APEM journal

Advances in Production Engineering & Management
Volume 15 | Number 1 | March 2020 | pp 107–117
https://doi.org/10.14743/apem2020.1.353

ISSN 1854-6250
Journal home: apem-journal.org
Original scientific paper

Communication and validation of metrological smart data in IoT-networks

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ABSTRACT

An Internet of Things–network (IoT– network) allows for the communication of data both within the network and to data hubs. However, the usefulness of the data depends on its ability to be interpreted correctly. For metrology data, effective use of the data is only possible if the numerical value, associated unit and uncertainty, expressed in a standard format, are also available. In order to develop, provide and distribute a formal framework for the transmission of metrology data on the basis of the International System of Units, European project EMPIR 17IND02 SmartCom was agreed between the European Commission and the European Association of National Metrology Institutes (Euramet). The SmartCom project aims to provide the methodological and technical foundation for the unambiguous, universal, safe and uniform communication of metrological smart data in the IoT and Industry 4.0. The project will increase the industrial capabilities and the provision of regulations for data exchange in the IoT. It will also assist countries within the European Union (EU) and those with an association agreement with the EU in developing products that are able to communicate in IoT environments worldwide. In addition to describing the general ideas and aims of the project, this article presents the research results achieved in the first midterm period.

ARTICLE INFO

Keywords:
Metrology;
Measurement metadata;
Information and communication technology (ICT);
Smart Data;
Data communication;
IoT-communication;
IoT-networking;
Digital calibration certificate

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Article history:
Received 27 December 2019
Revised 26 March 2020
Accepted 28 March 2020

1. Introduction

The current paradigm for industrial and engineering quality assurance is based on production processes that have short- to medium-term stability along with a significant investment in quality inspection. One of the goals of Industry 4.0 and data-centric engineering [1-4] is to use multiple sensors that measure all aspects of the production process. The resulting complete set of measured data can then be used to understand, in much greater detail, the performance of the system so that the process can be kept close to its ideal state, leading to reduced downtimes, fewer rejected parts, improvements in quality, better organised maintenance, better conservation of energy and resources, and increased business success. However, data-centric engineering depends on being able to assess the quality of the measurement information through the metrological concepts of traceability and uncertainty [5]. Rapid growth in digital communication such as cloud applications, distributed networks, smart devices and intelligent network architectures [3] demands new concepts for decision making based on reliable information.

Existing cloud storage and services provide state-of-the-art capabilities for storing data but, on their own, provide no information on the provenance of the data nor on how the data can be interpreted correctly. Smart data is used to overcome this situation. In the scope of this article, the term "metrological smart data" refers to digital information comprising metrology data formatted for further data consolidation and analysis of the data in Internet of Things-networks (IoT-networks). Such smart data provides metadata, such as measurement units and uncertainties, describing the meaning and purpose of the underlying data in a machine-understandable form. Thereby, benefit lies in using common standards for the provision of relevant metadata. More traditional data, such as raw data from measurement sensors or measurement data in calibration certificates, cannot be classified as smart. In many cases, such data has incomplete information (e.g. when a sensor outputs numerical values but with no associated unit) or the metadata can only be accessed by human-interpretation of a (paper) document.

Therefore, an essential component of a digitally-enabled metrology landscape for the IoT that can address the requirements of calibration, traceability and legal metrology [5, 6] is the automatic and secure communication of all relevant elements of the data and metadata formatted as smart data. This communication allows the unambiguous and correct interpretation of the data [7]. The interoperability of metrology data is severely degraded if essential information is lost or corrupted and current protocols do not address this issue.

In general, the confusion, ambiguity and incorrect interpretation caused by missing metadata, diversity of units, etc., represent significant risks for future investment in IoT–technologies. If the IoT is to bring its benefits to society, it must be founded on well-engineered principles, including those derived from the metrological concepts of traceability, uncertainty and interoperability. In addition, to avoid future loss of information and consequent impact on decision-making, and to make secure human lives and environment, the exchange of metrological information (measurement results and assigned information) must be defined for all measurement tasks.

Today, measurement results are communicated using base units of the International System of Units (SI) but also using domain-specific units such as foot, radian, inch, weber, gallon, etc. A BIPM brochure [8] provides guidance on using such derived units. However, this system is insufficient for the automated data processing required in the IoT, where information must be understood unambiguously and worldwide. One major goal of the research presented here is to define a data exchange format where the expression of measurement results in SI units [8-11] is mandatory. Optional information such as domain-specific or derived units will be covered, as well as additional information.

The presented research is focused on establishing the secure, unambiguous and unified exchange of data in all communication networks where metrological smart data is needed. It aims to develop, provide and distribute a formal framework for the transmission of metrological data based on the SI. The framework will be applicable to all metrology domains.

Furthermore, a worldwide-applicable concept for the use of digital calibration certificates (DCCs) will be made available for the first time. The development of demonstrators in two industrial domains will also prove the benefit and innovation potential for industry of the outputs of the project.

The most important scientific contributions of this research are:

- Establishing minimum required metadata models for the digital exchange of measurement data from a study of various international guides in the field of "traditional" measurement data and uncertainty representation,
- Establishing minimum required information to be contained in DCCs and requirements for the secure usage of DCCs from a study of standard documents and samples of "traditional" paper calibration certificates,
- Creating uniform metadata models that can help to facilitate interoperability of research data and increase reusability.

2. Research objectives, methods and the structure of research

The overall objective of the research is to provide the methodological and technical foundation for the unambiguous, universal, safe and uniform communication of metrological data in the IoT. Guidelines are being developed that can be used, for example, for the definition of pre-normative standards for the IoT and the supplementation of existing standards in order to define and harmonise the dissemination of measurement results and associated information. The specific objectives of the presented research are:

1. To define the requirements for a uniform, unambiguous and safe exchange format for measurement data and metrological information in an IoT network. The exchange format shall be based on the definition of SI units and meet central requirements from standards, guidelines and legal metrology.
2. To develop and establish secure DCCs. This objective requires consideration of exchange formats for administrative information, data transfer, cryptographic requirements, authentication and digital signatures.
3. To develop an online validation for services system for the types of data format as addressed under objectives 1 and 2.
4. To develop a reliable, easy-to-use, validated and secure online conformity assessment procedure designed for cloud system applications for legal metrology. The online conformity assessment procedure should also be applicable to calibration services and provide compliance with current international and European standards.
5. To build and validate demonstrators involving running applications from industrial stakeholders, to facilitate the uptake of the technology and measurement infrastructure developed in the project by the measurement supply chain, standards developing organisations and end users, and to work towards a European platform for metrological calibration services.

The idea of the research with the objectives is presented in Fig. 1. Technical realisation of the research is divided into 5 work packages:

- WP 1: Universal format for transfer of metrological data via digital communications,
- WP 2: Digital calibration certificate (DCC) considering technical and legal requirements,
- WP 3: Online validation of data formats and DCCs in digital communications,
- WP 4: Online conformity assessment in legal metrology,
- WP 5: SmartCom demonstrators.

Each work package is split into diverse activities, which are only briefly described in this section.

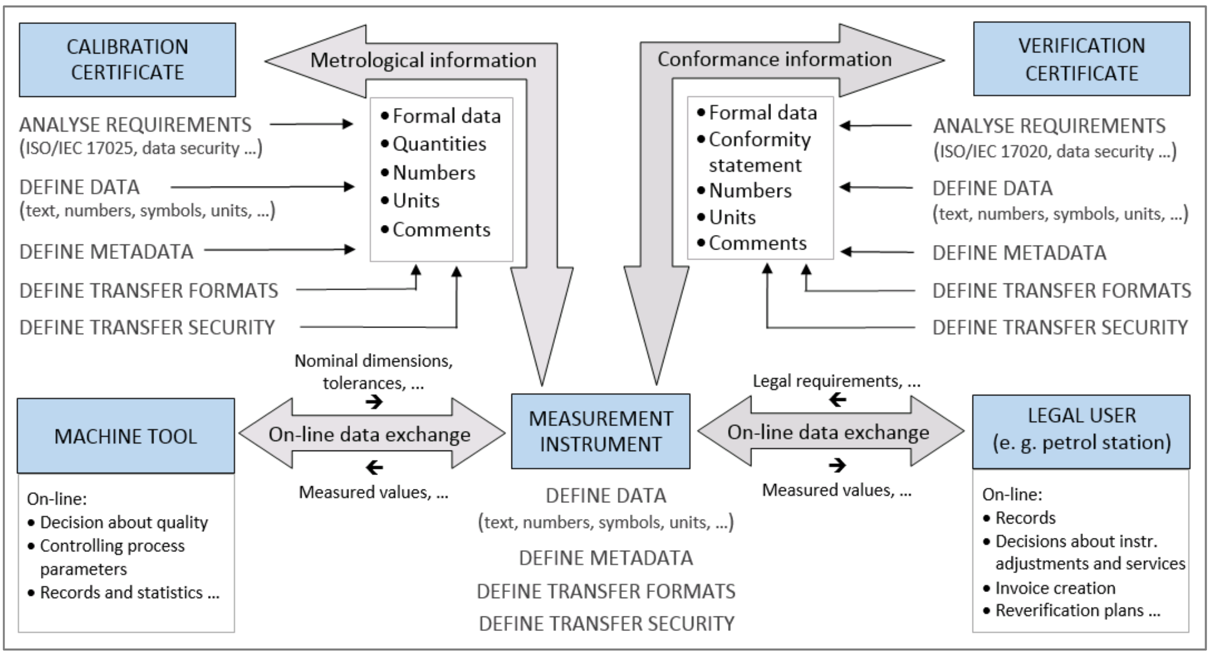

Fig. 1 Schematic presentation of the research goals and outcomes

2.1 Universal format for transfer of metrological data via digital communications

The aim of this work package is the elaboration and definition of a fundamental description applicable to all metrological data [5-7] used in digital communication. For the first time, and linked to the worldwide-established SI, project partners have defined the measures that are essential for the easy-to-use, safe, harmonised and unambiguous digital exchange of metrological data. The use of non-SI units has also been considered. The resulting universal format for the digital transfer of metrological data realises an implementation of the minimum requirements from guides in both metrology and Information and Communication Technology (ICT). This part of the research is complete and details are presented in Section 3.1.

2.2 Digital calibration certificate (DCC) considering technical and legal requirements

Within this work package, a universal structure of a DCC has been established. In order to obtain global acceptance of DCCs, the requirements for physical calibration certificates (paper form) of leading countries were first analysed. Using these requirements, a flexible and universal data structure was defined. The DCC was realised using extensible markup language (XML) [12, 13] with the metrological data represented according to the specifications developed in WP 1. In contrast to physical calibration certificates, new framework conditions required for digital communication [13, 14], such as the minimum requirements for transfer of encrypted data, authentication and digital signatures, will be developed and established (in a worldwide context and for the first time). Partial results are presented in Section 3.2.

2.3 Online validation of data formats and DCCs in digital communications

This work package aims to establish a worldwide accessible online service for all applications where metrological data is exchanged, and the validation of metrology information within a DCC. Best practice guides for this service will be produced in order to guide software engineers, purchasers of products used in "intelligent" communication networks, and managers of quality management systems. A classification of metrology data regarding its usability for machines has been developed. The highest classification, termed "Platinum" or "Next generation", refers to data provided using only SI base units. Other classifications include "Gold", "Silver" and "Bronze" while the lowest classification "Improvable" refers to data that does not include sufficient information, for example, omitting a measurement unit entirely. This part of the research is ongoing and is expected to be concluded in 2020.

2.4 Online conformity assessment in legal metrology

This work package will study requirements for a user-oriented and easy-to-establish online conformity assessment system that fulfils the general needs of legal preconditions. The research will focus on industrial users that develop sophisticated networks within digital networks and whose previous developments could not come to market due to restriction by national laws.

The online conformity assessment system will consist of three parts:

- XML-based communication interface [12],
- Unified user interface (UniTerm), and
- Security concept for the transmission of metrological information into a "world" outside the restricted and economic environment [13, 14].

This part of the research is ongoing and is expected to be concluded in 2021.

2.5 SmartCom demonstrators

Pilot applications (demonstrators) will be implemented in this work package to prove the metrological usability of the concepts developed during the research. The demonstrators will comprise the application of the validation system implemented in the TraCIM platform [15] on data from DCCs and an application of the UniTerm.

3. Midterm research results

3.1 Machine-readable SI format for the exchange of metrological data

This part of the research specifies the basic principles for the exchange of machine-readable data for all applications that transfer or require measurement data according to the specifications of the Système International d'Unités (SI) [8]. The research results thus provide the basis for the harmonised, clear, secure and economical exchange of digital measurement values for a universe in which digital data is being transferred in accordance with the specifications introduced below.

This new approach addresses the need for improvement in secure data communication in the sense of reducing the risk of incomplete and incompatible data exchange such as mixing up length measurement values with units inch and centimetre. Calculations combining such incompatible data can lead to catastrophic results. In safety-critical areas, a consequence could be loss of human life. Using the new approach will also improve the universality of communication, as the data and its metadata are based on common minimum required information from highly-authorative international guides such as VIM [5], GUM [7] and the BIPM SI brochure [8]. Other data models are in many cases very domain specific and hence only usable in their field of application.

For the digital exchange of metrological data, it is essential to associate at least one value to a corresponding unit [13, 14, 16]. These two pieces of information enable a statement to be made about the value of a quantity that can be interpreted according to the SI. Because of its indivisibility and fundamental importance, this form of representation is termed "atomic" (example: 1 kg).

The complete indication of a measured quantity may contain additional information such as a specification of measurement uncertainty [7] and a time stamp. For a single quantity, measurement uncertainty is usually expressed by a coverage interval corresponding to a specified coverage probability [7, 17, 18]. A time stamp [13] is required if probing is undertaken for time–variant materials (or substances) and if a measured quantity or a constant is interpreted over a longer period of time. Fundamental physical constants (e.g. the Planck constant) [19-21] have changed several times since the introduction of the SI [8].

In a digital network in which existing and new applications communicate with each other, even greater importance than before must be assigned to the SI. The ability to use the SI to describe all physical processes using only seven base units leads to an unprecedented clarity that is fundamental for the secure exchange of data.

It is important to distinguish between human-to-human and machine-to-machine interfaces. The specifications presented here primarily relate to an automated communication. It is essential for communication between machines and algorithms operating in an innovative digitised value chain.

The basic idea of the machine-readable format for SI units is presented in Fig. 2.

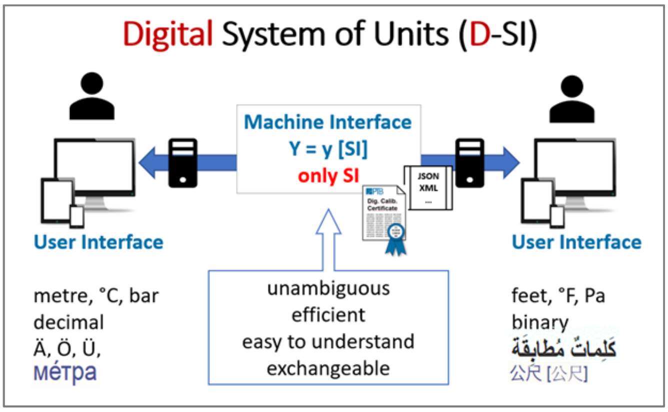

Fig. 2 Schematic presentation of the Digital System of Units (D-SI) as the universal format for the digital exchange of metrological data [22-23]

One of the research outcomes is also an adapter to allow the integration of non-SI units into the machine-readable D-SI data model [22-24]. This adapter is termed the “hybrid data model” or in short “hybrid”.

The outcomes of this research segment include digital formats for:

- Machine–understandable unit format for SI–base units and units provided by the BIPM SI brochure [8],
- Real quantities,
- Complex quantities,
- Lists of real quantities (vector of real quantities),
- Lists of complex quantities (vector of complex quantities), and
- Coverage regions (related to multivariate measurement uncertainty).

For reasons of space, examples are presented only for the cases of a real quantity and a hybrid data model (for non-SI units). The complete D-SI data model and a reference implementation in XML (extensible markup language) have been published [22–24].

Real quantity

The uniform data format for real quantities is shown in Fig. 3. The model contains the measurement value with a corresponding unit, the measurement uncertainty in the same unit and a time stamp.

The components of the real quantity type in Fig. 3 were defined by considering the requirements of the most important metrological normative documents such as SI brochure [8], GUM [7], VIM [5], ISO 80000 [10, 11] and CODATA [19-21]. The data types of the components consider important standards from computer science such as IEEE 754, RFC 362 (UTF-8) [14] and ISO 8601 [13]. An example of an extended real quantity XML format [24, 25] is shown in Fig. 4.

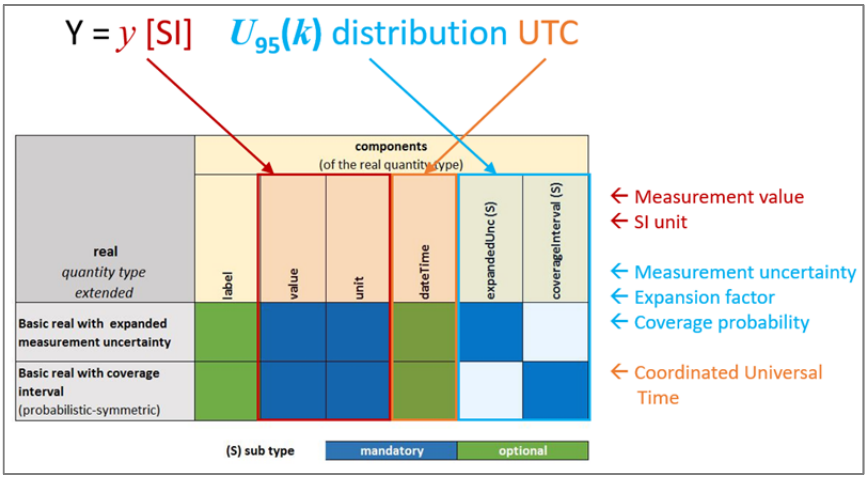

Fig. 3 Uniform data format for real quantity

```
<si:real>
    <si:label>temperature</si:label>
    <si:value>20.10</si:value>
    <si:unit>\degreecelsius</si:unit>
    <si:expandedUnc>
        <si:uncertainty>0.50</si:uncertainty>
        <si:coverageFactor>2</si:coverageFactor>
        <si:coverageProbability>0.95</si:coverageProbability>
        <si:distribution>normal</si:distribution>
    </si:expandedUnc>
</si:real>
```

Basic real

Expanded uncertainty

Fig. 4 Example of XML implementation of real with expanded uncertainty

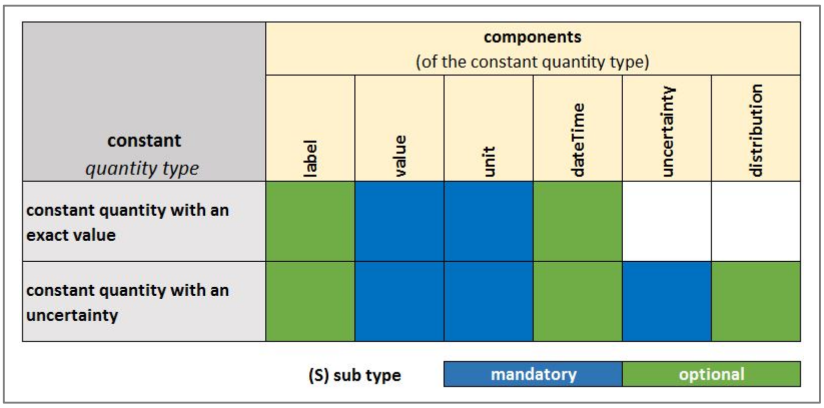

Fig. 5 Data model for machine-readable fundamental physical constants

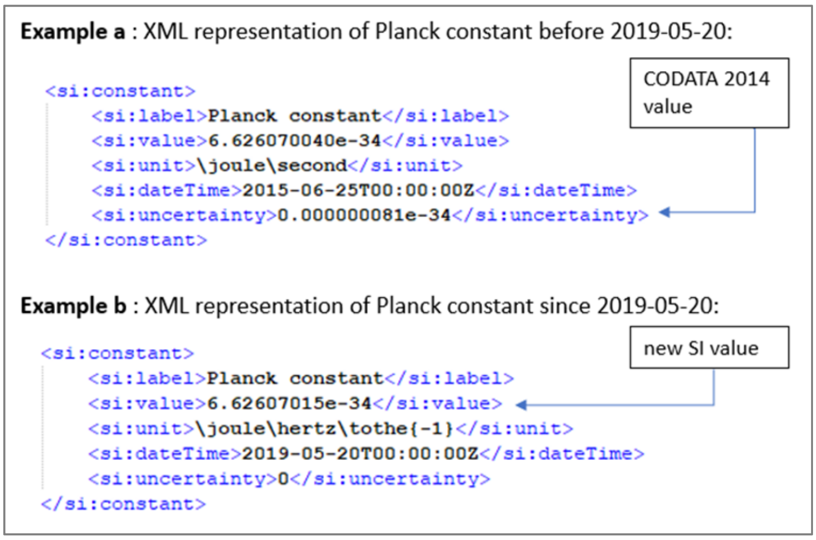

Fig. 6 Examples of XML implementation of fundamental physical constants [20]

Within metrology, fundamental physical constants [19-21] and mathematical constants are also very important. The D-SI model [22, 23] for a machine-readable representation and transmission of these constants is shown in Fig. 5.

Component "uncertainty" of the fundamental physical constants is the standard deviation of an experimentally defined constant. For constants from CODATA [19], "uncertainty" is the uncertainty reported in the CODATA list.

For values of mathematical constants that must be rounded the component "uncertainty" provides the standard deviation of a rectangular distribution that contains the exact value of the constant with 100% probability.

An example of a fundamental physical constant in XML format is shown in Fig. 6.

Hybrid data model for real quantities

It is recommended to use only the following units in the D-SI data model:

- The seven SI base units,
- Units derived from SI base units, and
- Non-SI units that are allowed to be used together with the SI.

It is however not recommended to use units that are not listed in the SI brochure [8]. An exception to this recommendation is recognised for internationally accepted systems of units and scales in the area of reference materials and in the area of reference procedures.

While the recommended units can be directly used as references for real and complex quantities in the D-SI data model, this approach is not permitted for unrecommended units. The hybrid adapter allows the integration of those quantities with an unrecommended unit into the machine-readable D-SI data model. The application of the hybrid data model requires conversion of the quantity with the non-SI unit into a quantity with an adequate SI unit. Both quantities are then collected together into one data element – the hybrid element. The hybrid data element must contain at least one quantity with an SI unit. The number of additional quantities with other units can be one or more.

A real quantity in hybrid comprises one real component that must state the quantity value in a SI-base unit. Furthermore, it can provide additional real quantities with SI derived units or non-SI units that convert to the real quantity with the SI-base unit. An example of an XML implementation of a real quantity in hybrid is shown in Fig. 7.

```
<si:hybrid>
    <!-- A: length from B converted to SI -->
    <si:real>
        <si:value>0.3048006</si:value>
        <si:unit>\metre</si:unit>
    </si:real>
    <!-- B: length with imperial unit foot -->
    <si:real>
        <si:value>1</si:value>
        <si:unit>ft(U.S. survey)</si:unit>
    </si:real>
</si:hybrid>
```

Fig. 7 Example of XML implementation of a real quantity with a non-SI unit in the hybrid data model

3.2 Digital calibration certificate (DCC) considering technical and legal requirements

In the future, calibration services will require the exchange of comprehensive digital content of all kinds between customers, applicants and calibration service providers. Digital interfaces must therefore be developed and provided in such a way that the following aspects are guaranteed: authenticity; completeness of the transmitted data; data integrity and manipulation protection as well as protection of confidentiality. The first step for the exchange of calibration certificates in a digital environment is to have a uniform and internationally recognised structure of such digital documents. The following specification sets out the basic design for the structure of a DCC that was developed in WP 2 of the SmartCom project.

This basic structure is founded on agreed standards, including ISO/IEC 17025 for calibration certificates [26] and internationally-accepted guides like the SI brochure [8], CODATA [19-21], VIM [5] and GUM [7].

Fundamental DCC-Layout

The DCC designed within the project is structured in four layers and is presented in Fig. 8. These layers contain both regulated data, which are mandatory, and unregulated data, which are optional and contain additional information that does not necessarily have to be machine-readable.

- *Administrative shell*
  The administrative layer represents regulated (administrative) data. It contains required information of core interest (i.e. is not optional), for the unambiguous identification and collection of administrative information of the DCC. This information includes the unique DCC ID, identification of calibration laboratory, customer and items.
- *Calibration results*
  This layer contains a regulated area of measurement results according to the rules for the D-SI format [22, 23]. Moreover, individual additional information can be entered here in an unregulated area, e.g. individual calibration information, considering influence conditions, calibration methods and individual results.
- *Individual information*
  For general, optional, and additional comments, calculation tables and graphics of any individual data formats, typically requested by the recipient of the certificate.
- *Optional attachment*
  Here, a human viewable file can be stored (e.g. PDF format), which will typically be a conventional analogue calibration certificate. This layer will not be machine readable.

The structure described above provides for the integration of all aspects of ISO/IEC 17025 [26]. Firstly, industrial applications have been considered and have proven to be suitable for industrial requirements. The metrological data included in digital certificates must consist of a numerical value and a corresponding unit as a minimum. These specifications are described in section 3.1.

The structure described above is not dependent on any programming language and will work with many file formats including XML and JSON. Used identifiers and correct expression of measurement results have been taken from worldwide harmonised guides and standards to ensure international (machine) readability of the documents.

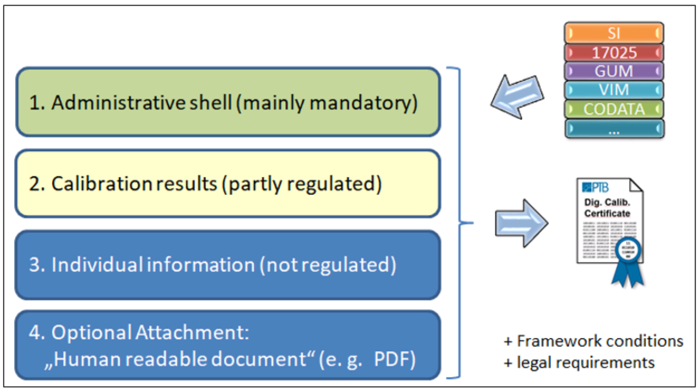

Fig. 8 General structure of digital calibration certificates

4. Conclusion

SmartCom is one of the first projects in metrology to define the universal minimum requirements for machine-readable data exchange in digital communication. The Digital System of Units (D-SI) metadata model presented in this paper can help developers of data formats to implement their data in an unambiguous, easy-to-use, safe and uniform way that is based on the International System of Units and other internationally accepted guides. It provides a data basis for representing data in future digital applications in metrology, such as: data for metrological services; data exchanged between virtual measuring instruments (DCC is virtual representation of properties of measuring artefacts and instruments). Analysis of big data is also facilitated if data is based on common terminology in metrology.

Digital calibration certificates (DCCs) are a very important application of the metrological data exchange. Using the principles from the D-SI, XML as machine-readable format and fundamental requirements from ISO/IEC 17025, a general structure for DCCs was specified.

In the future, DCCs will record all aspects of the calibrated items and make them available to a comprehensive quality management system. With these complete data sets, the performance of systems and processes can then be captured effectively and efficiently, allowing data analytic methods to provide information on optimised system performance. This activity leads to reduced downtime, less waste, significant improvement in quality, and ultimately greater economic success.

The work in the SmartCom project will be concluded in 2021. Until then, further tools will be developed to support the application of the DCC and D-SI [15]. The elaboration of aspects of cryptography will be of great importance for the transmission and use of DCCs. Suitable methods must be used to guarantee the integrity, completeness and authenticity of the calibration data. This area has proven to be particularly complex. No international standard in metrology is yet available for secure transmission, digital stamps and signatures or the withdrawal of digital data [27]. Preliminary approaches are using or envision the use of regulations such as the European eIDAS law [28] and blockchain technology in various areas such as Legal Metrology [29]. Finally, web-based services are being developed to help users of the D-SI and DCC to validate the correct usage of the data structure. PTB and NPL are planning to make available the validation services under the auspices of the TraCIM online test system.