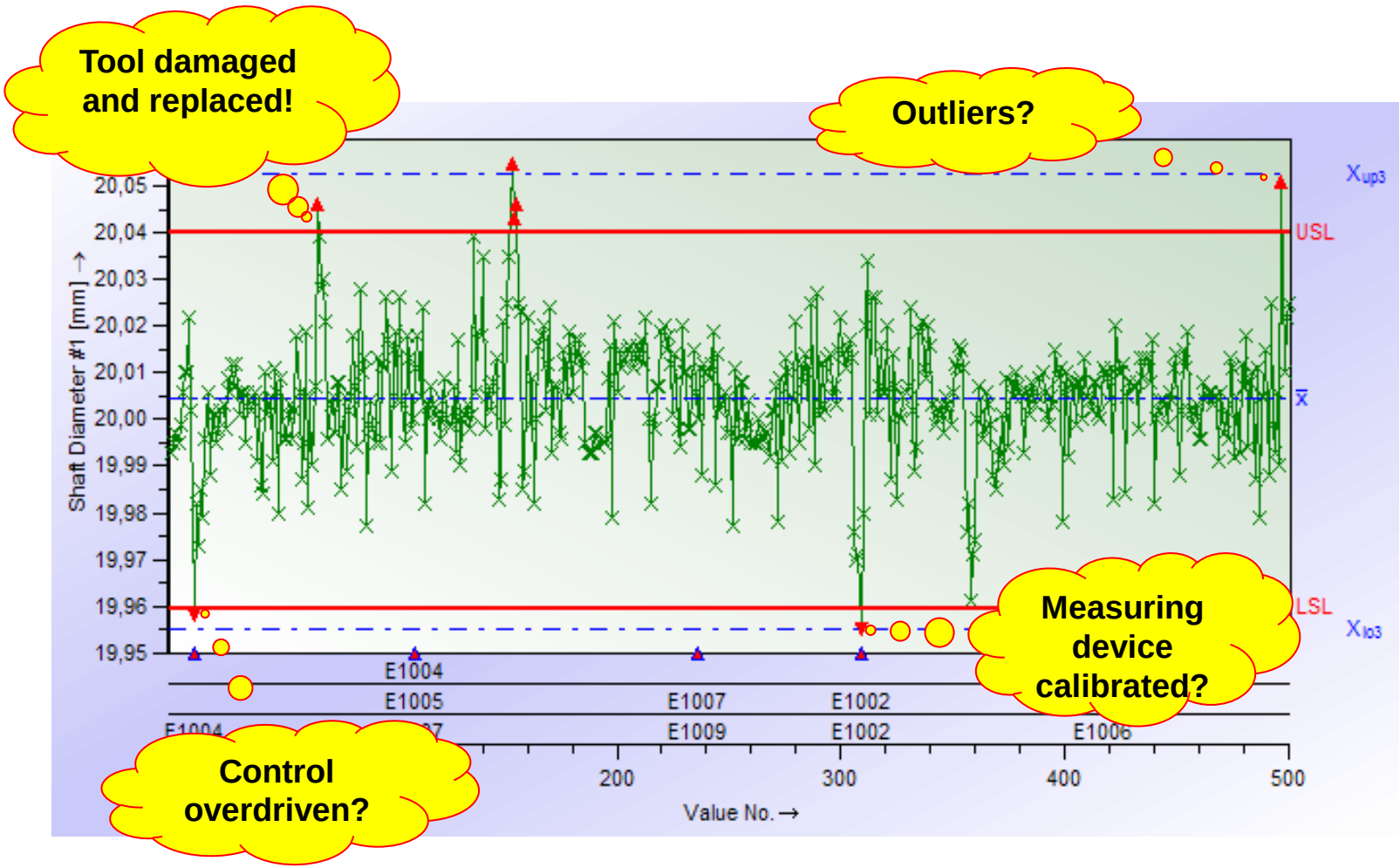
39	14,							
40	14,							



Is the Process Stable?



- Date and time of the recording of the measured values
- Inspector, appraiser, operator
- Machine
- Cavity (clamping point / spindle / casting mold ...)
- Measuring and test equipment
- Events, measures, causes
- Batch (part ID number / serial number /...)
- Reworking measures
- Condition of the raw parts
- ...

➔ Machine settings

- (rotational) speed
- feed
- tools
- cycle times
- coolant flow/temperature
- …

➔ Parts-related process parameters

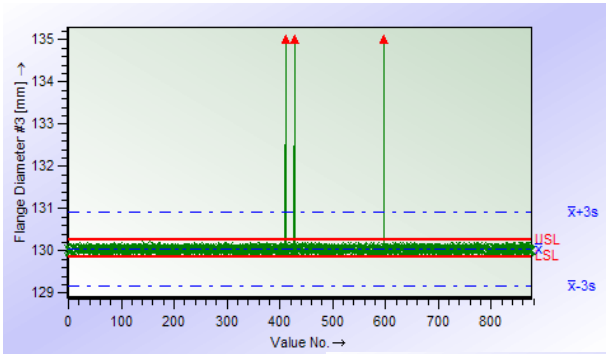
- semi-finished parts, raw parts
- condition and quality of the rough-machined parts
- process warm-up time prior to the sampling
- …

➔ Environment

- room temperature
- humidity
- air pressure
- building vibrations (location, floor)
- …

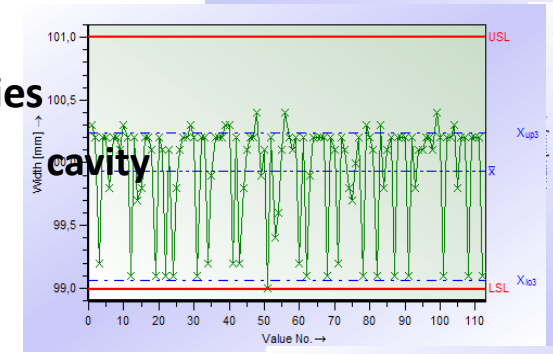
➔ **Outlier**

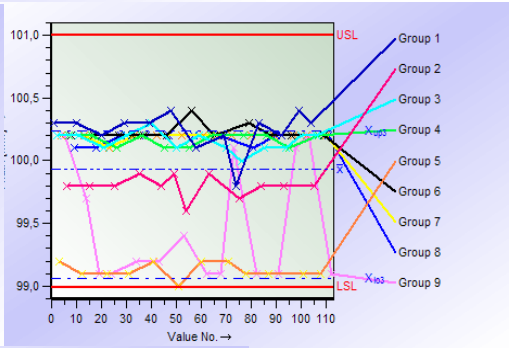
- **solution: monitor the input with the help of plausibility limits**



➔ **Blend of different cavities**

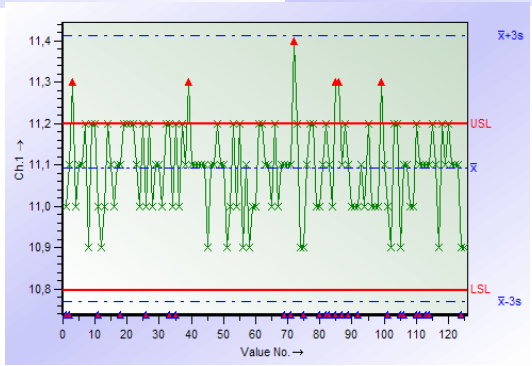
- **solution: evaluate each cavity separately**



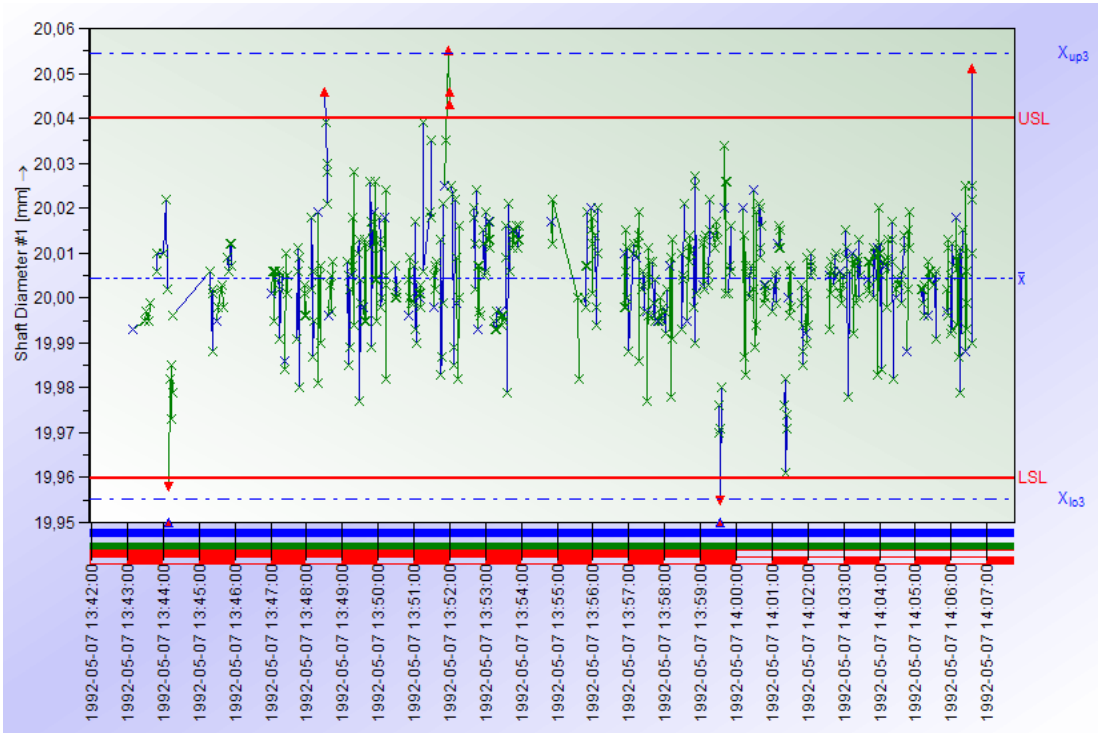


➔ **Measuring system – bad resolution**

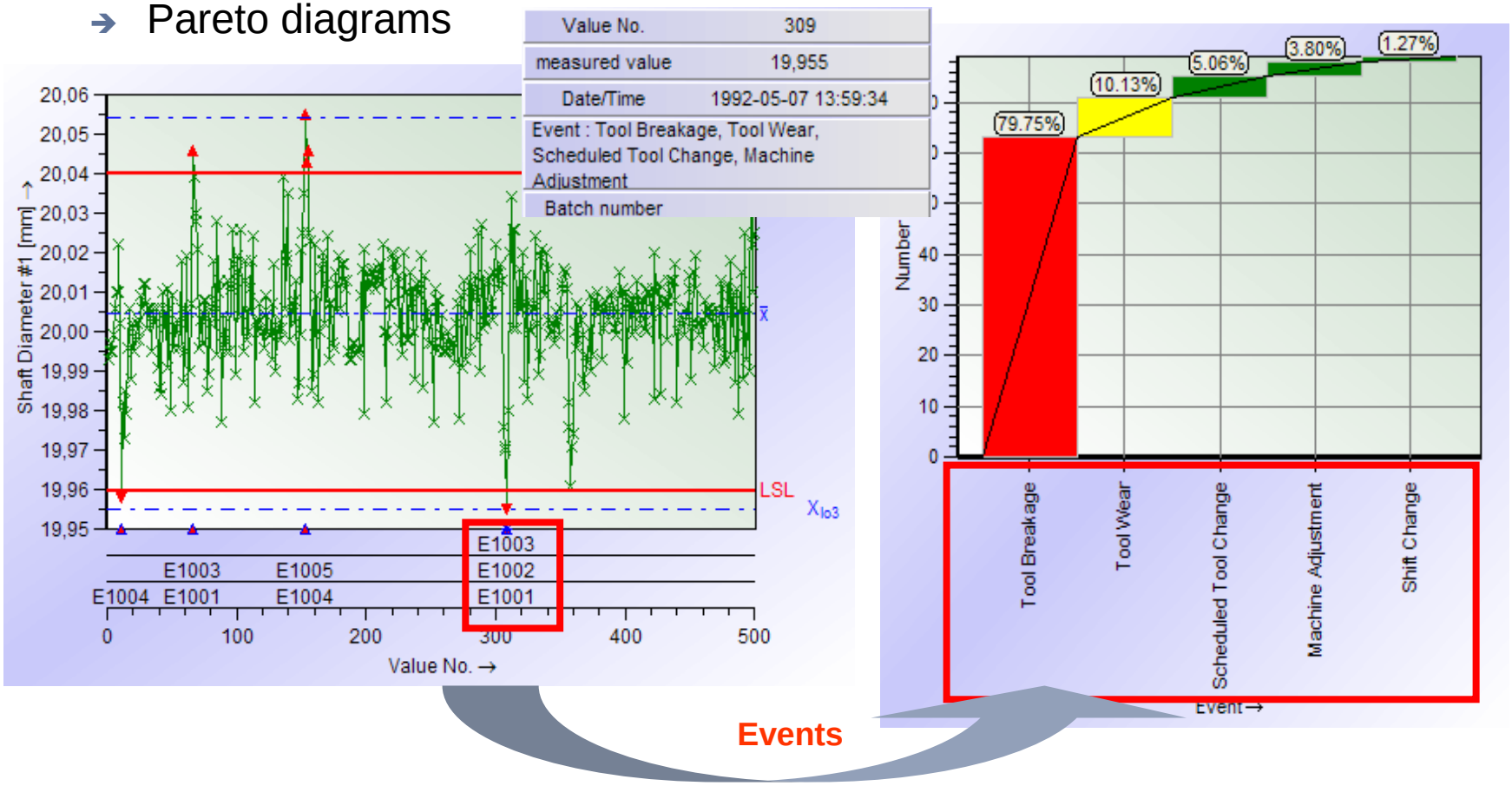
- **solution: make a measurement system analysis**

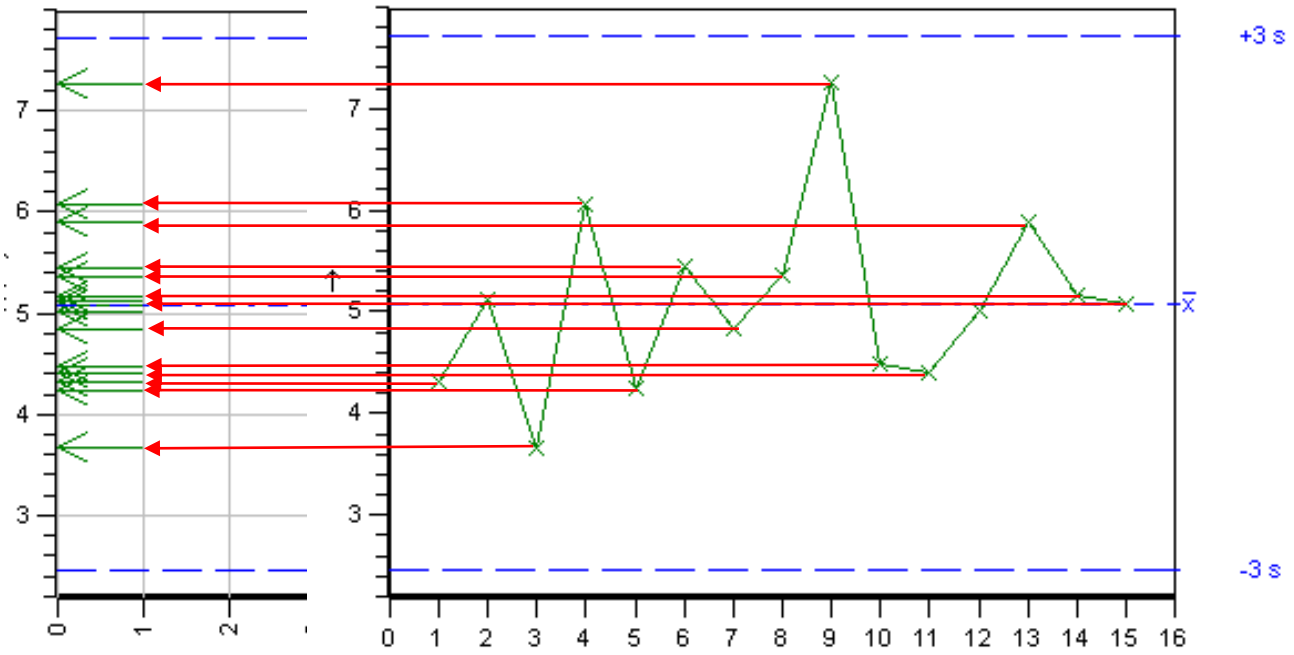


- Axis scale
  - time/date according to ID number
  - batch
  - real-time display
  - machines
  - cavities
  - operators
  - measuring and test equipment

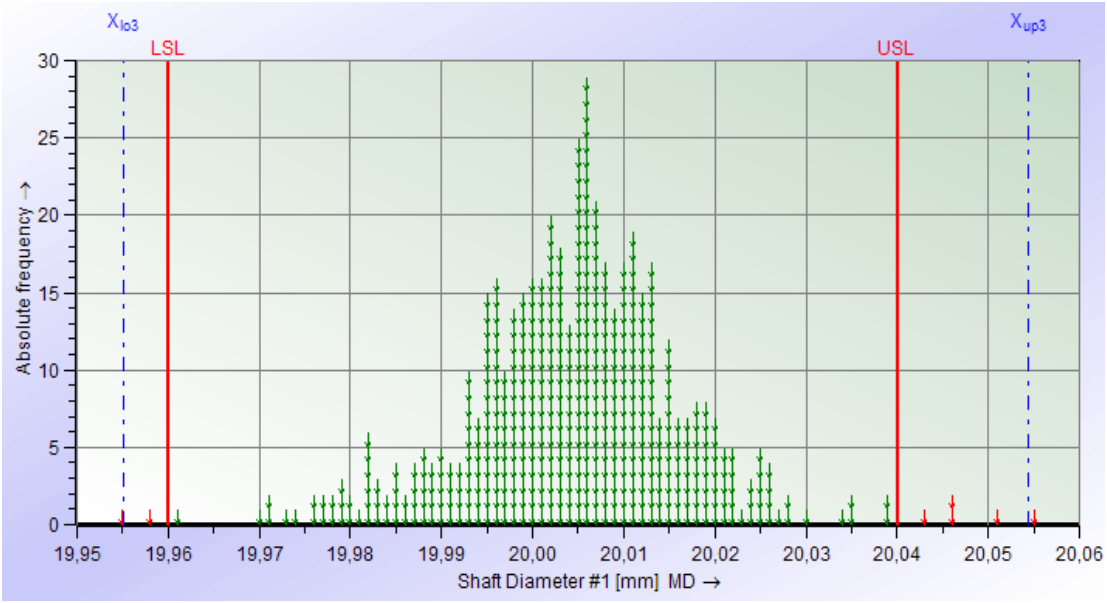


- Pareto analysis
- Pareto diagrams

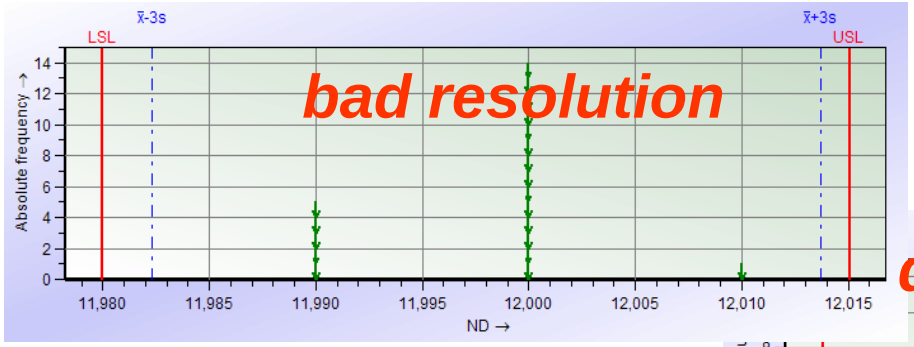


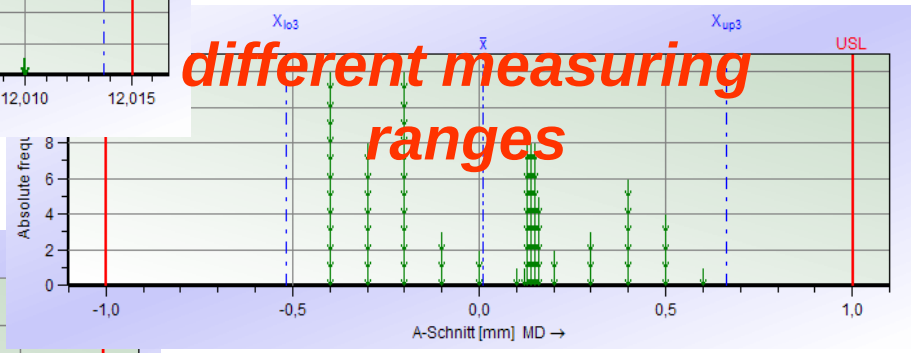

+3 s
-3 s
$\bar{x}$
7
6
5
4
3
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16

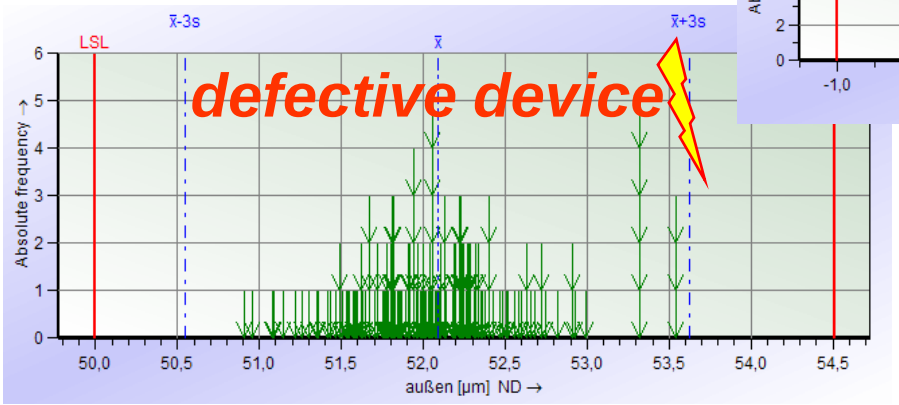
- Considerations regarding the value plot:
  - at least 5-7 visible levels
  - at least 20 levels are possible within the tolerance (i.e. %RE < 5% of the tolerance)
  - no irregularities in the display of the value plot



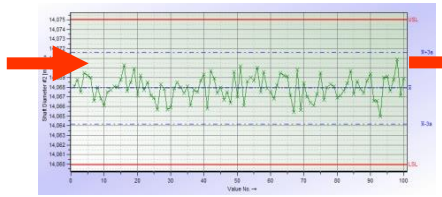
- Examples of bad data quality in the value plot

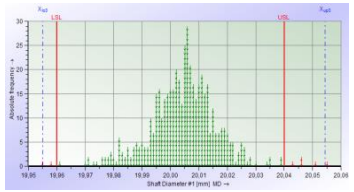


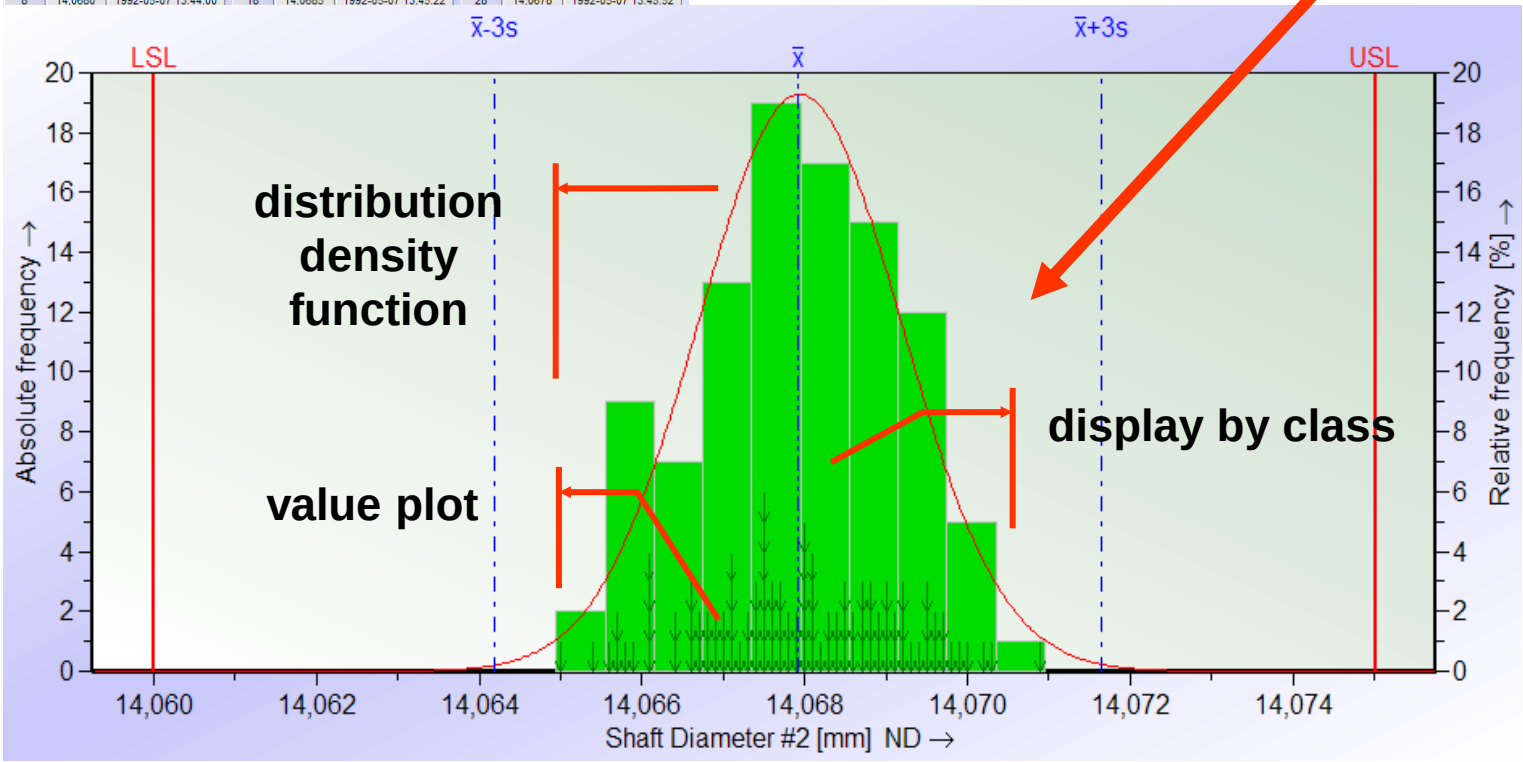




Part no.			1	Part descr.		Test 2		
Char.No.			1	Char.Descr.		Shaft Diameter #2		
i	x_i	Date/Time	i	x_i	Date/Time	i	x_i	Date/Time
1	14,0681	1992-05-07 13:43:08	11	14,0675	1992-05-07 13:44:10	21	14,0692	1992-05-07 13:45:30
2	14,0688	1992-05-07 13:43:28	12	14,0677	1992-05-07 13:44:12	22	14,0677	1992-05-07 13:45:32
3	14,0675	1992-05-07 13:43:32	13	14,0681	1992-05-07 13:44:14	23	14,0685	1992-05-07 13:45:36
4	14,0695	1992-05-07 13:43:36	14	14,0680	1992-05-07 13:44:14	24	14,0671	1992-05-07 13:45:38
5	14,0692	1992-05-07 13:43:38	15	14,0688	1992-05-07 13:44:16	25	14,0669	1992-05-07 13:45:40
6	14,0690	1992-05-07 13:43:50	16	14,0703	1992-05-07 13:44:16	26	14,0657	1992-05-07 13:45:48
7	14,0666	1992-05-07 13:43:50	17	14,0676	1992-05-07 13:45:18	27	14,0683	1992-05-07 13:45:50
8	14,0680	1992-05-07 13:44:00	18	14,0685	1992-05-07 13:45:22	28	14,0678	1992-05-07 13:45:52



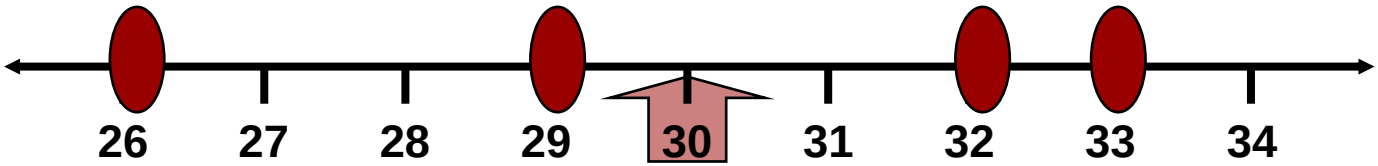


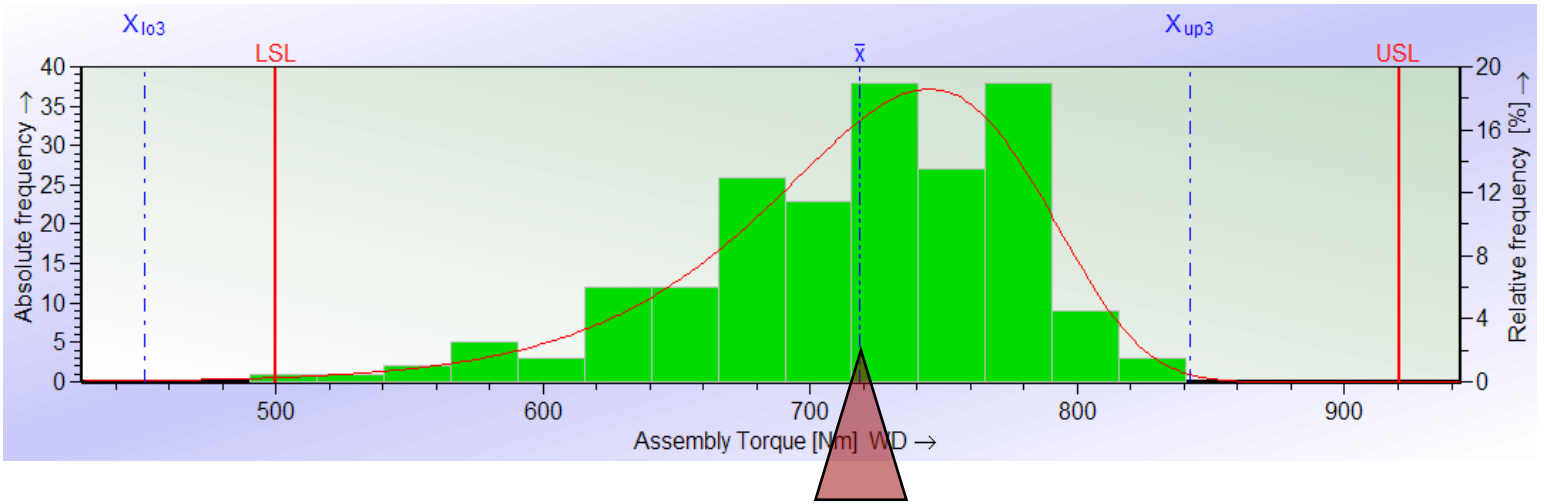


Arithmetic Mean

- The arithmetic mean is
- … the sum of all values divided by the nu
  of values.
- … the balance point of the distributio

$$\bar{x} = \frac{\sum_{i=1}^{n} x_i}{n}$$

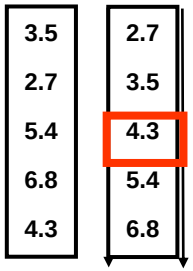




Median

➔ **Median for an odd number of values**

- **if the values of a series of measurements are sorted by absolute value and assigned to the ranks from 1 to n, the value in the middle of this sequence is the median**
  - **there are as many values to the left of the median as to the right**



$$\tilde{x} = x_{(n+1)/2}$$

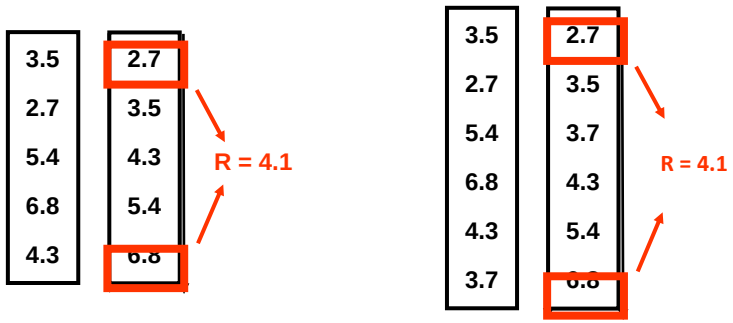
➔ **Median for an even number of values**

- **if there is an even number of values, the two values in the middle of the sequence are added and then divided by two**
- **the calculated value is the median of an even number of values**

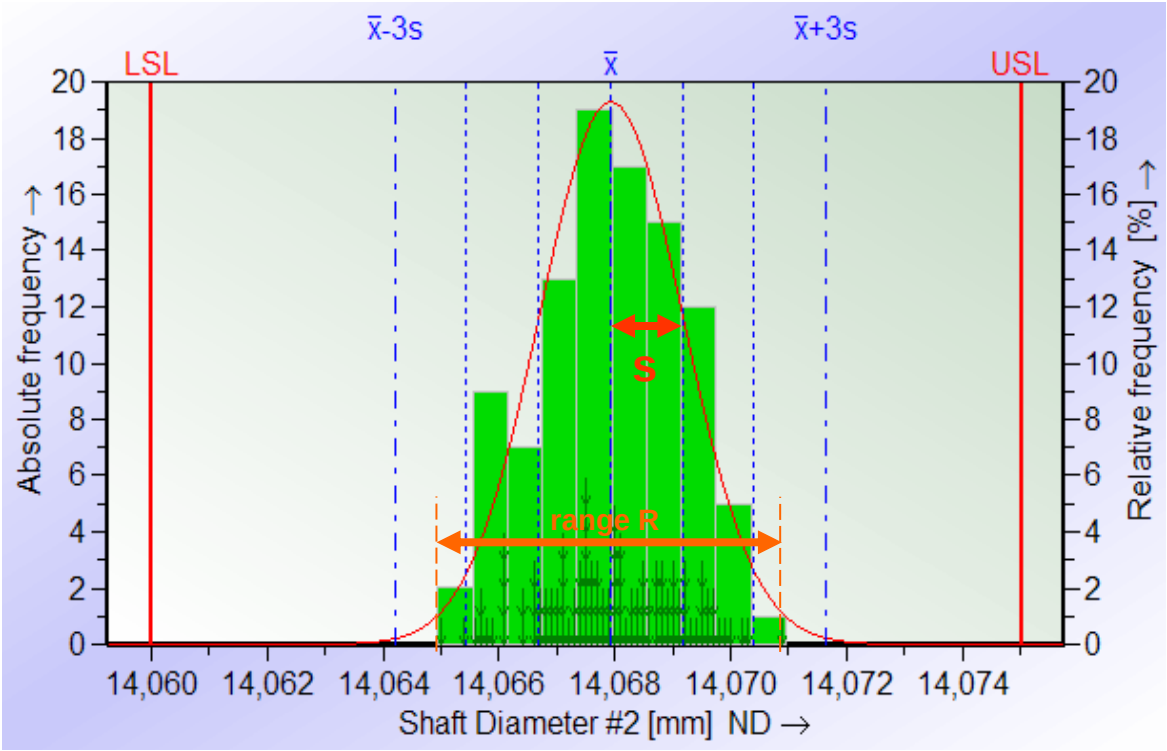
$$\tilde{x} = \frac{x_{n/2} + x_{(n/2+1)}}{2}$$

Range

- **Range: We select the minimum value and the maximum value of an amount of data. Now, we subtract the minimum value from the maximum value. The difference between these two values is called range.**



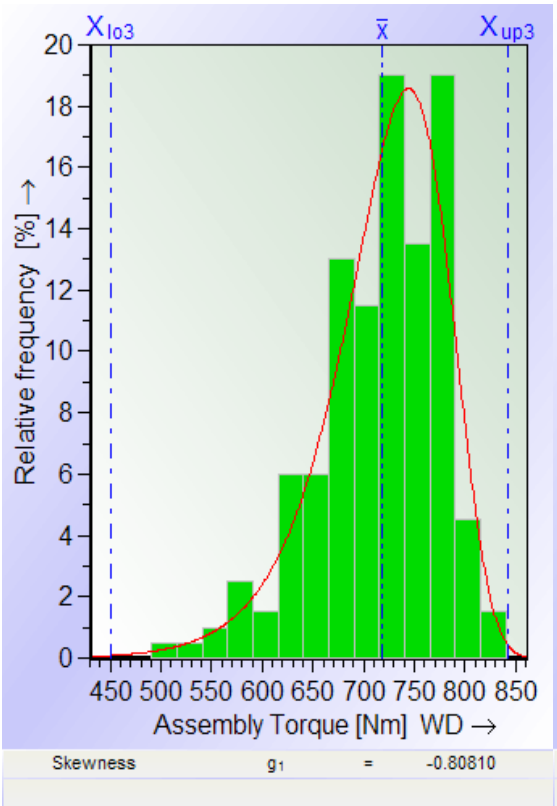
- The standard deviation s is the square root of the sum of squared deviations divided by the degrees of freedom (sample size minus one, n-1)



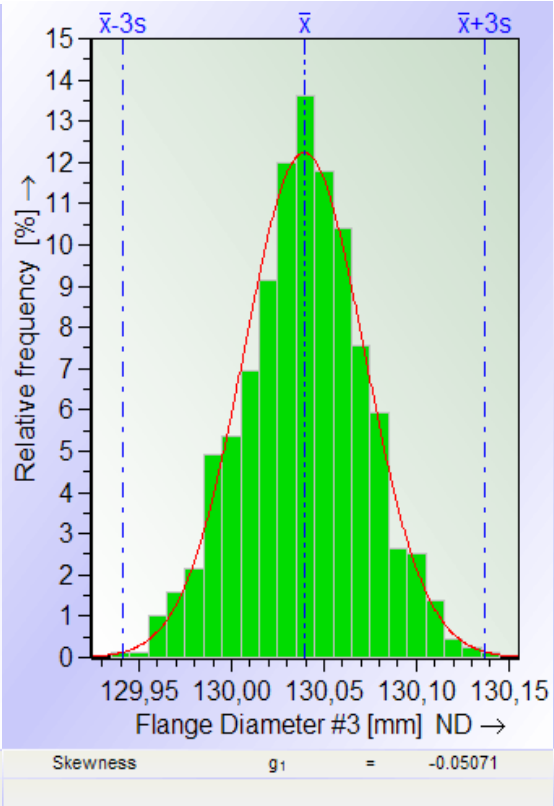
$$s = \sqrt{\frac{\sum_{i=1}^{n}(x_i - \bar{x})^2}{n-1}}$$

The standard deviation must not be mistaken for the range or the tolerance!

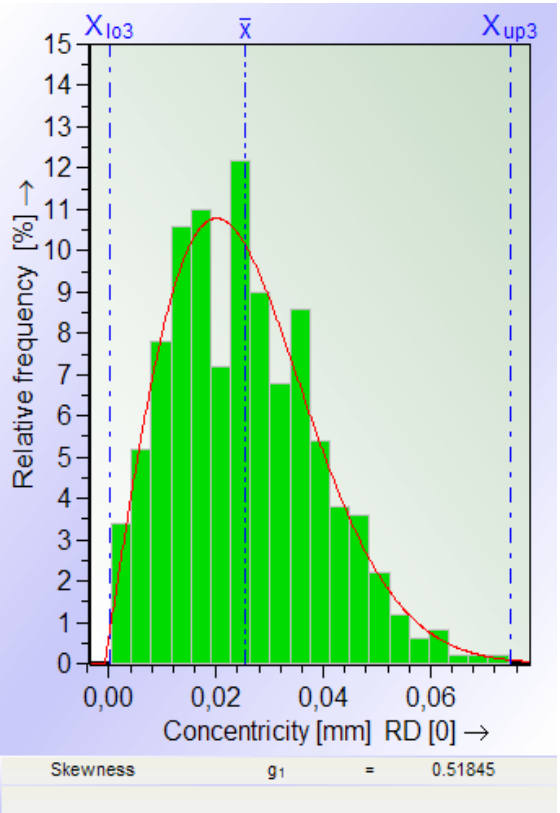
- The skewness describes the asymmetry of a distribution.



$g_1 < 0$

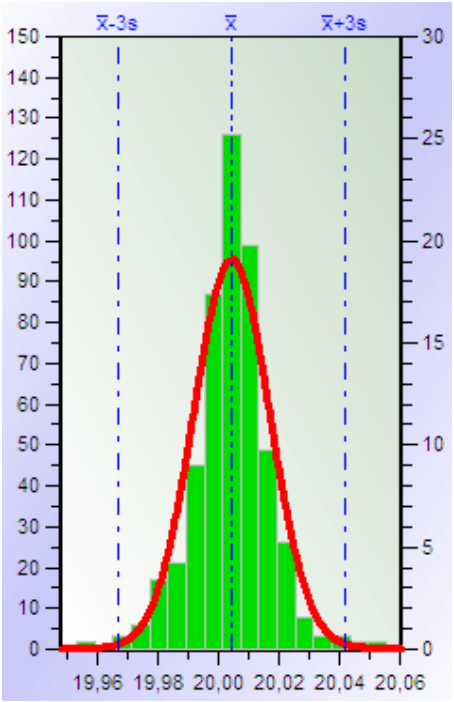


$g_1 = 0$

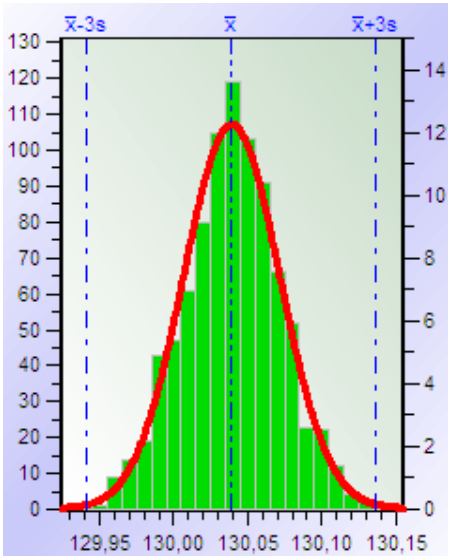


$g_1 > 0$

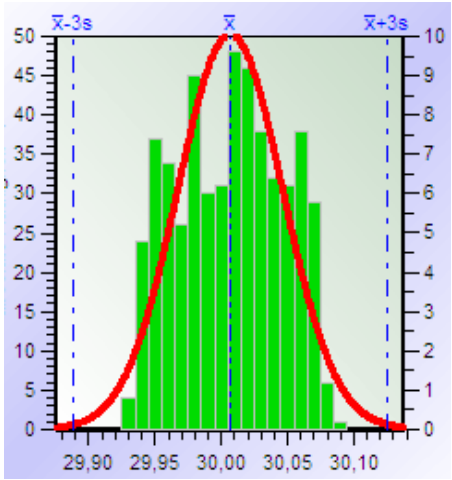
- The kurtosis b_2 describes the slope of a distribution.



$b_2 > 3$



$b_2 = 3$



$b_2 < 3$

- Location statistics
  - **minimum value/maximum value**
  - **median** $\tilde{x}$
  - **arithmetic mean** $\bar{x} = \frac{\sum_i x_i}{n}$
- Variation statistics
  - **range** $R = x_{max} - x_{min}$
  - **standard deviation** $s = \sqrt{\sum_i (x_i - \bar{x})^2 / n-1}$
- Form statistics
  - **skewness** **($g_1 = 0$ in case of normal distribution)**
  - **kurtosis** **($b_2 = 3$ in case of normal distribution)**

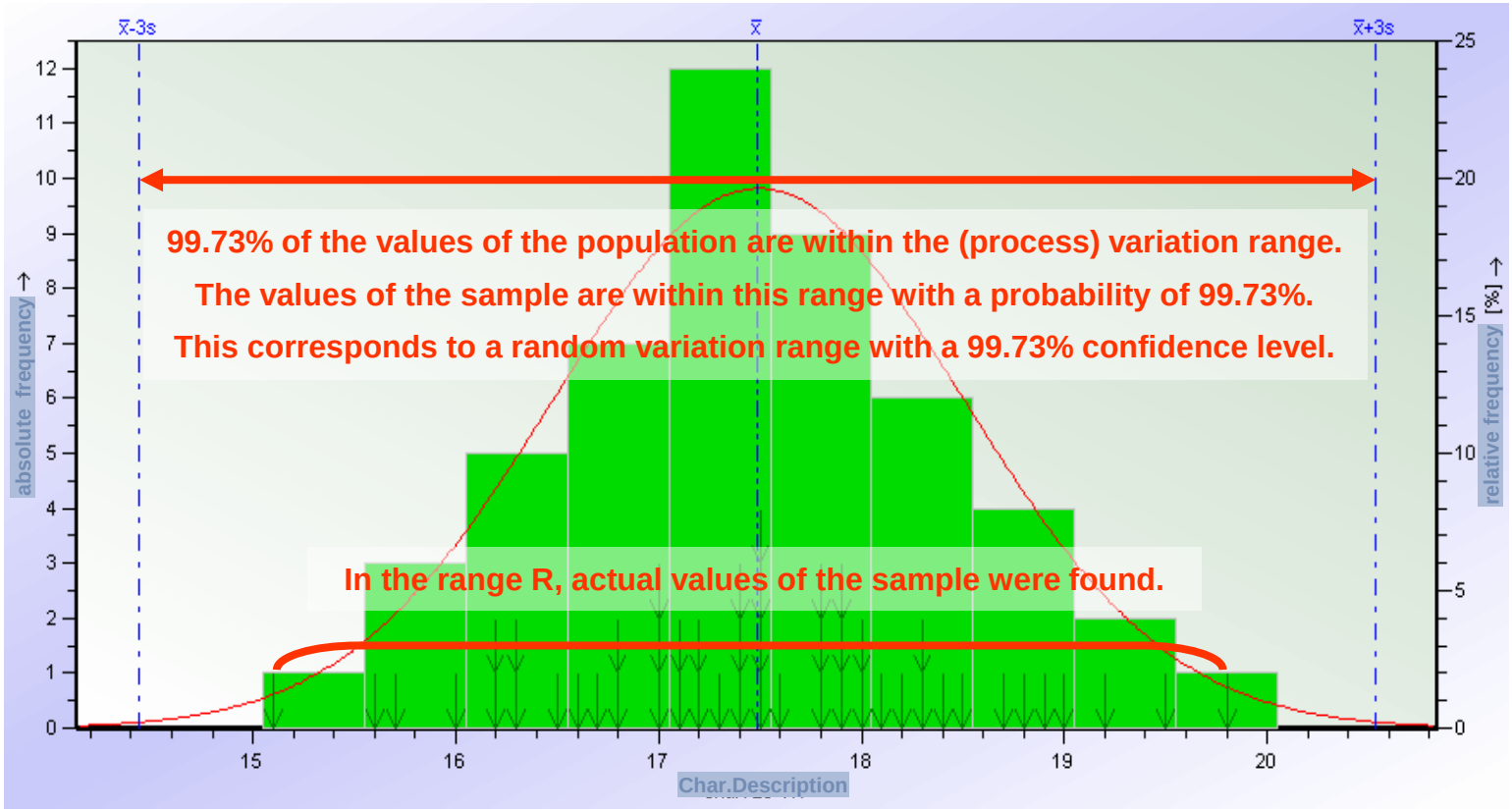
Random Variation Range

➔ **Range depends on the sample size.**

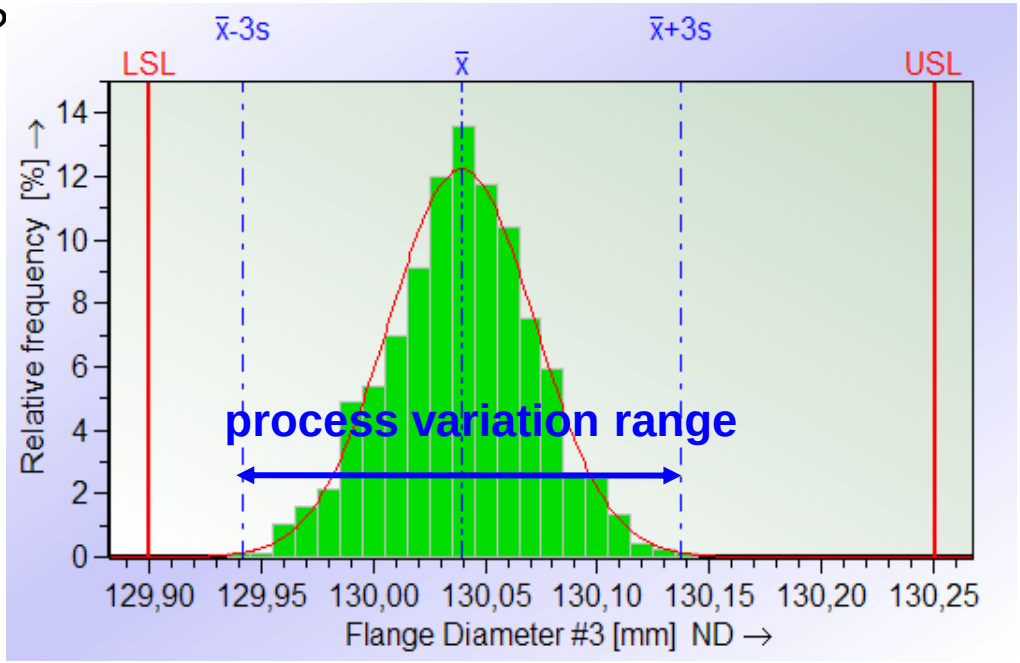
Char.Nr	Char.Description	$\bar{x}$	s	n = 15 R	s	n = 50 R	s	n = 500 R
1	Ch.1	10,11440	1,13497	R = 3,693	0,78494	R = 3,631	1,02523	R = 6,218
2	Ch.2	10,29747	0,80333	R = 2,580	0,90549	R = 4,015	1,04538	R = 6,236
3	Ch.3	9,91240	1,11886	R = 4,175	1,14252	R = 4,133	1,01157	R = 6,651
4	Ch.4	9,67720	1,04647	R = 3,167	0,90887	R = 4,465	0,94455	R = 5,498
5	Ch.5	10,10580	0,84367	R = 2,792	0,78263	R = 3,131	1,01174	R = 6,468
6	Ch.6	10,03840	1,06180	R = 4,230	1,06965	R = 5,733	0,94874	R = 5,955
7	Ch.7	10,38127	0,95627	R = 2,837	0,75918	R = 3,478	1,02039	R = 5,366
8	Ch.8	10,22133	0,59096	R = 2,027	1,04225	R = 4,182	0,98857	R = 5,294
9	Ch.9	10,04127	1,04759	R = 3,301	1,01187	R = 5,092	0,99312	R = 5,715
10	Ch.10	9,81407	1,00313	R = 3,672	1,09971	R = 4,756	1,02225	R = 5,993

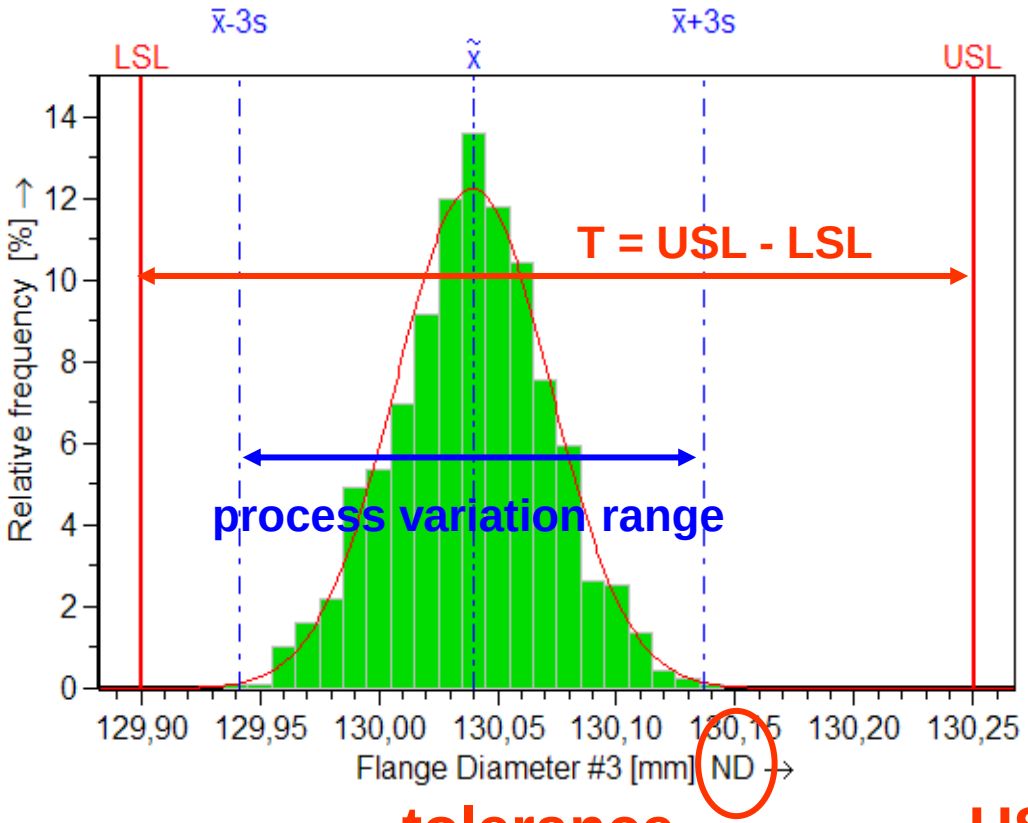
Random Variation Range

- Range of the measured values correlates with random variation range.

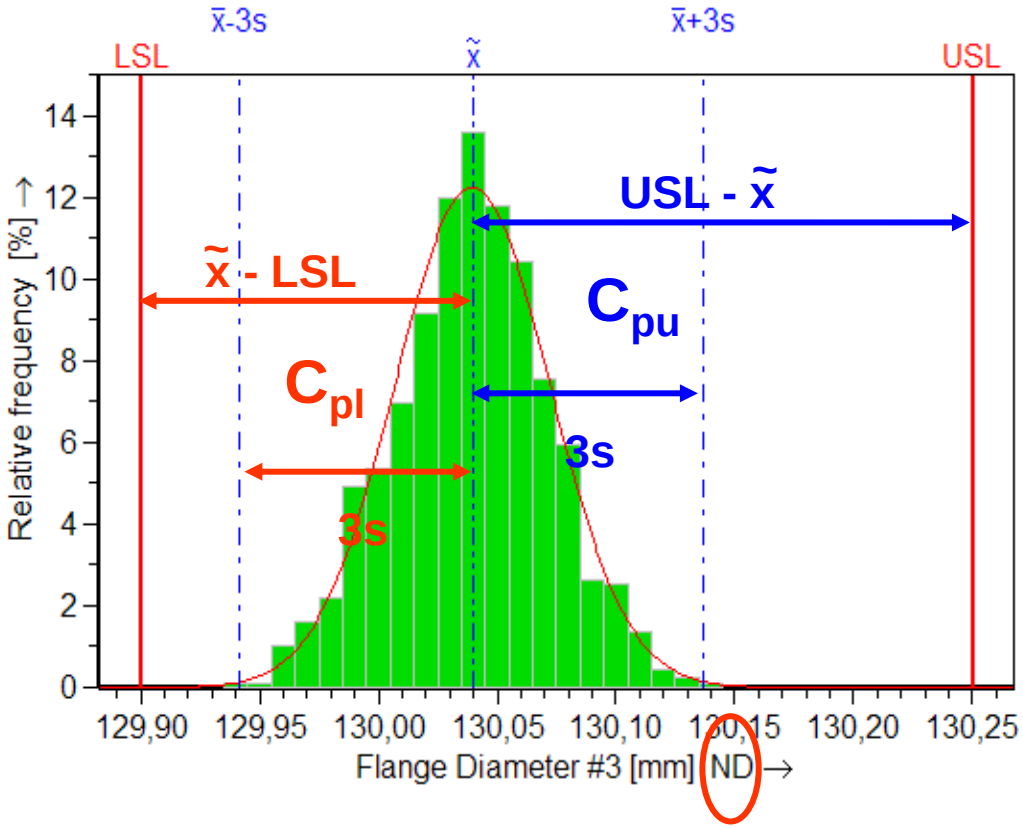


- How well does the process conform to the tolerance?
- How wide is the process?
- One possible answer:
  99.73% => +/- 3s
- Convention: process variation range = 6s





$$C_p = \frac{\text{tolerance}}{\text{process variation range}} = \frac{\text{USL-LSL}}{6\ s}$$

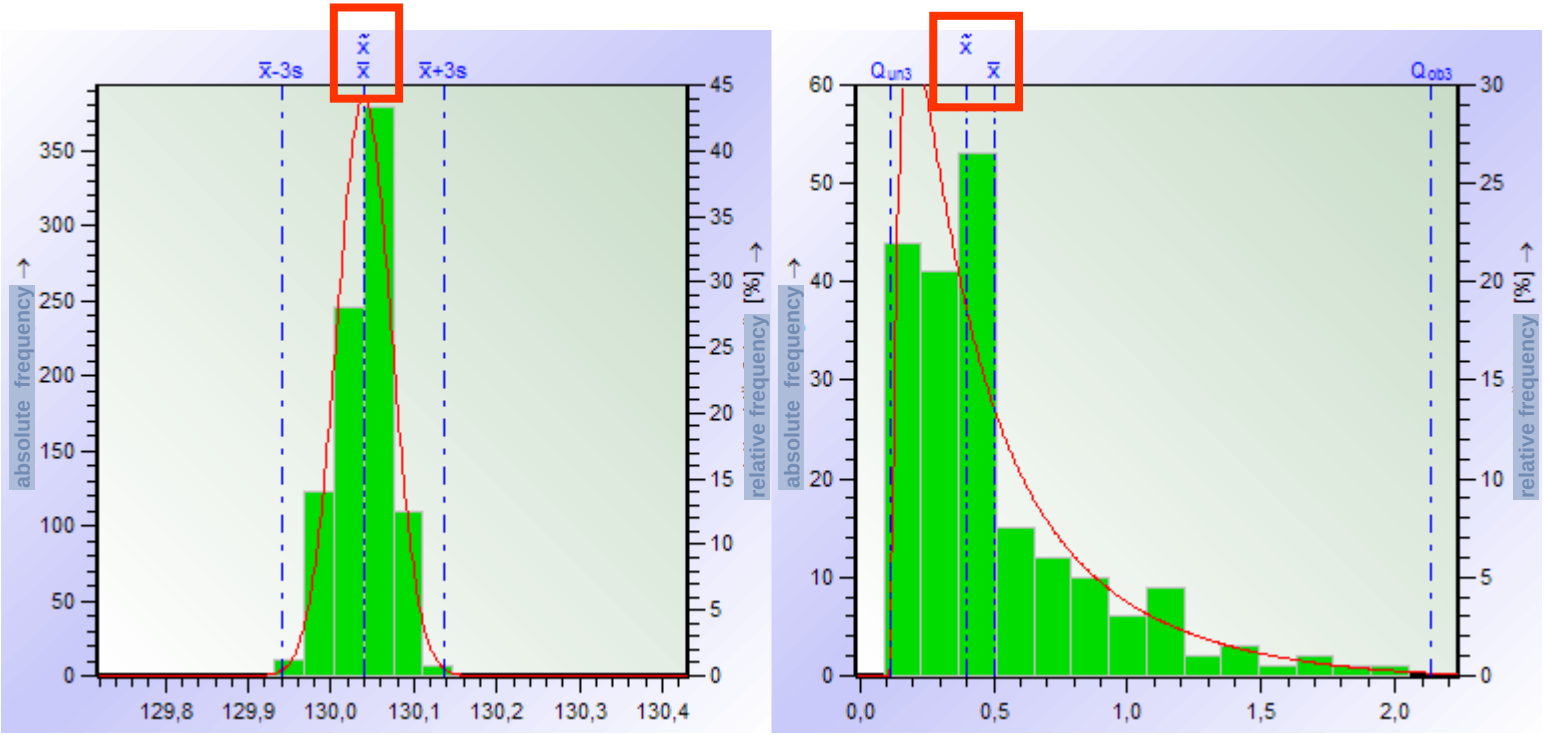


$$C_{pu} = \frac{USL - \tilde{x}}{3\,s}$$

$$C_{pl} = \frac{\tilde{x} - LSL}{3\,s}$$

$$C_{pk} = \min \{C_{pu}, C_{pl}\}$$

Median or Average?

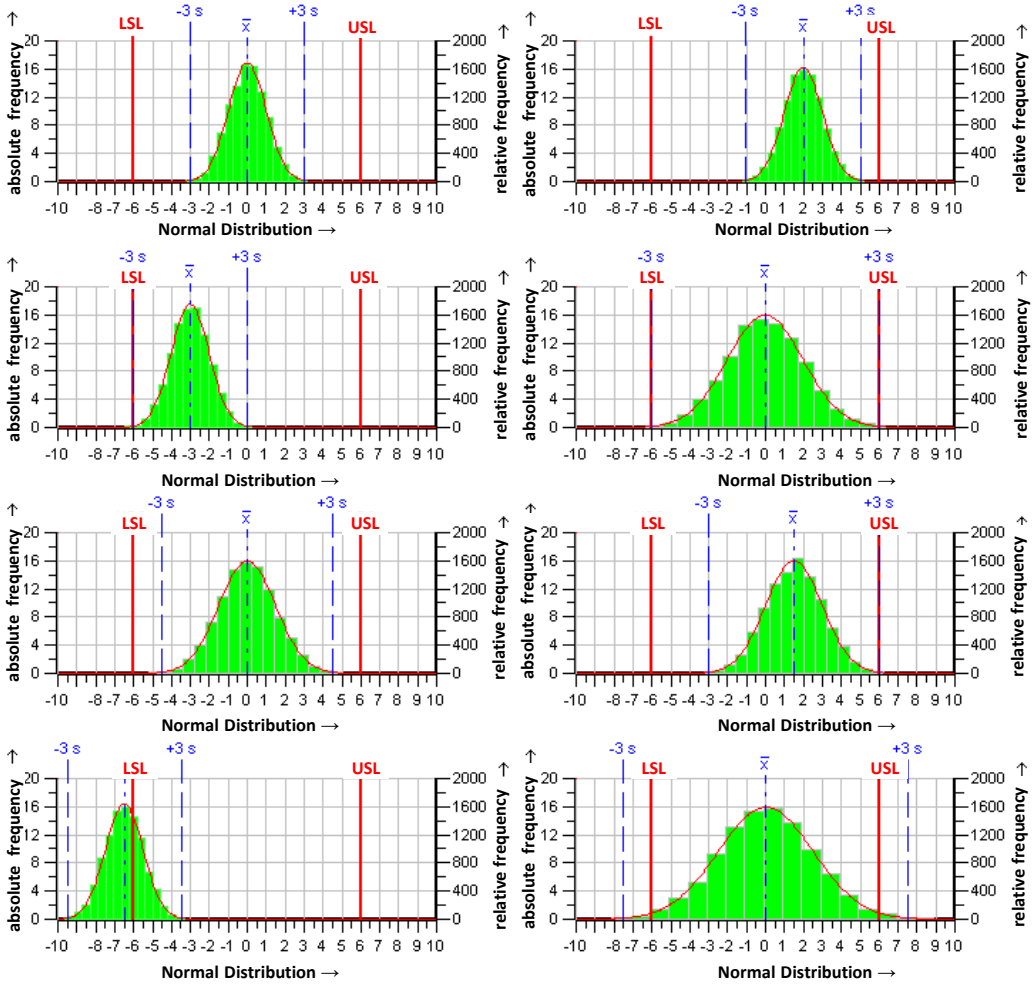


almost identical in normal distributions, but different in skewed distributions

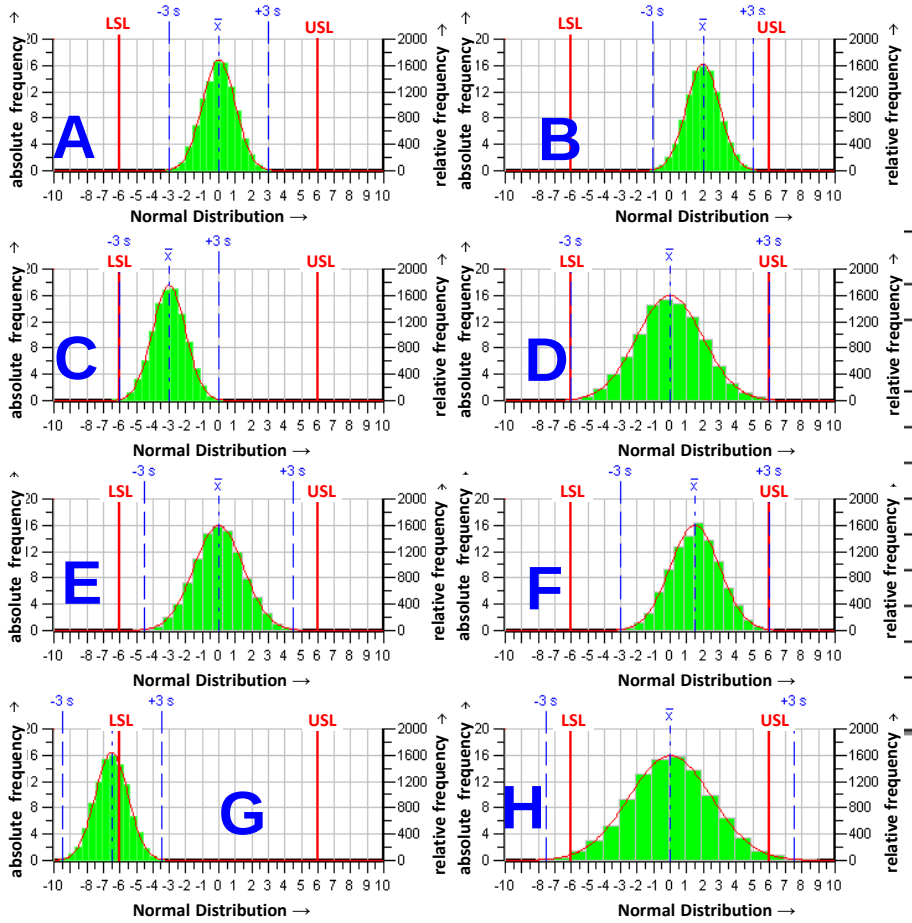
average is the “balance point“ of the distribution

median is the central value (50:50) and generally closer to the mode (maximum) in skewed distributions

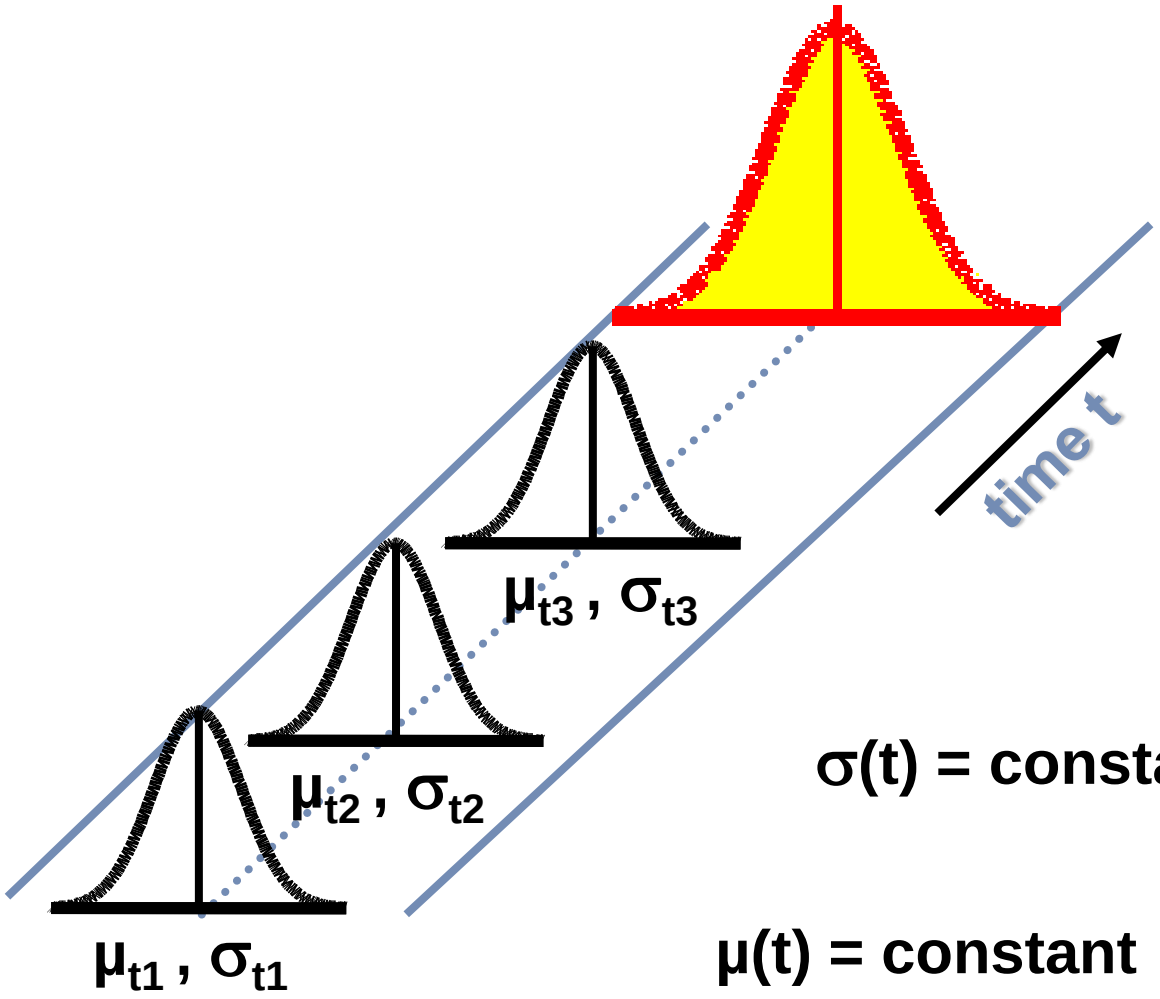
TQ039 Machine and Process Capability



Please Estimate Capabilities ... (Results)



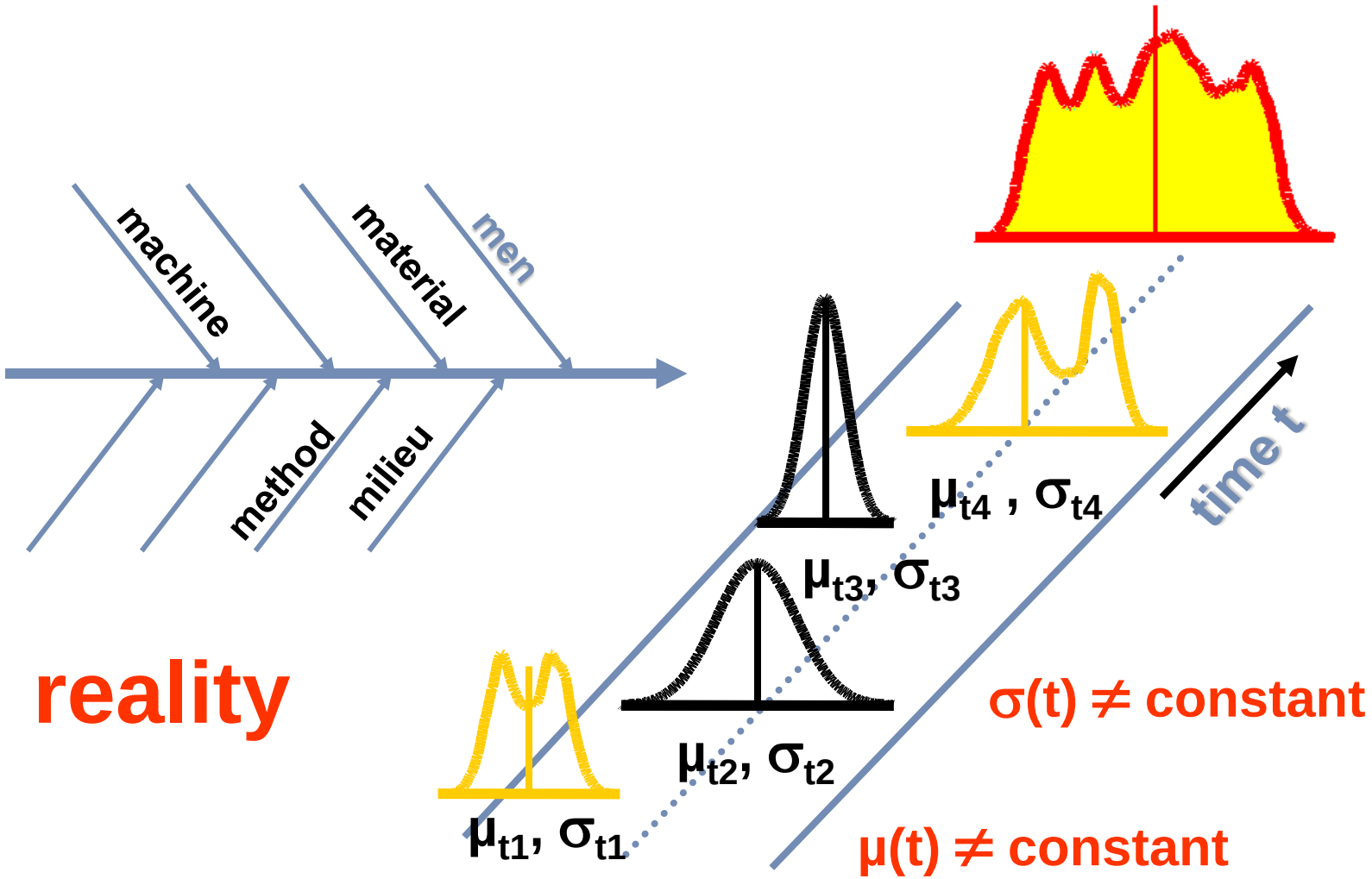
Kennwerte			
Merkm.Bez.	Index	Index	
A	2.01 (C_p)	2.01 (C_{pk})	
B	1.99 (C_p)	1.32 (C_{pk})	
C	2.00 (C_p)	0.99 (C_{pk})	
D	1.00 (C_p)	1.00 (C_{pk})	
E	1.33 (C_p)	1.33 (C_{pk})	
F	1.34 (C_p)	1.00 (C_{pk})	
G	2.00 (C_p)	-0.16 (C_{pk})	
H	0.80 (C_p)	0.80 (C_{pk})	



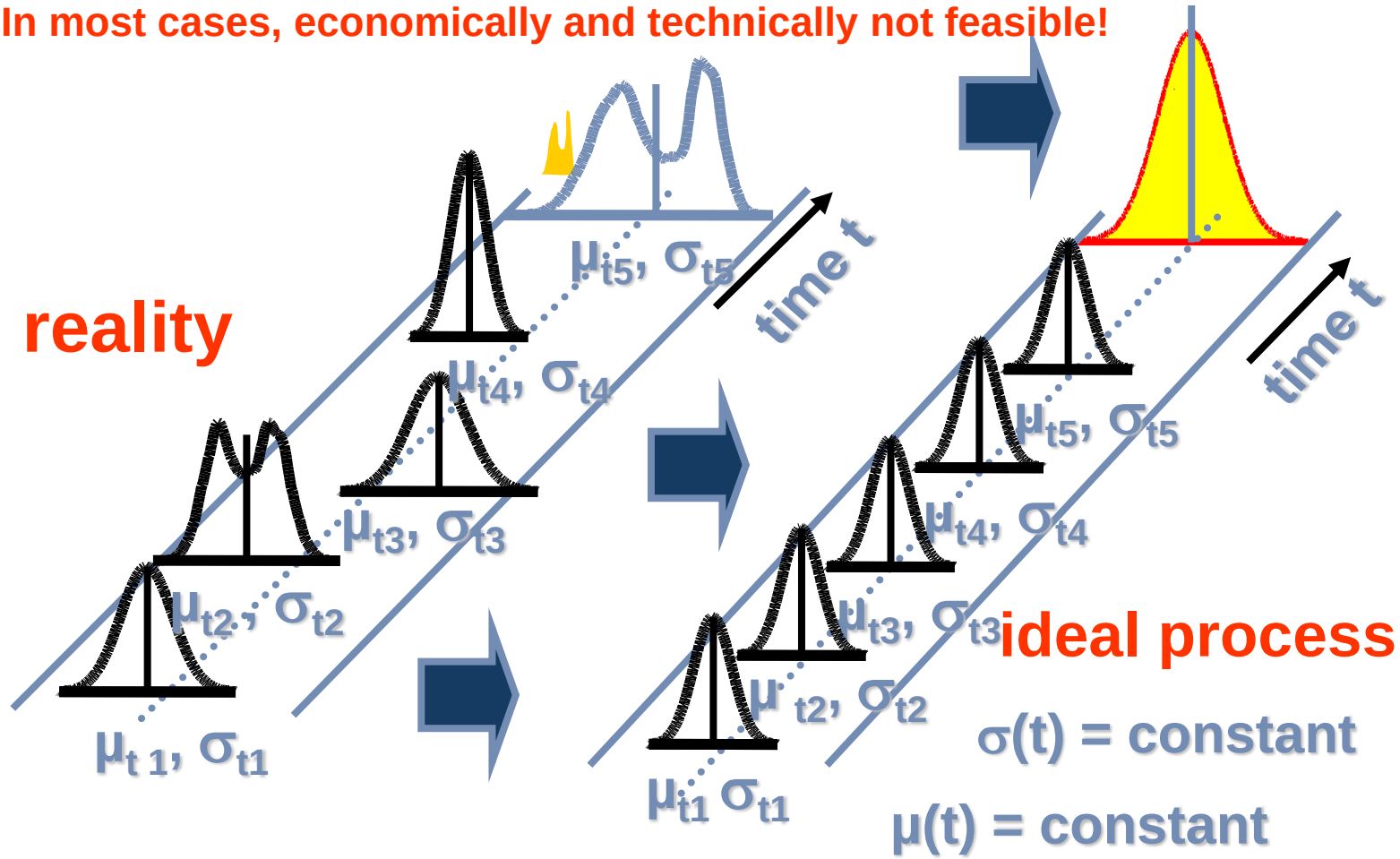
$\sigma(t)$ = constant

$\mu(t)$ = constant

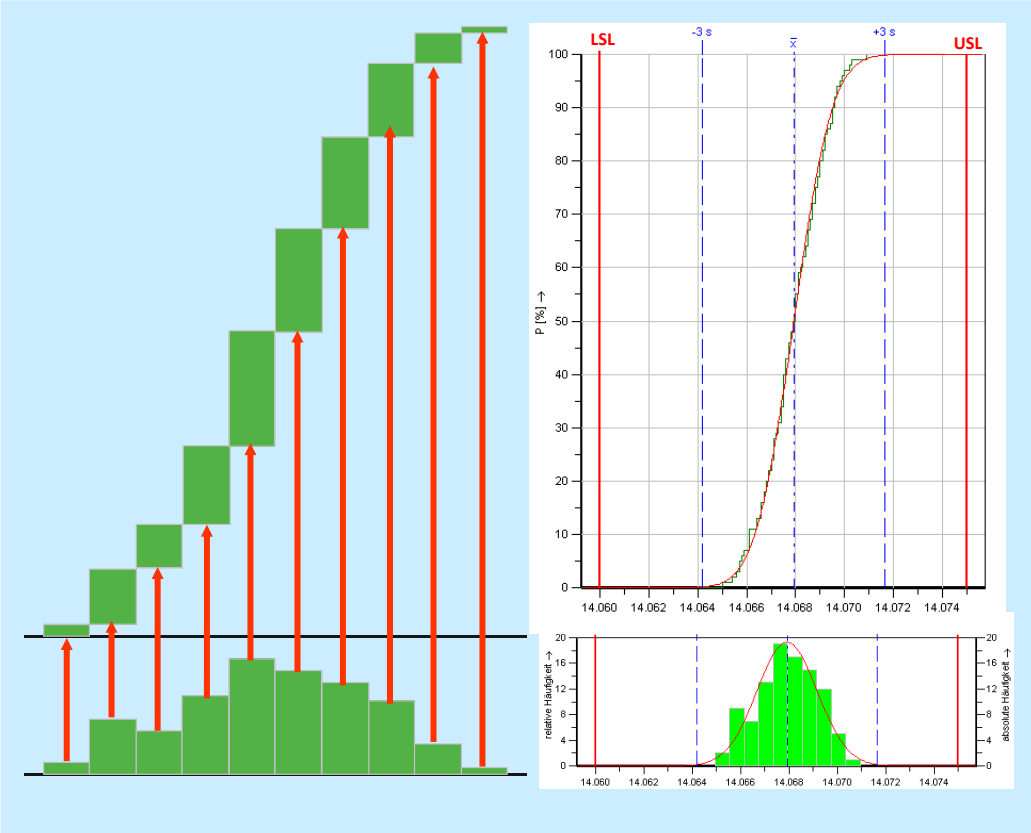

only 2 % of all processes are normally distributed


machine
material
men
method
milieu
reality
μ_{t4} , σ_{t4}
μ_{t3}, σ_{t3}
μ_{t2}, σ_{t2}
μ_{t1}, σ_{t1}
time t
σ(t) ≠ constant
μ(t) ≠ constant

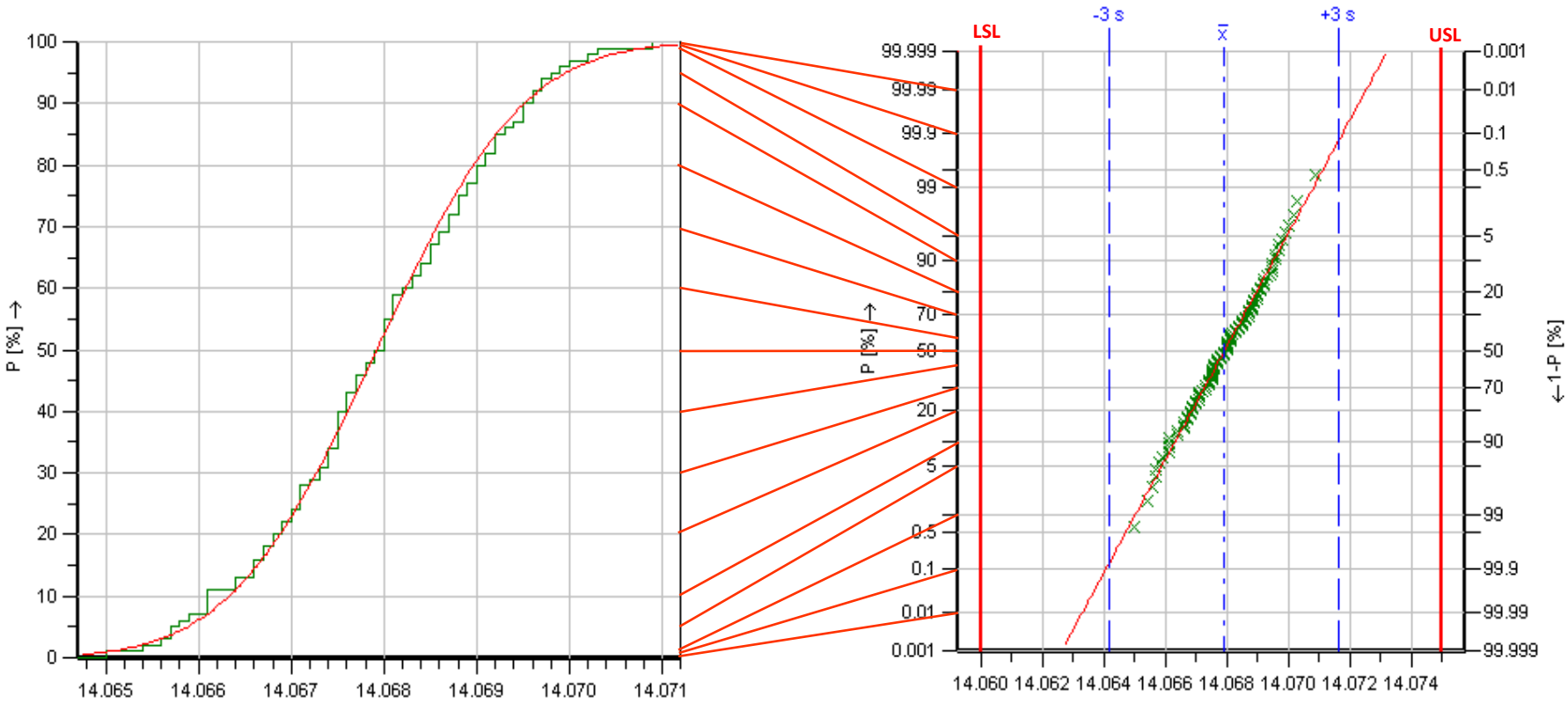
In most cases, economically and technically not feasible!



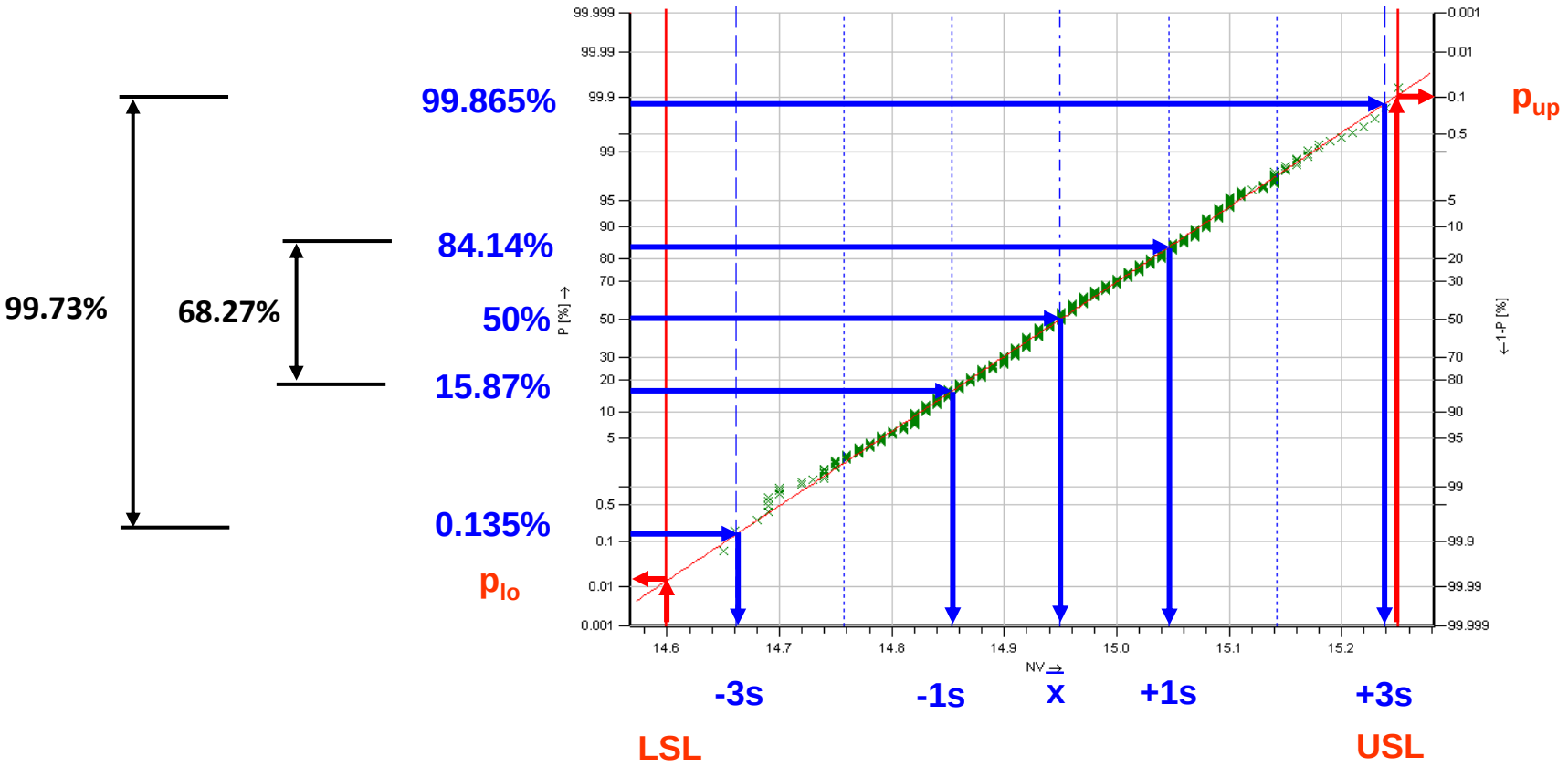
- **The histogram becomes a cumulative line.**



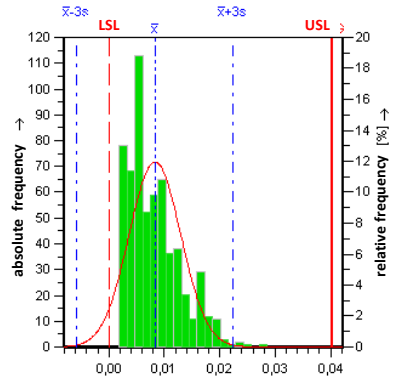
- **The cumulative line becomes a probability plot.**

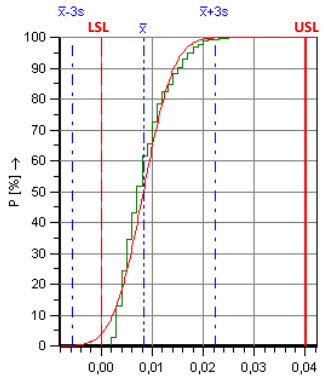


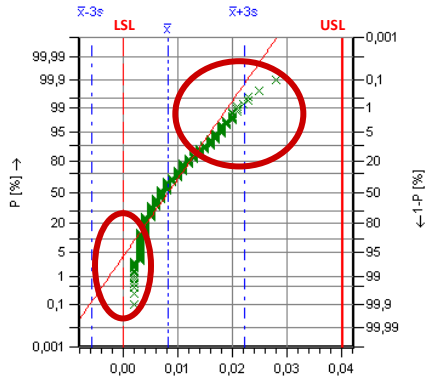
➔ **From the probability plot, statistical values are read.**



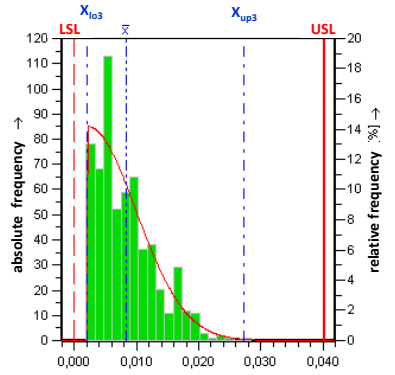
wrong selection of distribution shape

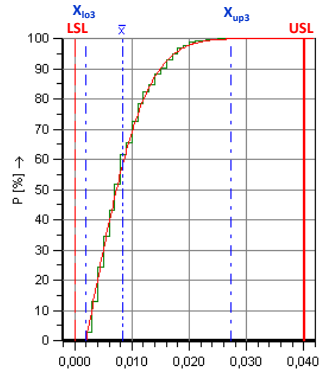


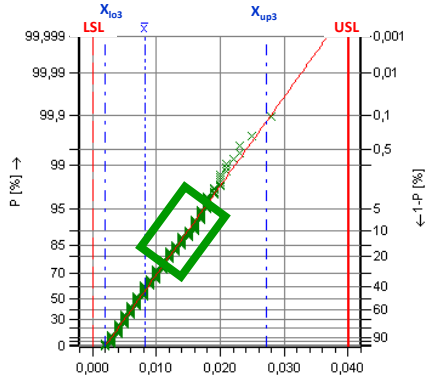




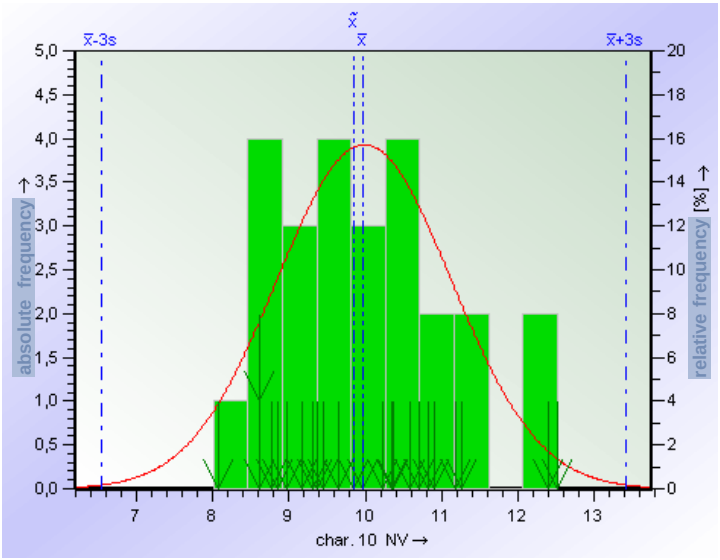
right selection of distribution shape







➔ **Correct selection of distribution model in case of few measured values**



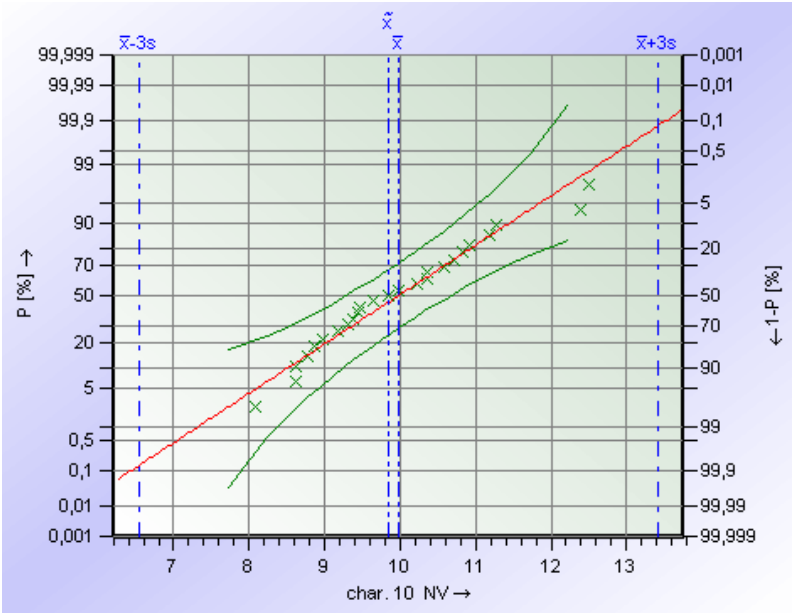
??????

Is that right?

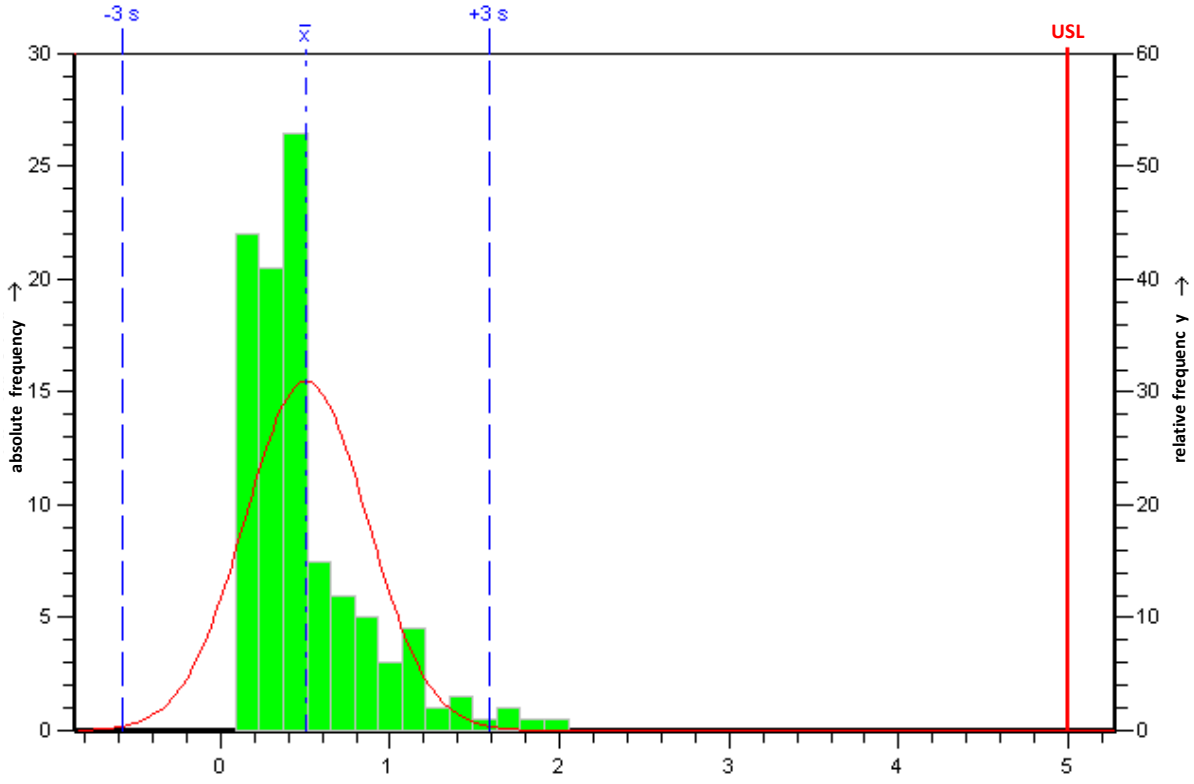
??????

all values within the confidence interval

no inconsistencies

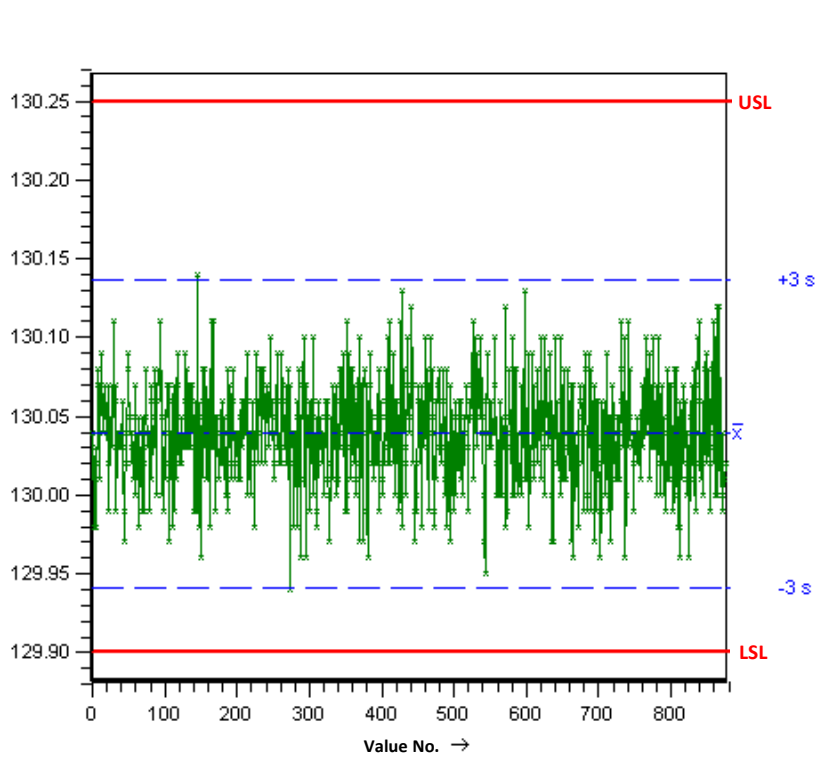


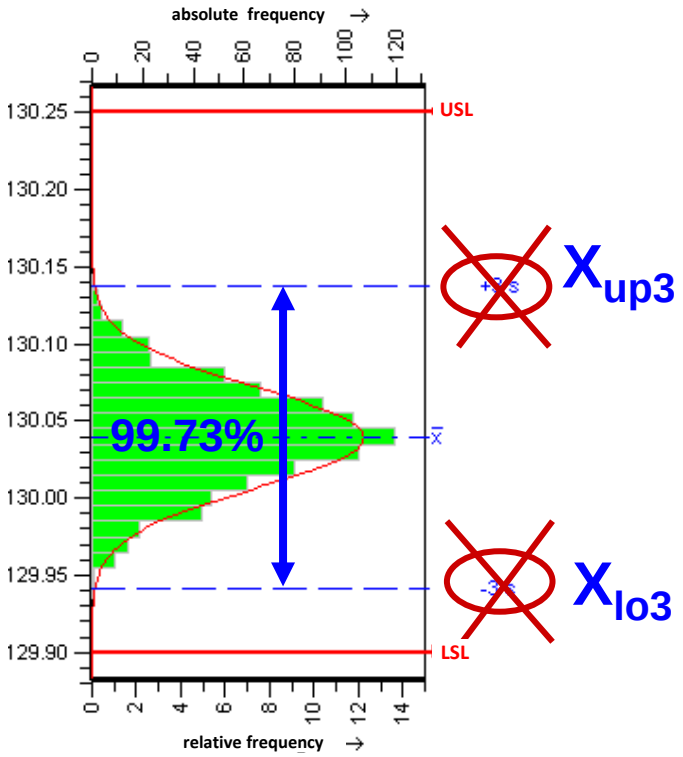
What is the standard deviation s here?



irrelevant !

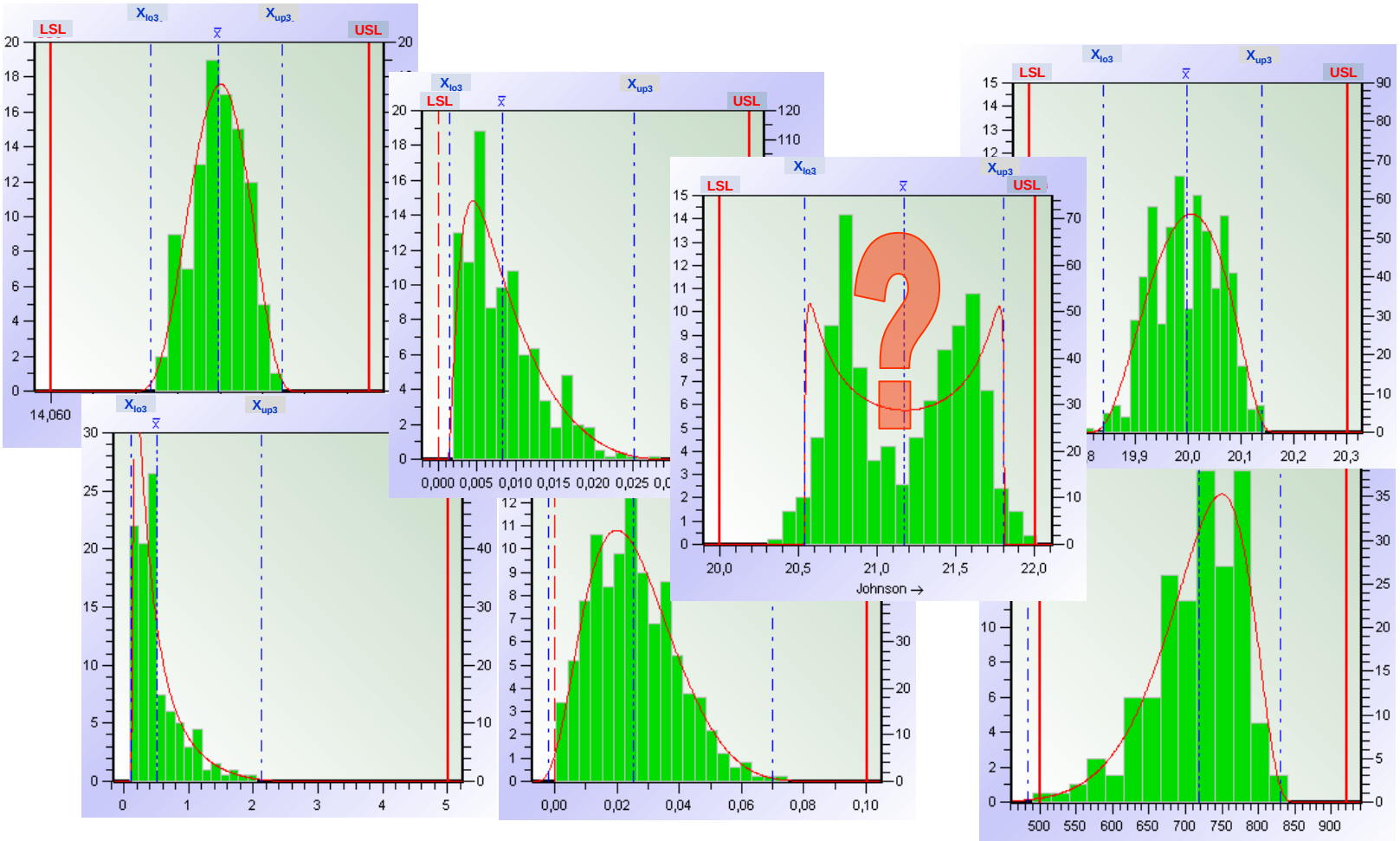
- Process nnd = not normally distributed
- Standard deviation cannot be interpreted
- Standard deviation cannot be used
- But: interpretation of the standard deviation can be used
- 99.73% of the values of any distribution model can be determined
- 99.73% percentile is limited by quantiles X_{up3} and X_{lo3}
- Process variation range = $X_{up3} - X_{lo3} = X_{0.00135} – X_{0.99865}$


130.25
130.20
130.15
130.10
130.05
130.00
129.95
129.90
USL
+3 s
x̄
-3 s
LSL
0
100
200
300
400
500
600
700
800
Value No. →

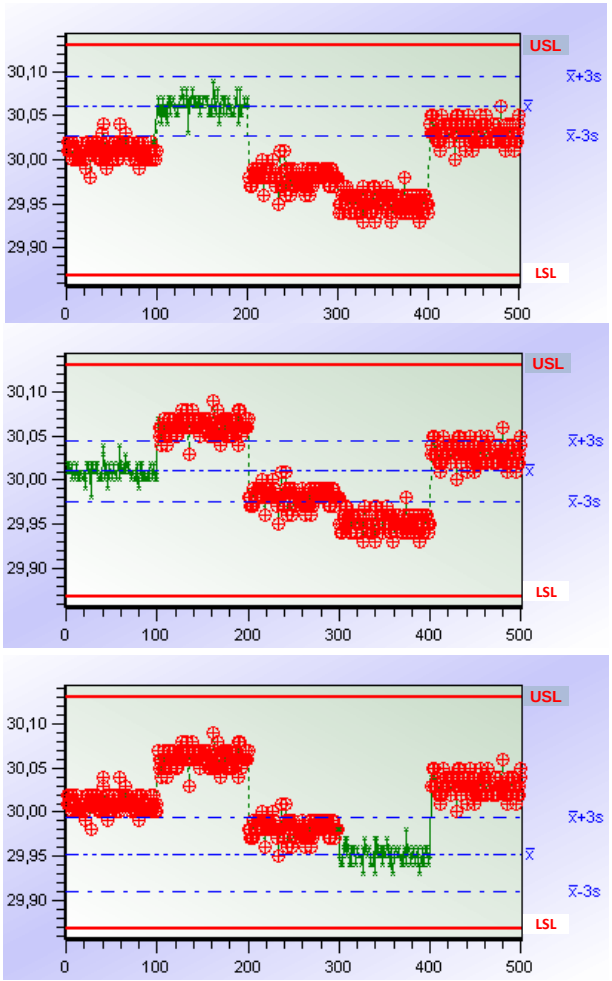

absolute frequency →
0
20
40
60
80
100
120
130.25
130.20
130.15
130.10
130.05
130.00
129.95
129.90
USL
99.73%
x̄
LSL
0
2
4
6
8
10
12
14
relative frequency →
Xup3
Xlo3

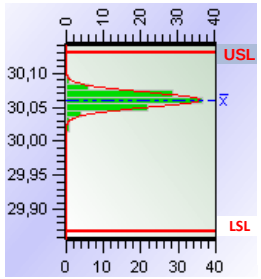
Johnson Transforms

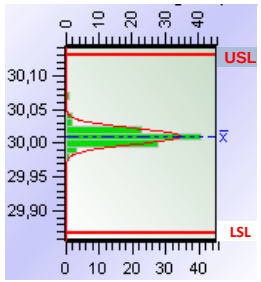
TQM 39 Machine and Process Capability

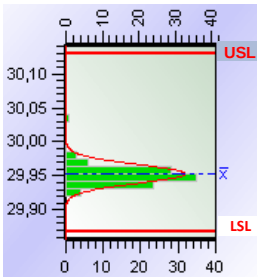


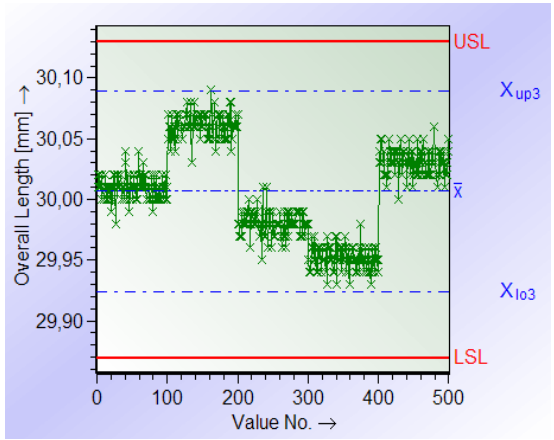
Extended Normal Distribution from ISO 22514 Machine and Process Capability

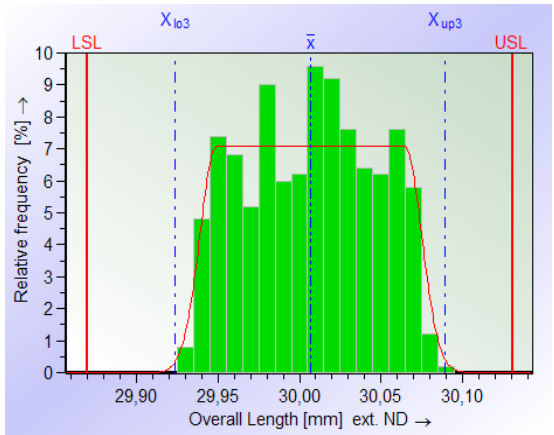




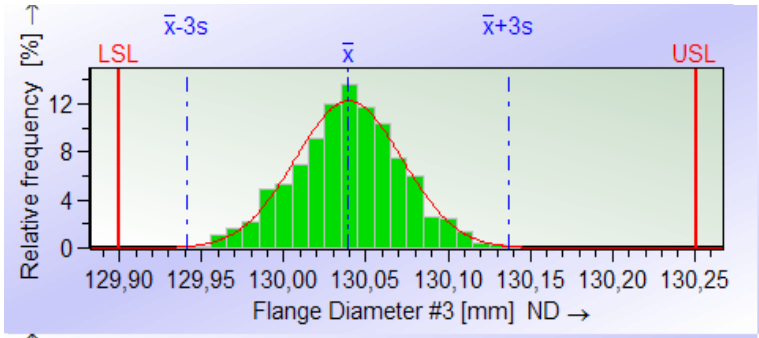


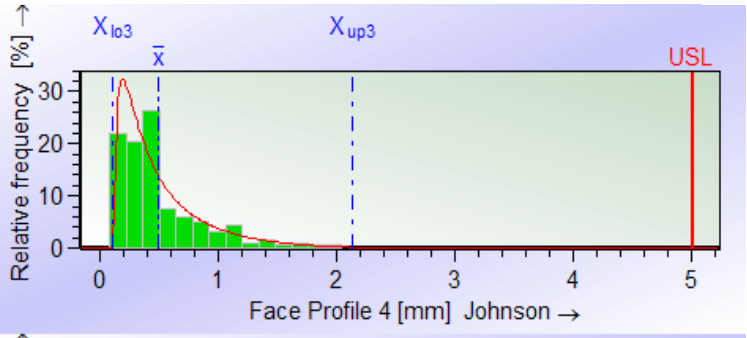


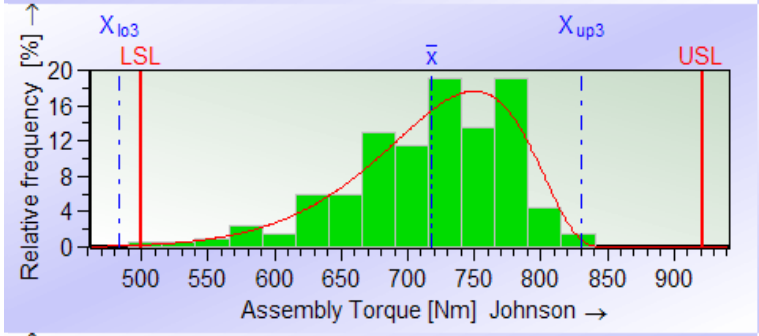


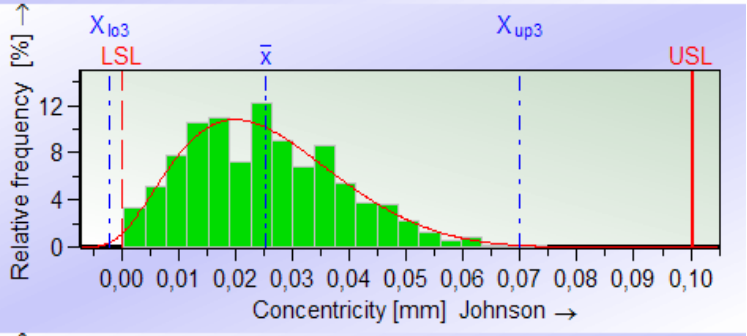


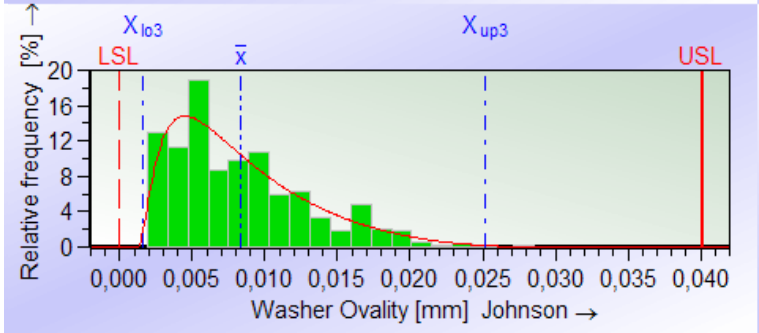
TQ039 Machine and Process Capability

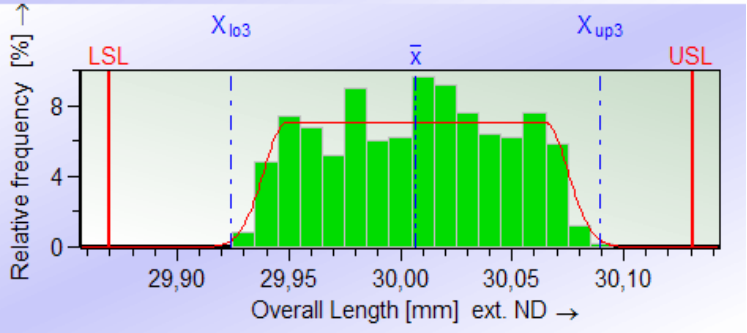


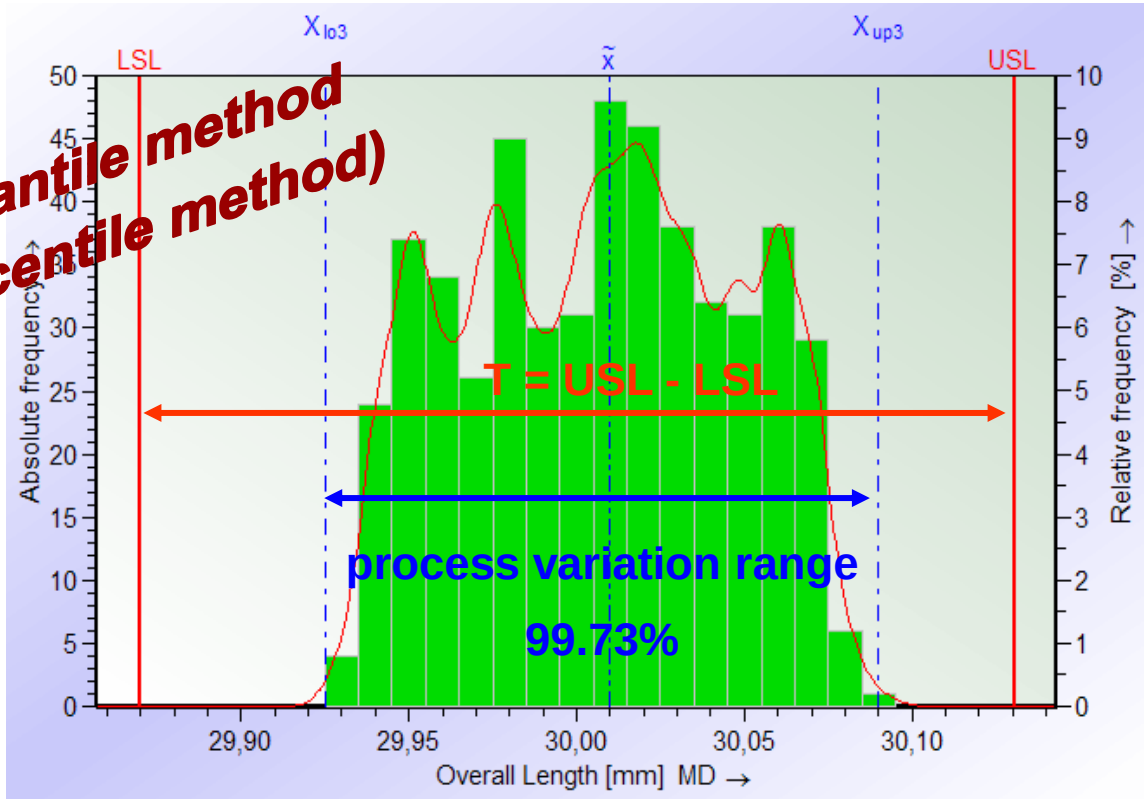




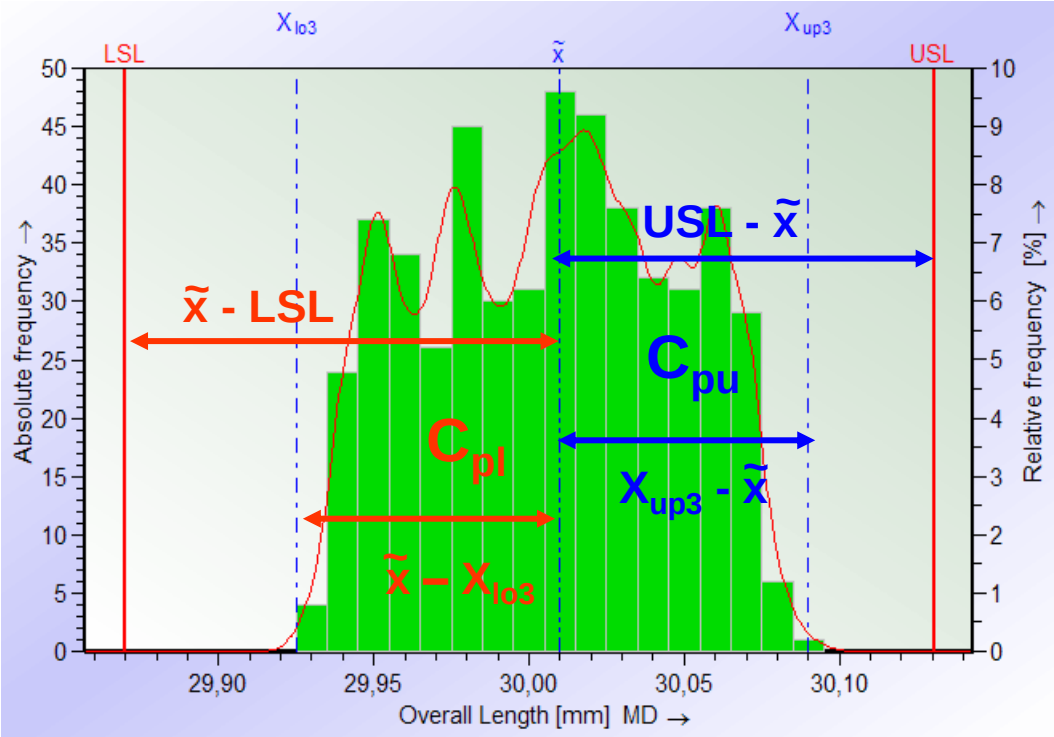








$$C_p = \frac{\text{tolerance}}{\text{process variation range}} = \frac{USL-LSL}{X_{up3} - X_{lo3}}$$



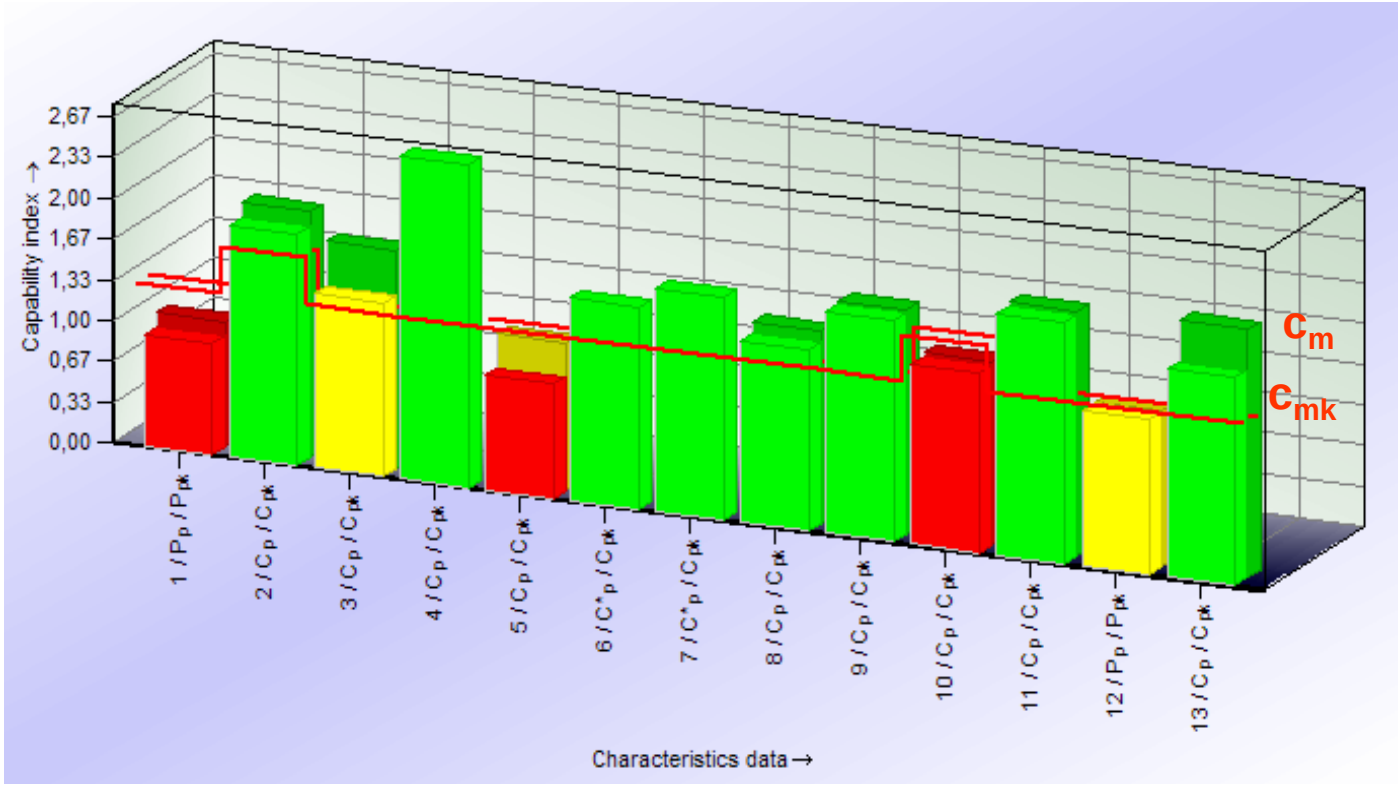
quantile method (percentile method)

$$C_{pu} = \frac{USL - \tilde{x}}{X_{up3} - \tilde{x}}$$

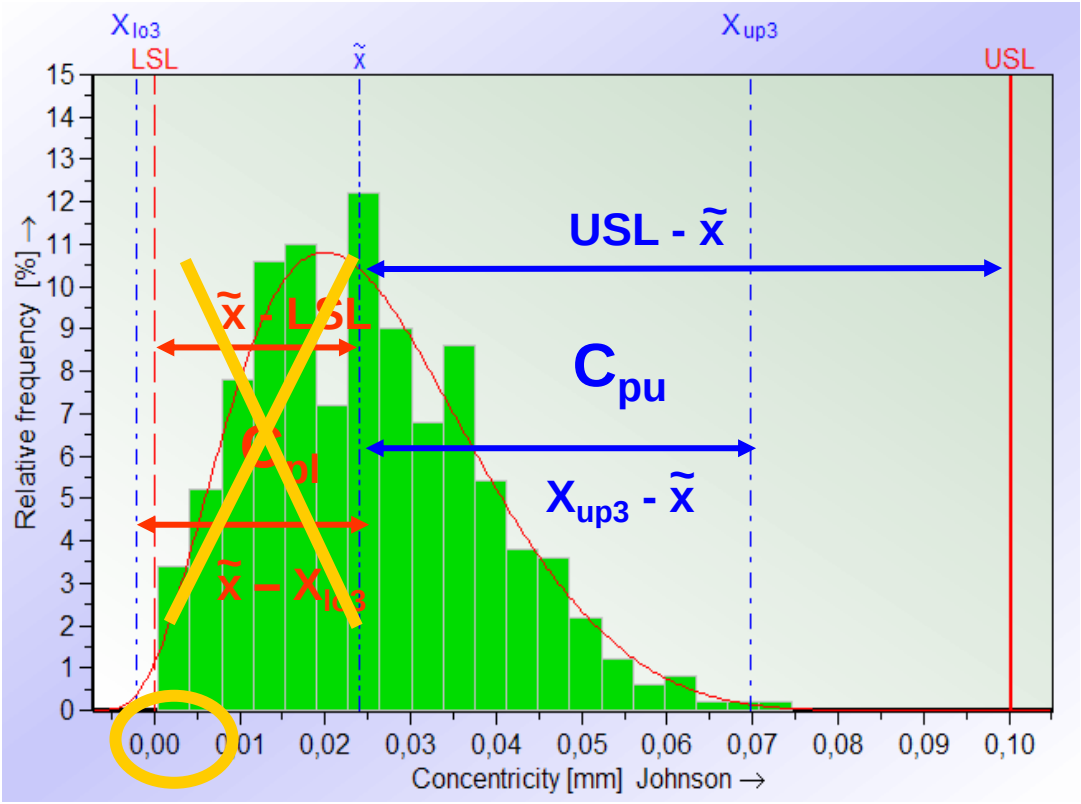
$$C_{pl} = \frac{\tilde{x} - LSL}{\tilde{x} - X_{lo3}}$$

$$C_{pk} = \min \{C_{pu}, C_{pl}\}$$

One capability index pair C_m/C_{mk} per characteristic!



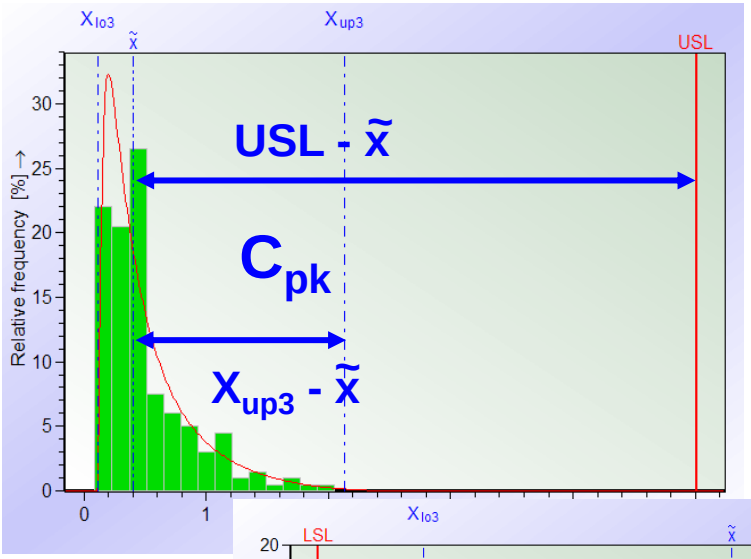
“capable machine“ means: <u>all</u> characteristics are capable



$$C_{pu} = \frac{USL - \tilde{x}}{X_{up3} - \tilde{x}}$$

$$C_{pl} = \frac{\tilde{x} - LSL}{\tilde{x} - X_{lo3}}$$

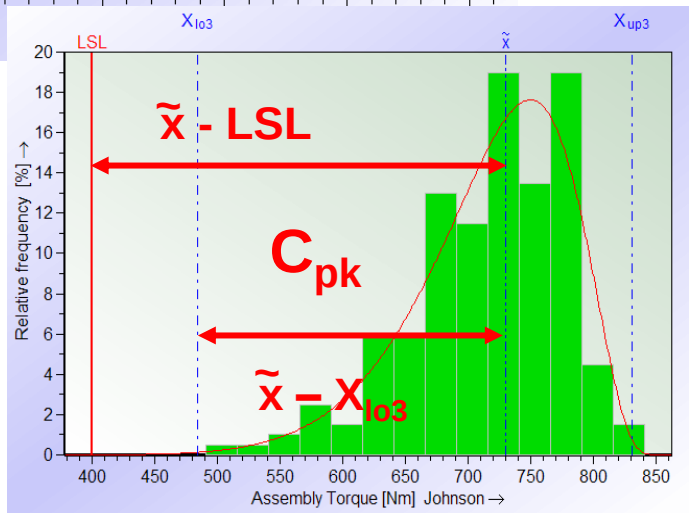
$$C_{pk} = C_{pu}$$



$$C_{pk} = \frac{USL - \tilde{x}}{X_{up3} - \tilde{x}}$$

~~C_p = ???~~

C_p cannot be calculated



$$C_{pk} = \frac{\tilde{x} - LSL}{\tilde{x} - X_{lo3}}$$

Table of Time-dependent Distribution Models

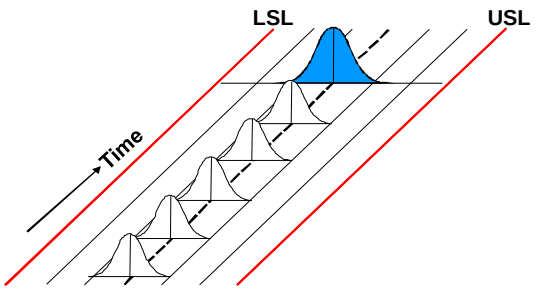
- ISO 21747
  process performance and **process capability statistics** for continuous quality characteristics

Characteristic	Time-dependent distribution models [c]							
	A1	A2	B	C1	C2	C3	C4	D
Location [a]	c	c	c	r	r	s	sr	sr
Variation [a]	c	c	sr	c	c	c	c	sr
Instantaneous distribution [b]	nd	1m	nd	nd	nd	as	as	as
Outcoming distribution [b]	nd	1m	1m	nd	1m	as	as	as
See Figure	1	2	3	4	5	6	7	8

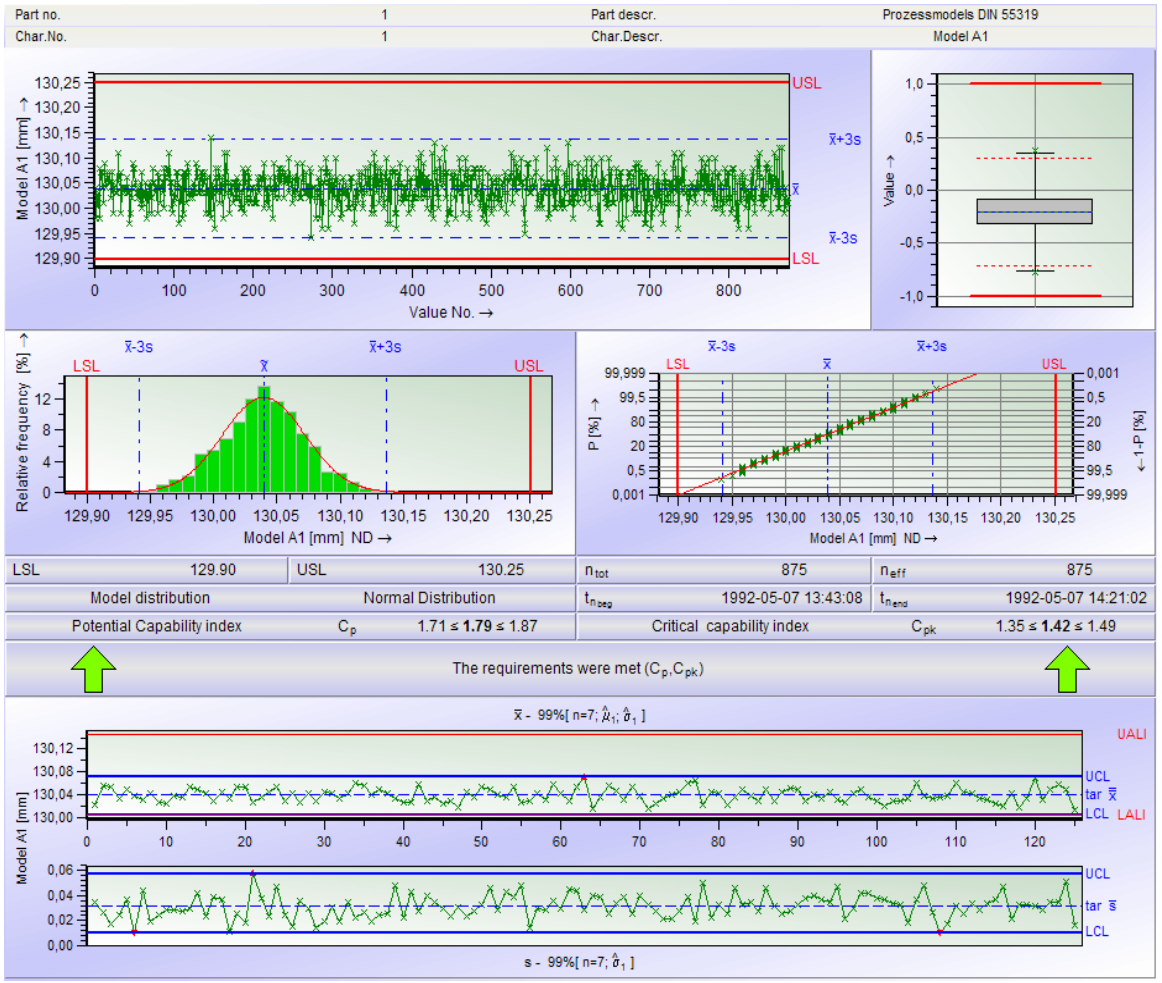
[a] Location/variation:
„c“ = the parameter remains *c*onstant;
„r“ = the parameter changes *r*andomly only;
„s“ = the parameter changes *s*ystematically only;
„sr“ = the parameter changes systematically and randomly

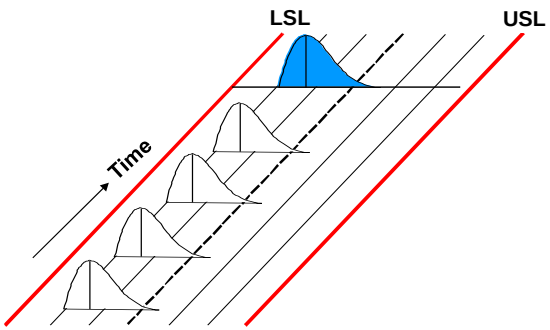
[b] Instantaneous/outcoming distribution:
„nd“ = *n*ormally *d*istributed;
„1m“ = not normally distributed, one mode only;
„as“ = *a*ny *s*hape.

[c] The choice of the model is a result of process analysis.

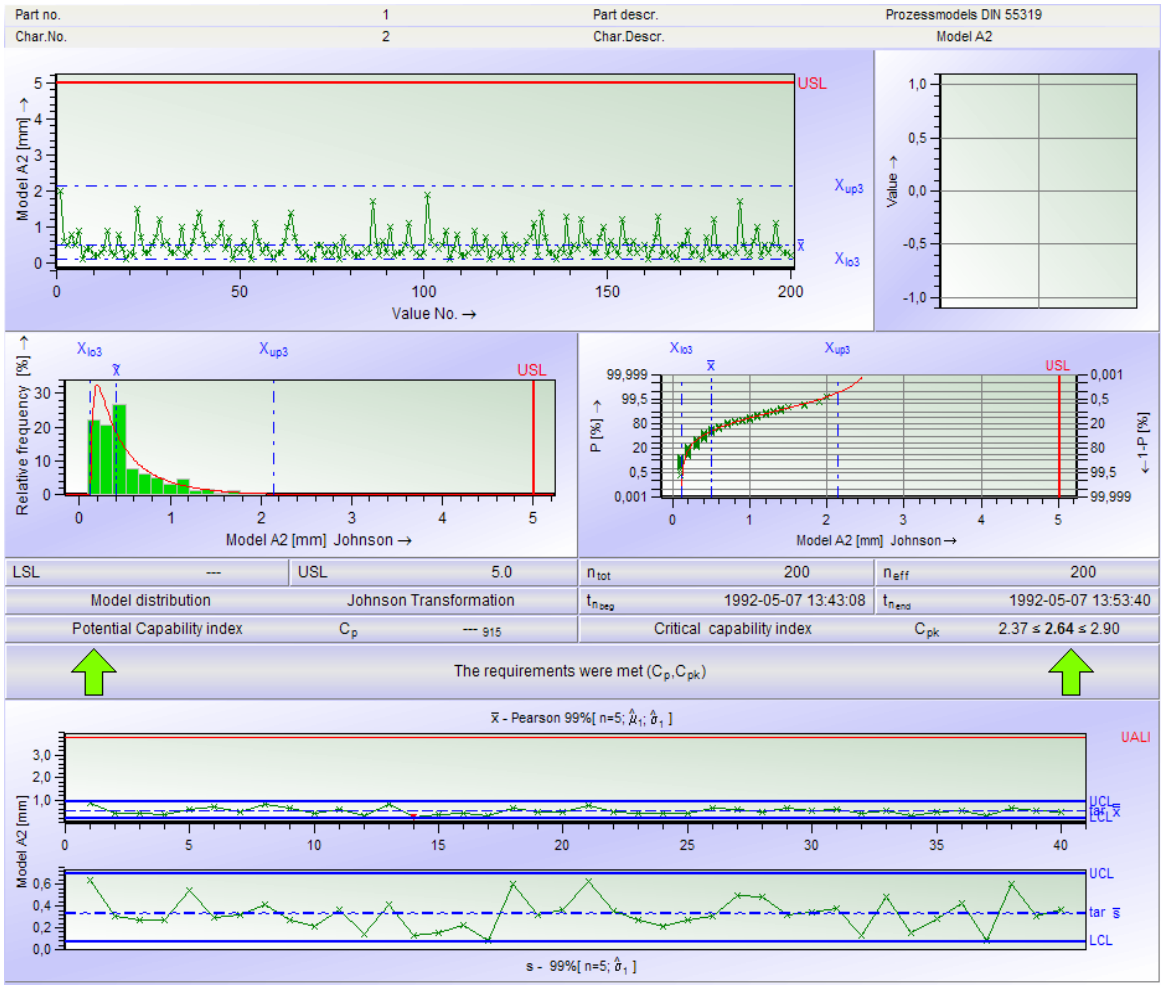


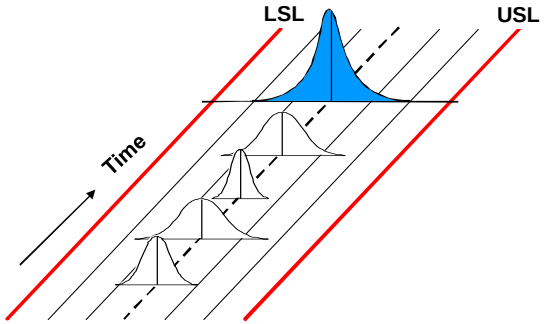
- **location remains constant**
- **variation remains constant**
- **skewness remains constant**
- **kurtosis remains constant**
  - **current distribution normally distributed**
  - **resulting distribution normally distributed**



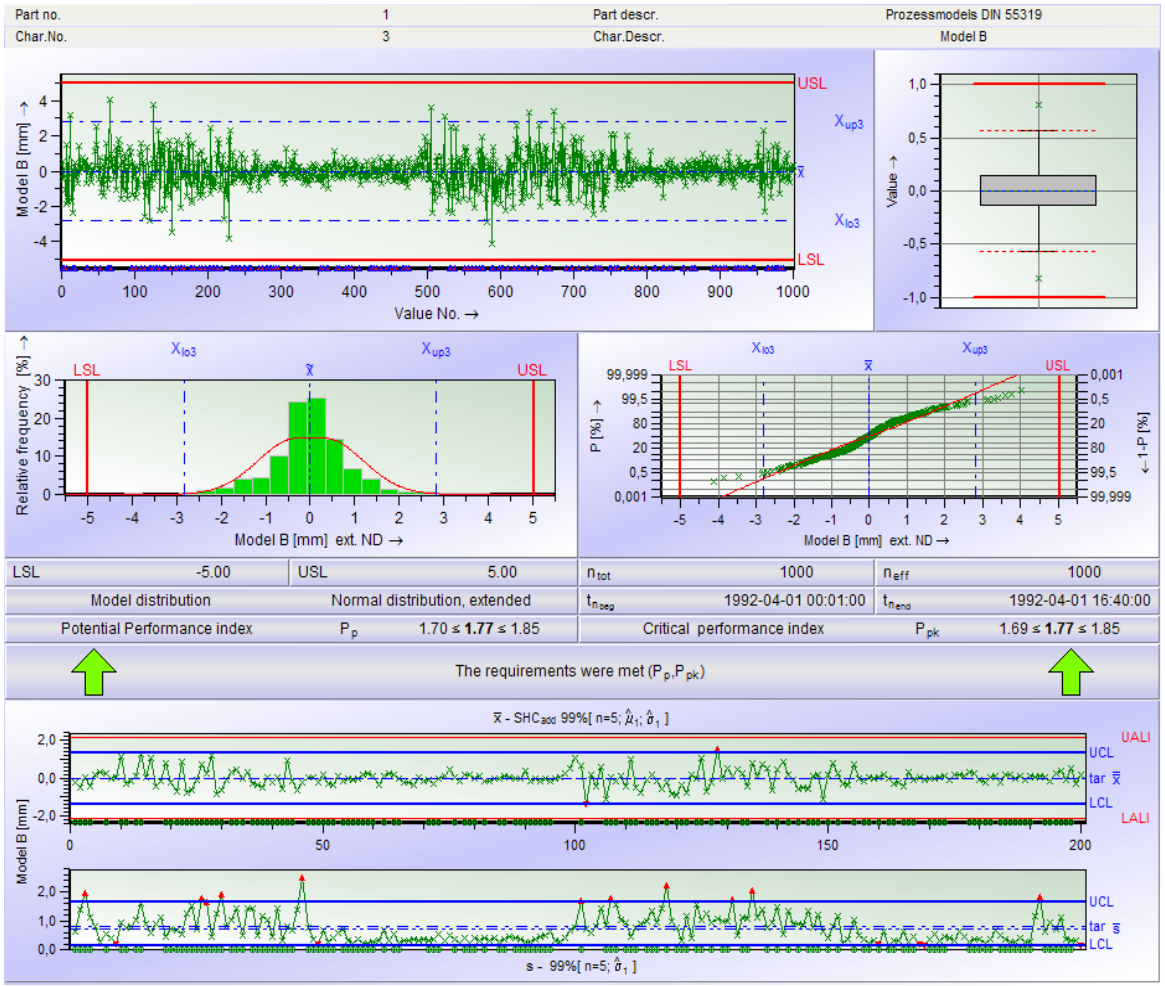


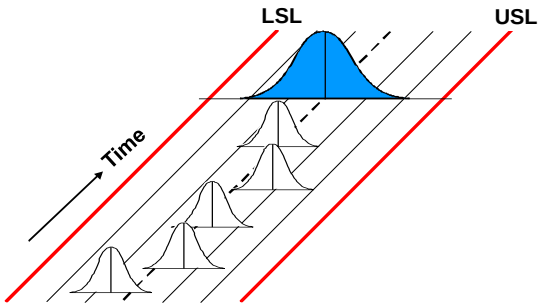
- location remains constant
- variation remains constant
- skewness remains constant
- kurtosis remains constant
- current distribution
  1m
- resulting distribution
  1m



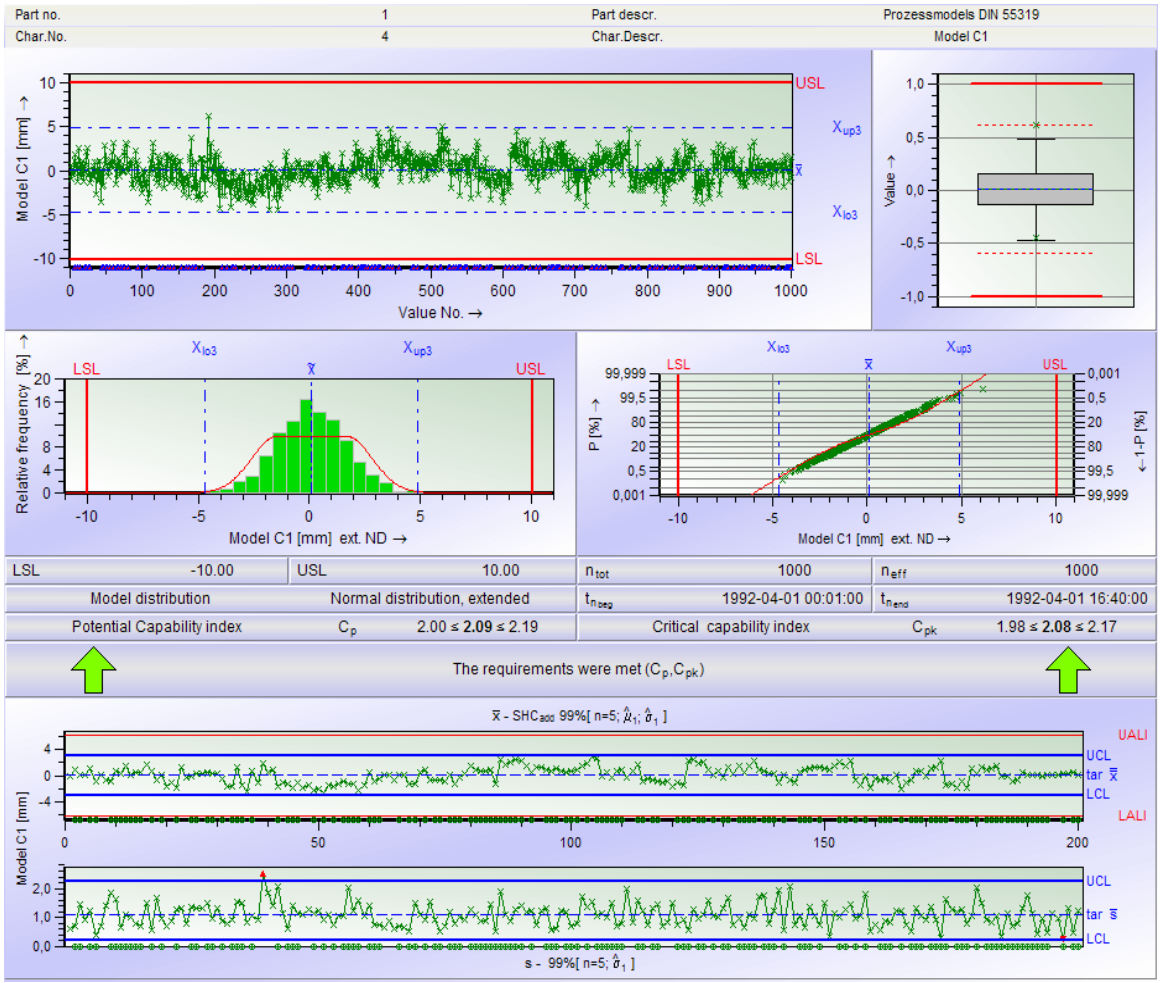


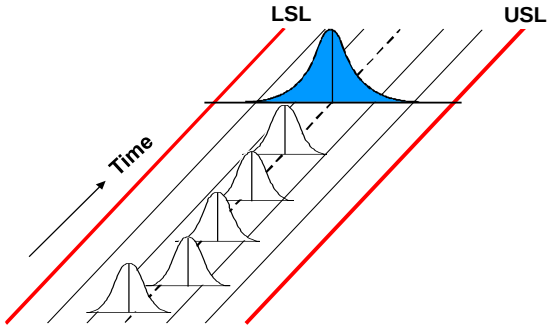
- location remains constant
- variation changes randomly
- skewness remains constant
- kurtosis remains constant
- current distribution nd
- resulting distribution 1m



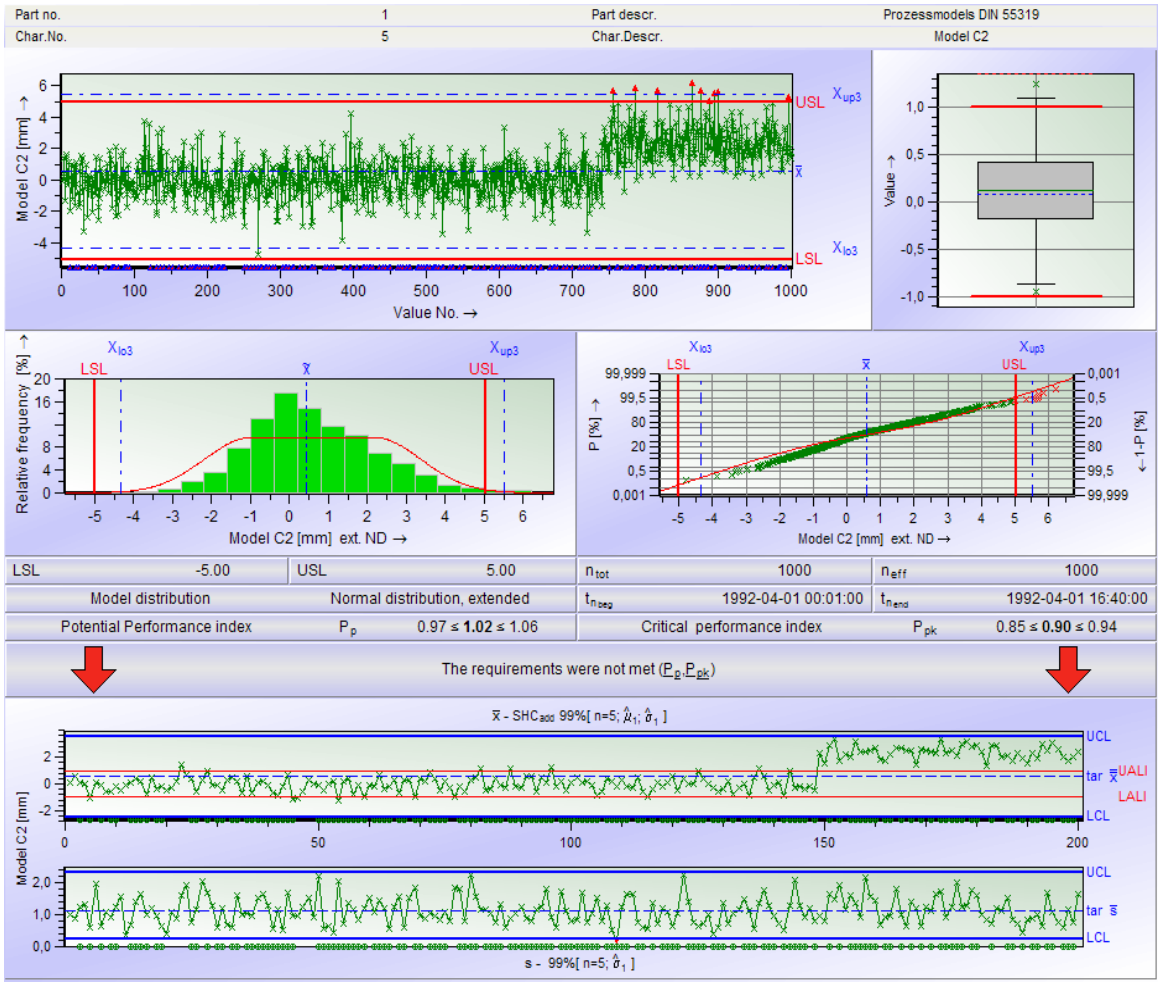


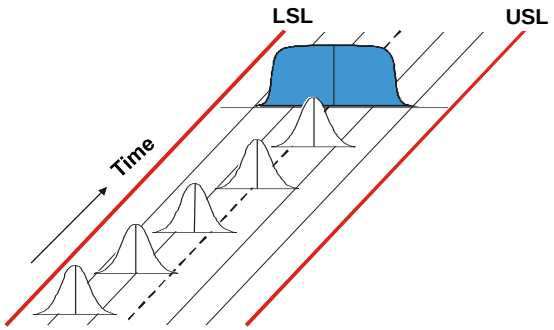
- location changes randomly (nd)
- variation remains constant
- skewness remains constant
- kurtosis remains constant
- current distribution nd
- resulting distribution nd



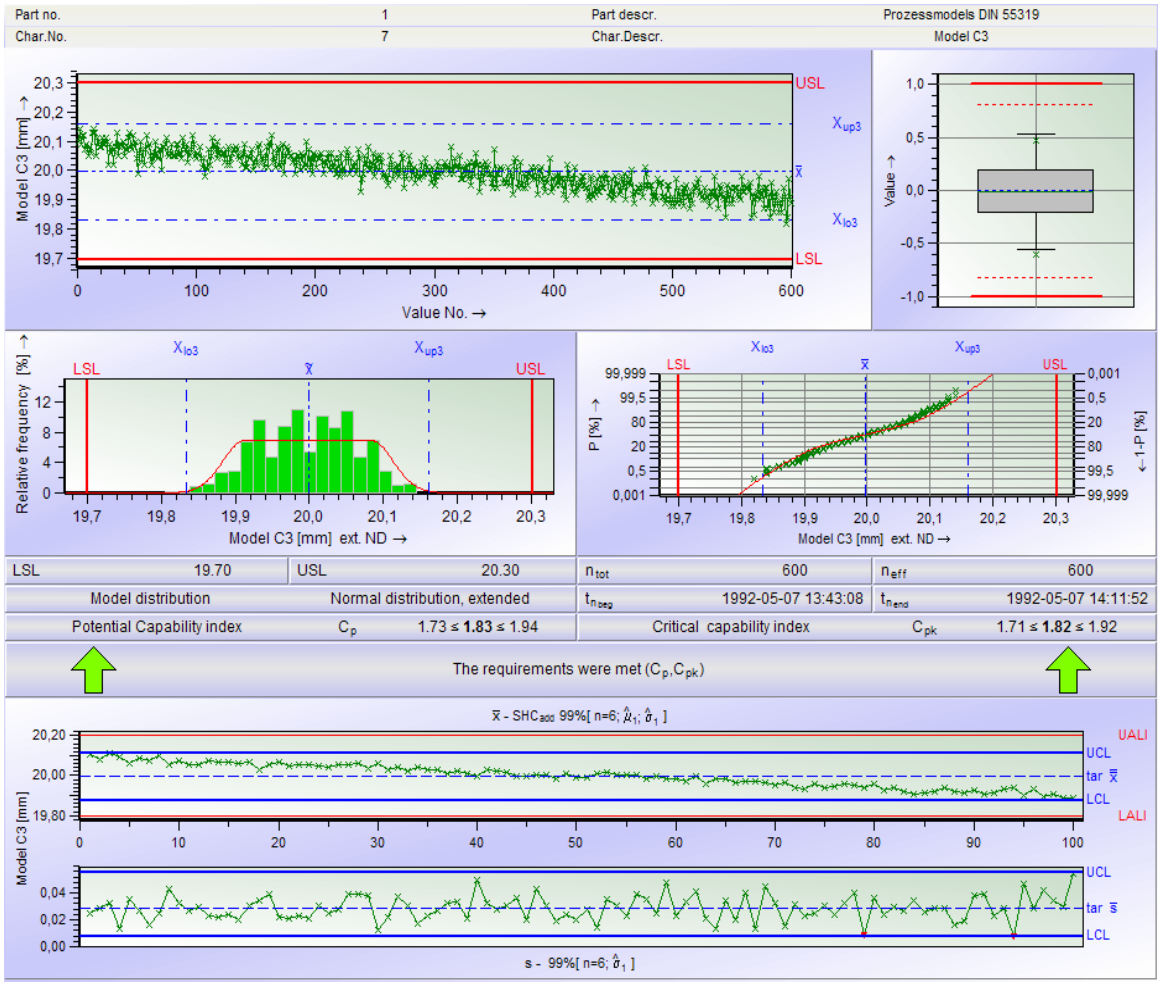


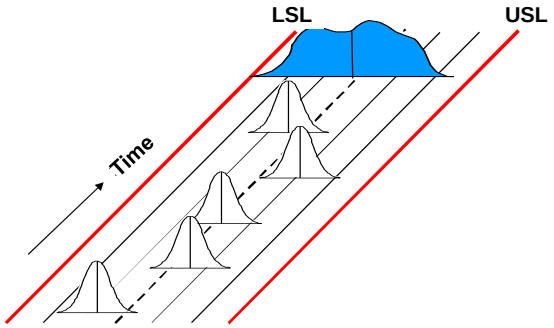
- location **changes randomly**
- variation **remains constant**
- skewness **remains constant**
- kurtosis **remains constant**
- current distribution
  nd
- resulting distribution
  1m



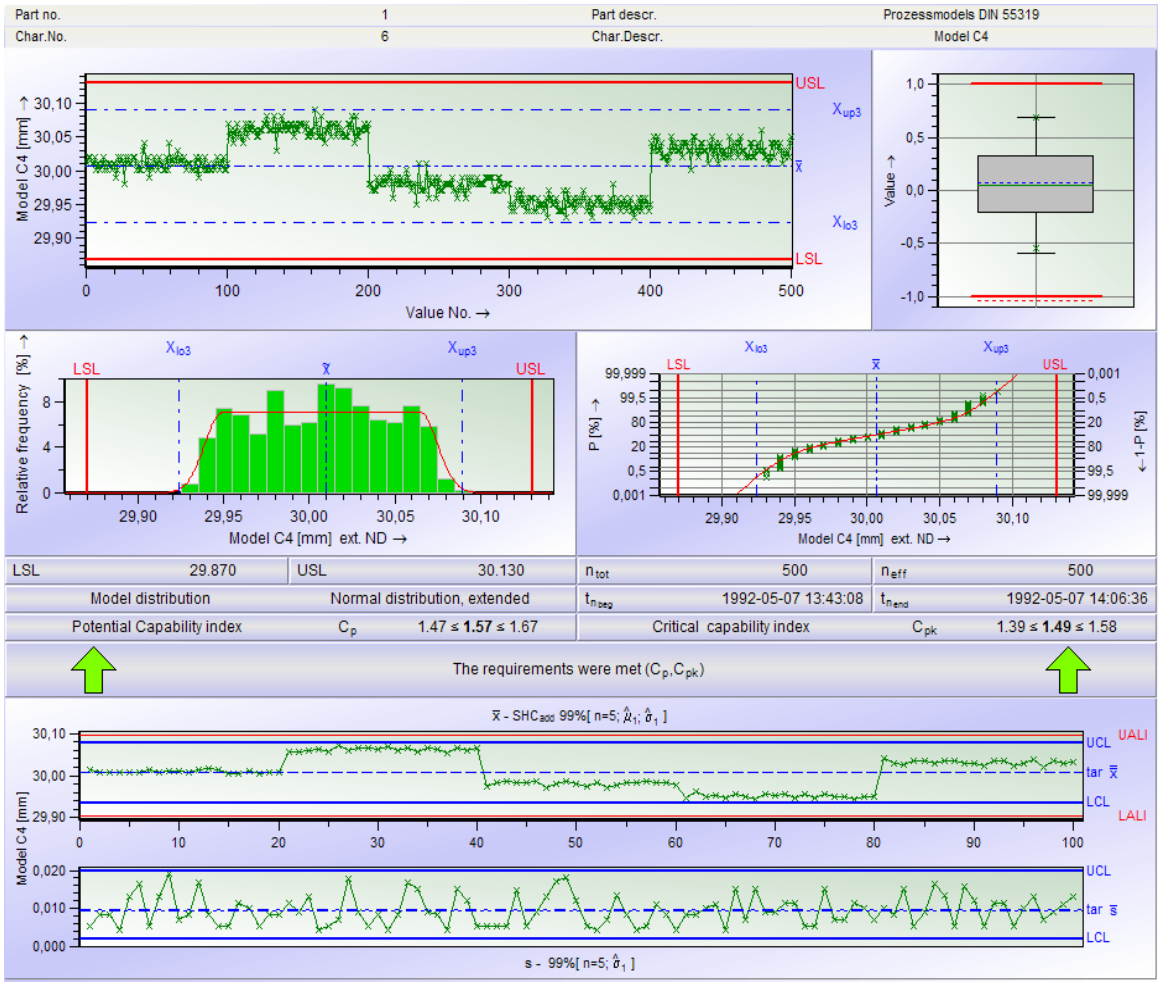


- location **changes systematically**
- variation **remains constant**
- skewness **remains constant**
- kurtosis **remains constant**
- current distribution **as**
- resulting distribution **as**

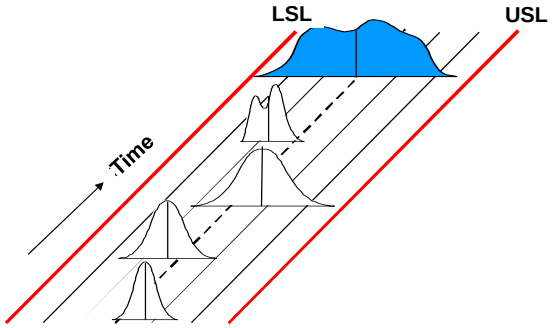




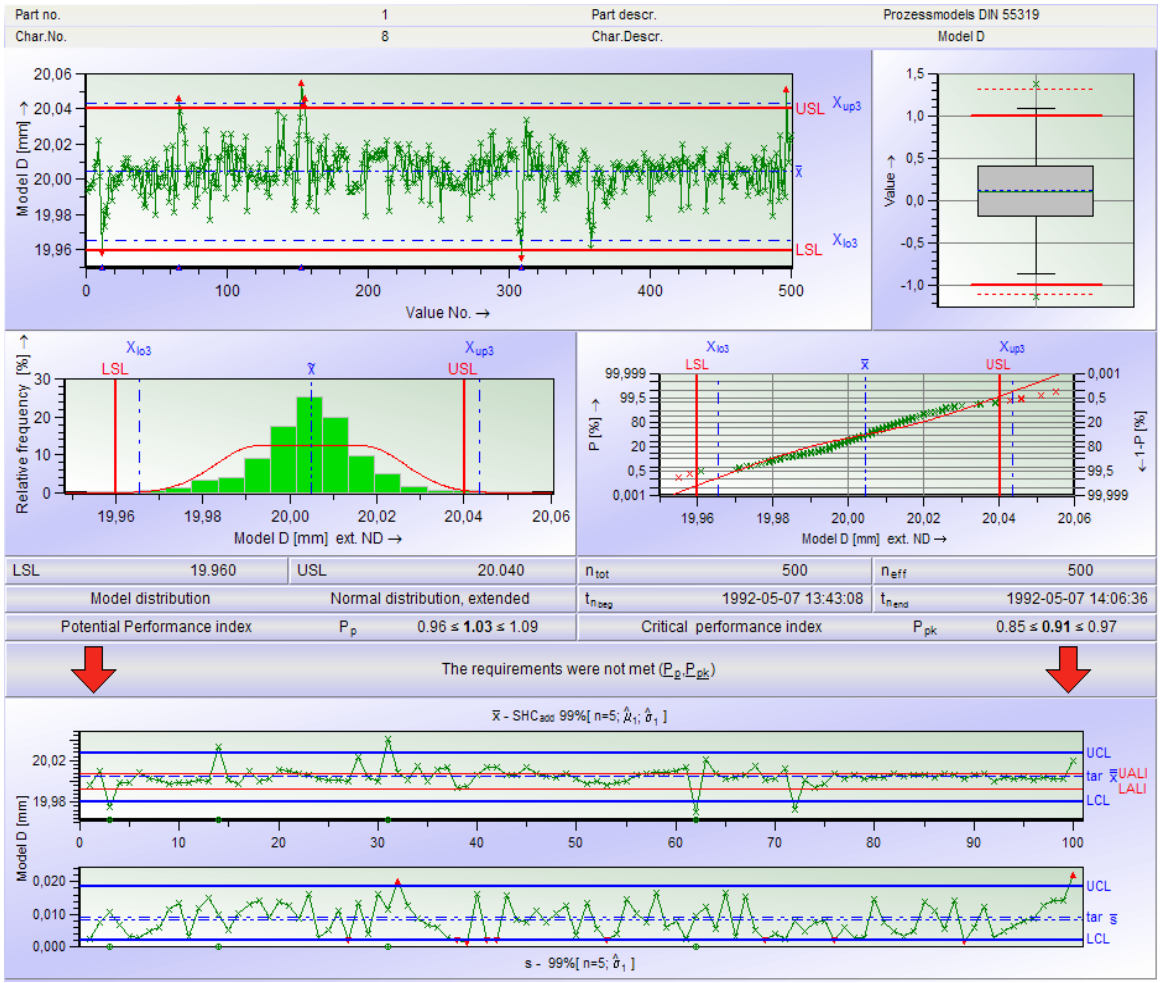
- location **changes systematically and randomly**
- variation **remains constant**
- skewness **remains constant**
- kurtosis **remains constant**
- current distribution **as**
- resulting distribution **as**



D – Disturbed Process and Process Capability



- location changes systematically and randomly
- variation ditto
- skewness ditto
- kurtosis ditto
- current distribution as
- resulting distribution as



Calculation Methods according to ISO 21747

Indices referring to and DIN 55319 (withdrawn)

Method[a]	Calculation ...	
$M1_{l,d}$ General geometric method	... with estimators for location μ and dispersion Δ	**M1** **M3**
$M2_{l,d,a}$ Explicit inclusion of additional variation	... with estimators for location μ, dispersion Δ and additional fluctuation μ_{add}	**M4** **M5**
$M3_{l,d,a}$ Alternate method for the explicit inclusion of additional variation	... with estimators for location μ, dispersion Δ and additional fluctuation μ_{add}	**M6**
M4 Excess proportions approach	... with estimators for upper and lower excess porportions	**M2**

[a] The subscript l refers to an equation for calculation of the estimator for the location μ.
The subscript d refers to an equation for calculation of the estimator for the dispersion Δ.
The subscript a refers to an equation for calculation the estimator for additional variation μ_{add}.

➔ **There are several alternatives per method (here M1):**

estimator for

$l = 1 \quad \hat{\mu}_1 = \bar{x} = \frac{1}{n}\sum_i x_i$

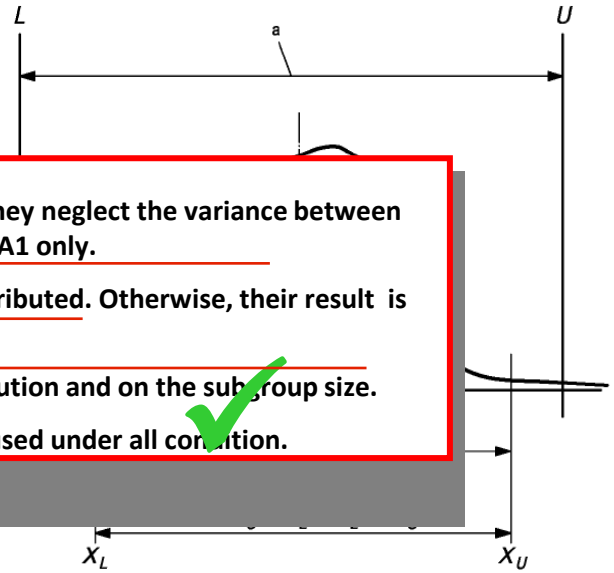
$l = 2 \quad \hat{\mu}_2 = \tilde{x} \quad (\text{median sample})$

NOTE 1 The estimators Δ for d = 1,2,3 estimate the subgroup variance only, they neglect the variance between different subgroups. They should be used for process model A1 only.

NOTE 2 The estimators Δ for d = 1,2,3,4 assume that the data is normally distributed. Otherwise, their result is biased depending on the distribution.

NOTE 3 The estimator Δ for d = 5 is biased. The bias depends on the distribution and on the subgroup size.

NOTE 4 The estimator Δ for d = 6 is the most general one, it can be used under all condition.



estimator for variation

$d = 2$	with	$\hat{\sigma}_2 = \frac{\sum s_i}{m \cdot c_4} \quad \left(\hat{=} \frac{\bar{s}}{a_n}\right)$	
$d = 3$	with	$\hat{\sigma}_3 = \frac{\sum R_i}{m \cdot c_4} \quad \left(\hat{=} \frac{\bar{R}}{d_n}\right)$	
$d = 4$	with	$\hat{\sigma}_4 = \sigma_t = \sqrt{\frac{1}{n-1}\sum (x_i - \bar{x})^2} \quad (\hat{=} s_{tot})$	
$d = 5$	$\hat{\Delta} = R$	$\hat{\Delta}_L = \hat{\mu} - \min(x_i); \hat{\Delta}_U = \max(x_i) - \hat{\mu}$	
$d = 6$	$\hat{\Delta} = X_{99.865\%} - X_{0.135\%}$	$\hat{\Delta}_L = \hat{\mu} - X_{0.135\%}; \hat{\Delta}_U = X_{99.865\%} - \hat{\mu}$	

$$C_p = \frac{U - L}{\Delta} \quad \text{with}$$

$$C_{pk} = \min(C_{pkL}, C_{pkU}) \quad C_{pkL} = \frac{\mu - L}{\Delta_L}$$

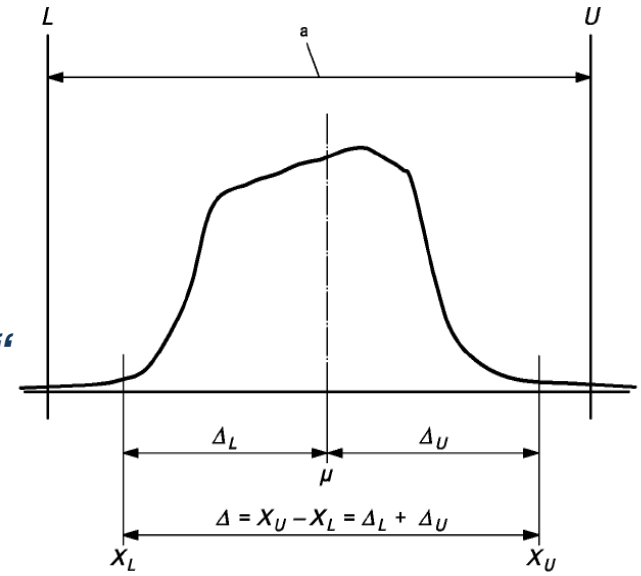
$$C_{pkU} = \frac{U - \mu}{\Delta_U}$$

estimator for location

$l = 2 \quad \hat{\mu}_1 = \tilde{x}$

"percentile method" / "quantile method"

general geometric method M1$_{2,6}$



estimator for variation

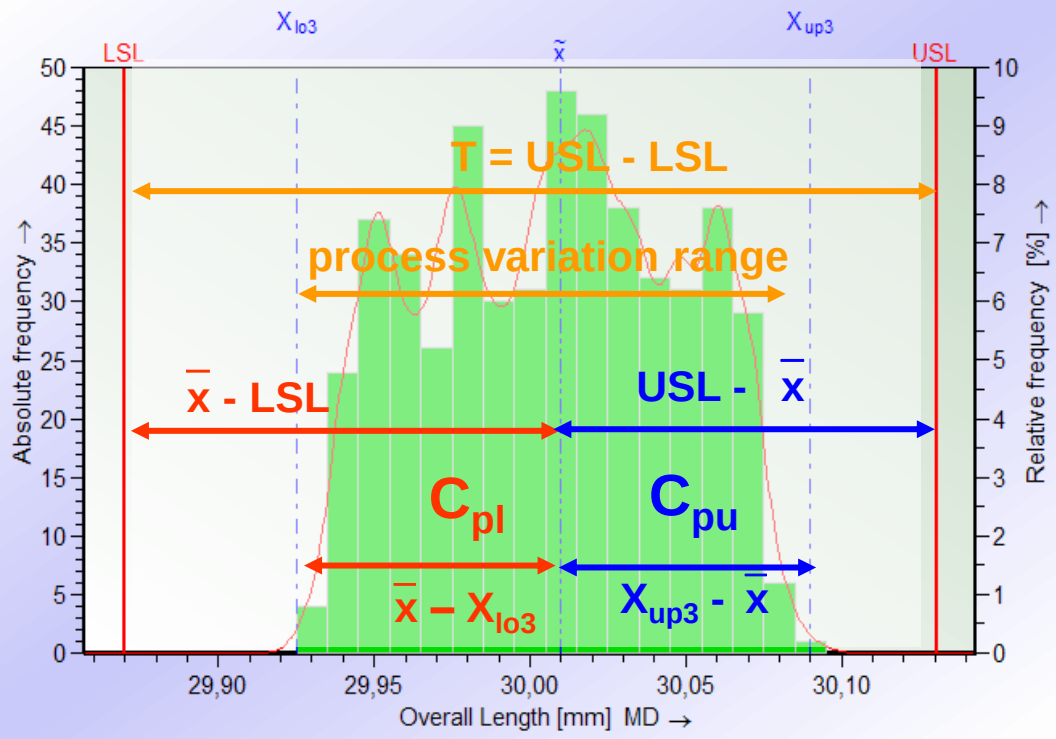
$d = 6 \quad \hat{\Delta} = X_{99.865\%} - X_{0.135\%}$

$\hat{\Delta}_L = \hat{\mu} - X_{0.135\%}; \hat{\Delta}_U = X_{99.865\%} - \hat{\mu}$

$$C_p = \frac{U - L}{\Delta} \qquad \textit{with}$$

$$C_{pk} = \min\left(C_{pkL}, C_{pkU}\right) \qquad C_{pkL} = \frac{\mu - L}{\Delta_L}$$

$$C_{pkU} = \frac{U - \mu}{\Delta_U}$$



percentile method

: quantile method

ISO 21747: general geometric method

process capability C_p
(process performance P_p)

$$C_p = \frac{USL-LSL}{X_{up3} - X_{lo3}}$$

smallest process capability index C_{pk}
(performance index P_{pk})

$$C_{pu} = \frac{USL - \bar{x}}{X_{up3} - \bar{x}}$$

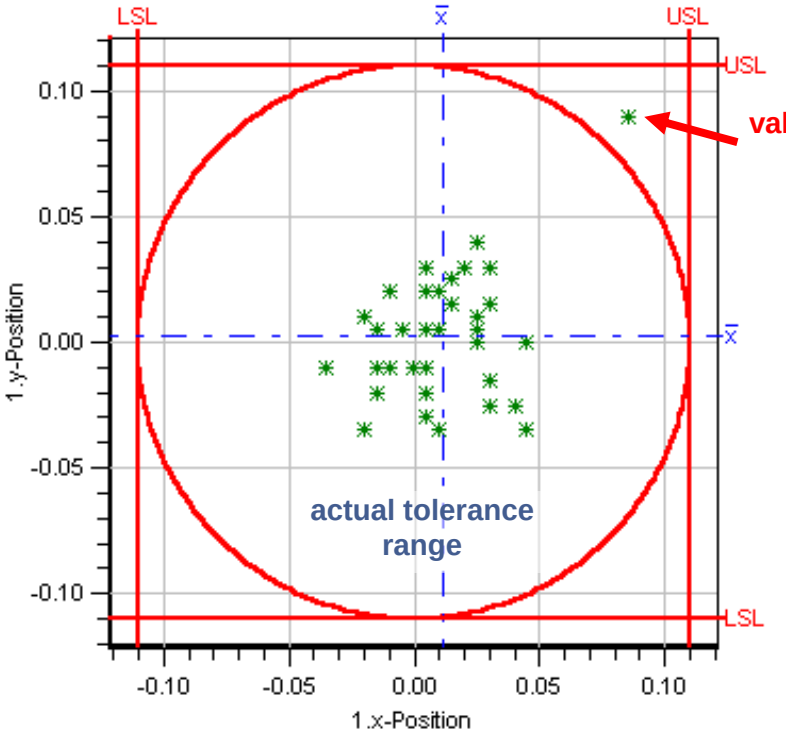
$$C_{pl} = \frac{\bar{x} - LSL}{\bar{x} - X_{lo3}}$$

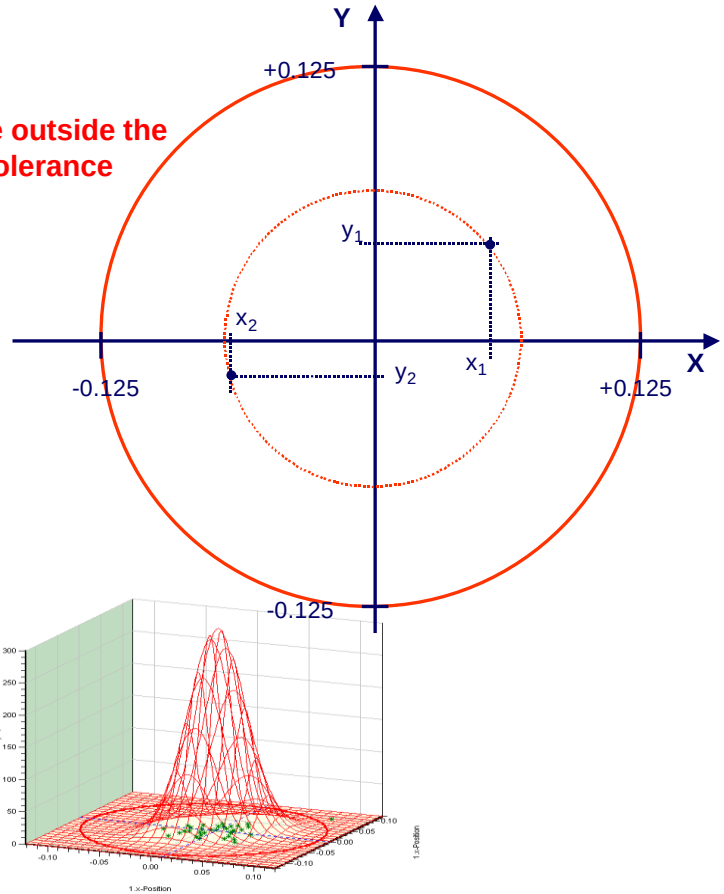
$$C_{pk} = \min \{C_{pu}, C_{pl}\}$$

➔ Requirements for report generation

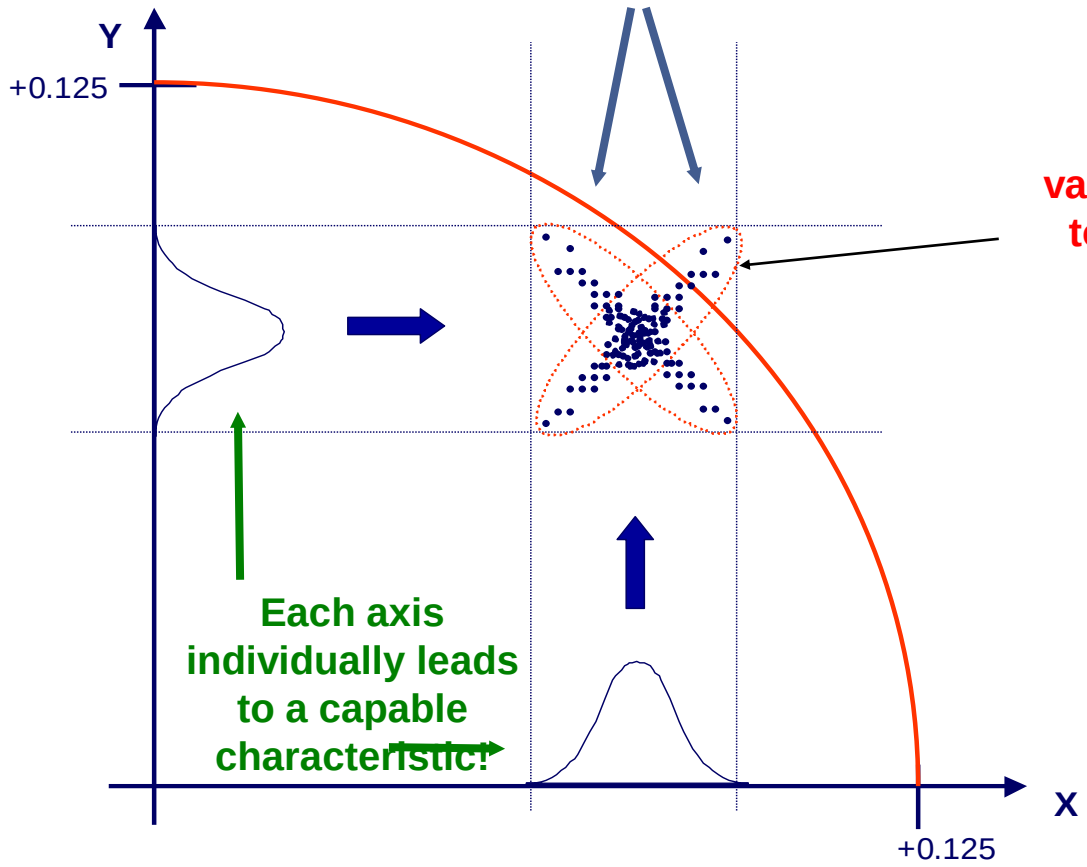
Process capability index	C_p = 1.68
Minimum process capability index	C_{pk} = 1.47
Calculation method	ISO 21747 $M1_{3,6}$
Number of values used for the calculation	2 000
Optional:	
- frequency of sampling;	5 parts/2h
- time and duration of data taking;	Sept./Oct. 2009
- choice of time distribution model justification;	C4 according to “Bosch 2005“ evaluation strategy
- measurement system gauge capability repeatability and reproducibility uncertainty resolution;	According to booklet 10 see D-Nr. xxxxxxx
- technical conditions (batches, operation, tools)	According to production plan

Positional Tolerances - Basics

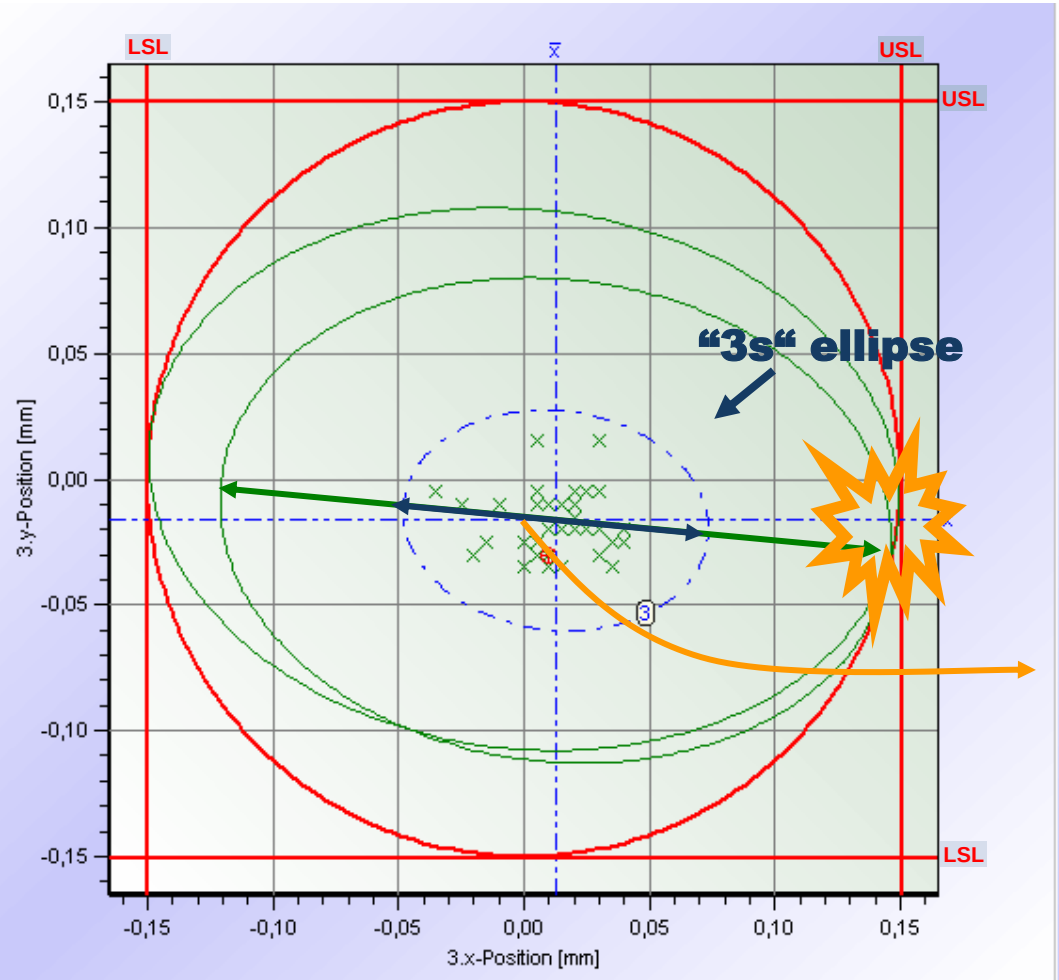




two possible results depending on the correlation:



Positional Tolerances - xy Plot

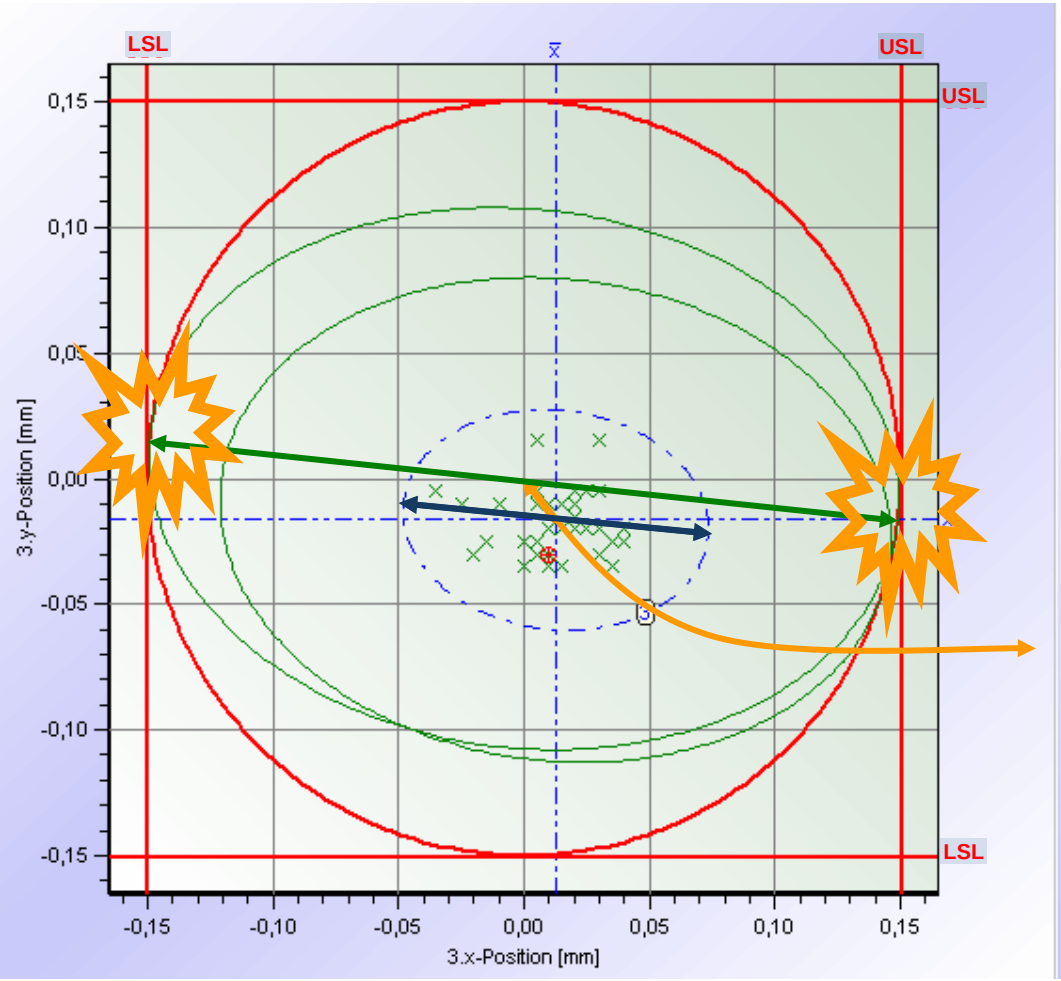


3.x-Position	
$\bar{x}$	0,01263
$\tilde{x}$	0,010
$T_m - \bar{x}$	-0,01263

3.y-Position	
$\bar{x}$	-0,01638
$\tilde{x}$	-0,020
$T_m - \bar{x}$	0,01638

P_o	1,95 ≤ **2,72** ≤ 3,53
P_{ok}	1,70 ≤ **2,42** ≤ 3,14

Positional Tolerances - xy Plot



3.x-Position	
$\bar{x}$	0,01263
$\tilde{x}$	0,010
$T_m - \bar{x}$	-0,01263

3.y-Position	
$\bar{x}$	-0,01638
$\tilde{x}$	-0,020
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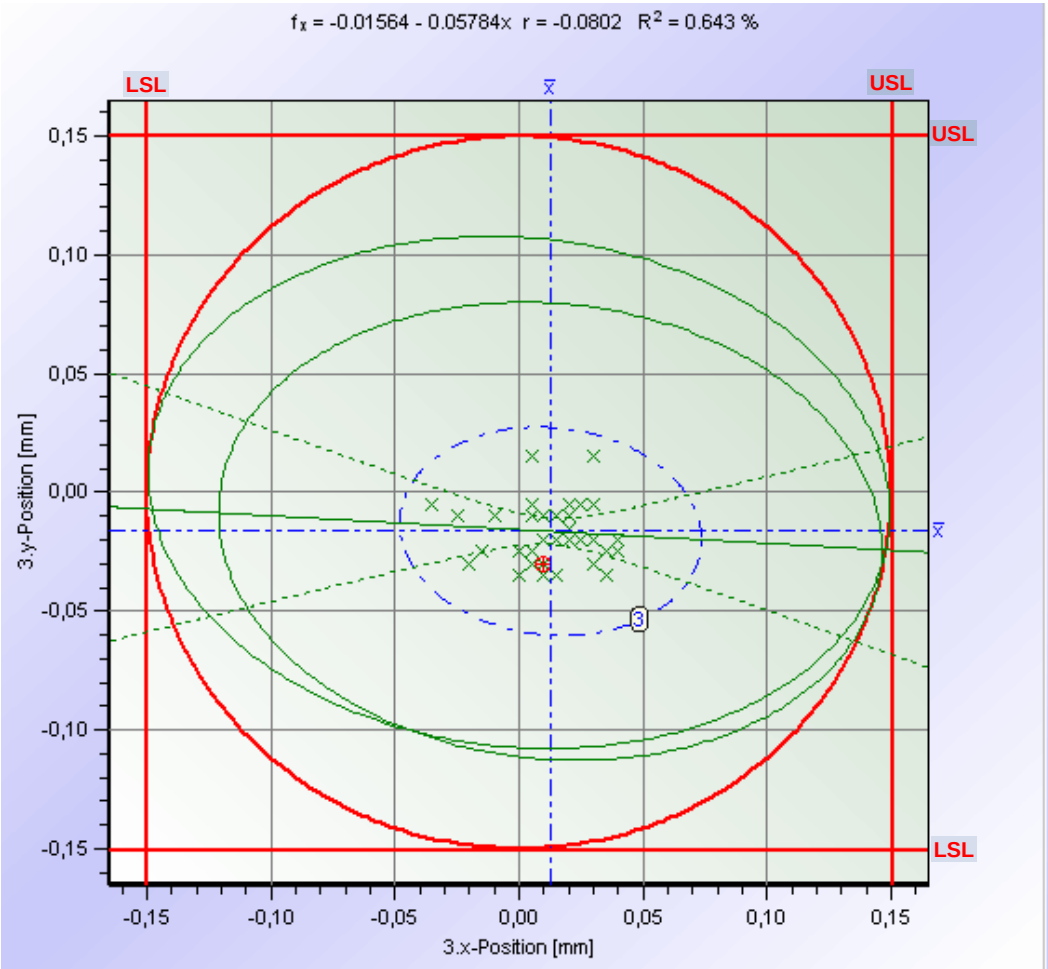
Positional Tolerances - xy Plot



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$\tilde{x}$	0,010
$T_m - \bar{x}$	-0,01263
3.y-Position	
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$\tilde{x}$	-0,020
$T_m - \bar{x}$	0,01638
P_o	1,95 ≤ **2,72** ≤ 3,53
P_{ok}	1,70 ≤ **2,42** ≤ 3,14

Many thanks for your interest and cooperation

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