Calibration and certification of industrial sensors – a global review

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Abstract: - The main objective of this paper is to describe the state of the art of the calibration and certification of industrial sensors, giving an approach on how companies can manage the sensors' calibration, namely the ones that are incorporated in the equipment.
For any industry it is essential to make products that satisfy the customers in terms of quality and, simultaneously, to be competitive in the market. The data obtained from the sensors placed in the equipment is one of the sources that helps to increase the performance, adding value for the competitiveness of the company in the market.
Sensors are responsible, in many sectors, to guarantee equipment availability and product quality. In this way, the certification of the company and of the equipment, not only guarantee quality and prevent unwanted and unforeseen costs, but also gives company credibility, namely from the customer's point of view.
This paper focus on the state of art of industrial metrology, namely sensors, standards and measuring tools, calibrations and the certification of calibration. It also includes a theoretical section about sensors, types of sensors, their operation and characteristics. Next, it is presented the theme of metrology and the measurement science, responsible for ensuring the quality and veracity of the data sent by the reading equipment. It also addresses the importance of metrological traceability and certified management systems, which are required to certify the sensors calibration, in order to guarantee the effectiveness of the measurements and, consequently, the rigor of operation of the associated quality system.

Key-Words: Metrology; Sensors; Traceability; Calibration; Certification; Condition Monitoring

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1 Introduction

When we talk about a company's quality image, we know that it is influenced by many factors. Its aptitude and competitiveness in the market are strongly indexed to the quality and reliability of the data used. We can also talk about the importance of this data in the maintenance policy implemented, and in the service and quality of maintenance performance. Through high-quality input elements it is possible to establish a reliable production process, ensuring high availability and stable product quality. [1]

When we talk about the use of sensors, we are talking about the reliability of the data obtained through them. This is where metrology, the science of measurement, comes in, and it is through it and the existing traceability pyramid that the company can guarantee the effectiveness of the sensors. Through an interrupted set of calibrations, from the pyramid top patterns of the industrial sensor, it is then possible to guarantee the reliability of the equipment.

A calibration corresponds to an issue of a calibration certificate and the placement of a label. Based on this information, a user can decide if the instrument is suitable for the application in question.

It is inferred that, without metrology and sensor calibration, the measurements performed are not reliable, and may lead to unwanted and harmful results in many situations. This means that without the support of metrology based on sensing, there would be measurement errors and unreliable data, which could result in uncontrollable risks and costs and, consequently, the loss of market confidence.

So, with the increase of the competitiveness among companies, namely based on the increasing of robotic and automation, and the increasing of customer demand, the certification of management systems has become an essential tool for their survival in the market. A certified company guarantees a set of established and recognized procedures, through which the conformity of products or systems is determined. Also, the calibration certification of the sensors is extremely important, because it guarantees the quality of the data. According to [2], the EN ISO 9001 standard involves the assessment of the company in several areas, one of which is the measurement instruments and its quality management, namely about inspection and testing.

Some requirements of this standard are as follows:

- selection of the appropriate equipment for the measurements to be made;
- equipment calibration at regular intervals, using certified standards;
- use of documented procedures;
- guarantee that the equipment has the required accuracy;
- certainty that the equipment indicates the calibration status, and calibration certificates are maintained;
- environmental conditions, storage, handling and safety are appropriate in order to maintain the validity of the calibrations.

This paper is structured in three sections: the first section is the introduction, where the topic under study is described; section two describes the state of the art and covers all topics related to the study, starting with the "industrial sensors", where an approach to this theme is made explaining their importance in the industry and, mainly, in the industrial maintenance area. In this way, it is described: the sensor's operation; its functions; the types of existing sensors; their performance characteristics. Then, in order to be able to explain how to maintain the reliability of the sensors for their perfect functioning, it is referred the importance of the "metrology". Here, the relation between this subject with the data reliability provided by the sensors is emphasized, which can, later, be used in the equipment conditioning maintenance. The metrology concept is described, as well as its areas of activity, wherein this research is focused on and the technical area where it is related. Additionally, it must be taken into account the traceability chain, which goes from the primary standard to the working standard, supported by consecutive calibrations. Therefore, it they are referred the concepts of: metrological traceability; standards; and calibration. Then, an approach to the type of calibration strategy that can be addressed by companies is made. They are referred some relevant concepts as follows: Preventive Calibration; and Predictive Calibration and On-line Monitoring (OLM), being this discussed in big detail. Finally, the calibration certificates is discussed: only through certified measuring instruments is possible to guarantee the reliability of the measurement results and to find the metrological traceability. Therefore, this chapter addresses this issue explaining the certification procedure, as well as the entities responsible for issuing the certificates (Calibration laboratories accredited with 17025: 2017). Finally, in section three, a conclusion of the study is made explaining the illation drawn from this paper.

2 State of the Art

2.1 Industrial Sensors

Sensors are one of the largest data sources used in Industry. Probably one of the largest sources in condition monitoring maintenance, since this type of maintenance is based on the equipment condition. It is necessary to make constant measurements to evaluate the health equipment. The sensors are responsible for continuously interpret the equipment condition.
According to [3], sensory technologies have grown very quickly in several areas such as: science; product design; electronics; photonics; mechanics; chemistry and biology. Sensors are used in the individual's daily life, as well as in companies, and are responsible for detecting audible, movement, optical or magnetic signals. The ability to have many small devices that transmit in real-time data physically distributed close to the detected objects brings new opportunities to observe and act in the world, which could bring significant benefits to humanity. [3]
So, sensors are responsible for making direct connection between a physical phenomenon and the data acquisition system, converting signals of physical quantities into electrical signals. They can convert the data received from a physical phenomenon, transforming it in order to be able to read it (Figure 1).
Then, leaving away the various nuances of domains and applications, a sensor simply measures something of interest and provides an output that can be useful. [4]

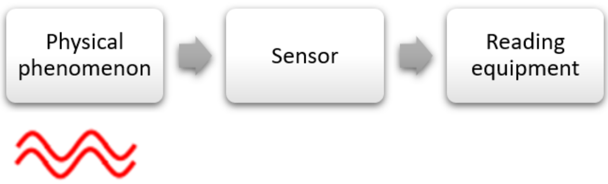

Fig. 1 - Basic diagram of the operation of a transducer

With the advancement of technology, namely computing, widespread communications, connectivity to the Web, smart mobile devices and integration in the cloud, the number of sensors increased. This evolution is illustrated in Figure 2.

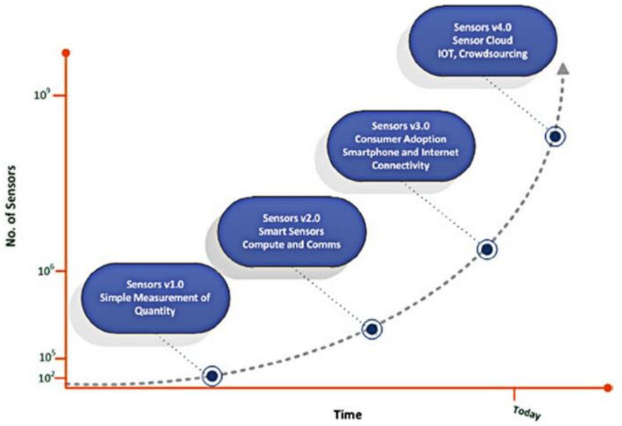

Fig. 2 - Evolution of sensors [Source: [4]]

The sensors convert a physical phenomenon into a measurable electrical signal. Some sensors do not respond naturally to changes in physical phenomena and it is necessary to recourse to a signal condition. Before digitizing the sensor output, the signal may need other components and circuits to produce a signal that can take advantage of all features of the measurement hardware and reduce the effects of noise from external interferences [5]. [6] adds that the sensors do not operate alone. They need a larger system consisting of signal conditioners and several analogue or digital signal processing circuits. This system can be a measurement system, data acquisition system or process control system, for example. The same author also says that sensors and their associated circuits are used to measure various physical properties, such as: temperature; force; pressure; flow; position; light intensity; etc. These are responsible for stimulating the sensor and the output of this is conditioned and processed in order to provide the corresponding measurement of the physical property.

[7] says that sensors can be used alone or together in order to monitor a specific situation in the same way as a human being, such as:

- manufacturing operations;
- conditioning of tools;
- inventory control;
- working in progress;
- identification of parts, tools, pallets, etc.

Nowadays, sensing in a factory can be considered more efficient, because it implies less supervision, namely in unmanned manufacturing. As the complexity of manufacturing processes increases, it becomes necessary to acquire additional types of information obtained through sensors. [8]

Process sensors are used to control the manufacturing process and their measurements allow a better understanding of the process, generating improvements. The connection between profit and process measurement is illustrated in Figure 3.

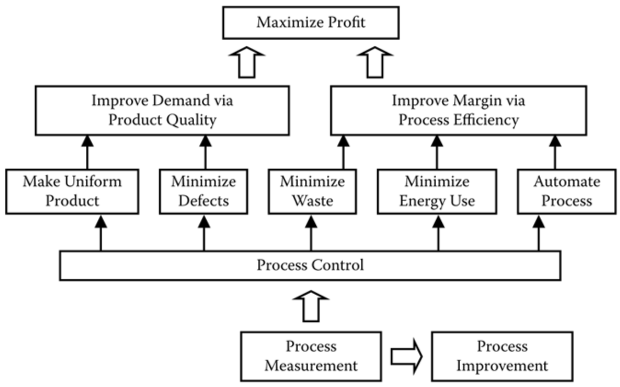

Fig. 3 - Crucial measurement process to operation and profitability [Source: [8]]

2.1.1 Type of sensors

According to [9], “there are many types of sensors, according to each type of condition variable. The reasons to choose a sensor are diverse, as are the type of output signal, the range of output values, the environmental conditions, the physical dimensions, and so on. Sensor signals may be digital or analog.”

This author also states that the sensor signals can be digital or analog. Digital sensors can have an interface to communicate with other devices. In turn, analog sensors no longer have this capability, which is why an analog-to-digital converter is needed to enable communication with other devices.

There are several different types of sensors, with different types of characteristics, being each of them designed to measure the variables of interest. We can characterize the sensors as active (with contact) or passive (without contact).

According to [6], [4] and [10], active sensors need to be connected with an external source of excitation. They generate an electric current when the external physical environment changes. It requires physical contact with the factor to be measured, disturbing its state.

The same authors explain that passive sensors generate their own electrical output signal without the need for external voltages or currents. They change their resistive, capacitive or inductive characteristics along with their physical parameters. An external power source is required to induce an electrical output. It does not require direct contact with the variable to be measured, aiming not cause a disturbance.

In Figure 4 can be seen some examples of sensors and their characteristics.

PROPERTY	*SENSOR*	*ACTIVE/PASSIVE*	*OUTPUT*
Temperature	Thermocouple	Passive	Voltage
	Silicon	Active	Voltage/Current
	RTD	Active	Resistance
	Thermistor	Active	Resistance
Force/Pressure	Strain Gage	Active	Resistance
	Piezoelectric	Passive	Voltage
Acceleration	Accelerometer	Active	Capacitance
Position	LVDT	Active	AC Voltage
Light Intensity	Photodiode	Passive	Current

Fig. 4 - Typical output sensors [Source: [6]]

Currently, there are transducers capable of taking measurements of practically all existing physical quantities (Figure 5). For example, for the temperatures measurement, there are thermocouples, thermoresistors, thermistors and the semiconductor junction, which convert the temperature of the medium with which they are in contact to a proportional analogue signal; for flow measurement, there are, among others, turbine flow meters, which generate a rectangular wave signal whose frequency depends on the flow speed; load cells are available for measuring voltages; for pressure measurement, there are several types of pressure transducers; etc. [11], [5], [10].

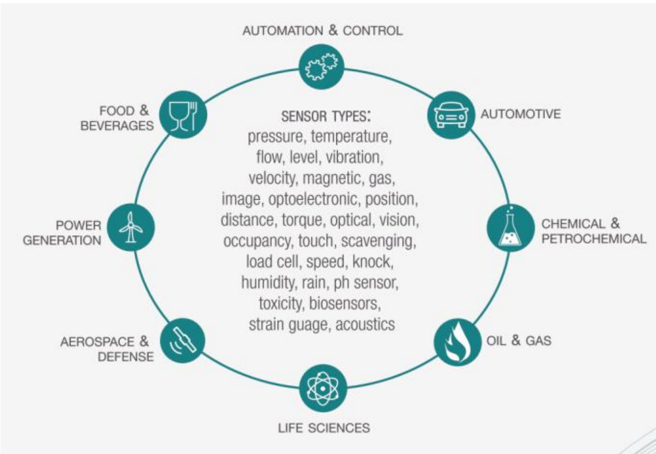

Fig. 5 - Different types of sensors and their markets [Source: [10]]

[4] characterize the different types of sensors as follows:

- *Mechanical Sensors*
  These sensors measure changes in a device or material as a result of an input that causes its mechanical deformation. Movement, speed, acceleration, and displacement are the changes that result in mechanical deformations and that can be measured. The sensor is described as electromechanical, when the inputs are converted directly to an electrical output
- *MEMS Sensors*
  MEMS (Micro Electro Mechanical Systems) are miniaturized, three-dimensional mechanical and electrical structure sensors, usually ranging from 1 to 100 mm. They are manufactured using standard semiconductor manufacturing techniques. Its constitution consists of mechanical microstructures, microsensors, microactuators, and microelectronics, which are integrated in the same silicon chip. The use of this type of sensors, with multiple axes of low energy consumption, ultra-compact and compact, allowed a high growth of electronic devices, such as: smartphones, tablets, game console controllers, portable game devices, digital cameras, etc. In the health field, these sensors are used as blood pressure monitors, pacemakers, ventilators, and respirators. The most used MEMS sensors are accelerometers and gyroscopes.
- *Optical Sensors*
  These sensors are responsible to detect waves or photons of light. It's including light in the visible, infrared, and ultraviolet (UV) spectral regions. They can measure changes in light intensity related to the emission or absorption of light by an amount of interest. They are widely used, among others, in automated doors and gates to ensure that there are no obstacles on the way, and in industrial applications, where they measure levels of liquids and materials in tanks or on factory production lines, in order to detect the existence of objects.
- *Semiconductor Sensors*
  These are low cost sensors, with high reliability, low energy consumption, long service life, and small dimensions. They are used in several applications, such as: Gas monitoring; Pollution monitoring; Breath analysers, for measurements of alcohol content in exhaled air; Monitoring of domestic gas, such as propane; Temperature, as in electronic equipment; Magnetism, for example, magnetometers for applications with six degrees of freedom; Optical sensor, such as detectors for devices attached to load on cameras.
- *Electrochemical Sensors*
  These sensors are responsible for measuring an electrical parameter of the sample of interest. They consist of sensors or electrodes, a reference electrode and, in many cases, a counter electrode. These electrodes are, usually, placed in contact with

a liquid or solid electrolyte. In the low-range-temperature (<140° C), electrochemical sensors are used to monitor pH, conductivity, dissolved ions, and dissolved gases. For measurements at high temperatures (> 500° C), such as the measurement of exhaust gases and molten metals, solid electrolyte sensors are used. They are categorized from the measurement performed. They have low energy consumption, high sensitivity, good precision and resistance to the effects of surface poisoning. In contrast, their sensitivity, selectivity, and stability are greatly influenced by environmental conditions, especially temperature.

- *Biosensors*
  These sensors detect an analytical of interest in chemical, environmental (e.g.: air, soil and water) and biological samples (e.g.: blood, saliva and urine) and use biochemical mechanisms for this. It uses an immobilized biological material, which can be an enzyme, antibody, nucleic acid or hormone, in an independent device. The biological material used in the biosensor device is immobilized in order to maintain its bioactivity.

2.1.2 Sensor performance characteristics

The sensors have several characteristics that define them, and through them; it is possible to choose the best sensor to use in each case. There are several sensors that can measure temperature, pressure, acceleration, voltage, acoustic, etc.; so, their manufacturers tend to focus on basic performance parameters. According to [4], “to truly understand sensors, and how sensors that measure the same measurand can differ, it is necessary to understand sensor performance characteristics”. Therefore, here it will be introduced each of their most important characteristics.

According to According to [6], [10], [4], [12] and International Metrological Vocabulary (VIM in Portuguese), [13], it is presented some of the most important characteristics of the sensors:

- *Sensitivity*
  Represents the relationship between the physical input signal and the electrical output signal. It is the ratio between a small change in the electrical signal and a small change in the physical signal. It is the change in input required to generate a change in the unit at the output. It can be expressed as the derivative of the transfer function in relation to the physical signal. Not all sensors have a linear output. If the sensor response is linear, the sensitivity will be constant over the sensor range. A good sensor has to have a lot of sensitivity, able to better detect the signals of the measurand, and a constant sensitivity that is maintained throughout the dynamic range. If the sensor response is non-linear, the sensitivity will vary within the sensor range. As an example, we can consider an accelerometer as a "high sensitivity" sensor, if it can detect a small change in vibration what would result in a large change in voltage.
- *Range or Dynamic Range*
  It represents the range of physical input signals that can be converted into electrical signals by the sensor. It describes the total range that the sensor can measure from the physical input parameters, such as light intensity, sound level or temperature, and converts them into readable electrical parameters. That is, it is the maximum capacity that the sensor can measure without distortion of the generated signal. The dynamic range can be indicated by the sensor supplier. There we can see the range over which other performance characteristics described in the data sheets are expected to apply. Typical units are: g; Kelvin; Pascal; Newton; etc.
- *Accuracy or uncertainty*
  Uncertainty is generally defined as the largest expected error between the actual and ideal output signals. According to VIM, measurement uncertainty is the non-negative parameter that characterizes the dispersion of the values attributed to a measurand, based on the information used.
  Accuracy, defined by VIM, represents the degree of agreement between indications or measured values, obtained by repeated measurements, on the same or similar objects, under specified conditions. [4] explain that it is generally considered by metrologists as a qualitative term, while "uncertainty" is quantitative. For example, one sensor may have better accuracy than another if its uncertainty is 1% when compared to the other with an uncertainty of 3%.
- *Linearity*
  Linearity represents how linear the output of the sensor values is within its dynamic range. That is, the ability of the sensor to maintain its sensitivity regardless of the signal generated. Linearity is usually specified in

terms of percentage, i.e., the percentage change in sensitivity between one value of its amplitude and another. Non-linearity can generally be a result of the conditions of the environment where the measurement is being made, such as: environmental changes, temperature, vibration, acoustic noise level, and humidity.

- *Repeatability*
  This characteristic represents the ability of a sensor to produce the same output value for the same applied input as the measurand. VIM characterizes fidelity or measurement accuracy under a set of repeatability conditions. Sensors with good repeatability will always reproduce the same values for the same measurement under the same conditions. The lack of repeatability can occur due to random fluctuations in environmental inputs or errors made by the operator. [13]
- *Noise*
  Noise is produced by the sensors that go along with the output signal. All electronic components of the measurement system produce some noise. Noise is generally distributed across the frequency spectrum. Too much noise produced by the sensor will impair the measurements made by it.
- *Resolution*
  According to VIM, the resolution is the smallest variation in the measured quantity that causes a noticeable variation in the corresponding indication, [13]. The resolution is defined as the minimum oscillation of the signal. Once these oscillations are temporal phenomena, there is some relationship between the fluctuation time scale and the minimum detectable amplitude. Depending on the type of measurement to be made, we can choose a sensor with a higher or lower resolution. Knowing that, if it is chosen a sensor whose resolution is too high for the application, it is unnecessarily expensive.
- *Bandwidth*
  It is the frequency range between the upper and lower cut off frequencies. That is, it is a frequency range where the sensor can read the physical signal produced. The sensors have finite response times to an instant change in the physical signal. Some sensors are represented as have decay times. This is the time after a step-change in the physical signal for the sensor output to decay to its original value. The reciprocal of these times corresponds to the upper and lower cut off frequencies, respectively.
- *Response time*
  It is the ability of the sensor to respond to the measurement, reacting to signal changings. It is sometimes referred to as a sensor time constant when it is subject to a step change. VIM says that the response time is "time interval between the moment when an input value of a measuring instrument or a measuring system is subjected to a sharp variation between two specified constant values and the instant when the corresponding indication is keeping within specified limits around its final value in a stable regime" [13].
  It represents the period of time required for the sensor to change its output after a change in the input value.
- *Reach*
  This characteristic represents the ability of the sensor to detect the minimum and maximum value of the input or output of the signal of the measurand. Then, there are the minimum and maximum input voltages that can be used to operate the sensor. If an input voltage is applied outside this range, the sensor may be permanently damaged.
- *Transfer function*
  A term used to refer exclusively to time-invariant linear systems. In the case of sensors, there is a relationship between the measurand and the electrical output signal. This relationship, if it is time-invariant, is called the sensor transfer function. There are sensors that are calibrated, obtaining a certified calibration curve, which guarantees this relationship between the input and output values.
  A mathematical formula (Equation 1) that describes the transfer function is usually expressed as follows:

$$S = F(X) \tag{1}$$

  Where:
  X - is the measurand;
  S - is the electrical signal produced by the sensor.
  It is rare to find a transfer function that can be completely described by a single formula; therefore, functional approximations of the actual transfer function are used.
- *Error*

Error is the difference between the measured value and the true value, where the true value is a reference to an absolute or agreed standard. Quoting VIM, error is the difference between the measured value of a quantity and a reference value. There are two forms of error: Systematic error - which reproduces inaccuracies that can be corrected with compensation methods, such as feedback, filtering and calibration; that is, a component of the measurement error that, in repeated measurements, remains constant or varies in a predictable way and random error, also called noise, what corresponds to a signal component that does not carry information.

- *Random error*
  Component of measurement error that, in repeated measurements, varies in an unpredictable way.

2.2 Metrology

This section deals with the concept of metrology and its relation with the data reliability provided by the sensors that are used in Condition Based Maintenance. According to [14], modern metrology introduces key factors such as downtime and product quality.

[15] refers that, in the field of applied sciences, measurements are not accurate, as they are always subject to errors due to various causes, human and materials. The qualification of an error to later quantify an uncertainty proves that the validity of the measurement result is doubtful. Therefore, evaluating measurement uncertainties generating errors is a very complex task.

According to the website of the Portuguese Metrology Society (SPM)[1], in the beginning, as today, measuring was taken as a unit. It is reasonable to admit that the first greatness concerned by Man was the time.

With the existence of well-defined metrics, it is possible to have coherence. For these metrics existing, there must be measuring instruments that prove the measurements are always the same, at any time and in any part of the world.

Therefore, the objective of Metrology is to guarantee the effectiveness and accuracy of the measurements made by these measuring instruments. [5]

According to the website of the Portuguese Quality Institute (IPQ)[2], “metrology, as a measurement science, provides reliable material support to the measurement system, essential in the sectors of the economy, health, safety, and the environment, constituting an essential technological infrastructure in modern societies”.

As time goes on, it becomes imperative for all societies to have references for units of measurement, in order to be able to maintain consistency in everything that is carried out on a daily basis; that is, with the existence of metrics, it is necessary to acquire standards that will become references in those same metrics.

In practice, everything in people's daily lives and, mainly, in the Engineering field, exists a metric, so it is essential to have good use of metrology in order to guarantee universal uniformity.

2.2.1 Concepts

Metrology is the science of measurement, whose main objective is to ensure that measurement equipment reproduces right values, internationally reproducible with similar quantities, [5]. [2] characterizes metrology as the science of measurement that comprises all aspects, both theoretical and practical, related to measurement, whatever its uncertainty and the domain of science and technology to which they refer, relating the processes, instruments, location, metrologist, etc., to each other.

The main objective of metrologists is trying to find ways to measure various physical quantities in the most accurate way possible. Atom sensors, such as atom interferometers and atomic clocks, are examples of a class of instruments that can measure these quantities with very high precision. [16]

In practical terms, metrology comprises a diverse set of aspects (for example, procedures, uncertainties, errors, standards, etc.) with the purpose of determining the value of magnitude, encompassing all theoretical and practical aspects of measurement, whatever the measurement uncertainty and the field of application. It comprises all aspects, both theoretical and practical, related to measurement, whatever their uncertainty and the domain of science and technology to which they refer. [17], [18], [19].

[15] explains that uncertainty reflects the way how a quantity is measured, and the confidence given to the result. The use of instruments in measurement involves calibrations and manipulations, requiring proper procedures and calculations.

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1 http://www.spmet.pt/historia.html (Access date: 03/04/2020)

2 http://www1.ipq.pt/pt/metrologia/apresentacao/Pages/Metrologia.aspx (Access date: 03/04/2020

According to [20] and [12], the task of metrology and metrologists is to achieve reliable measurement results that are necessary to ensure:

- the quality and efficiency of production in the industry;
- the justice in trade;
- the consumer protection;
- the health and safety of life;
- the protection of the human and animal environment.

To frame the various sets of terms related to metrology, the International Metrology Vocabulary (VIM)[3] was used as a reference, which appears in the context of world metrology and seeks the international harmonization of terminologies and definitions used in the fields of metrology and instrumentation.

2.2.2 Practical Areas

[20], [17], [18], [21], [22], [2], [12] explain that metrology can be divided into three fundamental areas of activity, as is shown in Figure 6.

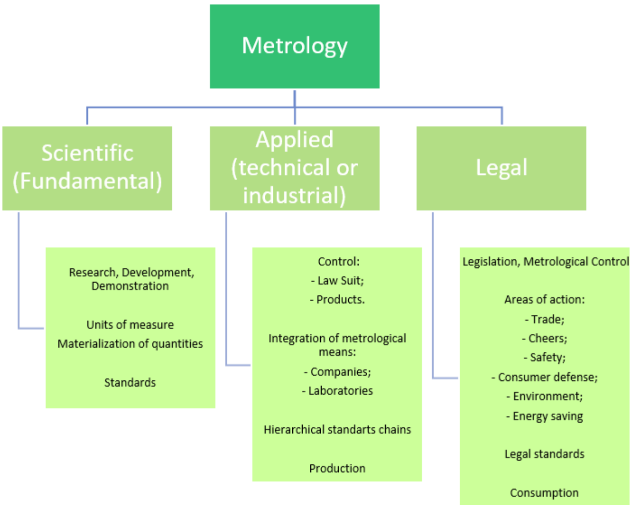

Fig. 6 - Metrology categories [Source: [18]]

In this paper, we only discuss the technical area, because it is essentially related to the productive activity (the theme under study). It exercises a certain control over processes and products that require an integration of metrology at the level of companies and laboratories; it takes into account a hierarchical chain of standards, existing in laboratories or companies/organizations, which are also traceable by primary standards that can be national or international. [23], [20], [24]

2.2.3 Traceability

With the objective to have international metric coherence, there must be a traceability chain. That is an uninterrupted set of comparisons that ensure the result of a measurement, or the value of a standard. Thus, it is guaranteed that the values of the standard, even being of a lower level, will agree with the higher ones.

According to VIM, the traceability is the property of a measurement result whereby that result can be related to a reference through an uninterrupted and well-documented chain of calibrations, each contributing to evaluating the measurement uncertainty.

In the context of Metrology (metrological traceability), the traceability is represented by a pyramidal shape, as can be seen in Figure 7.

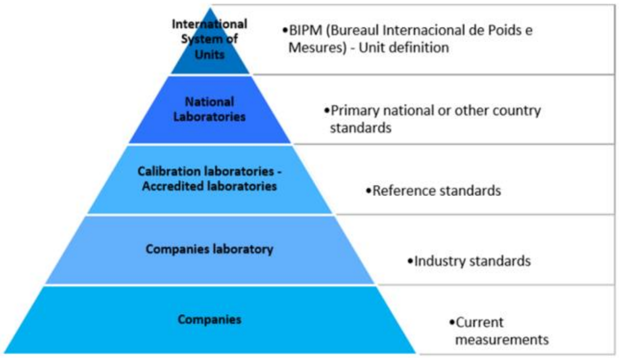

Fig. 7 - Pyramidal traceability [Source: [5]]

[25] argue that quality reliability is closely linked to the traceability chain and the availability of measurement standards. It also says that, in order to establish an appropriate traceability chain, measurement standards are required, traced back to the meter.

Traceability requires orderly and permanent records and is complemented with a succinct document related to metrology to translate the examination of each event of the procedure and what it represents. Thus, it is possible, for the user, to know the history of a process or instrument, [15]. This author also states that, through traceability, it is possible to know changes in equipment, facilitating the management of several aspects, such as:

- Varied use and proper adjustment of equipment in the workplace;
- Selection of equipment among others offered by different suppliers;
- Detection of greater or lesser accuracy (based on records).

[3] http://www1.ipq.pt/pt/metrologia/documents/vim_ipq_inmetro_2012.pdf (Access date: 07/04/2020)

At the manufacturing level, [26] show that ensuring the results of traceability of measurement during the production process is a guarantee of quality improvement. [17] says that the traceability of measurement must be guaranteed, allowing the necessary conclusions to be drawn about its metrological quality. Likewise, it is important to carry out the most relevant actions to ensure the correct indication of the measuring instruments, namely their regular calibration (industrial metrology) and the periodic verification of the measuring instruments according to legal regulations (legal metrology).
Traceability can be required by any customer in a contract, or by standards such as ISO 9000-9004 and ISO 14253. This requirement is made in order to guarantee the quality of the measurement and to protect the buyer. Consequently, any tool or equipment used in production must guarantee its measurement track. [21]

2.2.4 Standards

Calibration is used in order to keep the measurement and control instruments within the specified limits, and, for that purpose, a standard is used to calibrate the equipment, [27], [28]. It is necessary to have standards to be able to make a comparison between this and the equipment to be calibrated.
According to [25], "The reliability of quality assurance is closely connected with the traceability chain and the availability of measurement standards."
The units of physical quantities are reproducible, with the help of reference standards and measuring devices; so, these measuring devices play an exceptionally important role in the measurement unit. [22]
According to VIM, standards are defined as an achievement of the definition of a given quantity, with a determined value and associated measurement uncertainty, used as a reference.
There is a hierarchical structure of reference standards (Figure 8) and their calibrations (Figure 9): International Standards; Primary Standards; Secondary Standards; and Work Standards. It is through this structure and consecutive calibrations that it is possible to guarantee measurements from the primary to the working standard. The standards that rank higher in the hierarchy have higher quality and accuracy in measurements. That is why higher-level standards are used to calibrate lower-level standards.

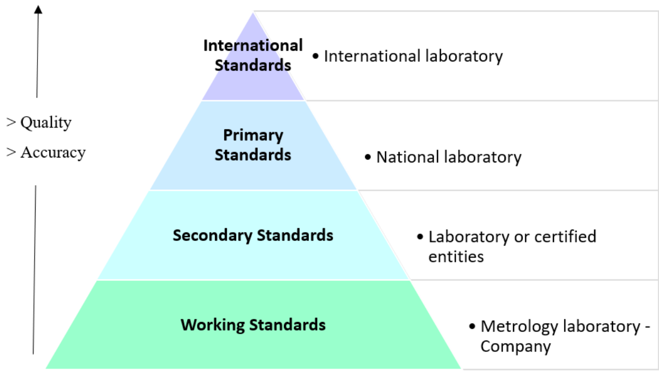

Fig. 8 - Measurement Standards Hierarchy

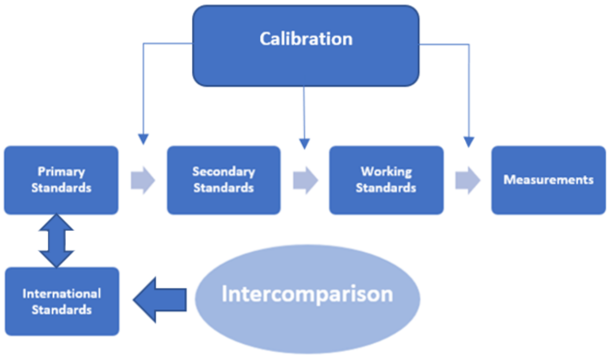

Fig. 9 - Standard hierarchy and calibration

Measurement standards traced back to the meter are used to establish a reliable traceability chain. Accredited calibration laboratories are responsible for providing calibration of work standards. This process involves a loss of precision at each stage and, in order to guarantee the production of the part within the tolerances requested at the end of the chain, the National Metrology Institutes need to calibrate as accurately as possible. [25]

2.3 Formal sensors calibration

In order to guarantee the reliability of the sensor data used in the industry, and to guarantee quality processes, it is necessary to carry out their calibrations.
According to [29], "The veracity of big data requires careful design of data-acquisition and calibration strategies and of feature-extraction and selection strategies, so that decision makers have clean, valid, and reliable inputs to use in making decisions."

2.3.1 Calibration

Calibration of reading instruments is a very important part of the asset management strategy; companies invest a lot of money in the acquisition of this type of equipment. For this reason, uncalibrated instruments, providing wrong values, can imply the companies spent a lot of money, namely because production downtime, safety problems, production of lower quality products, etc. [30]

Juran & Godfrey [31] says that, by ensuring the reading instruments are calibrated, the company is able to confirm that the product complies with the customer's requirements. If the instrument is in error, the company can reject good parts or accept bad parts, which will imply high costs for the company, sending a message to the customer that the company does not have a basic control system.

According to Eren [30], calibration has the following benefits:

- Determines whether measurements taken before calibration were valid;
- Gives confidence in future measurements;
- Ensures consistency and compatibility with those made elsewhere;
- It leads to repeatability and reproducibility of processes;
- Provides confidence that products meet specifications;
- Increases efficiency, ensuring that measurements are correct;
- Leads to the documentation of instrument and process performance to meet quality standards;
- Frequent calibrations can provide a graphical view of equipment uncertainty over time and lead to performance reliability;
- Measurements made within international standards promote global acceptance, thereby increasing competitiveness;
- Helps the validity of compliance of measurements and processes under varying conditions.

So, [12] characterizes calibration as being one of the metrology services of measurement instruments, which is a basic tool to ensure the traceability of measurement.

Calibration is a process of comparing an "unknown" element with an equivalent or better standard. It can be included in an adjustment to correct the deviation from the value obtained from the standard, which is represented by the standard deviation, [15]. It involves the determination of the metrological characteristics of an instrument achieved through a direct comparison with standards. [32]

According to Morris & Langari [33], the calibration is a comparison between the sensor output to be calibrated and the standard sensor output in relation to the same input value (measured quantity) applied to the two sensors. It also says that the calibration is carried out over a range of inputs in order to safeguard the entire sensor measurement range.

According to Eren [30], calibration provides consistency in readings and reduces errors, validating measurements universally. It also confirms that the calibration serves to reveal the individuality of an instrument, comparing it with a reference standard.

According to Eren [34], calibration is a set of actions and procedures that aim to clarify the relationship between the values of the indicated quantities of the measuring instruments under specified conditions, assigning values to the instrument's response to the reference standards.

Through the instrument calibration, we can obtain its calibration curve. [15] explains that the calibration curve is specific for each device and converts the gross measurement into the corrected measurement.

Statistical techniques are applied to calculate the calibration curves, readings averages and standard deviations; the data collection process for the creation of the calibration curve is fundamental for the success of the calibration program.

It is obtained by subjecting the instrument to a real value of the quantity to be measured, which is made through a standard device and, accurately, reads the gross measurement provided.

According to Morris & Langari [33], the calibration must be carried out in periodic intervals of time, because the characteristics of the sensors change throughout their useful life. According to the same authors, there are several reasons that cause a change in the sensors' characteristics, such as: mechanical wear and effects of dirt, dust, smoke, chemicals and temperature changes in the operating environment; these changes in characteristics will also depend on a lot about the use of the sensor, that is, on the time that it is under the operating environment. Although the causes of these changes, its storage also can cause some deviations, due to the aging of its components. [33], [31]

Then, the calibration quantifies the change in measurements, and will ensure that the reading instruments comply with the expected specifications.

Through a good instruments calibration management, the values provided by them can be used in the optimization of processes, asset control, equipment maintenance and plant safety, leading to a better management of the plant's performance. [30]

According to Juran & Godfrey [31], it is necessary to have calibration schedules, being these done according to class of equipment, varying in order to be able to maintain the accuracy, nature and extent of the measuring instruments. The same author also explains that the schedules at the beginning are established by judgments, being changed according to the results of the checks, allowing to establish greater economic efficiency.

Morris and R. Langari [33] say that there should also always be calibration records in order to maintain efficiency and effectiveness of the measuring instruments maintenance system. Complete documentation provides a description of the measurement conditions, instruments used, calibration systems and operated procedures. There should also be calibration records for each individual instrument. To begin with this process, there must be a declaration of the measurement limits defined for each documented measurement system. These limits are established by balancing the costs of the improved precision with the customer's requirements and also in relation to the general quality level specified in the quality manual.

The existence of a calibration record is an important part of knowing the data quality. These records can be saved in software or paper format. Data such are as follows: position ID, device ID, location, serial number and work order number, that can be transferred from one form to another suitable for engineers or managers to evaluate. The data must also contain: maximum errors, pass/fail notifications, calibration date and time, calibration frequency, who performed the calibration task, and so on. [30]

These documented calibration processes are a integrating part of the quality control system audit, and the calibration systems support this quality control system. [33]

So, the timing with which it is necessary to calibrate the sensors will depend on a great extent on their use and the environmental conditions with which they work. Having all these factors involved, it becomes difficult to define the vital regularity of sensors' recalibration, based on theoretical considerations; therefore, practical experimentation to define the time periods between calibrations is important. By defining the maximum allowed measurement error, knowing the rate at which the sensor's characteristics vary, it is possible to calculate the time interval until the sensor reaches the limits of its performance. The level of measurement error that an instrument reaches shortly before recalibration is the error limit that must be quoted in the instrument's documented specifications. [33]

The instrument's calibration history records will be the main basis on which this review is made.

In relation to the management of calibration procedures, this must be done by only one person; so, this function is done efficiently and effectively. A technician trained in metrology is the determining factor in the accuracy of the measuring instrument, [31]. A good calibration management will transmit security to the customer, ensuring the accuracy of the measurements made and, in turn, guaranteeing the quality of the product. The calibration procedures related in some way to the measurements used for quality control functions are controlled by the international standard ISO 9000. [33]

Then, it is necessary to organize correctly the calibration of the instrument to be successful. Thus, there are some factors to consider [30]:

1. The type of calibration process to be employed;
2. Calibration setup and the calibration process;
3. Calibration cycles;
4. Calibration records;
5. Calibration reports and report maintenance;
6. Factors that affect calibration;
7. Use of spreadsheets;
8. Mathematical approaches;
9. Internal versus calibration outsourced;
10. Reference standards to be used;
11. Hierarchy of benchmarks;
12. Traceability;
13. ISO 9000 requirements;
14. Work patterns;
15. Measurement uncertainties;
16. Uncertainties versus errors;
17. Random and systematic errors.

Speaking now of the instruments used for calibration, the standard sensors used, usually have greater precision than the sensors to be calibrated. Morris & Langari [33] tell that high-precision sensors are commonly used for calibrations.

The measuring instruments used for calibration at the company level, made by the instrumentation department, are called work standards. As they are instruments with relatively less use than process measurements, it can be concluded that they will keep their characteristics unchanged for much longer, although they will also always need to be calibrated, mainly due to the effects of aging. After a calibration program has been implemented for these instruments, they will be calibrated by secondary reference standards, which have greater precision. These calibrations are carried out by accredited calibration laboratories, which, at the end of the operation issue, gives a calibration certificate (mentioned in the preceding section), [33]. Tse & Morse [32] state that an instrument is "traceable" if the calibration standards can be traced back to the National Bureau of Standards.

Juran & Godfrey [31] summarize that the reference standards are used exclusively under the control of standards laboratories, composed by technicians, whose main interest is to maintain the accuracy of the calibration. Work standards are in the hands of production, inspection and test personnel, whose main interest is the control of the product and the process.

The standards used for calibration purposes should only be maintained for that purpose and should not be seen as substitute equipment for process measurements. Sensor replacements used for process measurements must be made by other sensors that have the same purpose. [33]

A calibration is usually carried out under ideal conditions; that is, charging and noise due to strange inputs are controlled, [32]. The same authors also say that calibration is normally carried out under ideal conditions because it is not possible, for a standards laboratory, to calibrate instruments for every imaginable service condition. Morris & Langari [33] add that the environmental control for the calibration of the measuring instruments must be taken care of, although sometimes it is not possible to achieve it and, even, sometimes, to be convenient to carry out the calibrations in the process plant. In these cases, the necessary corrections must be made for deviation from the calibration environmental conditions in relation to those specified.

Regarding the cost of calibration, it will depend on many factors, such as: the equipment to be calibrated; who calibrate them (internally or outsourcing); the number of instruments to be calibrated; where they will be calibrated (laboratory or plant); and the frequency of calibration, which is a major cost factor. [30]

Therefore, there are companies that can decide to acquire an accredited calibration laboratory and, the required quality only becomes economically viable for large companies that have a large number of measuring instruments in different factories. Typically, the most commonly used by small and medium-sized companies is to outsource the calibration service provided by several companies specializing in this area. [33]

In organizations, calibrations are conducted on site or in remote laboratories or sites. Large organizations may have several laboratories (called calibration laboratories) dedicated to different instruments and processes.

Laboratories are accredited by authorities in accordance to the guidelines of ISO 17025. Accreditation is the formal recognition that a particular laboratory is competent to conduct specific tests and / or calibrations. [30]

A successful laboratory calibration procedure, according to [30], requires the following basic steps:

- Selection of an appropriate benchmark with well-known values covering the range of interest;
- Conduct calibration curves (i.e., least squares adjustment) to establish the relationship between the measured and known values of the reference standard;
- Correction of measurements using calibration curves;
- Preparation of appropriate documentation of the calibration procedure, results, analysis and interpretation of the results for the customer.

Finally, a calibration originates a calibration certificate and the placement of a label. Based on this information, a user can decide whether the instrument is suitable for the application in question.

According to Morris & Langari [33], the calibration certificate must contain the following information:

- identification of calibrated equipment;
- calibration results obtained;
- measurement uncertainty;
- any limitations on the use of the calibrated equipment;
- calibration date;
- authority under which the certificate is issued.

Calibration labels, applied after the calibration has been carried out, must comply with the general requirements of ISO / IEC 17025 for the competence of testing and calibration laboratories. ISO 17025 requires the following issues [30]:

- all measuring equipment must be labelled in a safe and durable manner;
- the labels must clearly indicate the name of the calibration laboratory, calibration date, expiration date, equivalent of use and the authorized employee;
- the information on the label must be legible and durable under reasonable conditions of use and storage;
- when it is impractical to affix a label directly to an item, the label can be affixed to the instrument's container;
- temperature resistance seals can be used when needed;
- functional labels must contain reference standards.

Summing up, according to [27] and [28], the objective of a calibration system is to avoid the unreliability of the tool through the immediate detection of deficiencies. Every organization should prepare a written description of its calibration system, which should accompany the measurement of test equipment and standards, including:

- to establish realistic calibration intervals;
- to list all measurement standards;
- to establish environmental conditions for calibration;
- to ensure the use of calibration procedures for all equipment and standards;
- to coordinate the calibration system with all users;
- to ensure that the equipment is frequently checked by a periodic system or cross-checks in order to detect damage, inoperative instruments, erratic readings, and other performance degradation factors that cannot be predicted or predicted by calibration intervals;
- to provide timely and positive corrective actions;
- to establish decals, rejection tags, and records to label the calibration;
- to maintain formal records to ensure adequate controls.

The main reasons for using calibrated instruments, according to [12], are:

- to ensure that an instrument's readings are consistent with other measurements;
- to determine the accuracy of the instrument's readings;
- to establish the viability of the instrument.

Through calibration it is possible [19]:

- to assign the measured values to the indications;
- to determine corrections related to the indications;
- to determine other metrological properties, such as the effect of the influence quantities.

In short, the calibration is responsible for comparing a measuring instrument with a standard in order to determine the measurement error. Knowing this measurement error, it is possible to determine the exact value of the metric to be measured.

2.3.1.1 Maintenance of calibration

According to [35], “Data veracity is about the certainty of data meaning. This feature expresses whether data reflect properly the reality or not. It depends on the way in which data is collected. It is strongly linked to the credibility of sources. For example, the veracity of the data collected from sensors depends on the calibration of sensors.”

According to [35], “Data veracity is about the certainty of data meaning. This feature expresses whether data reflect properly the reality or not. It depends on the way in which data is collected. It is strongly linked to the credibility of sources. For example, the veracity of the data collected from sensors depends on the calibration of sensors.”

[36] says that the viability of the data provided is achieved through calibration. The same author also explains that there must be a validity of the calibration for long periods of time or, else, the integration of calibration verification procedures in relation to a reference standard as an integral element of the process. Although, the sensors are pre-calibrated, some manipulations can affect their measurements. [37]

Through frequent calibration, it is possible to combat instrument error. Therefore, calibration should be performed periodically related to the type of

instrument and its stability characteristics, by using standards that are properly maintained and traceable. The records of each instrument, tests used, patterns of traced tests used, and any adjustments made, must be kept. Due to the high price of traceable standards, it may be cheaper to use specialized instrument calibration services. [36]
The calibration frequency is based on the appropriate need, such as deviation in time expressed in the service history, according to the manufacturer's specifications and regulations. [15]
With the increase of the use of sensors in the industrial processes, we also can find a vast measurement field for the equipment used. For this reason, it becomes necessary to acquire calibration management strategies. As explains [14], a complete calibration, performed on large or complex machines can take several days. Therefore, it is necessary to define the best calibration strategy for the sensors, depending on their situation. Figure 10 shows, based on time, a type of preventive calibration done at regular periods. These calibration cycles must not exceed the time necessary for the sensor to exceed its tolerance. This type of strategy is not applicable for large or complex machines, due to the time needed for its calibration, since it is done more frequently and in regular time.

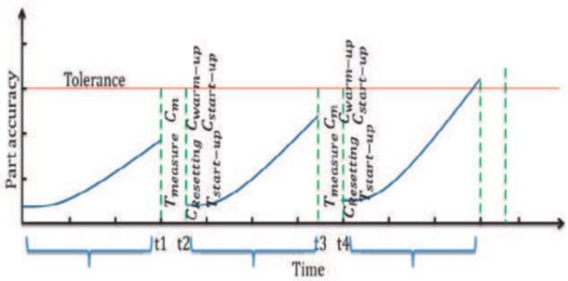

Fig. 10 - Preventive Calibration and adjustment at fixed rate [Source: [14]]

According to [27] and [28], the verification interval can be performed in terms of time (hourly, weekly, monthly), based on the amount of use (every 5,000 parts) or, in each batch. It must be based on stability, purpose, and level of use. Equipment that does not have specific calibration intervals, should be examined, at least, every six months and calibrated at intervals of, at least, one year. Sensor calibrations must be performed at a minimum of 95% of equipment with standards of the same type within tolerance when subject to regularly scheduled recalibration.
The Predictive Calibration strategy (PdC), when implemented correctly it can reduce unnecessary downtime for calibration and maintain the accuracy of the sensor (Figure 11). In this type of approach, periodic checks must be carried out, along with the application of the necessary technical knowledge, management strategies, and decision-making skills. A historical sensor verification database is built regularly, using relatively non-invasive methods, thus allowing calibration to be scheduled through a better-informed process. It is important to establish secondary KPIs associated with the measurement method; so, they indicate the poor performance of the sensor's accuracy. It is also necessary to define appropriate tolerances for the checks carried out, thus allowing to stimulate more interventions. [14]

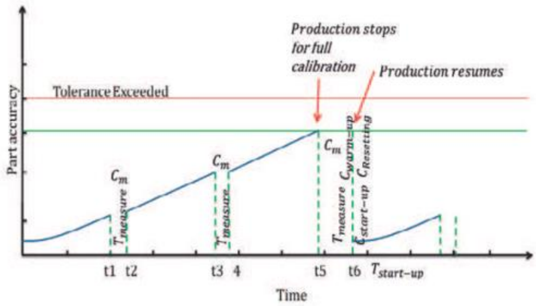

Fig. 11 - Predictive Calibration [Source: [14]]

The introduction of this strategy will bring new costs to the company, and, for this reason, it is important that these be compensated with the optimization of operational efficiency and the reduction of the total cost of downtime, related to unexpected and unplanned quality problems of the sensors. It will also reduce the overall downtime of a manufacturing facility, eliminating the sensor as the root cause of any subsequent failure in the production process. [14]
Another important calibration concept is the system calibration. The sensors can be calibrated individually, with separate calibrations, or the entire instrument chain can be calibrated, from the sensor input to the reading equipment. This will ensure greater accuracy, avoiding the accumulation of errors when multiplying the calibration of each component, taking into account any possible interaction among the components, such as low impedance correspondence, or excessive noise capture due to potential signal transmission arrangements and differentials or other factors. [36]
The interaction of the instrument and its installation can generate false readings in several ways; so, permanent instrument installations should always allow simple removal for calibration or built-in installations to allow calibration and reinstallation, without the risk of disturbing any factors that may affect readings. Economic and performance aspects need to be considered to decide the support for

checking machines and specific positional error handling policies. [14]
Finally, [27] and [28] argue that a calibration record system must be maintained in all instruments, including the following data:

- Usage history;
- Precision;
- Current location;
- Calibration interval and when due;
- Necessary calibration procedures and controls;
- Current values since the last calibration;
- Maintenance and repair history.

The same authors also say that test equipment and measurement standards must be labelled to indicate the date of the last calibration, by whom it was calibrated, and when the next calibration should take place. In this way, there is a visual indication of the maintenance status of the calibration. Both the calibration laboratory and the user of the instrument must maintain a bi-directional verification of the calibration.

2.3.1.2 On-line sensors calibration

As we saw above, the strategy used for maintenance is traditionally based on sensors' validation, involving their calibrations periodically, causing the reading instrument to be turned off and removed to be calibrated, causing, in some cases, very high costs. Many companies, aiming to maintain competitiveness in the market, adopt different calibration maintenance strategies, based on condition monitoring, allowing to minimize the downtime, increasing the processing availability. Condition monitoring allows early detection of failures, as an important issue in surveillance and diagnosis. This type of monitoring is called On-line Monitoring (OLM) and, according to [38], it can be implemented for instrument monitoring, equipment monitoring, or operation monitoring; however, the acronym OLM is commonly used for the extension of sensor calibration intervals.
The online monitoring systems, designed to monitor and diagnose sensors with online measurements during their measurements, were developed by researchers at the Nuclear Power Plants (NPP), providing generic online monitoring approval to reduce the calibration of the process instrumentation. In this way, it becomes possible to extend the calibration periods of the sensors, being able to improve the economic activity of the NPPs, avoiding failures that could occur during the calibration process. . [39], [40], [41], [38]
According to [42], OLM consists of estimating correct measurements that sensors must have read and constantly monitors the difference between the estimated values and the values read by the sensors.
[43] refers that "On-line monitoring evaluates the deviation of an instrument with reference to its process parameter estimate as determined by one of the predictive algorithms."
OLM is a technique non-invasive approach that is responsible to provides a more frequent assessment of instrument calibration in the real operating environment. It has the potential to mitigate problems with current calibration practices, allowing the identification of sensors that have deviations from the limits of tolerance to direct calibration activities during interruptions, [44].
[40], [45] and [43] explain that a typical OLM system collects data from reading instruments and processes them on an offline computer, which, subsequently, evaluate the individual deviation sensor channel, of the process channel estimate, as a time function. The concept online is used because the data collection is done during the operation, but it does not necessarily mean that the monitoring is carried out in real-time.
OLM evaluates the deviation of a sensor with reference to the estimation of process parameters, as determined by one of the predictive algorithms, and, in order to evaluate the sensor performance, the residual is used between the process estimation of the OLM model and the sensor output, [45]; in this way, it is possible to define the operational states of the sensor, (Figure 12).

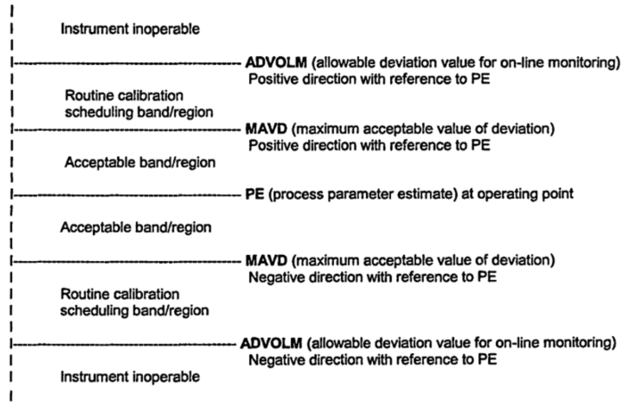

Fig. 12 - Deviation zones of sensor performance [Source: [45]]

If someone is not 95% confident that the instrument is within the MAVD (Maximum Acceptable Value of Deviation), it must be reset. If someone is not 95% confident that the instrument is within ADVOLM (Allowed Deviation Value for On-Line Monitoring), the instrument must be declared inoperative. [43]
In order to explain a basic monitoring system, we can use Figure 13 as an example, where we have a vector of sensor measurements (*x*) that is inserted into a

forecast model calculating the best estimates of the sensors (x'). Then, these estimates are compared to the measured values, allowing to calculate the differences called residuals (r). Subsequently, a decision logic module determines whether the residues are statistically different from zero, establishing the performance of each sensor. This module can also use predictive uncertainty values and deviation limits to determine the instrument's channel condition. [38], [45].

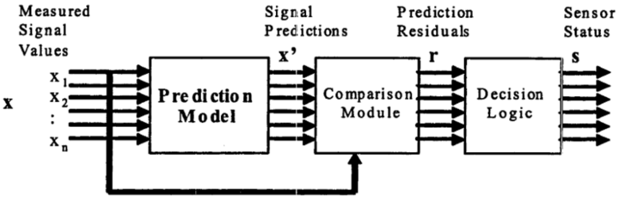

Fig. 13 - Sensor Calibration monitoring system diagram [Source: [45]]

The difference between expected (modelled) and actual (measured) behaviour, called residual, characterizes the system's deviations from normal behaviour and can be used to determine whether the sensor or system is operating in an abnormal state. [46], [47]

[38] state that OLM allows to reduce the number of unnecessary calibrations and, consequently, the reduction in the interruption time. It can also provide benefits with faster problem discovery and also allowing for more timely and convenient corrective actions than traditional calibration.

Periodic sensor calibration is expensive, time-consuming approach, and unnecessary maintenance actions that can damage the sensors. For example, when a sensor requires calibration, but it can be ignored, simply because the calibration interval has not yet passed, even if the sensor needs maintenance, this can cause unexpected stops and safety risks. Another example, and a major concern with periodic calibrations, is that performing maintenance on components that are working correctly, may cause a failure, [47], [46], [41] and [38]. OLM systems, on the other hand, monitor the condition of the sensor channel, identifying those that have been degraded to the point that justify their calibration. So, according to [38], online methods can help reduce maintenance costs, reduce the potential for calibration errors, increase instrument reliability, and, consequently, reduce equipment downtime.

[48] say that "An essential component for quality control is a low cost recalibration system which can be applied on-line during the production cycles (…)."

Schiff (2002) says that the justification for replacing traditional monitoring by online monitoring and calibration is:

- the proposed online monitoring technique should perform all necessary designated functions, better than or as good as the current traditional calibration, with the same or better reliability;
- if due to deficiencies inherent in the proposed technique, it cannot be demonstrated that it is better than or at least as good as current practice, the licensee must verify that the impact of the proposed technique on the safety of the facilities will be insignificant and the advantages of using it overcome deficiencies.

An OLM system consists of several components, the most common of which are: an offline computer, where a monitoring system exists; communication hardware and software tools for collecting process data; a history of process data; an OLM software, responsible for performing the analysis and presenting the results of the sensor calibration performance, [45]. The author explains that the first step in implementing online monitoring is the installation, testing, and verification of the data acquisition system, responsible for acquiring and storing the historical data files. In Figure 14, we can check the relative position of the typical data acquisition system in relation to the sensor. The data acquisition system generally receives data from the instrument in the form of a voltage output, whose online monitoring system resizes to the expected process units.

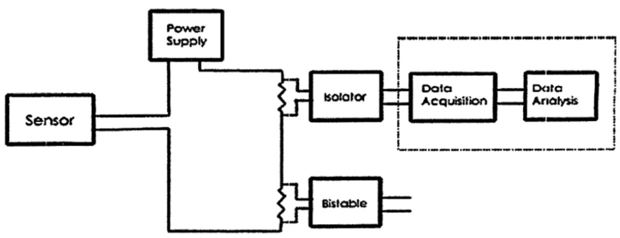

Fig. 14 - Instrument channel with On-line monitoring [Source: [45]]

The data transfer between the data acquisition system and OLM software can occur in batch mode or almost in real-time. The term batch mode means that the data files are stored somewhere and accessed by the online monitoring system at discrete time intervals, [45]. In Figure 15, we can verify the operation of a generic OLM system.

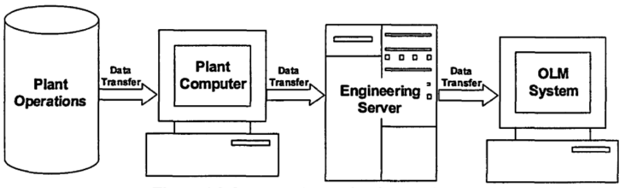

Fig. 15 - On-line monitoring system setup [Source: [45]]

So, in OLM, the sensor calibration is evaluated by comparing the measured data with the expected value of the sensor. The expected value can be measured using a variety of models, including physics-based models, neural networks, non-parametric models, etc. [44].

[45] and [47] refer that there are several empirical modelling techniques for online monitoring of the instrument channels performance, saying that these can be divided into two main categories: redundant; and non-redundant. [45] tell us that redundant modelling techniques only use the measurements of a group of redundant instrument channels to obtain the parameters' estimate, such as the simple average. Non-redundant modelling techniques, on the other hand, use a group of correlated, but not truly redundant, instrument channels to estimate the parameters.

For redundant equipment, a comparison of the instrument readings is made in order to distinguish between process deviation and instrument deviation. Redundant modelling techniques, according to [38], are techniques that use only the measurements of a group of redundant instrument channels, in order to obtain the estimate of the parameters. The author explains that the term "redundant" describes the instrument channels that measure the same process parameter in a similar operational range. Due to problems and disadvantages of redundant models, non-redundant models become the most used technique for OLM.

For non-redundant instruments, we have the empirical process' modelling. This estimate is updated frequently and compared with the output of the corresponding instruments to detect any deviation in the instrument output. This process modelling can also be used with redundant instruments, [40].

There are several modelling methods proposed to evaluate the sensor performance of redundant and non-redundant sensor groups. Figure 16 shows the summary of a selection of the most common modelling methods.

	Redundant vs. Nonredundant	Empirical vs. First Principles	Auto-Associative vs. Inferential	Parametric vs. Nonparametric	Key References
Multivariate State Estimation Technique (MSET)	Nonredundant	Empirical	Auto-associative	Nonparametric	Singer et al. (1995); Gross et al. (1997); Singer et al. (1997); Herzog et al. (1998)
Neural Networks (e.g., AANN, PEANO, RBF, etc.)	Nonredundant	Empirical	Both	Parametric	Eryurek and Turkcan (1991); Black et al. (1996); Park et al. (1996); Hines et al. (1996); Wrest et al. (1996); Tsai and Chou (1996); Hines et al. (1997); Nabeshima et al. (2002); Ayaz et al. (2003); Fantoni et al. (2003); Fantoni (2005)
Auto-Associative Kernel Regression (AAKR)	Nonredundant	Empirical	Auto-associative	Nonparametric	Garvey et al. (2006); Shumaker and Hashemian (2006); Garvey et al. (2007)
Cross Calibration	Redundant				Hashemian (1990) Hashemian and Petersen (1991) Hashemian (2007); Hashemian (2011)
Analytical Redundancy	Nonredundant	First principle-based	Inferential	Parametric	Crowe (1996); EPRI (2008b); IAEA (2008a)
Sensor Averaging (e.g., ICMP, ESEE, etc.)	Redundant				EPRI (1993a, b, 2008b); James (1996); IAEA (2008a)

AANN – Auto-Associative Neural Network
PEANO – Plant Evaluation and Analysis by Neural Operators
RBF – Radial Basis Function
ICMP – Instrument Calibration and Monitoring Program
ESEE – Expert State Estimation Engine

Fig. 16 - Modelling methods for OLM [Source: ([44]]

According to [45], for a modelling technique to be considered suitable for OLM, the model must:

- produce accurate results;
- produce repeatable and robust results;
- have a method for estimating forecast uncertainty.

Below, according to [45], a list of the basic steps for the development and implementation of the model is presented:

- *acquire "good" data*
  In this first stage, it must be ensured that the collected data is carefully reviewed, and its quality is guaranteed.
- *group sensors in ideal models*
  Here, the sensors to be used in each model must be selected, and this choice is more or less difficult depending on whether sensors are used for redundant or non-redundant techniques.
- *select training data*
  In this step the data is divided into training, verification, and validation data sets; the training data being used by the model to learn the relationship between the sensors, and the verification data is used to optimize the model parameters in order to reduce predictive uncertainty. The validation data is used to quantify the model's performance measures.
- *build and optimize predictive models*
  In this step, the models are optimized so, they minimize the predictive uncertainty, ensuring that they have a complexity corresponding to the complexity of the relationships to be modelled.

- *evaluate the model*
  Here, the model should be evaluated using criteria-based validation data. Here, the following must be taken into account: accuracy, which is a measure of how well the model's outputs correspond to the sensor data; robustness, which is a measure of how well a sensor forecast tracks the actual plant parameter when that sensor is drifting; overflow, which is a measure of how a drifting sensor input affects the prediction of other sensor values; and predictive uncertainty of the model.
- *uncertainty analysis*
  This step is performed after the model has been developed and optimized, and its uncertainty needs to be quantified.
- *transition to online mode*
  After the seven steps above, the OLM system can be implemented in an online or batch monitoring mode. At this stage, it may be necessary to retrain models with more up-to-date training data when changes in operational or environmental states are found.

A perfect model, as explained by [38], would be a model that make predictions of the sensor, not being significantly affected by degraded inputs and would be able to detect small faults and anomalies in the sensor.

But, as with any modelling paradigm, the predictions made have some level of associated uncertainty. Understanding and quantifying this uncertainty is an essential need to the development of an OLM system for monitoring sensor performance. [47]

The sources of uncertainty, according to [47] and [38], OLM can be categorized as:

- *process noise*
  which is the result of the normal fluctuation of the physical parameters of the process (for example, temperature, flow, pressure) over the true value of the process;
- *measurement uncertainty*
  which occurs due to several factors, including sensor accuracy, calibration accuracy (for example, calibration offset, error in converting sensor units to engineering units), environmental effects (due to temperature, vibration, pressure, etc.). These sources of uncertainty apply to the sensor;
- *electronic noise*
  where the transmission of measurements, through the instrumentation line, can induce additional noise, together with the conversion from analog to digital at the computer input;
- *modelling uncertainty*
  which results from input uncertainty (related to process noise, measurement uncertainty, and electronic noise, as described in the preceding bullet) and modelling error (resulting from model selection, model training, input selection, etc.).

The uncertainty inherent to the model's predictions affects the size of the failure that can be safely detected. [38]

In short, we have the Nuclear Regulatory Commission (NRC) conclusions for on online monitoring systems, [40]:

- the generic concept of an online monitoring technique is acceptable for online tracking of instrument performance;
- online monitoring has several advantages, including timely detection of degraded instrumentation;
- online monitoring can provide information about the direction in which the instrument's performance is going and, in this role, can be useful in preventive maintenance activities;
- although the proposed online monitoring technique, compared to the traditional calibration process, makes the results less accurate, it is considered acceptable that the precision provided by the estimation of process parameters is enough to assess the instrument's operability;
- compared to traditional calibration, due to lack of fuel, the online monitoring technique, when used as a whole, offers a greater guarantee of the instrument's operability throughout the plant's operating cycle.

2.3.2 Calibration Certificate

Only certified measuring instruments guarantee the reliability of the measurement results; this is only possible as long as the metrological parameters of the measuring instrument (working standards) are guaranteed by periodic calibrations, [2]. The calibration certificate records allow how the measurement traceability can be found.

According to the *Sociedade Geral de Superintendência* (SGS)[4], companies are responsible for ensuring that the equipment meets a wide range

[4] https://www.sgs.pt/pt-pt/construction/services-related-to-machinery-and-equipment/equipment-certification-and-calibration (Access date: 30/04/2020)

of international and regional regulations. Complete equipment certification and calibration services can help to ensure that products meet all relevant regulations. Calibration determines the performance of the measuring equipment. With routine calibration and adjustment of the equipment, it is possible to measure safely, ensure compliance, and avoid the costs of inaccurate measurements. It is necessary to obtain and maintain compliance through consistent procedures and comply with industry regulations and standards. The calibration is then responsible for establishing the relationship between the value of the quantity produced and the applied value and, through this process, its results are documented through a Certificate of Calibration (CC).

A current CC is, basically, a historical document, which should only be considered as a baseline control. The certificate will not guarantee that the meter is accurate at the time of measurement. This is just a statement at the moment, under certain conditions, a deviation between the indications of the device and a reference standard, [36], [15]. Therefore, before making potentially expensive decisions based on reading a transducer or instrument, it is recommended to obtain a calibration check before and after the critical measurement. Through this way it is possible to avoid breaking a machine in good condition based on a sudden drop in performance, but, conversely, it will support the decision to react if circumstances demand it. [36]

Starting with the acquisition of reading equipment, when purchasing them, there are factory certificates that serve as documentary proof of the sensor's accuracy. Industrial sensors, as they are equipment that can be subjected to very violent treatment, resulting in a significant change in their characteristics and, sometimes, in permanent damage, it is necessary that these be periodically calibrated, and that there is a calibration certificate that confirms the reliability of the measurements.

[49] refers that, “According to generally accepted practice, the calibration of measuring instruments may be carried out by an accredited calibration laboratory issuing a calibration certificate, which should contain information about the results of measurements with the associated uncertainty.”

The purpose of calibration certification, according to [50], is to calibrate and reset the certified value of the reading equipment, using traceability standards for this purpose. These work standards must be traceable by a qualified and certified laboratory (having a secondary reference standard tracked by a national laboratory that has a primary reference standard), through validated and internationally recognized calibration procedures that can certify the readings. This chain of traceability ensures that the certified value of the work standard is not more than three levels removed from the primary standards of the national laboratory. The CC is the end product of a test/calibration laboratory. It is delivered to the customer in the form of a document, which leaves the laboratory as a “product”. [51]

According to the website of the company Cachapuz[5], the conformity of equipment must be maintained consistently through procedures and methods that comply with technical regulations and international standards, such as: ISO 9001, ISO/IEC 17025, EURAMET, OIML, and ILAC. Calibration Certificates are a way that allows to control costs, and ensure the conformity and quality of equipment measurements.

The Calibration Certificates allow to know the main metrological characteristics of the equipment showing:

- periodic inspection of measuring equipment;
- consistency of the results;
- quality assurance of the measurements made on calibrated equipment.

It is important for companies that calibrate the sensors, that the equipment used by them is certified in the purchase and also every 12 months, not exceeding 18 months from the initial purchase or use. Certified equipment must have certification stickers, indicating the date of the last calibration and who performed the calibration and certification. The certification sticker must be clearly visible and made of resistant material. [50]

The same author also states that a new certificate is issued each time the equipment is calibrated, in order to guarantee the user's accuracy and traceability. Discarded or damaged reference equipment must be discontinued until it is verified, calibrated, or recertified.

[6] warns that the calibrations are not all the same and that in some calibration reports there may be terms such as, “nominal” or “typical”, or even lack of traceability or approval of accredited stamps. This will result in a decrease in attention on the part of the manufacturer to meet a specific tolerance in these specifications, reducing scrap, since less measured specifications mean less rejection. This, although it seems beneficial for the manufacturer, who obtains

[5] https://www.cachapuz.com/servicos/certificados-de-calibracao (Access date: 30/04/2020)

an additional profit, in fact it is not, since it will decrease the quality of its product and, consequently, the loss of confidence of the customer. Customers, in turn, also need to look beyond glossy paper and attractive graphics to ensure the integrity of the actual measured data contained in each manufacturer's calibration certificate.

Regarding the points that the CC for measuring instruments must contain: the measurement results, including measurement uncertainty and/or a declaration of conformity with an identified metrological specification, like ISO 17025: 2017 standard (General requirements for the competence of testing and calibration laboratories). Therefore, it is necessary to have an indication of the conformity of the calibrated measuring instrument with the established metrological requirements or separate metrological characteristics for the CC. It is necessary to have an assessment of the conformity about the object with the specified requirements, and the main requirement of these documents, being necessary to consider the measurement uncertainty during the conformity assessment. ([52]
According to [15] and [52], the CC of an instrument provides the deviation, being the uncertainty in that deviation called the calibration uncertainty. The sensor that user must consider in the measurement uncertainty calculation parameters includes:

- uncertainty about the calibration performed during traceability;
- uncertainty due to the accuracy of the device, if not corrected;
- uncertainty related to the deviation (fatigue) of the instrument between two calibrations;
- uncertainty related to the instrument's characteristics (reading, repeatability, etc.);
- uncertainty related to the environment, if conditions are different during calibration;
- instrumental uncertainty of the standard, its instability, changes in operating conditions, mutual influence of the standard and the sensor to be calibrated;
- the variation observed in the calibrated sensor readings.

[15] also explains that measurement uncertainties are parameters that depict the dispersion values during the measurement. In this way, the study of uncertainties aims to determine the capabilities of what measurement means.

3 Conclusions

Data acquisition has high importance but, even greater, is the information taken from that data, this is a valuable source for the companies' competitiveness. This what this paper addressed, namely the sensors in industries, responsible for obtaining data referring to various aspects of the companies. The paper also emphasises the importance of metrology in guaranteeing the reliability of measured values, as well as the importance of equipment certification.
The paper makes a theoretical approach about the topic under discussion, "Calibration and certification of industrial sensors - a global review", that addresses the following major subjects: Industrial Sensors; Metrology; Formal sensors Calibration; On-line sensors calibration; Calibration Certificate.
The first topic covered, "Industrial Sensors", was managed about the relevance of the reading instruments in the industry, as well as the types of existing sensors and their characteristics. It can be concluded that, these instruments are extremely important since they are responsible for translating the condition of the equipment in use, being able to extract from these the values about valuable information that could result in significant improvements in the company. It is a very important asset to follow unconditionally the conditioning maintenance.
About the second subject, "Metrology", this concept is discussed describing what it is and which is its focus on the industrial area. It can be inferred that without metrology and sensor calibration, the measurements performed would not be reliable, and may lead to unwanted and harmful results in many situations. The data obtained, without the use of metrology, from the equipment condition, is not the correct one; this can lead to maintenance measures not being implemented and, subsequently, to lead a rupture of the equipment and unexpected and consequently untimely stops, which can result in high costs for the company. It is also noteworthy that without metrological traceability, guaranteed by successive calibrations, it was not possible to trust on data measured by lower-level standards in the traceability chain.
Then, when the question is about "Formal sensors Calibration", the concept and how companies can manage this issue, in the most competent and effective way, it can be concluded that the calibration is responsible for ensuring metrological traceability and, consequently, for ensuring the veracity and effectiveness of the measurements made by the measuring instruments. It also can be found that without effective metrology system management, it can result in the use of the equipment out-of-date of

calibration state and subsequent loss of traceability to reference standards.

This paper also emphasises the importance of On-line Monitoring (OLM) aiming to maximize the equipment's availability. Through this calibration management system, it is possible to maximize, not only the use of reading instruments, but also the process equipment. In addition, it helps the asset management, allowing the anticipation of malfunction scenarios.

As final corollary, it can be said that through the calibration certification, companies can guarantee and prove the effectiveness of their measurements, using effective data, and eliminating measurement errors. So, without the support of metrology in large industries, there would be measurement errors and unreliable data, which, in turn, could result in uncontrollable risks and costs and, consequently, the loss of market confidence.

References

[1] B. Al-najjar and I. Alsyouf, "Enhancing a company's profitability and competitiveness using integrated vibration-based maintenance : A case study," *Eur. J. Oper. Res.*, vol. 157, pp. 643–657, 2004, doi: 10.1016/S0377-2217(03)00258-3.

[2] P. Guedes, *Metrologia Industrial*, 1st Editio. Lisboa: ETEP - Edições Técnicas e Profissionais, 2011.

[3] K. K. Iniewski, *Smart Sensors for Industrial Applications*. CRC Press, 2017.

[4] M. J. McGrath and C. N. Scanaill, *Sensor Technologies: Healthcare, Wellness and Enviromental Applications*. Berkeley, CA: Apress, 2013.

[5] A. Martins, "Gestão de Laboratório de Calibração de Equipamentos de Análises de Vibrações," Instituto Superior de Engenharia de Coimbra, 2019.

[6] J. Wilson, *Sensor Technology HandBook*. Elsiver Inc., 2005.

[7] P. Wild, *Industrial Sensors and Applications for Condition Monitoring*. London: Mechanical Engineering Publications, MEP, 1994.

[8] D. Scott, *Industrial Process Sensors*, 1st Editio. CRC Press, 2008.

[9] J. M. T. Farinha, *Asset Maintenance Engineering Methodologies*, 1st Editio. Taylor & Francis Group, LCC, 2018.

[10] KeysightTechnologies, "Fundamentals of Sensor Measurements Using a Digital Multimeter," 2016. [Online]. Available: https://www.keysight.com/zz/en/assets/7018-06443/white-papers/5992-3555.pdf. [Accessed: 05-Mar-2020].

[11] L. M. V Serrano, C. J. O. P. J. Alcobia, M. L. O. S. Mateus, and M. C. G. Silva, "Sistemas de Aquisição , Processamento e Armazenamento de Dados," *Soc. Port. Metrol.*, pp. 1–15, 2004.

[12] A. B. Martins, J. Rodrigues, and J. Farinha, "Laboratório de Metrologia no apoio à Manutenção de Condição," *15.º Congr. Nac. manutenção*, 2019.

[13] IPQ, "Vocabulário Internacional de Metrologia (VIM): Conceitos Fundamentais e Gerais e Termos Associados," 2012. [Online]. Available: http://www1.ipq.pt/pt/metrologia/documents/vim_ipq_inmetro_2012.pdf. [Accessed: 16-Mar-2020].

[14] A. Shagluf, A. P. Longstaff, and S. Fletcher, "Maintenance Strategies to Reduce Downtime Due to Machine Positional Errors," *Maint. Perform. Meas. Manag.*, 2014, doi: 10.14195/978-972-8954-42-0_25.

[15] A. Grous, *Applied Metrology for Manufacturing Engineering*, 1st Editio. Hoboken, NJ, USA: John Wiley & Sons, Inc, 2011.

[16] R. Krishnakumar, "Entangling Atoms for Quantum Metrology," Stanford University, 2017.

[17] A. R. F. Pires, "Organização de um Processo de Gestão de Recursos de Monitorização e Medição," Universidade de Coimbra, 2018.

[18] P. flávio da S. Santos, "A Metrologia na Indústria Aeronáutica," Instituto Superior de Engenharia do Porto, 2015.

[19] P. Flores and F. Marques, "Sobre a metrologia," pp. 1–32, 2018.

[20] P. Cabral, C. Sousa, E. Filipe, P. Couto, and P. S. Girão, "A Metrologia como ferramenta transversal da Engenharia." Ordem Dos Engenheiros, 2015.

[21] T. Lopes, "Implementação de procedimentos de metrologia na empresa Milon," Faculdade Engenharia da Universidade do Porto, 2015.

[22] semyon G. Rabinovich, *Measurements and Uncertainties: Theory and Practice*, 3rd Editio. Springer, 2005.

[23] A. I. A. Castro, "Implementação de um Laboratório de Implementação de um Laboratório de Metrologia Elétrica," Instituto Superior de Engenharia do Porto, 2015.

[24] J. C. da S. Neto, *Metrologia e Controle Dimensional*. Elsivier, 2012.

[25] A.-K. Wiemann, M. Stein, and K. Kniel,

"Traceable metrology for large involute gears," *Precis. Eng.*, vol. 55, no. September 2018, pp. 330–338, Jan. 2019, doi: 10.1016/j.precisioneng.2018.10.001.

[26] V. V. Skliarov, P. Neyezhmakov, and A. Prokopov, "Metrological assurance and traceability for Industry 4.0 and additive manufacturing in Ukraine," in *Smart Structures and NDE for Industry 4.0*, 2018, no. March, p. 26, doi: 10.1117/12.2292821.

[27] R. Smith and R. K. Mobley, *Industrial Machinery Repair: Best Maintenance Pratices Pocket Guide*, 1st Editio. Elsevier Science (USA), 2003.

[28] R. K. Mobley, *Maintenance Fundamentals*, 2nd Editio. Elsevier Inc., 2004.

[29] K. Singhal, Q. Feng, R. Ganeshan, N. R. Sanders, and J. G. Shanthikumar, "Introduction to the Special Issue on Perspectives on Big Data," *Prod. Oper. Manag.*, vol. 27, no. 9, pp. 1639–1641, Sep. 2018, doi: 10.1111/poms.12939.

[30] H. Eren, "Calibrations in Process Control," in *Instrument Engineers' Handbook*, 4th ed., vol. 3, no. January, B. G. Liptak and H. Eren, Eds. CRC Press, 2012, pp. 141–149.

[31] J. Juran and A. Godfrey, *JURAN'S QUALITY HANDBOOK*, 5th ed. McGraw-Hill Companies, Inc, 1998.

[32] F. Tse and I. Morse, *Measurement And Instrumentation in Engineering: Principles and Basic Laboratory Experiments*. CRC Press, 2009.

[33] A. S. Morris and R. Langari, "Calibration of Measuring Sensors and Instruments," in *Measurement and Instrumentation*, Elsevier, 2012, pp. 103–114.

[34] H. Eren, "Calibration Process," in *Handbook of Measuring System Design*, no. setpember, P. H. Sydenham and R. Thorn, Eds. Chichester, UK: John Wiley & Sons, Ltd, 2005, pp. 271–277.

[35] M. Khosrow-Pour, "Big data: Concepts, Methodologies, Tools, and Applications," 2016, no. 4.

[36] A. Davies, *Handbook of Condition Monitoring: Techniques and Methodology*. Springer Netherlands, 1998.

[37] H. M. A. Fahmy, "WSNs Applications," in *Wireless Sensor Networks: Concepts, Applications, Experimentation and Analysis*, Springer, Singapore, 2016, pp. 69–213.

[38] J. W. Hines, R. Seibert, and A. Usynin, *Technical Review of On-Line Monitoring Techniques for Performance Assessment. Volume 2: Theoretical Issues*, vol. 2. United States Nuclear Regulatory Commission, 2008.

[39] S. Lee and J. Chai, "An enhanced prediction model for the on-line monitoring of the sensors using the Gaussian process regression," *J. Mech. Sci. Technol.*, vol. 33, no. 5, pp. 2249–2257, May 2019, doi: 10.1007/s12206-019-0426-7.

[40] A. J. Schiff, *Power Plant Surveillance and Diagnostics*. Berlin, Heidelberg: Springer Berlin Heidelberg, 2002.

[41] M. Hoffmann, "PEANO — a tool for on-line calibration monitoring," no. January, 2004.

[42] A. A. Boechat, U. F. Moreno, and D. Haramura, "On-line calibration monitoring system based on data-driven model for oil well sensors," *IFAC Proc. Vol.*, vol. 45, no. 8, pp. 269–274, 2012, doi: 10.3182/20120531-2-NO-4020.00037.

[43] J. W. Hines, "On-Line Monitoring for Calibration Extension : an Overview and Introduction," U.S. Nuclear Regulatory Commission, 2009.

[44] J. Coble, P. Ramuhalli, R. Meyer, H. Hashemian, B. Shumaker, and D. Cummins, "Calibration Monitoring for Sensor Calibration Interval Extension Identifying Technical Gaps," in *Future of Instrumentation International Workshop (FIIW) Proceedings*, 2012, doi: 10.1109/FIIW.2012.6378348.

[45] J. W. Hines and R. Seibert, *Technical Review of On-Line Monitoring Techniques for Performance Assessment. Volume 1. State-of-the-Art*, vol. 1. U.S. Nuclear Regulatory Commission, 2006.

[46] J. B. Coble *et al.*, "A Review of Sensor Calibration Monitoring for Calibration Interval Extension in Nuclear Power Plants," no. August. Pacific Northwest National Laboratory, 2012.

[47] P. Ramuhalli *et al.*, *Uncertainty Quantification Techniques for Sensor Calibration Monitoring in Nuclear Power Plants*, no. April. Washington: Pacific Northwest National Laboratory, 2014.

[48] S. Dwivedi, Al. Verma, and J. Sneckenberger, "CAD/CAM Robotics and Factories of the Future '90," in *International Conference on CAD/CAM, Robotics, and Factories of the Future*, 1989, doi: 10.1007/978-3-662-39962-0.

[49] E. Bulska, "Metrological Traceability," in *Metrology in Chemistry*, L. N. in Chemistry,

Alexandre Batista Martins,
José Torres Farinha,
António Marques Cardoso

Ed. Springer, 2018, pp. 35–51.

[50] J. E. Gallagher, “Inspection, Testing, Verification, Calibration, and Certification,” in *Natural Gas Measurement Handbook*, Elsevier, 2006, pp. 387–406.

[51] M. C. Gupta, “Document control: status of calibration/test certificate,” *Accredit. Qual. Assur.*, vol. 15, no. 10, pp. 591–593, Oct. 2010, doi: 10.1007/s00769-010-0682-9.

[52] I. Zakharov and P. Neyezhmakov, “Peculiarity of measurement instruments verification by results of their calibrations,” in *2017 11th International Conference on Measurement*, 2017, no. Imi, pp. 19–22, doi: 10.23919/MEASUREMENT.2017.7983526.

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