Basics of Industrial Metrology

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As known, cyber-physical systems and ICT technologies in general are the backbone of the fourth industrial revolution (also known as Industry 4.0 in Europe). However, flexibility, efficiency, resilience and, above all, high-quality smart manufacturing could not be achieved without the essential contribution of measurement science. This is supposed to play a key role also for the development of value-centric, fully sustainable organizations envisioned in the forthcoming fifth industrial revolution. The most recent measurement techniques and technologies (e.g., networked and distributed measurement systems, advanced sensing solutions, machine-learning-based diagnostic solutions) supporting process and product monitoring in smart manufacturing companies are essential to reach specified quality targets and/or to ensure compliance with given technical, regulatory or legal requirements. Industrial metrology comprises all organizational and measurement procedures, techniques and technologies that contribute to reach the aforementioned goals, thus improving both customers' satisfaction and company competitiveness. In [1], Savio et al. highlight the strong economic benefits of industrial metrology in four different case studies. In particular, it turns out that, despite relevant initial investments, Internal Return Rates (RRs) ranging between 20% and 44% can be achieved with payback times shorter than three years. A pre-Brexit survey reports that UK companies using measurement standards are twice as likely to export goods compared with companies of the same size that instead make a marginal use of metrology within their processes, with an estimated impact on yearly turnover that ranges from 1.7% to 5.3% [2].

This tutorial paper presents some key industrial metrology definitions, management issues and challenges. After an overview of the role of measurement and monitoring activities in quality-oriented industrial organizations and a description of the difference between instrument calibration, verification and adjustment, two pillars of industrial metrology such as the concepts of measurement process and metrological confirmation are introduced. Finally, the criteria to select and to review the time intervals between subsequent metrological confirmations is presented and an adaptive policy to review the duration of such intervals is described.

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1. Measurement requirements in quality-oriented industrial organization

Quality-oriented organizations usually follow a Plan-Do-Check-Act (PDCA) management model, also known as Deming cycle (see Fig. 1). The ultimate goal of this approach is continuous quality improvement. On the basis of customers' specifications, market and third-party requirements and context- or organization-related constraints, first the activities of a given process are carefully planned ("Plan" step). Then, the steps to carry out such activities are actually implemented ("Do" step) and monitored both to check the correctness of process operations and to evaluate performance through appropriate indicators ("Check" step). Finally, from outcomes, monitoring results and other possible feedback information, corrective, preventive or improvement actions are taken (Act Step) to revise process planning and eventually to improve it.

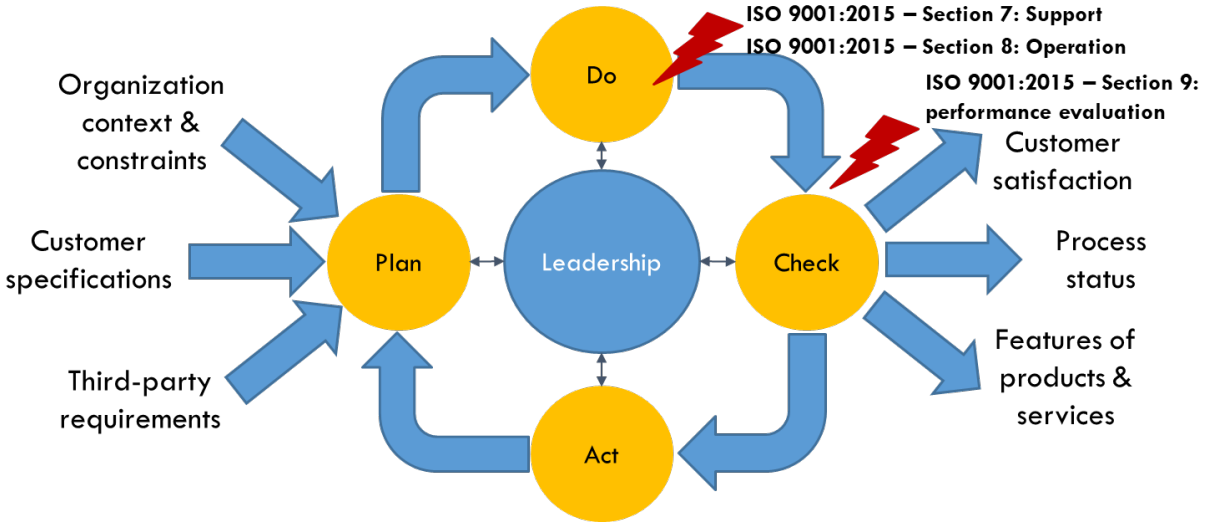

Figure 1 – The PDCA management model (Deming cycle) for quality-oriented organizations.

Within this general framework, the purpose of measurement-related activities in a typical industrial scenario is twofold, i.e.,

- Monitoring the crucial steps of each process, particularly (but not only) the manufacturing ones;
- Testing the conformity of products or services to specifications.

In this regard, the ISO Standard 9001:2015 on quality management systems explicitly states that "an organization shall provide the resources needed to ensure **valid** and **reliable** results when **monitoring** or **measuring** the conformity of product or services to requirements" (clause 7.1.5.1) [3]. More in general, the crucial role of measurement-related tasks emerges directly or indirectly

in at least other three sections of the ISO 9001:2015 Standard, i.e., for process support (Section 7), operation (Section 8) and performance evaluation (Section 9). As far as the performance evaluation is concerned, it is clearly stated in Section 9.1 that the organization has to decide [3]:

- Which quantities need to be monitored and measured;
- The methods for monitoring, measuring, analyzing and evaluating the collected data to ensure valid results;
- When and how often monitoring and measurement activities as well as the processing of the collected data must be performed.

Of course, an organization must evaluate the performance and the effectiveness of the adopted **Quality Management System** (QMS) by retaining appropriate documented information as evidence of the results. To achieve this goal, first the organization has to define the performance and acceptance requirements on process inputs and outputs. Then, suitable monitoring and measurement methods have to be chosen to offer customers products/services under controlled conditions and compliant with given quality or legal requirements.

Such general steps are critically important especially in Industry 4.0 and 5.0 scenarios, where the proper and reliable fusion of large and heterogeneous sets of data collected through networks of different kind of sensors and/or from distributed measurement devices is in the core of any smart and sustainable manufacturing process. In fact, bad or missing data due to sensors failure or degradation may not only lead to wrong decisions based on poor or corrupted information flows, but they may also disrupt the correct operation of automation and control laws, thus drastically affecting the quality of industrial outcomes and products.

Two interesting examples of Industry 4.0 mechatronic applications where industrial metrology plays a central role are described in [4]. In the former case study, a test bench for the dynamic calibration of three-axis accelerometers in the low frequency range is proposed. This test bench consists of a servo-motor controlled by a Programmable logic controller (PLC) driven by a high-accuracy angular encoder. The servo-motor is used to excite an accelerometer under test by applying a given motion low. In this application, the mechatronic model and control parameters must be properly optimized through Design of Experiment (DOE), Analysis of Variance (ANOVA) or Response Surface Methodology (RSM), and they should be constantly monitored to ensure adequate accuracy.

In the latter case study, a test bench for non-woven tissue cutting is instrumented with different kinds of sensors for predictive maintenance, i.e., to detect impending faults or even to prevent failures at an early stage by using both physics-based modeling and data-driven, machine-learning-based approaches.

Of course, in both the aforementioned examples and whenever some quantitative analysis supporting an industrial process is needed, neither reliable process monitoring, nor compliance to the wanted requirements are possible, unless sensors and measurement instruments are properly calibrated. In this regard, it is important to recall briefly the difference between instrument calibration, verification and adjustment [5].

- **Calibration** consists of two steps. First, it establishes a relation between one or more physical quantities (whose values must be known with uncertainty provided by appropriate measurement standards) and the corresponding indication(s) returned by the instrument under test. Then, this relation is used to return measurement results from such indication(s).
- **Verification** includes all activities aimed at providing objective evidence that a given item fulfils specified requirements. For instance, in the specific case of measuring equipment, instrument accuracy limits must safely lie within given *Max Permissible Error* (MPE) limits. If legal metrology aspects are involved, the verification of a measuring system pertains to the examination, marking and/or issuing of a compliance certificate.
- Finally, **adjustment** refers to a set of actions performed on a measuring equipment so that the indications provided by an instrument correspond to known values of the quantity or quantities to be measured. A well-known example of instrument adjustment is the auto-zero function (often improperly called *self-calibration*), which is built-in in many electronic equipment.

Of course, if the verification of an instrument is successful with high confidence (namely if the wanted accuracy requirements are met), instrument calibration can be postponed. On the contrary, when instrument calibration is performed, further maintenance or adjustment actions may be required, e.g., if some accuracy limits are violated in one or more operating conditions or if some crucial metrological characteristics are unexpectedly different from the required ones. In general, since the results of QMS-driven monitoring and measurement activities depend also on the metrological status of the measuring equipment, the ISO 9001:2015 Standard explicitly states in Clause 7.1.5.2 that the measuring equipment shall be:

- Identified to determine its status;
- Periodically ***calibrated*** or ***verified*** against references ***traceable*** to national or international standards;
- Safeguarded from ***adjustment***, damage or deterioration that would invalidate its calibration.

If an organization discovers that the validity of measurement results is compromised or the measuring equipment is found to be unfit for the intended purpose, the organization must take appropriate corrective and recovery actions timely and effectively. To handle this kind of issues properly, a QMS should be supported by a Measurement Management System (MMS).

2. Role of Measurement Management Systems (MMS)

An MMS is a set of interrelated or interacting elements aimed at ensuring that measuring equipment and measurement processes are fit for their intended use. The goal of an MMS is twofold [6], i.e.,

1. Ensuring that specified quality requirements are met;
2. Reducing the risks that measurement equipment and processes produce incorrect results.

Such risks, usually split into **Consumer's Risk** (CR) and **Producer's Risk** (PR), may have severe economic and/or legal consequences for companies. Given a generic quantity $\boldsymbol{x}$ chosen as a performance or quality indicator, the corresponding measured quantity $\boldsymbol{y}$ and the compliance interval $A=[\mu_x-S,\ \mu_x+S]$ (where μ_x is the target value of $\boldsymbol{x}$ and S is the specification limit), CR and PR are defined respectively as [7], [8]:

$$CR = \Pr\{\boldsymbol{x} \notin A | \boldsymbol{y} \in A\} \text{ and } PR = \Pr\{\boldsymbol{x} \in A | \boldsymbol{y} \notin A\} \quad (1)$$

The CR refers to the probability of wrongly accepting an out-of-compliance item or service. The CR costs for companies are both direct (e.g., repair or replacement costs) and indirect, as they can greatly and unpredictably grow due to the loss of reputation towards customers, which can be further boosted by social networks. Also, in some cases (e.g., whenever legal metrology requirements must be met), the CR costs may comprise possible economic sanctions imposed by national or international authorities.

The PR depends instead on the probability of wrongly excluding compliant items or services. The related costs are mainly due to the waste of materials, labor and energy. Therefore, the PR costs are usually more predictable and potentially lower than the CR ones. Of course, both CR and PR should be kept as low as possible, e.g., by properly keeping both the target measurement uncertainty and the amount of guard-banding under control [9].

An MMS can be useful to achieve this goal. Through an MMS, the measuring equipment can be handled in a cost effective manner not only for calibration, verification and maintenance purposes, but over the whole lifetime cycle from acquisition to final disposal.

The general requirements of an MMS are specified in the ISO Standard 10012:2003 that was reviewed and confirmed in 2022 [6]. This Standard is complementary to other norms in which it is explicitly mentioned (e.g., the ISO Standards 9001:2015 and 14001:2015), and it should not be confused nor it is supposed to replace the ISO/IEC Standard 17025:2017 that is instead aimed at the accreditation of testing and calibration laboratories [10].

Likewise the ISO Standard 9001:2015, also the ISO Standard 10012:2003 relies on a Deming cycle approach. In Clause 7 of [6], the two central elements to be considered for MMS implementation are identified and properly defined. They are:

- The **measurement process**, namely the set of operations to determine the value of a quantity;
- The **metrological confirmation**, i.e., the set of operations required to ensure that measuring equipment conforms to the requirements for its intended use.

According to the ISO Standard 10012:2003 (Clause 7.2), a measurement process consists of three main steps, i.e., *design*, *realization* and *recording* (see Fig. 2).

- The *design* step is needed to establish kind of measurements to be performed (i.e., measurands and target uncertainty limits), instruments to be used (including their metrological characteristics), measurement methods, and personnel's technical skills.
- The *realization* step includes all the activities needed to perform measurements under controlled and therefore repeatable conditions. Such conditions depend on: chosen equipment, quantities of interest and of influence, adopted procedures, environmental and operating conditions. The realization step must also include measurement uncertainty evaluation (possibly based on the Guide to the Expression of Uncertainty in Measurement and it supplements [11]-[13]), which is essential to report measurement results correctly.
- Finally, the *recording* step involves the preparation of all documents showing the compliance of the whole process.

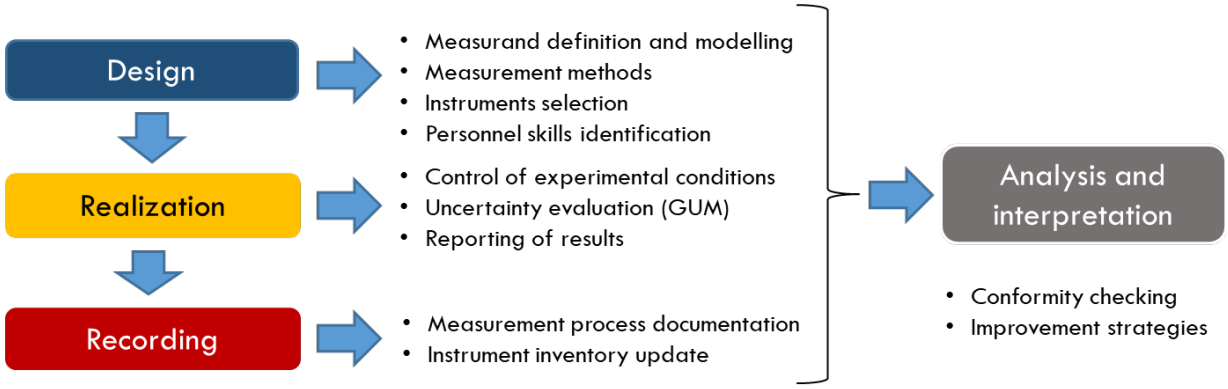

Figure 2 – Main steps of a measurement process according to the ISO Standard 10012:2003 [6].

It is worth emphasizing that the general methodology outlined above has been the subject of further studies over the last few years [14], which led to the identification of at least other two additional steps of a measurement process, one before and the other after those listed above. On the one hand, the **design step** should be regarded as a part of a broader **planning step.** This means that, before designing how to perform measurements, it is essential

1. To specify formally the ultimate goal of such measurements and
2. To develop a model describing the relation between the main physical quantities of interest and influence.

On the other hand, reporting and recording measurement results only is quite useless without a final **analysis and interpretation** of such data. In other words, a follow-up step is needed in which measurement results are further analyzed to support both technical and management decisions (e.g., future process planning) and to learn lessons for the future.

The ISO Standard 10012:2003 partially acknowledge this need in Chapter 8, where it is explicitly stated that "the metrological function shall plan and implement the monitoring, analysis and improvements needed to ensure conformity of the MMS with this Standard, and to continually improve the MMS" [6]. As a result, the instrument inventory must be periodically checked and updated, instrumentation conformity must be verified and suitable improvement strategies have to be defined. Thus, a metrological confirmation process must be implemented. Metrological confirmation relies on both calibration and verification. A simplified flowchart of the metrological confirmation process is shown in Fig. 3. After establishing the target accuracy limits and other metrological requirements, the adopted instruments have to be calibrated. If the equipment is new, usually the calibration certificate provided by the instrument's manufacturer is sufficient; otherwise

instruments calibration must be performed by an accredited laboratory (i.e., compliant with the requirements of Standard ISO/IEC 17025:2017 [10]) and it has to be properly documented.

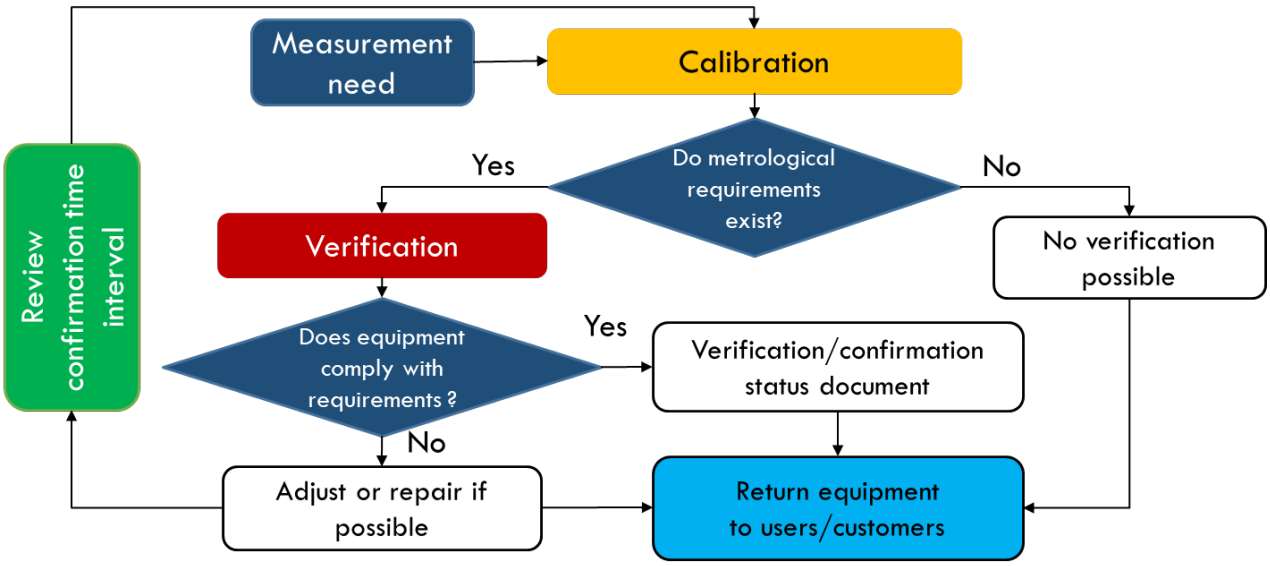

Fig. 3 – Simplified flowchart of the metrological confirmation process according to the ISO Standard 10012:2003.

If some application-specific metrological requirements exist, then a further verification step is needed to check if the instrument is suitable for the intended purpose. For instance, the calibration certificate of a laser rangefinder alone, although formally required, does not automatically imply that instrument's accuracy or range are suitable for the distance measurements that a company has to perform within a given industrial process.

The most common metrological requirements for verification are:

- Expanded uncertainty $U \leq MPE$;
- No significant systematic contributions or biases in measurement results;
- Good ***repeatability*** (namely the instrument capability to provide similar results over a short period of time when the same measurement procedure, the same operators, the same measuring system, same operating conditions and same location are chosen [5]);
- Adequate ***stability*** (i.e., instrument metrological properties tend to remain constant in time [5]).

If the verification step is successful, the confirmation status of a given instrument is properly documented and the instrument can be returned to users (or customers if calibration/verification

are external to the organization). If the verification step fails, the instrument should be adjusted, repaired (if faulty) or even replaced when unrecoverable problems are discovered. Afterwards, the time to the next metrological confirmation (particularly calibration) should be determined.

3. The metrological confirmation interval problem

How to determine the time interval between subsequent metrological confirmations is a well-known industrial metrology issue, which may have a relevant impact on company costs. If we denote with $C_T(T)$ the total costs directly or indirectly related to the measurement and monitoring operations during a metrological confirmation interval of duration T, it follows that

$$C_T(T) = C_{MET}(T) + C_{CR}(T) + C_{PR}(T) \quad (2)$$

where C_{MET} refers to the costs related to calibration and/or verification operations, while C_{CR} and C_{PR} are the CR and PR costs, respectively. Even though no univocal expressions for such costs exist, all terms of (2) are roughly proportional to the amount of measuring equipment that a company has to manage, they are hardly scalable and, of course, they also depend on T, although with an opposite trend. Indeed, the metrology-related costs $C_{MET}(T)$ monotonically grows if T decreases, not only because frequent calibrations and verifications require the service of a (usually external) accredited laboratory and/or internal labor costs, but also, and above all, because calibration and verification reduce instrument availability, thus slowing down productivity or, in the worst cases, even the interruption of the monitored industrial process. On the other hand, relaxing T excessively may unexpectedly and unpredictably boost the CR- and PR-related costs, with severe consequences for companies especially when legal metrology requirements are involved. Based on the remarks above, the optimal calibration interval could be found by minimizing function (2). However, quantifying such costs in practice is very hard, as they depend on several context- and company-related factors, which are rather specific and hardly generalizable.

The ISO Standard 10012:2003 does not provide any clear criterion on how to establish the duration of metrological confirmation intervals. This problem is instead partially addressed in the ILAC-G24:2007/OIML D10:2007 Guidelines [15]. In particular, two sets of guidelines are mentioned in [15], i.e. those to choose the initial calibration intervals and the methods to review such intervals over time. The initial calibration intervals must be chosen on the basis of:

- Instrument manufacturer's recommendations;
- Expected extent and severity of use;
- Environmental quantities of influence;
- Target measurement uncertainty;
- MPE limits (e.g., established by legal metrology authorities);
- Adjustment of (or change in) the individual instrument;
- Influence of the measurand (e.g., high temperature effect on thermocouples);
- Existing data records about instrument metrological behavior.

The decision on the initial calibration interval should be made by expert personnel for each instrument or group of instruments, possibly keeping into account the information (if available) from other calibration laboratories.

The interval duration review should instead be based on one of the following policies, i.e.

- **Calendar-time automatic adjustments ("staircase" methods)**. These techniques compute the calibration intervals based on the results of the last few calibrations. If an instrument is found to be metrologically compliant to the intended purpose within a given threshold (e.g., 80% of the MPE) one or more times, the following calibration interval is extended; otherwise its length is reduced. This approach is rather simple to implement, but not so simple to manage in practice, since it requires that each instrument is handled individually, which might be complicated in organizations where many instruments are employed. Some further details on one of such staircase methods are reported in subsection 3.1.

- **Calendar-time control charts.** Such control charts rely on the same approach commonly adopted for statistical quality control, but they are applied to instrument calibration/verification. In this case, significant calibration points for each instrument are chosen and the results are plotted against time to estimate the dispersion of results and/or to detect possible drift phenomena. From data analysis, the calibration intervals can be computed with various optimization techniques (e.g., to minimize the risk of exceeding given upper or lower specification limits or to minimize the sum of Type I and Type II errors probabilities [9]). Unfortunately, control charts can be hardly applied in the case of bulky equipment or frequently used instruments, as they would be too impractical or too expensive.

- **“In-use time” policies.** Such policies are just variations of the previous ones in which the intervals between calibrations is determined considering the hours of actual use instead of the calendar time. Such solutions are more effective whenever the measuring equipment is used in harsh environmental conditions that may contribute to the degradation of its metrological performance. Examples of measurement devices that are calibrated with this policy are the thermocouples used at extreme temperatures or instruments that may be subject to mechanical wear with use. The main benefit of “in-use time” policies is that the number of calibrations (and the related costs) depend directly on the actual time an instrument is used.

- **In-service checking or black-box testing**. Such techniques are also variations of the “staircase” methods and of the control charts. In this case however, only some critical metrological parameters of an instruments “are checked frequently (once per day or even more often) by a portable calibration gear, or preferably, by a “black box” made up specifically to check the selected parameters” [15]. If the instrument fails the verification based on black-box testing, then it must be fully calibrated. The main benefit of this class of methods is that they tend to maximize instrument availability for the user. Their main drawback is instead that some pending metrological problems (e.g., affecting some parameters that are not monitored by the black-box device) are not detected promptly, thus invalidating the results quite before users may realize it.

- **Other model-based statistical approaches**. The statistical distribution of some crucial metrological characteristics of a class of measurement instruments as well as the probability that such characteristics are no longer compliant with the intended requirements can be also estimated if suitable stochastic models are defined. This is for instance the case of atomic clocks, whose phase noise is modelled by a Wiener process with drift [16]. Once the stochastic model is chosen, its parameters can be computed through numerical fitting. Afterwards, the model can be used to estimate the time after which a new calibration is recommended with a known level of confidence. The main drawback of purely statistical techniques is that large sets of data of homogeneous instruments are needed to build trustworthy stochastic models. However, usually this approach is feasible only for metrological institutes or large calibration laboratories.

As qualitatively shown in Table I, no interval review policy is superior in all respects to the others, as all of them exhibit some advantages and disadvantages. Ultimately, the preferable approach depends on the type of instrument as well as on the application whereby the measuring equipment is used. Furthermore, it should be noted that any adopted policy is also affected by management and maintenance aspects.

Table I – Qualitative comparison between different methods to review calibration interval duration [15].

	Staircase methods	Control charts	In-use methods	In-service methods	Statistical model methods
Reliability	Medium	High	Medium	High	Medium
Effort	Low	High	Medium	Low	High
Workload balance	Medium	Medium	Bad	Medium	Bad
Applicability	Medium	Low	High	High	Low
Instrument availability	Medium	Medium	Medium	High	Medium

3.1 The Simple Response Method (SRM)

Among the "staircase" methods for calibration interval review, the most straightforward one to use is probably the so-called Simple Response Method (SRM) [17]. When this policy is adopted, the duration of metrological confirmation intervals changes adaptively depending on the outcome of the last confirmation only, i.e.,

$$T_n = \begin{cases} T_{n-1}(1+a), & \text{if confirmation successful} \\ T_{n-1}(1-b), & \text{if confirmation fails} \end{cases}, \quad n>1 \qquad (3)$$

where T_n denotes the duration of the n-th interval, $a>0$ and $0<b<1$ are two constant parameters (namely the degrees of freedom of the method) and T_0 is the initial interval that should be chosen on the basis of available a-priori information, as explained in Section 3. As a rule of thumb, parameters a and b should be kept reasonably low (namely, in the order some percent with $b \geq a$)

both to be conservative (in this way the calibration intervals change gradually in the transient phase) and to avoid excessively large oscillations around a possible optimal interval in steady-state conditions after convergence is reached.

Assuming that the time to out-of-conformity of a given instrument can be modeled by a Weibull random variable with probability density function [18]

$$f(t) = \alpha\beta t^{(\beta-1)} \cdot e^{-\alpha t^{\beta}} \ , \ t > 0 \tag{4}$$

(where $\alpha, \beta > 0$ are the parameters of the distribution) and that an "adjust always" policy is adopted anytime a calibration is performed, it can be shown that the probability that an instrument meets the metrological confirmation requirements after the nth calibration (for $n>1$) is approximately given by the following recursive expression [17], i.e.

$$R_n \cong R_{n-1}^{(1-b)^{\beta}\left(\frac{1+a}{1-b}\right)^{\beta R_{n-1}}} \xrightarrow[n\to\infty]{} \frac{\log(1-b)}{\log\left(\frac{1-b}{1+a}\right)} \tag{5}$$

It is worth noting the Weibull distribution is a very flexible and general reliability model, which includes the classic exponential distribution as a special case when β=1. Moreover, if β >1 the failure rate grows with time and for β =2 this is exactly linear. The relevance of expression (5) is twofold. First of all, the steady-state asymptotic value of R_n depends on the SRM parameters only, regardless of the underlying Weibull model (4), although this definitely affect the duration and the trend in the transient phase. This result suggests that the asymptotic limit of (5) can be successfully applied also to other distributions (it was indeed successfully used also to determine the calibration intervals of Cesium clocks [16]).

Secondly, for a given target probability of compliance to metrological requirements and a given value of a or b, the asymptotic limit in (5) can be used as a design criterion to compute the value of the other parameter, even if the underlying reliability model is totally or partially unknown. Fig. 4 shows the results of the comparison between the values returned by (5) (solid lines) and the probability of compliance computed through extensive Monte Carlo simulations (dashed lines) with values of a and b that were purposely exaggerated to check the validity of (5) under stressed conditions (i.e., for a=0.1 and b=0.55 or a=0.3 and b=0.4, respectively). In both cases, T_0= 12 months and the parameters of the Weibull distribution are α=0.0006 e β=2. The excellent agreement between theory and simulation results is rather clear.

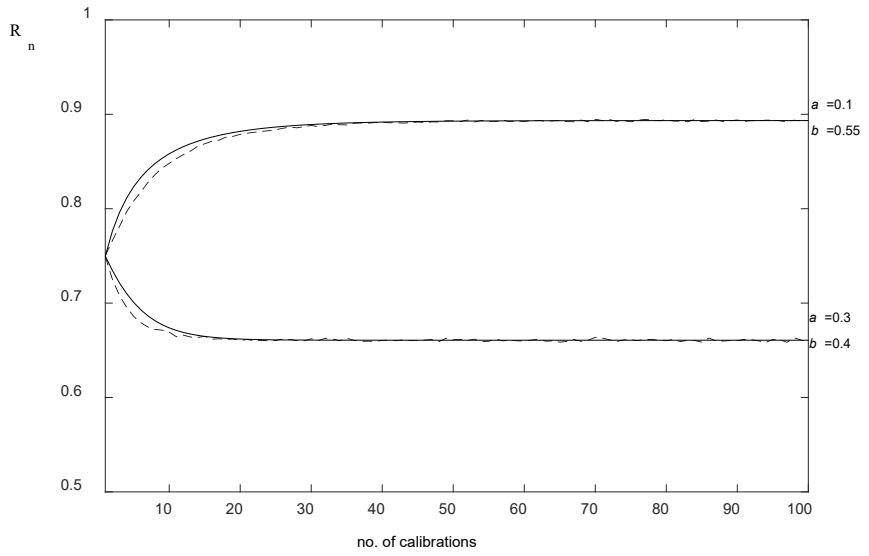

Fig. 4 – Theoretical (solid lines) and Monte Carlo simulation-based (dashed-lines) probability curves of meeting the metrological confirmation requirements as function of the number of calibration when the time-to-out-of-conformity is modeled by a Weibull distribution with parameters α=0.0006 e β=2.

It is worth noting that the previous analysis is performed as a function of the number of calibrations. A dual reliability analysis as a function of calendar time in the very same conditions (Weibull distribution with "adjust always" policy at calibration) reveals that the asymptotic limit of the probability to meet the metrological confirmation requirements is different from (5) and it is given instead by

$$\lim_{t\to\infty} R(r) \cong \frac{b}{a+b} \tag{6}$$

Although further studies are needed to validate this limit from the theoretical point of view, also expression (6) could be also used as an alternative design criterion for the SRM method, when the calendar-time rather than the number of calibrations is considered in the analysis.

4. Conclusions

Industrial metrology is essential to meet the wanted quality requirements of smart manufacturing companies and to improve their competitiveness in a global scenario. The ISO Standard 9001:2015 clearly states that measurement and monitoring activities have to permeate the industrial processes and must be used to support decisions. As a consequence, the Quality Management Systems (QMS)

should also rely on suitable Measurement Management Systems (MMS) ensuring not only that the measurement processes are implemented correctly, but also that the measurement results meet the uncertainty requirements specified by the market, the customers or existing regulations. To achieve this goal, metrological confirmation plays a crucial role. The metrological confirmation process essentially relies on periodic verification and calibration operations with instrument adjustment and repair if needed. Due to the high potential costs of MMS implementation and calibration services (especially when large amounts of instruments are considered), apparently the time interval between subsequent metrological confirmation should be as long as possible. However, in practice, the duration of such intervals must result from the tradeoff between the metrology-related costs and those resulting from growing Consumer's and Producer's risks, which may greatly and unpredictably grow when non-conforming measuring equipment is used. Different policies to review the duration of metrological confirmation intervals exist. Among them, the so-called staircase methods can provide good flexibility and performance, provided they are characterized and designed properly.

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