All-Around Approach for Reliability of Measurement Data in the Industry 4.0

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The concepts of Industry 4.0 and "Factory of the Future" move the factory itself towards a completely inter-connected framework, including its supply chain, able to create autonomous flow of data and information for reliable decision making. The achievement of objectives connected to these concepts is expected to strongly improve the efficiency, reliability and competitiveness of the factory organization, with reference to all of the involved activities [1].

Although many engineering aspects are obviously of interest, metrological issues assume a relevant role in this scenario [2], [3], due to many reasons:

- The application of sensors based on new low-cost technologies, like MEMS as an example, allows us to realize new measuring solutions, based on embedded, miniaturized, digital devices and/or on sensor networks [4]–[7]; furthermore, these set-ups make the interaction between the instrument and the process tighter, asking for a clear identification of the specific needs of measuring and production issues [1];
- Reliable synthetic results are needed even though a huge amount of data is available; that requires very careful monitoring of the effect of using advanced algorithms to process data for assessment of the quality of information; probably, different layers have to be considered for measurement data processing and synthesis (edge and cloud layer, etc.), [8];
- Managing the security and integrity of data during their whole lifecycle, with respect to all of the situations and the actors involved, is a duty to be faced from a completely new point of view, taking into account the increased connectivity and new scenarios of data processing, sharing and storing [9], [10];
- The approach to satisfy "old" and new requirements for the measuring management system: traditional requirements like uncertainty assessment and traceability of measurements are still valid [11], while the boundary identification of the measurement system and the capability of separating from an operational point of view measuring equipment and the production process, in order to keep the measurement process under control, should be probably re-discussed [12]–[14];
- People involved in the management of the measurement assets of a company should be aware of the new issues, with reference to hardware and software innovations and to the new environmental operating conditions; and
- Technical and economic consequences of implementing the updated set up have to be considered together, in order to allow us to realize integrated and practicable solutions; in fact, only in this way will the novelty of this scenario realize all of the predictable advantages, in particular in Small or Medium Enterprises (SMEs).

The interest of industrial operators in many cases is not completely spontaneous with reference to some of the above aspects such as, for instance, the uncertainty assessment in field operations. Nevertheless, more and more industrial sectors managed by quality management systems, by sector quality standards (e.g., aerospace and automotive industries) and by good manufacturing practices (e.g., pharmaceutical industry) need to carefully consider the uncertainty evaluation, in order to accomplish the conformity assessment requirements.

Literature analysis highlights two main areas of interest:

- a *metrological approach*, which is mainly interested in the aspects connected to the assessment of measurements at the field level and of the data processing results; and
- a second one, mostly connected to the requirements of *legal metrology*, focused on having data stored, transmitted and processed in a secure way, without the possibility of any malicious intrusion or tampering.

If the first area of interest is considered, the topics reflect on handling of digital sensors and sensor networks, including:

- synchronization, in particular in dynamic applications [1];
- identification of the real operating conditions of embedded sensors [15], [16];
- in line and on-line calibration of digital sensors, also taking into account the need to reduce the cost of services according to the reduction of cost of sensors themselves [4], [5];

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- standards for new types of calibrations; and
- edge or cloud computing [8].

The second approach is more interested in the security, inaccessibility of data, and the transparent traceability of accesses and operations on data, and it has been preliminary developed to realize compliance of the measurement systems with the requirements of legal metrology [9], [10].

All of these contributions are valuable, nevertheless more and more in modern applications measurement topics require to be treated as a unique and coherent process, managed in a skilled and conscious way. In this way, the whole lifecycle of data has to be considered with reference to both the single steps and/or applications and having also in mind the interrelationships among the following activities, starting from the design of the sensor installation to the measurement procedure, up to the data synthesis for decision-making.

Therefore, interpretation of traditional metrological concepts in an updated way, could be the tool to use both new technical solutions and new organization models in an effective way, taking advantage of the tight connection among devices and production process.

Of course, interpreting the measurement process effectively in the Industry 4.0 scenario requires a multidisciplinary approach, including measuring concepts, but also hardware, software and information technology knowledge and solutions. Based on this multidisciplinary knowledge, improving the skills of people involved in measurement processes with respect to these topics is a mandatory aspect, being a fundamental contribution to achieve efficacious solutions.

Finally, economic considerations are of concern with reference to hardware, software and services, due to the need to implement a harmonic solution, which could be considered interesting in multiple applications. Implementing metrological services in an economic way is not a trivial achievement, if the typical costs of a measurement management system are considered, and even more so in the actual organization. Fig. 1 gives a graphical summary of the workflow to build reliable information from measurement data.

According to the previous considerations, the aim of this paper is to analyze the main areas of interest throughout the measurement process, from the data acquisition to the data storing. Some useful issues are provided to interpret in a coherent and refined way the challenges proposed by the data lifecycle, on the whole. The first section of the paper is dedicated to "metrological aspects," according to the classical point of view, but declined considering the needs of the new context. Synchronizing digital networks of sensors, digital calibration, in-line and on-line calibration and the problem of cost of these actions will be deepened. Data processing, according to the need for big data processing, are discussed for the purpose of posing the problem and the outlining requirements for other issues.

Some discussion on the present status of the standards is also given. The way to propose this approach of digitalization is presented, and the subsequent section is devoted to the presentation of concepts and solutions able to make safe data, which could be valid at the acquisition stage. The opportunities given by Blockchain technology are presented; the paper describes how to apply this software environment to the applications of measurement data security in different situations, like fog and cloud layers or throughout the supply chain. Finally, the paper proposes a simple architecture, able to give an example of tools and actions useful for the above requirements, and conclusions end the paper, together with ideas for future work.

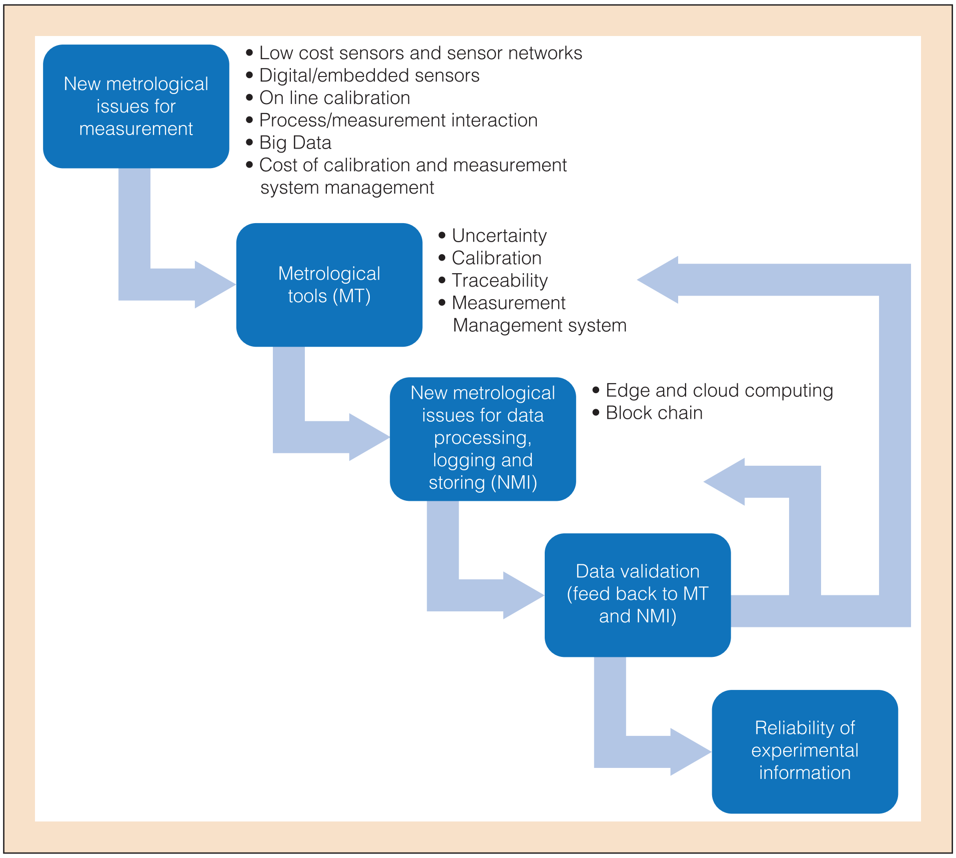

Fig. 1. Flow diagram to build reliable information from measurement data.

Metrological Aspects

In this section, the main aspects connected to measurement systems, data processing and standards are discussed, and in particular:

- Sensor synchronization in sensor network
- Calibration
- Traceability assurance
- Uncertainty assessment in big data processing
- Requirements of standard and of ISO EN 10012, in particular [12].

Sensor Synchronization in Sensor Networks

More and more networks of digital and low-cost sensors are used, like digital MEMS sensors for measurement of different quantities, such as temperature, vibration, force, etc.

Synchronous data are useful, and mostly in dynamic application, but phase of single measurement is difficult to assess due to local analog to digital conversion and different data rates. Synchronization should be also guaranteed in data transmission by the protocol, and this aspect is not trivial [1].

As an example, the availability of networks of low-cost accelerometers makes possible modal analysis of large structures for health monitoring, based on a large amount of measuring points; the impact of time synchronization error should be corrected [17], [18], or, better, it should be prevented. Calibration methods aiming at this purpose are now under study by National Metrological Institutes [19].

Calibration

International standards for calibration of mechanical and thermal transducers in many cases consider calibration procedures based on reference instruments, whose output is an analog signal [20], [21]; therefore, sometimes defining a "digital sensitivity" appears to be a quite new proposition, to be harmonized in the standard itself [4].

New technologies propose sensors which are very low cost and able to be embedded on the measuring point to locally measure the quantity of interest, allowing a better monitoring of the production process.

Mass production of low-cost sensors requires also that the calibration cost is strongly reduced with respect to the procedure for traditional instrumentation.

Some proposal for mass "in line calibration" by the producers are suggested, but they are typically for static conditions, and dynamic calibration seems to be difficult to realize [4]. The issues that motivate the interest towards in-line calibration, to be performed in dynamic conditions, have been extensively investigated in [20], [21]. Authors in [19] confirm the need to deepen these aspects, also by National Metrological Institutes.

Embedded sensors allow a closer interaction between control of the process and the process itself, and this situation is a big opportunity. On the other hand, it is impractical or impossible to remove them from the measuring point for calibration purposes [22].

Many proposals exist in literature to provide an on-line calibration:

- Transfer of the reference throughout the network: a reference signal could be transferred where the calibration occurs (electrical signals) or the reference located near the transducer to be calibrated could be activated at the due time [13], [23];
- High performance devices are inserted into the network, together with a large number of low-cost sensors, mainly for calibration purposes; this configuration makes it possible to remove the high-performance measurement systems to guarantee traceability by means of laboratory calibration [14];
- "Smart calibration" with careful monitoring of the disturbing quantities by other sensors, improving precision and reducing bias effects; sometimes, this effect could be improved by a suitable design of the measurement principle, reducing the possibility of bias [24];
- On site auto-calibration by a series of specific measurements, even though they are mainly valid for static calibration.

Traceability

Traceability is a very important aspect, since it is universally acknowledged that traceability of measurements is a mandatory requirement [4], [5], [11]. Most of the above described techniques are helpful to realize the reproducibility of data, therefore improving traceability of results.

To some authors, the possibility of carefully modelling and monitoring the specific contribution of measurement uncertainty and errors will further improve traceability of results [10], without limiting the acknowledgment of traceability only to an unbroken chain of documented calibrations.

Data Processing

Big data processing and use of advanced algorithms like machine learning (ML) mainly impact the capability of modelling uncertainty propagation throughout the whole process of data analysis, including feature extraction, selection, ML application for classification and/or clustering [25]. Currently, the main efforts are devoted to the identification of measurement uncertainty models for sensors and sensor networks, including synchronization effects and digital data transmission. This probabilistic information should be used to feed an uncertainty flow and propagation, which is now modelled by a Monte Carlo simulation as a worthy starting attempt.

Nevertheless, a good idea is to try modeling some single steps of the procedure, and reducing the uncertainty contributions as much as possible, in order to maintain the process under control [1].

Updating Standards, Particularly ISO 10012

In the following section, general and specific aspects are summarized, with the aim of proposing an updated point of view that will continue to guarantee the metrological requirements of devices and measurement processes. At the same time, continuity should be assured with the basics of the requirements for the measurement management system, considering also the need for a reliable and practicable trade-off between the requirements of the standard and the related efforts, also in SMEs context.

Some general aspects of ISO 10012 to be considered for the discussion are summarized below:

- Capability of separating, from an operational point of view, measuring equipment and production processes, in order to keep the measurement process under control;
- Capability of defining the boundaries of the measurement system to be managed by the measurement management system, according to the principles and guidelines of this standard;
- Capability of identifying and labelling the specific measuring equipment in new configurations (embedded sensor, networked sensors, telemetering, etc.);
- Definition of the calibration context and of the possibility of auto-correction with respect to multi-sensor systems, networked and/or smart sensors;
- Production process modelling as a support to the measurement process analysis;
- Traceability assessment in multi-sensor systems with auto-correction possibility;
- Environmental conditions definition and control, i.e., metrological requirements, which are difficult to define and to guarantee, since they strongly interact with the production process conditions;
- Assessment of people skills and of the training needs;
- Criteria to be set with respect to the needs of the activity of the measurement management system on the whole: this is commensurable to the risk of failure to comply with the specified requirement (with reference to measurement process design, monitoring and assessment, etc.).

Blockchain Technology in Metrology

General Issues for Use of Blockchain

Today there is an increasing need that, once stored, the data is considered certain, secure and unchanged over time. This guarantees the absolute reliability of future processing of the same data on which statistical or even predictive calculations can be made. The main problems can arise about the heavy computation load required to satisfy a procedure for data management with a blockchain [26]. For this reason, sometimes the Blockchain is used not so much to store the data itself and process it, but to verify if the data is exactly what was originally produced. This process is called "notarization" [27].

In many papers, Blockchain is considered able to support instrumentation management in industrial applications, in particular for legal metrology, [9], [10]. In some cases, there could be an interaction when the cloud is used for data processing, increasing the processing capability in the so called "distributed measurement systems" [10]. The main problems arise when there is a heavy computation load required to satisfy a procedure for data management with a Blockchain [26]. Some authors suggest dividing instruments into classes of critical and less critical ones, and some other suggest providing Virtual Machines (VM) for data management; therefore, the microcontroller eventually on board of transducers should be not used in this specific action [9].

Blockchain in general, and its use in measurement data management in particular, shows an increasing number of applications, even though critical considerations should be made for its use [28] and specific knowledge of this technological opportunity is required.

Blockchain is a technological protocol belonging to the category of technologies based on distributed archives (Distributed Ledger) [29]. Distributed Ledger Technology (DLT) use a distributed ledger, governed in such a way as to allow access and the ability to make changes by multiple nodes in a network without the use of a centralized authority.

Blockchain is a DLT characterized by a register replicated on multiple nodes capable of containing in a chained way a series of blocks of information with transactions. Each transaction is an operation involving two subjects belonging to the Blockchain. Each block is added to the chain using a method based on consensus, distributed on all the nodes of the network, or with the participation of all the nodes that are called to contribute to the validation of the transactions present in each block and their "inclusion" in the register, according to Fig. 2 and Fig. 3. The Blockchain allows guaranteeing the immutability of the transaction data, thanks to the "mathematical" chaining of the blocks. Each participant has a pair of keys by means of which they can digitally sign their transactions.

Two types of Blockchain actors exist: externals and internal ones. As shown in Fig. 4, externally there are users or measuring devices (IoT) which connect to the Blockchain via a secure protocol implemented by the Connector and transmit the data (step 1 in Fig. 4).

External users correspond to an internal Account (the black triangle in the figure). In theory, only one account could be used for all devices. The Account can perform operations

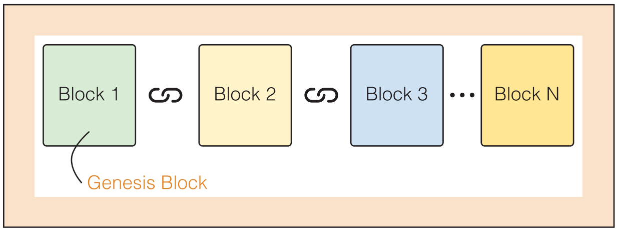

Fig. 2. Blocks chained.

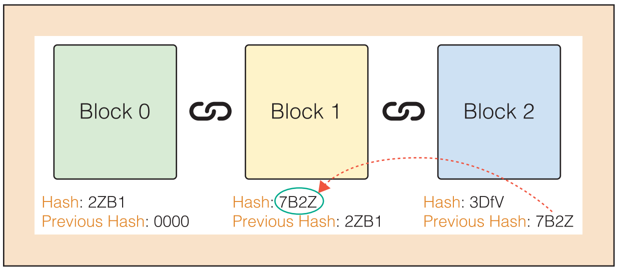

Fig. 3. Blocks chained through a hash algorithm after acceptance through a consensus.

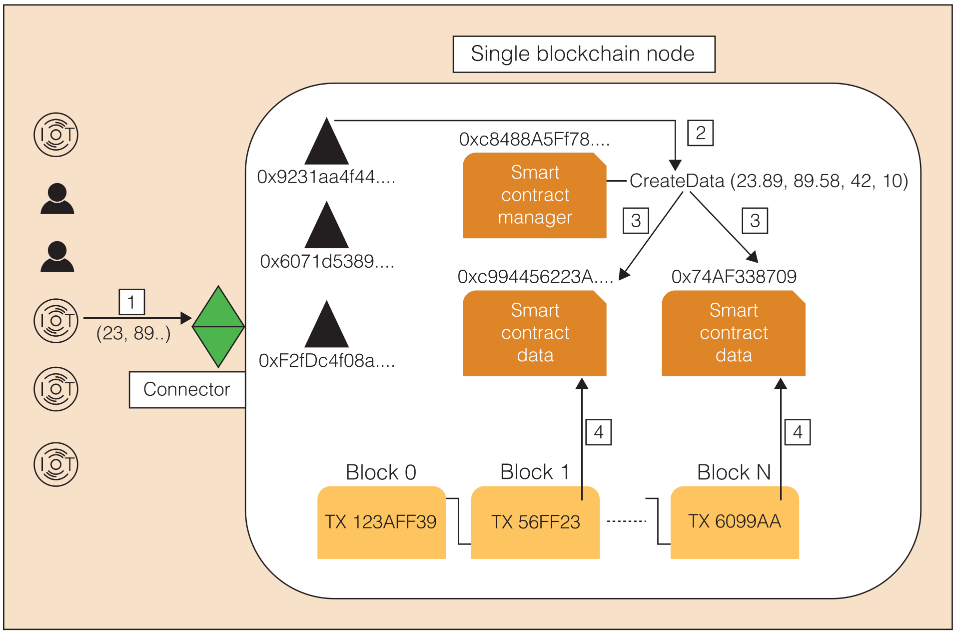

Fig. 4. Actors inside the blockchain architecture.

on the main Smart Contract by forwarding the data received from the devices (step 2). The latter creates the Smart Contract which contains the data just transmitted (step 3). This operation is recorded in the Blockchain with a transaction, making the data just transmitted immutable at this point (step 4).

Technological Infrastructure for the Experimental Application

Smart Contracts are deployed on the Blockchain. They contain code, which, following the rules implemented in a specific programming language, allow transactions to be carried out automatically according to the various conditions that arise from time to time. Smart Contracts are also able to store data from various measuring instruments in Blockchain, thus making them immutable and verifiable subsequently [30]. In the case of large amounts of data, Smart Contracts can contain not data but a hash of data to reduce significantly time and storage space.

The implementation of an architecture that uses the Blockchain to record measurement data (or at least data hashes) must also take into account the following aspects

- Efficiency in terms of energy consumption, with an increase in the number of transactions per unit of time
- Assessment of security aspects (Disaster Recovering, Integrity, Continuity)
- Evaluation of usability aspects (API and simple Interfaces)
- Evaluation of the necessary computing capacity and of the volume of data to be archived (e.g., cloud systems)

In Fig. 5, the graph produced in real time by an IoT device reveals the temperature and humidity measurements inside a refrigerator truck, needed to guarantee the cold chain, which is mandatory for some products (e.g., frozen food, special pharmaceutical products). The data are sent directly to a Blockchain of type Ethereum where there are Smart Contracts that record the measurements. The data also reveal the position to trace the route taken, useful to demonstrate that one has traveled the optimal route for insurance or energy efficiency purposes. On the right (in red), we can see the data that are considered out-of-range.

Technological Infrastructure for Managing Large Amounts of Data

Once we have acquired large amounts of data, as depicted in Fig. 5, they can be used in two ways: in making reports to process the final data, or to instruct advanced algorithms and/or processing tools. These algorithms can act predictively and

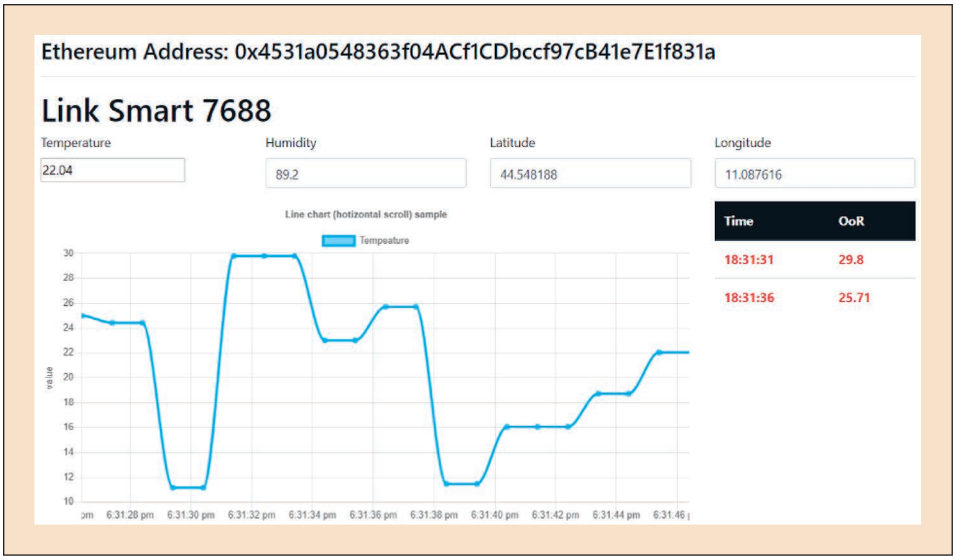

Fig. 5. Example of data from a sensor and inserted into blockchain once per second.

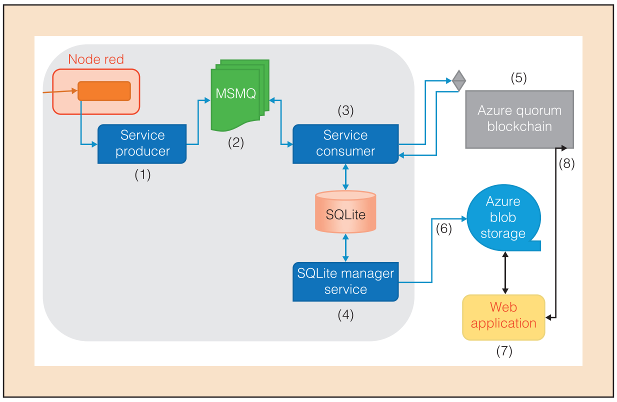

Fig. 6. Example of data produced by a machine (or measurement device).

provide information on any events that could occur in future times according to a certain probability (artificial neural networks). In advanced measuring systems, these algorithms can predict anomalous behaviors which can compromise the stability (metrological properties constant over time) and metrological traceability.

Practical Example

Some use cases of automatic machines have been created, producing data that are stored in a database and in a Blockchain infrastructure [27]. A subsequent reading will allow us to verify the incorruptibility of these data. This procedure can be carried out using data from any device that performs recording or measurement activities. An operating scheme is depicted in Fig. 6, where the numbers in brackets represent the following steps:

1. Data arriving from machine (or device)
2. Data are recorded first in a Transactional Queue
3. Data are read by a consumer and recorded in a local Data Base
4. Data are managed by a Service
5. Data are recorded in a Blockchain Smart Contract
6. Data are recorded in a Cloud Data Base and
7. Data are used by a Web Application
8. Data are verified through the Blockchain

Conclusions

The authors believe that paying due attention to the issues highlighted above is of extreme interest in this evolutionary moment that companies must face, not only large companies but also SMEs of the supply chains most involved. Deepening aspects, which represent a cultural consolidation of the international manufacturing experience, taking into account the innovation that the digital revolution has launched, represents the main interest that this relationship wants to express. New knowledge must be produced to provide critical directions and skills to people who will face the introduction of new technologies in measurement processes. Innovation must be pursued without making discounts on the levels of reliability and credibility of the numbers associated with the transactions of goods and services, and researchers and technicians must be aware of this.

The issue of reliability of measurements in the digital age, as mentioned, is not limited to sensors only but involves everything related to digital data management, an articulated chain of skills that is brought into play to ensure that signals/data are not altered throughout the measuring, processing, sending and storage process.

For this reason, an articulated set of actions is required, based on both reinterpreting metrological concepts, according to the new sensor types and interaction between measuring and production processes and on the introduction of innovative technologies for data analysis and storing. An approach such as the Blockchain will ensure high measurement reliability to allow further processing by feeding predictive algorithms that will provide us useful information in the management of future processes.

Future work, by means of the analysis of real test cases, will allow these concepts to be refined step by step, for effective application in a modern industrial scenario.

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