

SUPPORTING MEASUREMENT UNCERTAINTY ANALYSIS IN INDUSTRIAL APPLICATION

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Abstract – Among industrial metrologists the analysis of measurement uncertainty is often considered a very difficult task and thus omitted. The process of determining measurement uncertainty is analysed from a practitioner's perspective to identify the obstacles. Existing methods and tools for support are discussed to determine remaining needs for the development of assistance offers and derivate underlying causes for the slow implementation of measurement uncertainty analysis in industrial practice.

Keywords: measurement uncertainty, user support, qualification, industrial application

1. INTRODUCTION

A statement of measurement uncertainty is an indispensable part of a complete measurement result, as it provides an information about the reliability of the given value. Thus, the appropriate determination and statement of measurement uncertainty is of high importance for all fields of application of measurement results, in scientific work as well as in industrial quality inspection.

To provide a standardized method to determine the uncertainty and thus enable a valid interpretation and comparison of its value, in 1993 the "Guide to the expression of Uncertainty in Measurement" (GUM) [1] has been published. With minor corrections in 1995, it has been valid since and has gradually come to wide use in science and legal metrology. Nowadays, scientists in metrology are usually well familiar with the concept and procedure of measurement uncertainty analysis.

The original GUM was purposefully kept rather simple, focusing on linearisable measurement systems and using rather basic statistic concepts, to facilitate the use in practice and enable a quick establishing of the new standard method. Experience shows that this scope well covers most measurements in industrial application. Yet, to widen the area of application, various amendments ([2], [3]) have been published and implemented mainly on a scientific level.

In industrial application, on the contrary, the determination and statement of measurement uncertainty still is very uncommon, despite the fact that the consideration of measurement uncertainty is required in according standards ([4], [5]) and is of high economic importance in customer-supplier-relations as well as for the control of manufacturing processes [6]. Instead, practitioners prefer other methods to evaluate the suitability of a measurement method, mostly

based on statistical observations of a measurement process, e.g. [7], although the gain of information there is much lower than when determining the measurement uncertainty [8]. Accordingly, the percentage of metrologists who are familiar with basic concepts of measurement uncertainty analysis or perform this task in their professional life is remaining rather low since many years, as found in various surveys (2004: 10 % "ever worked with a measurement uncertainty budget" [9], 2012: 50 % "ever was asked about measurement uncertainty"; 0 % (!) "sound knowledge about the basics" [10]).

This situation finally may result in high economic loss for the companies and also indicates, that the metrological chain is not consistent down to the shop floor level. As this is very undesirable for practitioners in industry as well as representatives of legal metrology and final customers, the reasons behind this phenomenon have to be analysed and need for further scientific work has to be identified.

2. PROCESS ANALYSIS OF MEASUREMENT UNCERTAINTY DETERMINATION

To understand the reluctance of establishing measurement uncertainty analysis as a standard method in industrial application, the underlying process according to GUM [1] is analysed from a practitioner's perspective and the respective problems are identified.

2.1. Ideal procedure

In a systematic approach, the steps necessary to evaluate the measurement uncertainty can be structured in five phases (Fig. 1) [11]:

1. Description of the measurement process and documentation of available knowledge
2. Definition of a mathematical model to describe the relation between the quantity and the indicated value under consideration of the influences identified in the first steps
3. Quantification of all relevant quantities, i.e. determination of an estimate for the value of the considered influences as well as for their likely deviation
4. Combination of these data according to the defined model and determination of the best estimate for the measurement result as well as the according measurement uncertainty according to given rules for calculation. [1], [2], [3]

- Evaluation of the measurement result and analysis of the established budget of measurement uncertainty in order to identify need or possibilities for improvement. [4], [5]

The performance of steps 1-3 requires the transfer of the general concepts of GUM to the given measurement task. These tasks have to be executed carefully and with results specifically defined for each single measurement task. Contrarily, steps 4 and 5 are executed based on general rules and are essentially the same for each measurement task.

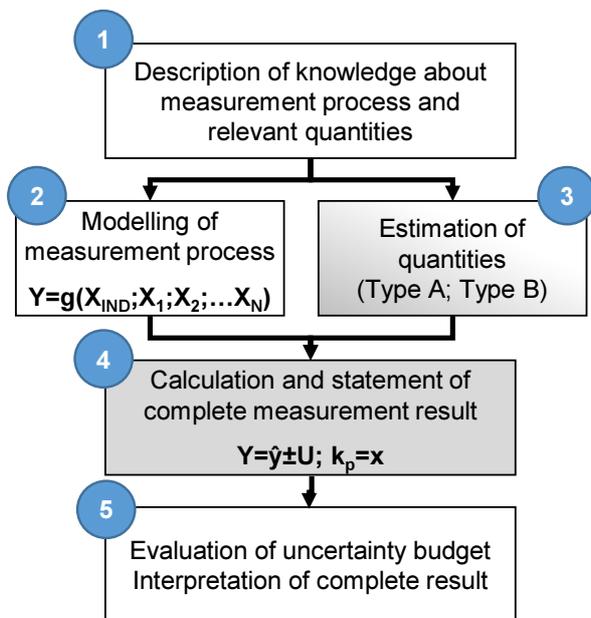


Fig. 1. Procedure of uncertainty evaluation according to GUM and need for assistance (based on [11])

Y: Measurand; X_{IND}: Indicated value; X_i: Influencing quantity
grey filling: support available; no filling: no support available.

2.2. Difficulties in practical application

The following analysis of the procedure for uncertainty determination under conditions of industrial practice is based on the author's experiences during teaching courses for manufacturing metrology in general as well as measurement uncertainty in particular for metrologists working in industry, mainly in quality inspection for own production and lots delivered by suppliers or in company-related internal calibration laboratories. Thus, some insight in the background of observed problems is possible, yet, the observations are subjective.

Very often, already the first step of describing the existing knowledge and the relevant influence quantities on the process puts up major problems. For, especially with complex measuring devices, the relevant influence quantities are not sufficiently known to the metrologist. Also, the details of the measurement process are often somewhat unclear.

By this, it is not just meant that some workings of the measuring device are unclear, e.g. the underlying physical laws in an optical device based on refraction or the routines of evaluation algorithms. On such level, the system could be considered a "black box" and the description would focus on the relation between input and output, given by information

from calibration certificates or suitable specifications by the manufacturer. But instead, even the influence of such parameters that have to be defined by the metrologist, are unclear. Thus, the measurement process itself is not well described and obtained results are somewhat difficult to even reproduce at the same measurement device, let alone compare with those gathered with different devices. Of course, this is not only a problem for the analysis of measurement uncertainty, but it shows up prominently here.

The second step requires the transfer of the now gathered, but so far only linguistically described and often implicit knowledge in an explicit, mathematical description of the process. The translation of a general description to a formula may seem an easy enough task for a scientist, yet it is typically considered very hard by a practitioner. This is due to the fact, that the education of metrologists in industry usually is much more focused on practical implementation than on theory and working with mathematics is not a typical part of daily work [9], [10].

This problem also shows up for the third step, estimation of quantities. Here, especially the description of quantities of Type B by their respective parameters is considered difficult as it again demands the translation of general information to a statistical concept. The repeated observation for Type A, on the other hand, is seen as pretty straightforward, although the actual calculation of mean and standard deviation resp. standard uncertainty may cause problems, if it is done without software tools.

For the fourth step of combining the identified uncertainty contributors to calculate the measurement uncertainty, similarly, the basic approach propagated by the standard GUM [1] is easily understood while the actual calculation may provide difficulties, if done without software. In a way, also the Monte Carlo method as proposed in GUM Supplement 1 [2] is well accepted as it is (not completely correctly, though) identified with the well-known repeated performance of a measurement for statistical process analysis.

The final step of analysing the uncertainty budget and interpreting the complete measurement result, e.g. in comparison to manufacturing specification, then usually is understood easily and provides no problems as such. Yet, if conclusions have to be drawn on how to actually improve the measurement process in case the measurement uncertainty is too high, the basic lack of understanding that showed up in the very beginning also will result in difficulties.

Thus, overall three major problems can be identified for the determination of measurement uncertainty in industrial application:

- The actual calculation of uncertainty propagation and statistical parameters.
- The definition of a mathematical model to describe the measurement process and of statistical descriptions for the related quantities.
- A general lack of understanding for the performed measurement; this is not caused by, but prominently showing up in connection with uncertainty analysis and thus has to be considered as a main obstacle.

4. ANALYSIS OF EXISTING SUPPORT TOOLS

To support the determination of measurement uncertainty in industrial application as well as in science, a number of support tools has already been developed.

4.1. Calculation tools

Most prominently is the support for the actual calculation of measurement uncertainty and statistical evaluation of measurement data for Type A quantities. To this aim, a number of specific software is available [12]; the methods applied there are continuously developed both for scientific and commercial purposes, especially with regard to Monte Carlo simulation methods (e.g. [13]). While sporting slightly different features and setups and resulting specific advantages and disadvantages, overall, the available software tools efficiently support the processing of data and the determination of the measurement uncertainty value from a given model equation. So, overall, the obstacles resulting from the demand for performing calculations have been removed. This might be due to the fact, that the rules applied there are universal. Thus, the execution of step 4 along with parts of step 3 can be sufficiently eased (Fig. 1), and indeed is usually not a source of major problems if a calculation software is available.

4.2. Assistance for modelling

The situation is far less positive when support for defining the mathematical model and describing Type B quantities is considered.

In one approach, it is tried to facilitate modelling by providing ready-made elements and thus remove the necessity to build a model for the actual task at hand from scratch. In guidelines or standards, recommendations have been given (e.g. [14], [15], [16], [17] among many others) on the set-up of models and the consideration of typical elements. Although this somewhat eases the task, by metrologists in industrial practice these general concepts are often considered as still too abstract for ready application on a specific measurement task.

Consequently, it has been tried to eliminate the necessity to define a model at all. For this, standardized models for typical measurement tasks have been defined in industrial guidelines, e.g. [19], or as feature of calculation software [12]. But the application of one generic model for a large class of measurements without its proper understanding often may result in an unacceptable oversimplification and typically does not allow to properly take into account available information and experiences. This aspect is even more aggravated, if the additional problem of a lack of understanding for the whole measurement process is considered. Thus, it becomes clear, that standardized or half-standardized models typically cannot thoroughly enough be checked regarding their suitability and bear the danger of unnoticed mistakes and unfitting assumptions.

Thus, in another approach it is tried to support the definition of an individual model for the measurement task at hand, by introducing a graphical description of the process that might be more intuitive than a mathematical formula [20]. Building on this concept, methods have been refined and

widened. On the one hand, a method for the overall description of the system using predefined components has been proposed [21], thus combining the graphical representation with the idea of prepared standardized models. On the other hand, a method has been described to allow the automatic generation of a measurement equation, which subsequently can be inversed into the required equation of evaluation, starting from a graphical model of the measurement [22]. Thus, the generation of the mathematical description is facilitated. The definition of a suitable and sufficiently detailed graphical model as such still is no trivial task remaining for the operator. Therefore, a systematic approach and a concept for further assistance has been proposed in former work [23].

Experience in practical application shows, that although there is such a wide variety of supporting means and methods to facilitate the step of defining a model and describing the influence quantities, it is still very hard for users in industrial application to define models on their own. Yet, the defined tools and methodology provide a very good base for teaching and consulting, as they ease the communication. Thus, models that have been set up with the support of an expert or trainer are well understood and can be easily modified later.

The main obstacle to defining a model on their own and starting the procedure of measurement uncertainty analysis consequently might not anymore be the modelling itself, but the problem of incomplete understanding of the underlying measurement process. As a main obstacle the insufficient training of operators can be identified, regarding the topic of measurement uncertainty as well as general qualification for their task. Suitable course offers have been developed to impart the required knowledge (e.g. [24]), yet, the unfortunate tendency of some organisations to reduce short term costs for course fees and rather risk much higher long term costs for erroneous or dubious measurement results may have prevented a noticeable improvement so far.

5. CONCLUSIONS

The analysis of measurement uncertainty is still not widely established among practitioners in industrial application, although it is required by various standards and also bears advantages in its evaluation for supplier-customer relations and optimized production control. The analysis shows that the procedure of standard GUM as such should allow for a proper establishment in practice. Yet, the actual implementation of uncertainty analysis is hindered by various obstacles. To overcome these difficulties, suitable tools and educational offers already have been established. As a main hold-back thus the attitude of industry towards measurement uncertainty analysis has to be considered. Currently, it is not clear to most practitioners that the evaluation of measurement uncertainty is not just a despicable duty but a useful asset. Also, a general desire to reduce the basic qualification of staff concerned with metrological tasks hinders the progress.

Thus, future initiatives have to target several levels of action: The informational needs of industry have to be met to introduce the benefits of stating comprehensive measurement results. At the same time, suitable training opportunities have to be provided to meet the needs of practitioners in industrial

application. This has to be accompanied by a continuous efforts to better establish qualified measurement uncertainty analyses among the calibration chain, first of all among the accredited laboratories.

On a wider perspective, the observed conflict and delay in introducing the concept of measurement uncertainty to common industrial application also suggests a memento for the ongoing discussion about amending or changing the GUM: For basic rules regarding the concept of measurement uncertainty, an eye has to be kept on practical applicability, especially common sense comprehensibility of procedures and interpretability of gathered results.

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REFERENCES

- [1] JCGM 100:2008, GUM 1995 with minor corrections. Evaluation of measurement data — Guide to the expression of uncertainty in measurement, JCGM/WG 1, 2010, corrected version. (via: <http://www.bipm.org/>).
- [2] JCGM 101:2008, Evaluation of measurement data — Supplement 1 to the “Guide to the expression of uncertainty in measurement” — Propagation of distributions using a Monte Carlo method, JCGM/WG 1, 2008. (via: <http://www.bipm.org/>).
- [3] JCGM 102:2011, Evaluation of measurement data – Supplement 2 to the “Guide to the expression of uncertainty in measurement” – Extension to any number of output quantities. JCGM/WG 1, 2011, (via: <http://www.bipm.org/>).
- [4] ISO 14253-1, Geometrical Product Specifications (GPS) - Inspection by measurement of workpieces and measuring equipments - Part 1: Decision rules for proving conformance or non-conformance with specifications, ISO, 1998.
- [5] ISO 14253-2, Geometrical product specifications (GPS) - Inspection by measurement of workpieces and measuring equipment - Part 2: Guidance for the estimation of uncertainty in GPS measurement, in calibration of measuring equipment and in product verification, ISO, 2011.
- [6] A. Dietlmaier, *Der quantifizierte Nutzen eines Messergebnisses – Grundlage der Wirtschaftlichkeitsbewertung von Messeinrichtungen*. Erlangen, 2012. (<https://opus4.kobv.de/opus4-fau/files/2097/AdrianDietlmaierDissertation.pdf>)
- [7] Reference Manual: Measurement System Analysis - MSA, A.I.A.G., 2003.
- [8] T. Werner, W. Hartmann and R. Kessel, “Messprozess-eignung und Messunsicherheit – Abgrenzung und Nutzen“, *Sensoren und Messsysteme 2010 - Vorträge der 15. ITG/GMA-Fachtagung*, pp. 359-366, Nürnberg, Germany, 18.-19.05.2010.
- [9] A. Weckenmann, S. Beetz and T. Werner, „User Needs Analysis. Leonardo da Vinci Pilotprojekt „Europäisches Ausbildungskonzept für Koordinatenmesstechnik“, Erlangen, 2004 (http://www.cm-train.org/dokumente/una_de.pdf).
- [10] T. Werner, W. Plowucha, W. Jakubiec and A. Weckenmann, “Creating a web-based course on measurement uncertainty in international co-operation”, Joint International IGIP-SEFI Annual Conference 2010, pp. 84-85 and CD-ROM, Trnava, Slovakia, 19.-22.09.2010.
- [11] A. Weckenmann, K.-D. Sommer, and B. Siebert, „Qualität für Messergebnisse - Messunsicherheit nach GUM“, *tm Technisches Messen*, Vol. 73, Nr. 4, pp. 189-199, 2006.
- [12] A. Weckenmann and T. Wiedenhöfer, „Software zur Unterstützung bei der Ermittlung der Messunsicherheit“, *tm Technisches Messen*, Vol. 72, Nr. 5, 2005, pp. 278-285.
- [13] R. Kessel and R. Kacker, “Correlation in Uncertainty of Measurement – A Discussion of State of the Art Techniques”, XIX IMEKO World Congress, Lisbon, Portugal, 6.-11.09.2009 (http://www.imeko2009.it.pt/Papers/FP_479.pdf).
- [14] DKD-3: Angabe der Messunsicherheit bei der Kalibrierung. Physikalisch-Technische Bundesanstalt, 2002.
- [15] S. Bell, *Measurement Good Practice Guide No. 11 (Issue 2). A Beginner's Guide to Uncertainty of Measurement*, National Physical Laboratory, Teddington, 2011 (via: <http://www.npl.co.uk>).
- [16] S. L. R. Ellison and A. Williams (Eds.), *Eurachem/CITAC guide: Quantifying Uncertainty in Analytical Measurement*. Third edition, 2012, (via: www.eurachem.org).
- [17] ISO 20988, Air quality – Guidelines for estimating measurement uncertainty, ISO, 2007.
- [19] VDA, Band 5 Prüfprozesseignung, Eignung von Messsystemen, Mess- und Prüfprozessen, Erweiterte Messunsicherheit, Konformitätsbewertung, VDA, 2010.
- [20] K. D. Sommer and B. R. L. Siebert, “Systematic approach to the modelling of measurements for uncertainty evaluation”, *Metrologia*, vol. 43 (2006), pp. 200-210, doi:10.1088/0026-1394/43/4/S06
- [21] S. Heidenblut, R. Kessel, K. D. Sommer and A. Weckenmann, „Ein Modellbildungskonzept für die praxismgerechte Bestimmung der Messunsicherheit“, *tm Technisches Messen*, Vol. 74, Nr. 10, 2007, pp. 494-506.
- [22] R. Kessel, „GUMCAD – Ein graphischer Editor zur Modellierung von Messprozessen“, *Messunsicherheit praxismgerecht bestimmen, VDI-Berichte 1947*, VDI, Düsseldorf, 2006, pp. 397–408.
- [23] R. Kessel and T. Werner, „Effiziente Modellierung für die industrielle Praxis - Unterstützung für die Modellbildung als Basis der Messunsicherheitsbestimmung“, *Messunsicherheit praxismgerecht bestimmen, VDI-Berichte 2216*, VDI, Düsseldorf, 2013, pp. 13-32.
- [24] M. Dragomir, S. Popescu, W. Plowucha, M. Marxer, “Blended Learning in the field of Measurement Uncertainty. Experiences from the MUVOT project”, *Quality - Access to Success*, 13 (Suppl. 5), pp. 127-130, 2012.