Smart Metrology: The Importance of Metrology of Decisions in the Big Data Era
Annarita Lazzari, Jean-Michel Pou, Christophe Dubois, and Laurent Leblond

The beginning of the 21st century has seen the birth of a new industrial revolution, the digital revolution: the ability to store data from various sources (in particular through related items) in unprecedented big quantities and to exploit them through more and more high computing capabilities using artificial intelligence techniques (AI). In this new scenario called “Big Data,” data reliability becomes an indispensable property: the large amount of data collected and their analysis are completely useless if untrusted information is stored that cannot help understanding a complex reality. Here is the role of metrology: to ensure the reliability of measured data. Smart Metrology is the implementation of a revised metrological function, oriented to reliability, rather than simply on complying with standards: ensuring reliability of measurements, knowing and mastering measurement uncertainty to make relevant decisions. This paper is a summary of issues for business metrology.

Smart Metrology
Metrology plays a much more important role than what, in fact, is usually entrusted to it in the industrial world. Quality certification has often confined industrial metrology to the model that is used in legal metrology, a model that however seems completely inadequate to industrial requirements. In the light of the new era that is beginning, it becomes important to reflect and to reposition the mission entrusted to metrology, so that it fully enters the heart of the incipient revolution of industrial practices.

The mathematician Didier Nordon describes metrology as a bridge between geometry (the science of forms) and algebra (the science of numbers) [1]. This bridge associates a quantity (value) with all types of entities: the length of a room, the concentration of active substance in a solution, the energy efficiency of a building...

This quantification, made universal through the International System of Units, induces a chain of decisions ranging from defining the requirements (tolerances) through process management to the declaration of conformity. This chain manipulates numbers that express the ability of entities to perform their functions, either the ability of a drug to heal a patient or a mechanical piece to fit the set to which it is destined. This applies to all types of entities and functions.

In a perfect world, things are very "algebraic." It is sufficient that the value materializing the magnitude (as defined in VIM3 [2], Definition 1.1) belongs to the tolerance interval that expresses the need for the entity to be considered compliant. This means verifying whether this value is greater (>) than a minimum value and / or lower (<) than a maximum value.

But in reality, the result of a measurement (or measure) cannot be limited to a single number. In definition 2.9, VIM3 [2] states that the result of a measurement is the set of quantity values being attributed to a measurand together with any other available relevant information.

So, we do not have a single value to make decisions, but a set of possible values, some of which may be compliant, and others not. This misunderstanding of the real value of the entity raises doubts about its compliance, therefore a risk for the decision to be taken at any level of the above chain. The metrology service is born from a need, managing the risk of getting incorrect measurement results that could have an impact on the quality of the product. Therefore it is important to understand this passage so that not to reverse things: "impose our metrology, because it is written in standards."

Smart Metrology focuses on assessing risks and balancing them to "just what is needed."

Industry 4.0 and How Important it is to Insert Metrology
From a world characterized by scarcity of information where industry had to be satisfied with only a few data (not always reliable as it was hoped for) for making decisions, we are going to a very different world where the question becomes: "how to take full advantage of all available information?" This change of context requires a correlated change in the way of thinking to produce the best effects.
Widespread thinking of “worst case” is actually very expensive, both economically and in terms of sustainable development.

**The Notion of Risk**

The concept of Risk is increasingly integrated in our lives as well as in industry. The concepts of “Customer Risk” and “Supplier Risk” are often mentioned. This, of course, involves the principle of sharing risks. However, this semantics is sometimes misleading.

Measurement uncertainty, the result of the imperfection of all the factors involved in producing the measurement result, is at the root of the risk. Since the measurement is not right, the actual value is greater or less than the declared value. In trade, the principle of risk sharing is easily understandable. If the weighed object is actually “heavier” than what is shown by the balance, the customer is favored with respect to the merchant, and if it is less heavy, the merchant is the winner. In this world, the world of legal metrology (i.e., trade metrology), risk sharing is key to the whole strategy. Legal metrology, organized by the state for nearly 200 years, aims to ensure fair trade, ensuring that risks are the same for everyone, the trader and the customer.

In the industrial world, on the other hand, the problem is different. The example of a measurement result in medical biology helps to understand the difference. Imagine the case of a patient who is actually sick (or an item which is "not conforming" in the general case), but whose medical analysis gives a “not sick” result (or, in the general case, whose testing gives a “conforming” result). We are here in the classic case of Customer Risk (i.e., declaring conform a non-compliant entity), and it is understood that if the patient does not receive treatment that could improve his situation, he suffers damages, even fatal. In the reverse case described by the Supplier’s Risk (i.e., declaring a conforming entity not conform), the healthy patient is considered ill and unjustly suffers unnecessary treatment. If the treatment consists of a three-month chemotherapy cycle, everyone will realize that the risk is not of the “supplier” (in this case, the laboratory that has performed the measurement) but it is also suffered by the patient.

And it is the same in all cases. The wrong decisions thought as “Supplier Risk” are ultimately still at the customer’s charge. When the mechanical parts are mistakenly repaired or a series of vaccines are mistakenly destroyed, the cost necessarily affect the end user in the price of the conforming products. A company, in one way or another, charges its own decision making mistakes on its customers, or it disappears...

The JCGM-WG1 [3] published in 2012 the document JCGM 106 [4] that became the same year, ISO Guide 98-4 [5]. This Standard explains that risks for customer and supplier are not just due to the uncertainty of measurement. In fact, in order for client risk to exist, there must be actually non-conforming entities. Irrespective of the measurement uncertainty, if there are no non-compliant entities, the Client’s Risk is zero. On the other hand, there is not the Supplier’s Risk, because it is always possible, due to measurement uncertainty, to measure compliant entities in a non-conforming manner. The calculation of risks therefore, requires knowledge of the properties of the entities to be measured, in addition to the measurement uncertainties. This knowledge is called a priori knowledge. This a priori knowledge is one of the keys of Smart Metrology. A Smart Metrologist will therefore have to focus on its assessment and this is a first mission that differentiates him from the traditional metrologist.

Without going into mathematical demonstrations that are not the subject of this article, it is necessary to understand that the evolution of these risks (customer and supplier) is not symmetric. In other words, when you earn 1% on your customer’s risk, you may lose, depending on the case, several percentage points or even several dozen percentage points, for the supplier’s risk. Knowing, as we have seen, that the two risks are ultimately on the customer’s side, it is indispensable to question the importance of over-winning one to the detriment of the other, knowing the consequences of both situations.

Efficiency, which can be defined as efficiency at the right cost, is thus sometimes a subtle balance between Customer Risk and Supplier Risk that must be sought in any field. Smart Metrology is committed, through its practices, to achieving this efficiency, but its mission is not limited to this. Measurement is at the center of industrial decisions, from the expression of needs to conformity, and Smart Metrology naturally accompanies all of the services of the company. The right need, the pertinent setting, and the right decisions are therefore at the heart of Smart Metrology.

**The Worst Case Consideration**

Legal Metrology, which has secured risk sharing for 200 years, largely inspired the current practices of the industrial world. In a sector (trade) where we had to eliminate the doubt, legal metrology had such a success that we all unconsciously embedded the false idea that the measures are right.

The industry, more recent than trade, was built on the belief that measurements were correct, a false principle that however, has not prevented success. We produce cars, airplanes, vaccines, medical biology, and everything around us, believing that the measures are right. ISO 14253-1 [6] allows us to understand in part what has happened (Fig. 1).

By comparing its recommendations of “apparent common sense” (Fig. 2) with the reality of industrial practices (Fig. 3), we better understand all of the unexploited potentials of metrology.

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**Fig. 1.** The strategy proposed by ISO 14253-1 to take account of uncertainty.

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**Diagram:**

- Conformity zone
- Zone of doubt

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Our beliefs in measured values have led to specifications that have the same properties as the "conformity zone" of the standard. The "security" has been taken between the actual need (specific) and the declared need... to be sure! But reducing tolerance has two very important consequences:

1. Production tools are over-sized in relation to the real needs.
2. An “explosion” of the Supplier’s Risk (erroneously declaring non-conforming entities actually conform) that damages customers.

Some are reassured by evoking a “quality” situation in consideration of the “worst case.” But this argument is misleading because asking too much means to consume too much and spend too much, so it is ultimately a shortage of quality! The customer expects functionality at the right cost, which is the ultimate goal to which companies need to target. The Smart Metrologist, to the extent that he is one of the makers of relevant decisions, is de facto one of the pillars of this perspective.

Thanks to the Big Data era, having more information to understand the world as it stands, the industry will be able to optimize its practices to move to the strictest need. Risk management must become the tool of this improvement. Is it not also said that opportunity is the positive side of risk?

From Metrology of the World “in the Worst Case” to Smart Metrology

In the “metrological” practices of companies, especially those undertaken after the ISO 9000 quality standards, it is possible to describe costly and often useless practices, despite their apparent relevance. We will describe the three main themes often addressed by metrology to explain why they do not match the need and how Smart Metrology offers different and more relevant solutions.

Monitoring vs. Calibration

One of the pillars of Legal Metrology is the periodic verification of the instruments used for trade. From a legal point of view, all of the holders of such instruments are required to keep up to date the metrological records of their instruments, otherwise they risk being brought to court. This particular register reports the results of the regular checks provided by law. The risk for an owner of such regulated instruments is not that the instrument is declared non-conforming at the expiration date, but that it has not been checked before the expiration date imposed by the decree. In this world, there is no impact assessment to determine whether non-compliance may or may not have consequences for customers. The only problem is the legality of the possible mistake, and the only obligation is to comply with the deadline.

In the industrial world, on the other hand, a non-conformity found at the time of the necessary verification imposes an obligation to analyze the possible consequences that may have on past production. If necessary, a corrective action may be activated until organizing the return of all doubtful entities, especially if the risk arising from such non-conformity entails serious consequences for end customers.

Since the problems between legal metrology and industrial metrology are not the same, it is unlikely that the appropriate solutions will be the same. The metrological verification (that issues a judgment), which follows a calibration (that records the differences), only validates the past. In short, we can in principle be relatively quiet for the past if the instrument was found to be conform, but we cannot say anything for the present and especially for the future. In industry, decisions are taken daily and their appropriateness makes sense only if guaranteed every day, not in a year or two as the custom wants in the periodic calibration / verification.

The Smart Metrologist is aware of this everyday problem and does not hide behind a practice that does not satisfy him. He tries to assure the conformity of the instruments every day and, at best, he sends the instrument to calibration only if he has doubts about its “health.” In this context, and unlike traditional metrology, which often measures its performance by observing the rate of instruments that return ‘conform’ from the verification (which, however, underlines the uselessness to send them), the Smart Metrologist focuses on an indicator that is totally different. He tries to ensure the conformity of the instruments at all times and sends them to the calibration only in case of doubt. If his doubt is confirmed (the tool has a problem and really deserves to be repaired or reformed) and the company also does not suffer complaints from customers or suppliers because of the measurements, he can affirm that his detection capability is efficient. So, with regard to periodic calibration, do just what is needed. The principle of “conditional periodicity” is valid: make calibration in case of doubt!

In this context, therefore, it is not a blind calibration / verification but ensures that an abnormality can be detected, by one method or another. The first of these methods, quite simply, is to make your colleagues aware that when a tool gets a shock, it should be taken to control for testing. No complex math, no elaborate statistics, but simple common sense.

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X represents the position of the measured value.

Fig. 3. Industrial practices.
Sometimes monitoring methods can be more complicated or even they have to be formalized to try to detect a drift and hence prevent it. Here, Smart Metrology can use existing documents on this topic [7], [8].

There are documents that define methodologies to define the calibration periodicity [9]-[11]. Smart Metrologists will have to apply them to master calibration intervals and calibrate only when it is really needed, but none of those documents claim to have found a solution to predict the date of an accident. Therefore, only monitoring allows us to meet the permanent industrial need of appropriate decisions based on a measurement result. A Smart Metrologist does not pay attention to a more or less arbitrary calibration / verification program. He makes sure himself that he has the means to detect an anomaly when it occurs and keeps this detection capacity daily. Risk management, seeing or not seeing an anomaly, is at the center of his daily worries.

The Famous MPE

The issue of maximum permissible error (MPE) is a recurring problem in metrology. However, and contrary to legal metrology that knows in advance the use of regulated instruments, industrial metrology requires that the measurement uncertainties estimation is mastered to assess the need for metrological performance of the instrument. Many metrologists would like to find in a norm the indisputable value of this maximum permissible error... Unfortunately, it can only be known by themselves! In fact, each measurement process (Fig. 4) is singular, and therefore, the impact of the measuring instrument on the quality of the final result (measurement uncertainty) is different. In reality, the statistical concepts needed to evaluate industrial uncertainties are not so complex that only mathematical experts have the ability to understand them and use them.

To make it simpler, it is only sufficient to understand the variances (standard deviation squares) that are added when dealing with random independent errors and the averages that are algebraically added when the errors in question are systematic. And measurement errors are often a blend of these two types of errors.

Everyone will understand that the notion of MPE, borrowed from and relevant for legal metrology, does not really make sense in the industrial world. If the instrument error is random, we need to know its variance and the methods often adopted to switch from MPE to variance are often questionable. If it is of a "systematic" type error, we must know it to correct it, or add it linearly to the uncertainty resulting from random effects.

Moreover, to affirm to have found a maximum error by comparing the instrument only with some measuring points (between 3 and 10, rarely more) again is nonsense. VIM3 [2] proposes a new calibration definition that will allow us, when widespread, to answer the "systematic / random" issue and the number of calibration points. The Collège Français de Métrologie (CFM) has published a guide [12] that deals with this topic. It also provides metrologists with free software downloadable from their website, M-CARE, which allows them to perform all calculations.

It is deduced that only the metrologist of the company is capable of mastering the necessary measurement processes. Believing that a standard written by others can meet, without adaptation, their own needs can cost dearly, either in "over-quality" (the standard imposes MPE more stringent respect to their own need) or in "sub-quality" (the norm imposes MPE less severe than their own need).

It is of course possible to define MPE, distinguishing, if necessary, the systematic or random effects for instruments of the same type that are used interchangeably between them in a company. In this case, the verification ensures that the performance of each instrument is not degraded and can continue to be used instead of one other without any negative consequences for the company. But in any case, the assessment of the overall uncertainty that integrates all of the factors (measurand, operators, environment, instrument, procedure, etc.) must be done to handle it appropriately. Therefore, the standards that address the measurement uncertainty [13]-[16] are essential tools for Smart Metrology.

Finally, on the MPE theme, it is useful to remember that ISO 14978 [17] par. 6.1.2 states: Standards for specific measuring equipment, except for a few examples (eg ISO 1938 and ISO 3650), shall not include any numerical values for MPEs and MPLs but shall include empty tables for MPE or MPL values as a guidance for the user of the standard (MPL= Permissible limits of a metrological characteristic). Norm then states very explicitly that it is up to users to define the metrological performance of their instruments, not the standard.

The Capability

The issue of considering uncertainty of measurement for the declaration of conformity is also a recurring problem in industrial metrology. We have previously seen how ISO 14253-1 [6] intended to handle uncertainty and we have found that current tolerances had the property of "conformity zone."

In the context of statistical process control (SPC), the matter of the capability of a production process to achieve the entities complying with the tolerances required is analyzed through statistics. This is to address the problem of "standard" production, for which the measurement of all the entities produced would be impossible (or too expensive). Recall that SPC
is based on controlling the average and production dispersion to ensure the ability to produce entities that conform to a non-conforming rate accepted through contractual targets on calculated indicators. SPC is therefore addressed with the two issues of sampling effects and measurement uncertainties. For these, it is expected to ensure the reliability of the measures by introducing the concept of "capability of the measurement process," also called "capability." In this context, the objective is clear: the measurement errors must be negligible compared to the dispersion of the process we are trying to measure. This measurement errors property can thus be summarized as the ratio between measurement uncertainty and dispersion:

\[ \frac{U}{6s} \leq C \]  

(1)

In other words, if the process dispersion is adapted to the required tolerance, the process uncertainty that measures the samples taken must remain below 10% of the required tolerance.

The value that should be chosen for C is however problematic because the real underlying problem is the risk of deceiving (customer risk or supplier risk) and ISO Guide 98-4 [5] explains that this simple coefficient is not enough. Again, a "golden" universal digit for C would have organized many metrologists, but we must not dream, as it never can exist to the extent that it depends on the:

- Sharing of customer risks and supplier risks between interested parties;
- Feature of processes of realizing entities.

The Smart Metrologist solves this problem by trying to balance the risks as both are endured by the customer. ISO Guide 98-4 [5] has developed the concept of "guard bands," that is, a "revision" strategy of the expressed tolerance. The standard explains how this review can be guided by the goal of achieving a customer risk, despite significant uncertainty. The authors defend (see [18]) an option that includes the fact that since both risks are at the expense of the client, the guard bands should be controlled by optimization of the risks-weighted sum. So defined, decision-making limits (new tolerance after the application of guard bands) are chosen rationally and documented, with full knowledge of cause. Once again, Smart Metrology is characterized by the constant search for effective mastery of decisions. The Smart Metrologist is not concerned only with MPE issues and periodicity issues but must be the guarantor of reliable data production every day in his business. By guaranteeing reliability in everyday life, he is then able to detect an anomaly as soon as it occurs, which means to protect itself from a slow drift, although possibly unclear, of the instrument, but also, and perhaps above all, manage all factors of the measurement process, including the operator. The operator is in fact one of the "key" factors of the measurement process, since he is the one who has more, if not the only, ability to detect an anomaly.

The awareness of operators is not limited to the observation or abnormal uses of an instrument, but must also take into account a priori knowledge. Developing the operator's ability to detect an anomaly by himself is the only true guarantee for the reliability of the data. A doubt value (i.e., substantially different from what the operator expects) must induce an action, for example a counter measure with another tool, or another operator.

Improving the knowledge of the measured entity by taking into account a priori knowledge is a goal of the Smart Metrologist. Without going into mathematical details, the metrologist must always remember that a measured value is the algebraic sum of the real value sought and the measurement error that occurred at the time of measurement. Consequently, the measured value can be explained by an almost infinite number of combinations of \( V_{\text{real}} + V_{\text{unseen}} \). Knowing the probability of a given real value (a priori knowledge) and the probability of a given measurement error (knowledge of measurement uncertainty), it is possible to calculate the probability of any possible combination (which is simply the product of the probability \( V_{\text{real}} \cdot V_{\text{unseen}} \)). This calculation is enough to look for the most likely combination to give the most probable value as "real" value, taking into account those actually measured. This is an application at the service of Smart Metrology, what statisticians call Bayesian inference [19].

**Conclusions: The Role of Smart Metrology in the Company**

Despite thirty years of quality certification, metrology has not really gotten its recognition. Focused on practices that, as we have explained, are ultimately not within its true goals, it is, however, doing so until this moment (and is the minimum), to respond to the auditor's requirements. Now a historic opportunity opens. Without reliable data, the industry will not be able to benefit from the new Big Data technologies at its disposal. By neglecting these new tools, it would lose not only the competitiveness of its competitors, but perhaps more importantly, it would not seize the opportunity to register resolutely, demanding only the strict necessity, in an approach of conservation of the resources needed for the humanity.

Appropriate decisions are at the heart of industrial performance and sustainable development. Since, as we have described, metrology is one of the pins of this need, it must assume this role.

The Smart Metrologist needs to get out of his office, since his place is not in front of a computer to plan, implement, and monitor a performance against MPE data that is often arbitrary or defined in a disconnected way compared to real business needs. He should be "on the machine" in which measurements are made, to ensure, strong in his knowledge, that they are truly representative of the reality they are trying to describe. His role is in the mastery of all factors that contribute to a measure, through the acquired technical knowledge. From the method to the operator, from the environmental to the intrinsic quality of the measurement that seeks to quantify, he must make sure everything is under control, and a simple green label on the instrument, though obviously necessary, is probably not enough.
References


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