Good practice guide for assessing the fitness for purpose for dimensional measurements on machine tools

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1 Introduction

This good practice guide provides procedures for assessing the fitness for purpose of on-board metrology systems and measuring processes for dimensional measurements of workpieces on machine tools. Assessing the fitness-for-purpose is required in order to determine whether or not a machine tool is meeting accuracy specifications and is capable of manufacturing as well as inspecting features (geometries) on a machined part with respect to the required accuracy. This ensures a reliable ´go´ or ´no-go´ decision based on the obtained measurement result and the achievable measurement uncertainty. It provides an overview why a fitness for purpose assessment is necessary, how it is done, and how to deal with uncertainties and tolerances.

1.1 Terms and definitions

Fitness for purpose of on-board metrology systems or measuring processes can be defined as its qualification for a destined test task, exclusively considering accuracy demands. When assessing fitness for purpose a distinction is made between the uncertainty of only the measuring on-board system, and the uncertainty of the whole measuring process. The following definitions are used:

- **On-board measuring system:**
  Set of one or more measuring instruments, assembled and adapted on a machine tool to give information used to generate measured quantity values within specified intervals for quantities of specified kinds. [1]
- **Measuring process:**
  Interaction of interrelated utilities, actions, and influences which produce a measurement. [5]

Considering the definitions above, a simplified description could be as follows: A measuring process is the total of all actions (e.g. alignment, clamping, handle), devices (e.g. a machine tool, touch probe), and items (e.g. measurement object, environmental conditions) that are necessary to measure a geometrical feature or might influence the measuring result of measurements while the part is still clamped onto the machine. In contrast, the measuring system can be considered as a subset of the measuring process (e.g. a machine tool equipped with touch probe).

2 Measurements

When assessing the fitness for purpose for tactile measurements on a machine tool by using artefacts, one can distinguish between using calibrated material standards, or using workpieces or workpiece replicas, which are produced and measured on the machine tool under investigation and calibrated afterwards, for instance, on a coordinate measuring machine. While the first approach is suitable for assessing the fitness-for-purpose of the measuring system, the second approach is used for assessing the fitness-for-purpose of the entire measuring process including the manufacturing process. A workpiece replica is a part that has been produced on the machine tool under investigation and allows similar measurement tasks as they are performed on the real workpiece. In any case, the touch probe has to be carefully calibrated, and geometric errors of the machine tool should be compensated. Moreover, the probing points for the on-machine measurement and for the calibration as well as the diameter of the used stylus tip should be the identical, especially if the measured part has significant form deviations or a rough surface.

2.1 Use of material standards for assessing the suitability of the measuring system

By using material standards the fitness for purpose of the measuring system can be assessed with or without considering clamping effects to the measurement. If clamping effects are considered the material standard will be clamped onto the machine tool and its geometrical features will be measured n times. Afterwards the standard will be unclamped, handled, clamped again and its geometrical features will be measured anew. This measurement cycle is depicted in Figure 1.

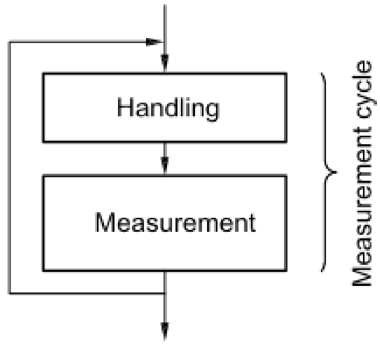

Figure 1: Measurement cycle [3]

If clamping effects are not considered the material standard will be clamped on the machine and its geometrical features will be measured several times in a row. No matter which of these procedures will be used, the measurements have to be carried out for a sufficient number of repetitions (20 are recommended) to generate reliable statistical data. Following this the assessment of the fitness for purpose is carried out by using the measured data and comparing it to the calibration of the material standard. This is described in detail in Subsection 3.1.

2.2 Use of workpieces or workpiece replicas for assessing the suitability of the measuring process including the manufacturing

The procedure for using workpieces or workpiece replicas is similar to that already described above. First of all a blank is clamped onto the machine tool and the workpiece is machined out of the blank. After the machining is finished all specified geometrical features will be measured several times (20 repetitions are recommended) in the same clamping by using the on-machine measuring system. Following this the workpiece will be unclamped, a new blank will be clamped and the process repeats. The assessment of the measuring process can be carried out by comparing the on-machine measurements of a feature to its calibration. To this aim at least three machined workpieces must be calibrated on a CMM to ensure reliable data. The analysis of the measurements is similar to those for using material standards and described in detail in Subsection 3.1. The benefit of using workpiece replicas to assess the fitness for purpose of on-machine measurements is that influences due to variations in the machining process can be considered in the uncertainty budget.

3 Measurement results and uncertainties

For on-machine measurements, there is a large number of error sources which contribute to the measuring errors. Figure 2 gives an overview of potential error sources. Of course, not all influences contribute significantly to the measuring error in all cases. For example, for tactile measurements on a machine tool the main influences are geometric errors of the machine tool, errors of the probing system, temperature induced effects and maybe dirt, while sound or light in general have no influence on the measuring errors. On the other hand, there may be special cases where it is necessary to consider additional errors sources which are not included in Figure 2.

In the following the experimental uncertainty determination by measuring artefacts described in the previous section will be explained. The presented procedure is adopted from ISO 15530-3 [3] and VDA 5 [4]. The advantage of such an experimental uncertainty determination is given by the fact that most of the uncertainty influences on the measurement system or process are also present during the test measurements of the artefacts. This is in contrast to other methods like the uncertainty estimation with Monte-Carlo simulations, where processing parameters are not taken into account.

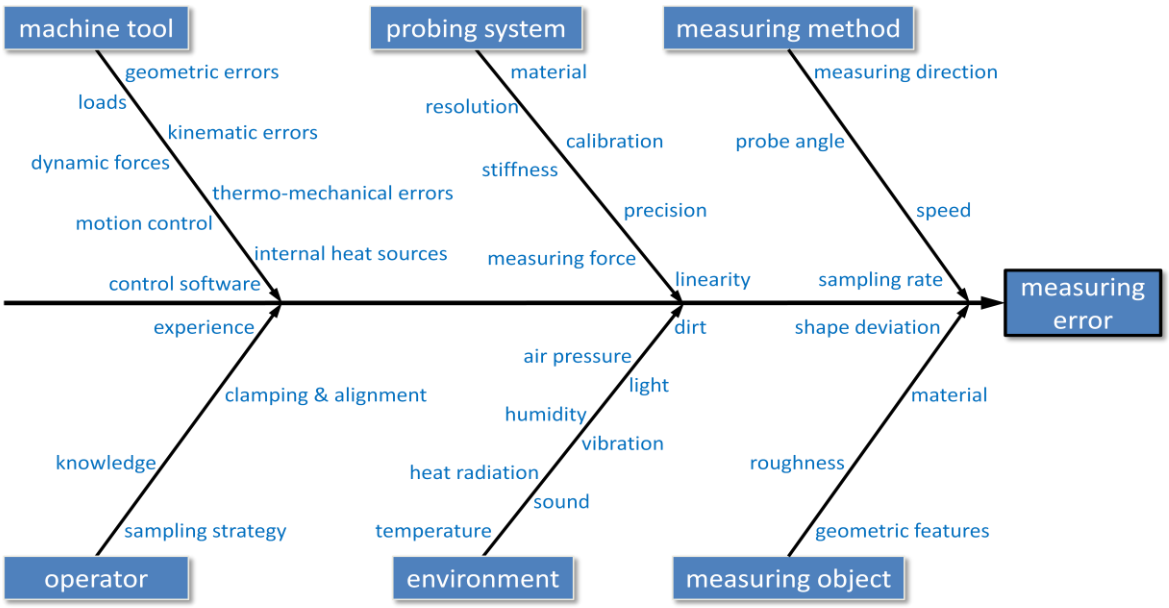

Figure 2: Possible error contributions

Figure 3: Measuring of feature y-width

3.1 Task specific uncertainty for on-machine measurements

For a workpiece's feature that was measured n times (for the same workpiece) on the machine tool one gets the measurement results $y_1, \ldots, y_n$, the mean value $\bar{y}$, and the standard deviation s_y, i.e.

$$\bar{y} = \frac{1}{n}\sum_{i=1}^{n} y_i \quad ; \quad s_y = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(y_i - \bar{y})^2}.$$

The calibration of the workpiece's feature on a coordinate measuring machine gives the calibration result x_{cal}, with the corresponding uncertainty u_x.

Systematic error

The total systematic error b for a measured feature is defined as the difference between the mean value $\overline{y}$ of the measurement results on the machine tool and the calibration value x_{cal}, i.e.

$$b = \overline{y} - x_{cal}.$$

Since the calibration value was determined in the laboratory at a temperate of 20 °C, this error b also includes the effect of thermal expansion of the workpiece, as measurements on machine tools are in general performed at temperatures different from 20 °C. However, if the temperature of the workpiece during the measurement on the machine tool is tracked, the systematic error can be corrected by the effect of thermal expansion, leading to

$$b_t = \overline{y} - x_{cal} - \alpha \cdot (\vartheta - 20\,°\mathrm{C}) \cdot |x_{cal}|,$$

where α is the coefficient of thermal expansion, and ϑ the workpiece temperature.

An example of a systematic error is given in Figure 4. Assuming a feature such as a diameter or a width is measured 10 times in row (blue marks) and the mean value of this measurements is calculated (green mark), then the systematic error is the difference between the mean value of the 10 measurements to the calibration value (red mark) of the measured feature.

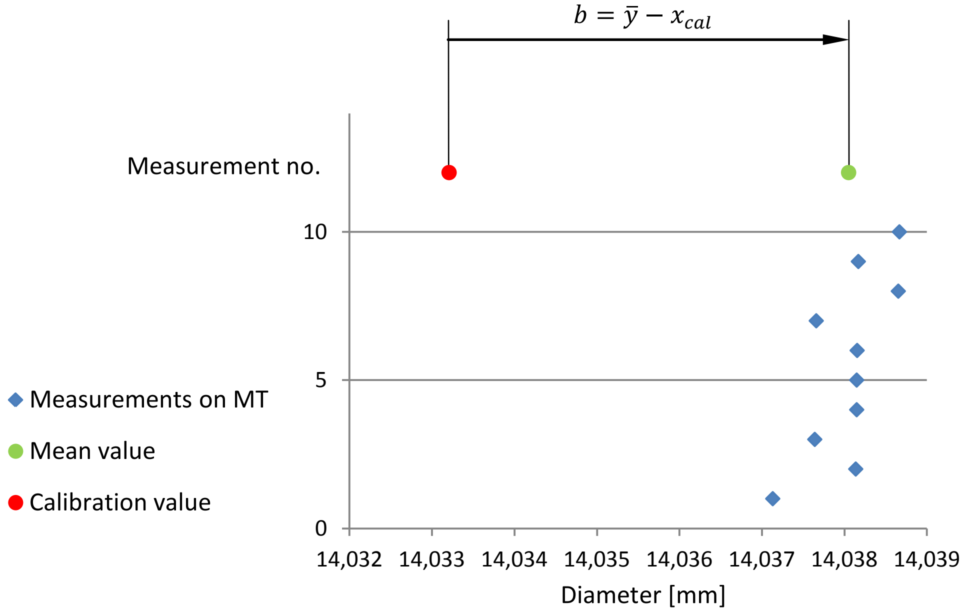

Figure 4: Example of a systematic measurement error

The just described calculations shall further be used to determine the uncertainty of the measuring system. Therefore m different workpieces or workpiece replicas are produced on the machine tool. Each part should be measured n times on the MT directly after the production in the same clamping. Here n should be at least 10 (recommended 20) and m at least 3 (recommended 5). The trustworthiness of the results will increase with an increasing number of n and m. In case that a material standard is used the standard should be handled, clamped, measured and finally unclamped m times. In each clamping the measurements are repeated n times.

This repetitions will lead to m mean values, m standard deviations, m calibration values and uncertainty (when a material standard is used, there is only one calibration value), and m systematic errors, i.e. one has values

$$\bar{y}_j, s_{y,j}, x_j, u_{x,j}, b_j, b_{t,j} \quad ; \; j = 1, \dots, m.$$

Measurement result

As systematic error of the measuring system the mean value of the systematic errors of the individual measurements is taken, i.e.

$$\bar{b} = \frac{1}{m} \sum_{j=1}^{m} b_j.$$

If the systematic error is significant compared with u_p and u_{cal}, it is suggested to correct the measurement results by the systematic error. This means, if the measurement for a part produced and measured on the machine tool yields for a certain feature the value y, then the final measurement result is given by

$$y_{cor} = y - \bar{b}.$$

Uncertainty budget

Based on the values of the individual measurements, the uncertainty of the measuring system u_{MS} (i.e. the uncertainty of y_{cor}), respectively the expanded uncertainty $U_{MS} = 2u_{MS}$ can be calculated. At least three contributions shall here be considered: The uncertainty u_p given by the maximum standard deviation of the measurements,

$$u_p = \max_{j=1\dots m} (s_{y,j}),$$

the calibration uncertainty u_{cal} given by the maximum calibration uncertainty,

$$u_{cal} = \max_{j=1\dots m} (u_{x,j}),$$

and the uncertainty u_b of the systematic error.

There are different approaches of assessing the uncertainty of the systematic error b. If the measurement result is not corrected by the systematic error, the error fully contributes to the uncertainty, thus

$$U_{MS} = 2 \cdot \sqrt{u_{cal}^2 + u_p^2 + b^2},$$

where is assumed, that the uncertainty u_b of the systematic error can be neglected. However, if the measurement result is corrected by the systematic error, the uncertainty u_b of the systematic error has to be considered for the uncertainty budged i.e.

$$U_{MS} = 2 \cdot \sqrt{u_{cal}^2 + u_p^2 + u_b^2}$$

If the systematic error is relatively small and can be considered as distributed around zero, according to [5] one can assume a rectangular distribution of the systematic error between $-|b|$, and $|b|$, hence the uncertainty is given by

$$u_b = \frac{|b|}{\sqrt{3}}, \qquad \text{hence} \qquad U_{MS} = 2 \cdot \sqrt{u_{cal}^2 + u_p^2 + \frac{1}{3} b^2}$$

However, for large systematic errors with a clear direction, confirmed by measurements on several workpieces, the above approach overestimates the uncertainty of the systematic error. In this case, the systematic error is assumed to be uniformly distributed in its range, and therefore the uncertainty is given by

$$u_b = \frac{1}{2\sqrt{3}} \left(\max_j (b_j) - \min_j (b_j) \right).$$

Figure 5 shows the deviations of the corrected measurement results $y_{cor} = y - \bar{b}$ from the calibration value for a feature that was measured 10 times on 5 different workpieces. The uncertainty of the measurement is given by the red lines. One can see that the distribution of the points is consistent with a 95 % coverage interval for the expanded measurement uncertainty U_{MS}.

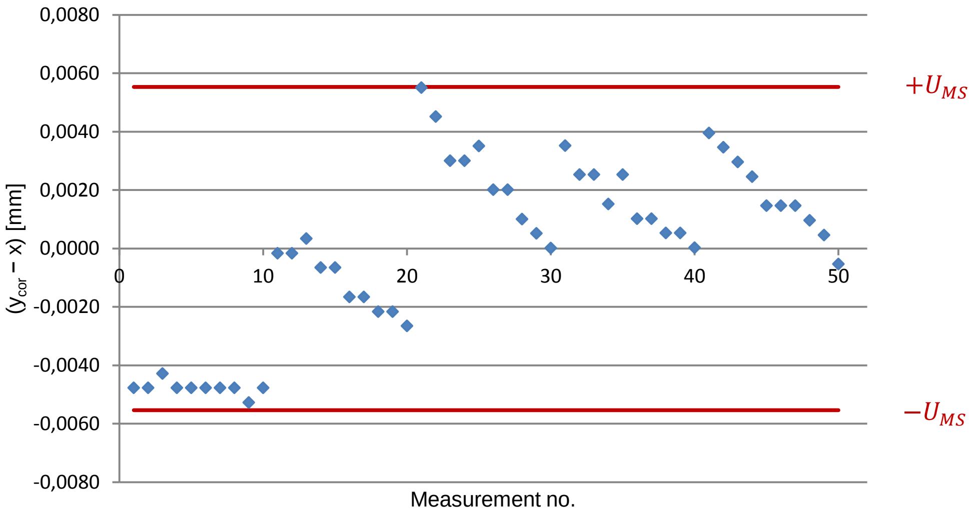

Figure 5: Deviation of corrected measurements from the calibration value

Uncertainty of the measurement process

For the uncertainty of the measurement process, additional uncertainty sources have to be considered. These are mainly temperature induced effects or uncertainties caused by the clamping, as far as these effects are not covered by the uncertainty of the systematic error. Other possibly contributions are uncertainties associated with material and manufacturing variations.

4 Assessing the fitness for purpose

4.1 Definition

According to ISO 14253-1 [2] the decision whether a workpiece feature meets its design criteria within the specified tolerance must be based on the expanded measurement uncertainty (U_{MP}) of the complete measurement process. A measured feature can be accepted as within the specified tolerance if the measurement result is above the lower specification limit plus the measurement uncertainty or if it is below the upper specification limit minus the measurement uncertainty (Figure 6). Likewise, it is outside of the specification if the measurement result is less than the lower specification limit minus the measurement uncertainty or if it exceeds the upper specification limit by more than the measurement uncertainty. For the measurement results that fall into the range of the specification limits plus or minus the measurement uncertainty, the so-called uncertainty regions (see Figure 6), a final decision of whether the feature meets the design specifications cannot be made based up on the performed measurement. Therefore, the region of conformity decreases with increasing measurement uncertainty.

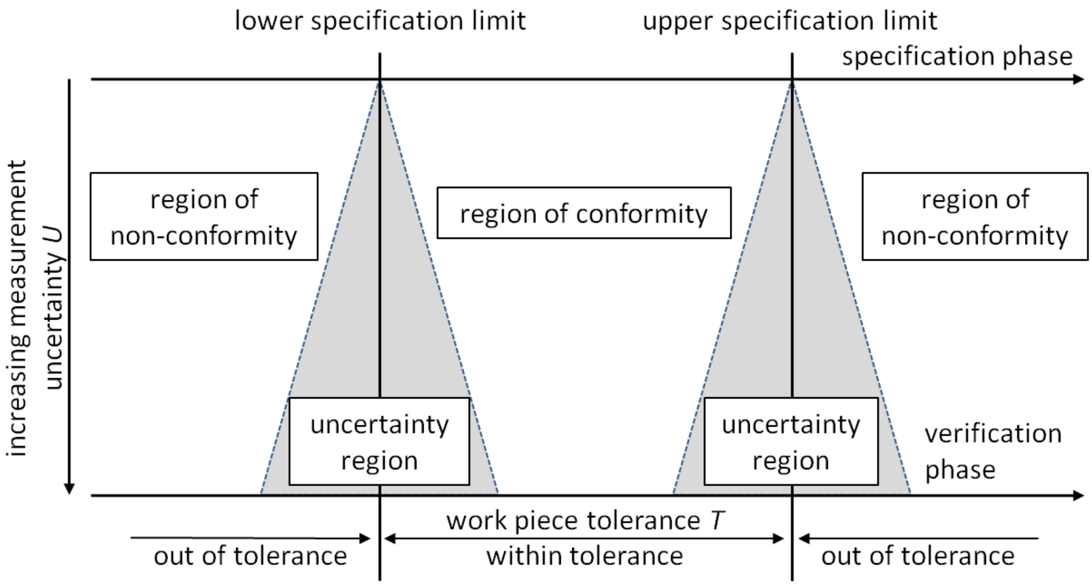

Figure 6: Explanation of decreasing region of conformity due to increasing measurement uncertainty (adopted and modified from DIN EN ISO 14253 Part 1 [2])

4.2 Qualification characteristics and minimal measurable tolerances

Recall that for assessing fitness for purpose a distinction is made between the uncertainty of only the measuring system, and the uncertainty of the whole measuring process. Considering only the measurement system, according to [5] the quotient of the double of the expanded uncertainty U_{MS} and the tolerance must not exceed 15 %, i.e.

$$Q_{MS} = \frac{2 \cdot U_{MS}}{T} \leq 15\,\% \quad \Longrightarrow \quad U_{MS} \leq 0.075 \cdot T.$$

Here, T is the tolerance of the measured feature defined as the upper specification limit minus the lower specification limit.

Taking into account also the additional uncertainty influences that contribute to the measuring process, the quotient of the double of the expanded uncertainty U_{MP} and the tolerance must not exceed 30 %, hence

$$Q_{MP} = \frac{2 \cdot U_{MP}}{T} \leq 30\,\% \quad \Longrightarrow \quad U_{MP} \leq 0.15 \cdot T.$$

A more practical description of the fitness for purpose of a measuring system or measuring process is the declaration of minimal measurable tolerances of the measurement system given by

$$T_{min} = \frac{2 \cdot U_{MS}}{Q_{MS,max}} \qquad \text{with} \qquad Q_{MS,max} = 15\,\%$$

and

$$T_{min} = \frac{2 \cdot U_{MP}}{Q_{MP,max}} \qquad \text{with} \qquad Q_{MP,max} = 30\,\%\,,$$

respectively.

The flow chart given in Figure 7 shows the complete procedure of assessing the fitness for purpose of a measuring system and measuring process.

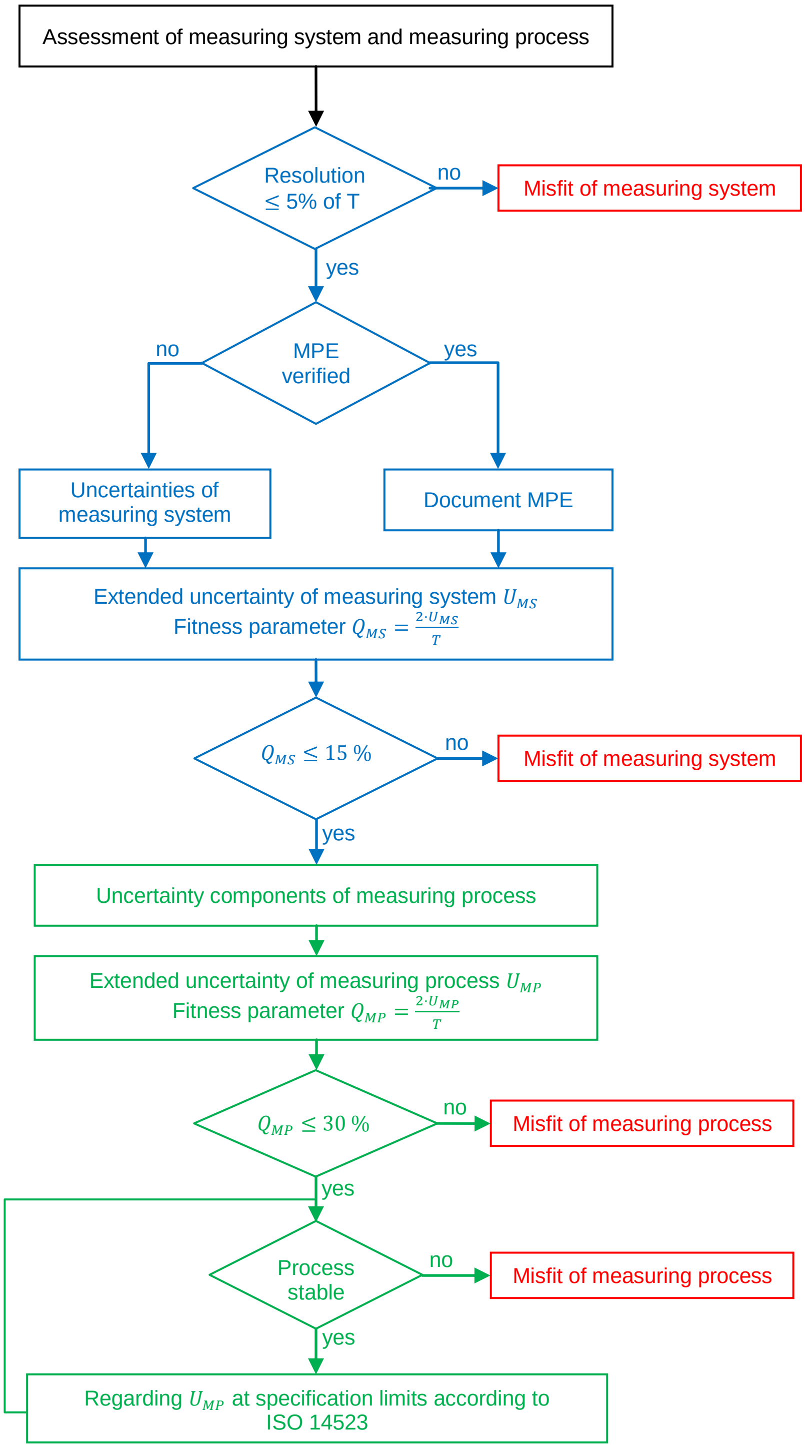

Figure 7: Flow chart of a fitness for purpose assessment ([4], p. 42)

5 Nomenclature

α	Coefficient of thermal expansion
ϑ	Workpiece temperature
b	Systematic error
b_t	Corrected systematic error
$\bar{b}$	Mean of systematic errors b of individual workpieces
Q_{MP}	Qualification limit of the measuring process
Q_{MS}	Qualification limit of the measuring system
s_y	Standard deviation of y
T	Tolerance
U_{MP}	Expanded uncertainty of the measuring process
U_{MS}	Expanded uncertainty of the measuring system
u_b	Standard uncertainty associated with the systematic error
u_{cal}	Standard uncertainty associated with the calibration
u_p	Standard uncertainty associated with the measurement procedure (standard deviation)
x_{cal}	Calibrated value
y_{cor}	Corrected measurement result
y_i	Indicated measurement value
$\overline{y}$	Mean of indicated measurement values

6 References

[1] International vocabulary of metrology – Basic and general concepts and associated terms (VIM); German-English version ISO/IEC Guide 99:2007, Corrected version 2012.

[2] ISO 14253-1: 200; Geometrische Produktspezifikation (GPS) – Prüfung von Werkstücken und Messgeräten durch Messungen – Beiblatt 1: Leitfaden zur Schätzung der Unsicherheiten von GPS-Messungen bei der Kalibrierung von Messgeräten und bei der Produktprüfung

[3] ISO 15530-3: 2004, *Geometrical Product Specifications (GPS) – Coordinate measuring machines (CMM): Technique for determining the uncertainty of measurements – Part 3: Use of calibrated workpieces or measurement standards*

[4] VDA, “Qualitätsmanagement in der Automobilindustrie 5 – Prüfprozesseignung” *2. Auflage*, 2010.

[5] VDA, “Qualitätsmanagement in der Automobilindustrie 5.1 – Rückführbare Inline-Messtechnik im Karosseriebau”, *Ergänzungsband zu VDA Band 5, Prüfprozesseignung*, 1. Ausgabe 2013.