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THE QUALITY INFRASTRUCTURE IN THE DIGITAL AGE: BEYOND MACHINE-READABLE DOCUMENTS

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Abstract – Digital transformation is challenging and changing the basic pillars of the quality infrastructure – metrology, standardization, accreditation, conformity assessment and market surveillance. The individual organizations are thus preparing and implementing digital transformation strategies to address the novel challenges and to make use of the new opportunities and possibilities. However, most of these developments still have a human-centric, document-based point of view. In this contribution we outline how the individual developments can be interconnected in the future and what a document-less digital quality infrastructure may look like.

***Keywords*: quality infrastructure, digital certificates, smart standards, cloud, API, artificial intelligence**

1. INTRODUCTION

The quality infrastructure is based on the interaction of metrology, standardization, accreditation, conformity assessment and market surveillance. It is underpinning trust and confidence in products and services as well as in international trade and economies. The digital transformation challenges the quality infrastructure in various ways. Consider, for instance, the digital transformation of the energy transition. Without smart grids, which digitally support the interaction between decentral energy supplies, a successful energy transition will be very difficult to achieve. Reliable measurements of power consumption and grid parameters as well as their communication via digital infrastructures are an important building block in this process. Therefore, many countries have introduced so-called “smart meters” as an important initial step in this direction. Such smart meters combine metrological requirements with security-related and verification-related requirements. This underlines the necessity of strong interdisciplinary collaboration and effective coordination, as it requires core metrological competence as well as digital expertise.

Digital, machine-readable certificates, automation, data science and cloud-based processes have been considered in metrology in the recent years [1]. The combination and integration of these developments into a coherent metrological infrastructure for the digital age has also been addressed recently, see, e.g., [2]. However, these developments still employ the use of (digital) documents, human-readable information, and in general a human-centric point of view. The standardization community, in contrast, has published a strategic outlook into a document-less digital future recently [3]. The authors in [3] introduce five levels of digital transformation maturity in standardization:

- Level 1: digital documents such as PDF
- Level 2: machine-readable documents such as XML
- Level 3: machine-executable content
- Level 4: machine-interpretable content
- Level 5: machine-controllable content

Definitions and insights into the meaning of these topics is given in the subsequent sections.

The discussions and considerations for metrology, for instance in [1, 2] and elsewhere, typically focus on Level 2. Some authors, such as in [4, 5], considered semantics and a general interpretation of metrological metadata by machines. However, a general strategy for the quality infrastructure beyond Level 2 has not been considered yet.

An important aspect in the discussion of the digital transformation of the quality infrastructure (QI) is the interconnection of the developments within the individual pillars, i.e., not only focusing on developments in, e.g., metrology or standardization. This is an essential aim of the German initiative “QI-Digital” for the national QI. On the international level, several organizations of the QI recently have signed a joint statement on collaboration in the digital transformation with a similar aim.

This contribution aims to introduce the interconnections and joint processes rather than individual developments. The paper is structured as follows. Sections 2-4, respectively, introduce Levels 3-5 of digital transformation in standardization as defined in [3] and their interpretation for the quality infrastructure. Section 5 outlines a potential path of developments towards Level 5. Finally, Section 6 gives a summary and outlook.

2. LEVEL 3 IN THE QI

Level 2 of digital standards is defined in [3] as the use of machine-readable XML documents. Content elements can be identified by a machine based on standardized XML elements, so-called “tags”. For instance, a certain paragraph may be specified as “definition” and another one as "mandatory specification" or "recommendation". A machine, i.e., a software, can then distinguish these elements from other parts of the text. The actual content of the paragraphs, however, still needs to be interpreted by humans.

To this end, Level 3 as defined in [3], extends the basic XML structure of Level 2 to a granular machine-readable definition of a standard – making it machine-executable. That is, elements such as tables, figures, definitions, etc., are all defined using digital objects. Such a digital object may be itself defined using XML tags, semantic structures, or other means. Therefore, in digital systems the granular stipulations contained in the XML can be used independently, e.g., by a software. For instance, the software in a calibration laboratory may extract the relevant parameters and metadata elements for preparing and controlling the calibration process.

In metrology, discussions about granular, machine-readable representation of units of measurement have been started a few years ago [5, 6]. For instance, the D-SI data model [6] contains a digital representation of measurements with a very fine granularity. As an example for a machine-readable representation, consider the below digital representation of the information from a force measurement given in the language JSON:

```
    "si:real": {
       "si:label": " force",
       "si:value": 12.3,
       "si:unit": "
\kilogram\metre\second\tothe{-2}" }
```

The measurement information contains a label "si:label" to specify the measured quantity, the actual numerical value of the measurement "si:value", the unit of measurement "si:unit" in a machine-readable format. These representations allow a software to find the information, i.e., the specific data, based on the identifier, the key such as "si:unit". In a larger context, this is given in a hierarchical way. For instance, the values for the above key "si:real" could themselves be part of a series of measurements or other block of information.

The label could also be given as a reference to a machine-readable glossary, ontology, or other format [4]. It is worth noting that the current provision of the vocabulary in metrology, the VIM [7], does not comply with the machine-readable requirements of Level 3 digital maturity, and could thus not be used for this purpose.

For digital calibration certificates (DCC) there are proposals which correspond to Level 3, regarding the granularity of machine-readable information [8]. Each content element is encapsulated in an XML tag, which itself may be encapsulated in a hierarchy of tags. In this way, information in the DCC can be found and interpreted by a software. This is important, for instance, for the use of calibration information in industrial automation, i.e., industry 4.0. Note that, similar as for the D-SI example above, the machine-readability could be further improved by providing the actual information in a machine-readable way. For instance, the term "temperature min" could itself be defined in an ontology.

Another aspect considered in [3] is the evolution of content creation. For standardization this starts with the preparation of the actual content of a standard. For Level 3 digital standards the content creation needs to consider the granular elements, use of semantics and interoperable terminology. In a similar way, the creation of certificates in metrology and accreditation must be adapted. That is, software tools are needed that create, e.g., standardized XML certificates and translate the measured values and other required information into proper XML tags and content.

So far, the developments for Level 3 digital maturity in standardization and metrology have been carried out individually. Only recently, for example within the initiative QI-Digital, organizations have begun to discuss the integration of these approaches. However, a coordinated approach is important to ensure compatibility of digital systems and to reduce the complexity of implementations. For instance, a software to design machine parts according to standardized tolerance specifications may use information from standards and from measurements. For the automation of processes and effective digital support of users, the tolerances specified in the standard need to be compatible with those from the digital representation of measurements.

3. LEVEL 4 IN THE QI

The Level 4 digital maturity of standards requires the content to be semantically sufficiently enriched with context information to make it interpretable by a machine, e.g., a software. That is, background information, relation to other content elements, and other context metadata are integrated in a machine-readable way.

The DCC XML already has technology built in to address Level 4 properties – for instance with the metadata contained in the tag definition. Consider for example the XML tag *<dcc:quantity>*, which could have an additional metadata "dcd:*refType*" to provide information about the context. If such metadata was using machine-interoperable and machine-interpretable terminology, ontologies, or other machine-readable semantics, it would comply with the Level 4 requirements. Further comprehensibility for machines could be achieved by agreeing on domain (measurand) specific good practice such as a common representation of results from temperature calibration. Developments from the Semantic Web community are even suggesting to have the whole data structure defined on principles of the Resource Description Framework (RDF) where all element tags (e.g., "dcc:quantity" or "si:real") have a defined context. A general approach could employ the "open-world paradigm" of semantics, e.g., by defining interconnected ontologies for the different topic areas, context types and applications. In this way, the interoperable machine-readability of context would be achieved whilst avoiding endless discussions on strict harmonized definitions.

In a similar way, certificates in conformity assessment, accreditation, and market surveillance need to be extended with machine-readable context metadata to satisfy Level 4 digital maturity. This shows again the necessity for an interdisciplinary *cross-QI* approach of defining corresponding terminologies, ontologies, and other semantic infrastructures. Machine-readable context metadata must be interoperable between the pillars of the QI and needs to be consistent throughout the whole product lifecycle.

As outlined in [3], software tools for the creation of digital standards will play an important role. That is, today's use of standard office tools will be replaced by software specialized in the interoperable definition of content and context metadata. The general approach to the creation of a standard is basically the same irrespective of the standard's content. Hence, the development of a unique software tool for the creation of Level 4 compliant digital standards is reasonable. In metrology, though, the creation of the actual certificate is only the final step at the end of the process. For instance, all relevant data and metadata for the DCC comes from different sources before and during the calibration. Moreover, the actual calibration is going to be a highly automated process – starting from the integration of administrative metadata. Thus, there will not be a unique software tool for Level 4 digital maturity documents in metrology. This situation is similar for conformity assessment, accreditation, and market surveillance, which all rely on the integration of data and information from different sources.

To remove the need for a unique software, we propose the establishment and implementation of common guidelines, minimal requirements and standards for terminologies, ontologies, and general semantics enabling a flexible data integration across different tools and digital devices. If the software, databases, and digital processes comply with such specifications, interoperability between different infrastructures can be achieved.

Content management and content delivery also change significantly with the shift from Level 3 to Level 4 digital maturity of standards [3]. Given the availability of machine-readable context metadata and content, a software could create custom standardization documents to meet specific end-user needs. The user specifies the desired information, scenario, and background. The software then finds, acquires, and compiles the corresponding information from the available standardization sources. This scenario can directly be translated to conformity assessment, accreditation, and market surveillance. For instance, the person responsible for the accreditation specifies the required information, certificates, and documentation. A software could then acquire and compile this information into a report. Alternatively, a software tool may continuously integrate the information sources required for an accreditation. This would allow status monitoring for the company-internal quality management as well as a direct creation of a report for the accreditation process. A prerequisite for this is the availability of commonly accepted software tools, approaches for the immutability of relevant information, as well as standardized interfaces between different tools and platforms.

4. LEVEL 5 IN THE QI

Level 5 digital maturity of standards adds artificial intelligence and machine-controllable content to the machine readability of content [3]. That is, standards can be amended, augmented, and further extended by machines, i.e., software, based on data-driven analyses and other sources. With such an approach, standards can adapt easier and faster to the ever-increasing pace of developments in technology, economy, and society. However, this also changes the way we as humans approach the standardisation process. Instead of writing a standard document, rules and procedures for an automated update of standards must be defined. A first application area benefiting from machine-controllable content could be standardized terminology. Small changes of core definitions can typically have a substantial impact on existing data and documentation. Machine control has the potential to allow for more frequent smaller changes at much lower cost than it is done manually today.

In metrology, similar questions will come up with the use of automated and remote calibration. That is, it must then be specified under what circumstances the outcome of the calibration can be fed into a calibration certificate. This, in turn, will affect the accreditation procedures as well. Today, the accreditation of a calibration laboratory also includes the competence of the staff members performing the calibration. With automated and remote calibrations, software will take over a large amount of work. Thus, accreditation or certification of such software may need to be considered.

In market surveillance and conformity assessment, Level 5 digital maturity could mean that software automatically validates the compliance with standards and regulations based on automated measurements. For instance, an AI software may predict the reliability of a measuring instrument based on other measured data with calibrated instruments. The outcome of this prediction could then result in an automatically generated conformity statement. Of course, this would require reliable measures against fraud, manipulation and cyber criminality. For instance, blockchain-based may be an option to this end, see Section 5.

Similar to levels 2-4, the interoperability of platforms, data models and interfaces in standardization, metrology, accreditation, conformity assessment, and market surveillance is an important requirement for an effective and efficient digital quality infrastructure. This is even more important when software can automatically create content, prepare certificates and conformity statements.

5. TOWARDS A DIGITALLY TRANSFORMED QI

The evolution from the current Level 1 of digital maturity in the quality infrastructure to a Level 5 can only be achieved on a step-by-step basis and with a close collaboration of all involved organizations. It requires the following developments:

- Machine-readable semantics (PIDs, ontologies, etc.)
- Application and platform interfaces (e.g., APIs)
- Interoperable data models.

The machine-readable semantics include the transformation of human-oriented glossaries and definition lists into machine-readable knowledge representations. For instance, the VIM [7] could be transformed into a thesaurus with specified relations between the terms, and then into an ontology as semantical representation of the definitions. At the same time, similar developments could be carried out in standardization, regulation, etc. With regular exchanges between these individual developments, one could avoid inconsistencies, ensure later interoperability, and minimize duplication of work. Some QI organizations already have founded strategic task and working groups, which could serve as contact points. Examples are the CIPM Task Group on the "Digital-SI", APMP Digital Transformation Focus Group, EURAMET Working Group on Digital Transformation. The recently signed joint statement of collaboration between QI organizations is an excellent starting point for a joint development towards Level 5.

The availability of data and information between different organizations by providing mutual interfaces is a possibility to implement digital processes that involve more than one organization. For instance, in a conformity assessment of a product, information from a calibration certificate, about the accreditation status of the issuing laboratory as well as specifications from a standard may be needed. When all this information was in one place (or could be found in a single point of contact), it could be easily accessed and processed by a software. In fact, it makes no difference for the software whether this information is distributed across the various sources, provided it can be found and accessed via interfaces. In other words, the relevant information should be provided in accordance with the FAIR principles: findable, accessible, interoperable, and re-usable. Originally, the FAIR principles were an initiative from the scientific community for an efficient and effective open access to research data. However, the underlying principles and philosophy can also be applied to accessible and interoperable digital platforms and information in the quality infrastructure. In particular the "I" in the FAIR principles, requires interoperable data models and interfaces. For instance, information and data representation in a calibration certificate should ideally be very close, at least consistent, with the representation of similar information in a digital standard, an accreditation platform, etc. This minimizes the complexity of software and thereby the risk of development bugs.

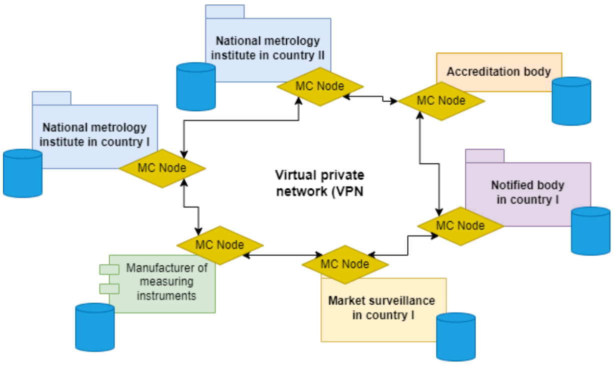

Fig. 1 General principle of the "Metrology Cloud" as a basis for a "QI Cloud" as distributed infrastructure [9]

Initial developments towards the mutual access to information and data relevant for the digitalization of processes in the QI is the initiative "European Metrology Cloud" [9]. As illustrated in Fig. 1, the "Metrology Cloud" is a secured network of participants from the quality infrastructure. In this concept, data owners share their data with the network via mutual interfaces provided with the Metrology Cloud. That is, no data is circulated between parties unnecessarily, whilst still being able to support and streamline processes in the QI. Data being shared via such a network can be anything - from measured data sets to simple references or metadata elements. A software could then realize the automation of the QI processes based on the available data. Moreover, each network participant has a certain role, which specifies the information that is visible and accessible. As part of the initiative "QI-Digital", the original Metrology Cloud will be further developed into an infrastructure that supports the digitalization of general processes in the quality infrastructure – the "QI Cloud".

6. SUMMARY AND OUTLOOK

Today, the general use of digital technologies in the quality infrastructure is at Level 1 of digital maturity [3]. Current developments in metrology for the further uptake of modern digital technologies is focusing on Level 2. As we have shown, though, some of these developments already provide a reasonable starting point for proceeding towards Levels 3 and 4. For instance, the use of XML-based certificates enables machine-readable documents (Level 2), and with appropriate semantics also documents with machine-executable (Level 3) and machine-interpretable (Level 4) content. However, these developments would still rely on a document as the medium of transporting the information and statement. In a digital world of interconnected systems and automated processes, the use of documents is not necessary, though. Therefore, an important aspect towards Level 5 is the shift from a document-based quality infrastructure to one where statements of conformity, traceability to national standards, and compliance with standardization requirements can be mutually accepted without a (electronically) signed document.

This paradigm shift would accelerate the uptake of digital technologies, digitized processes and – finally – the use of artificial intelligence in the quality infrastructure significantly. A measuring instrument could simply indicate its compliance with standards, regulation, and the traceability of its measured values to a software acquiring and analysing the measurement data.

Prerequisites of a successful implementation of Level 5 are the agreement on mutually accepted trustworthy digital platforms, the development of interoperable data interfaces and semantics, and the adherence to the FAIR principles and their underlying philosophy.

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