

The DX schema as a modular concept for metrological certificates and reports

Justin Jagieniak^{1*}, Shan Lin¹, Moritz Jordan¹, Muhammed-Ali Demir¹, Lutz Doering¹,
Thomas Engel², Wiebke Heeren¹, Jan Loewe¹, Shanna Schönhals¹, Siegfried Hackel¹

¹*Physikalisch-Technische Bundesanstalt (PTB), Bundesallee 100, 38116 Braunschweig, Germany,
justin.jagieniak@ptb.de, shan.lin@ptb.de, moritz.jordan@ptb.de, muhammed.demir@ptb.de,
lutz.doering@ptb.de, wiebke.heeren@ptb.de, jan.loewe@ptb.de, shanna.schoenhals@ptb.de,
siegfried.hackel@ptb.de*

²*Siemens AG, Friedrich-Ludwig-Bauer-Straße 3, 85748 Garching, Germany,
engelthomas@siemens.com*

**Corresponding author: justin.jagieniak@ptb.de*

Abstract – The Digital Calibration Certificate (DCC) has been the first metrological quality related document that has undergone a thorough analysis and requirements assessment process in order to develop a fully machine-actionable digital process that fulfills the requirements of the ISO 17025. During this, still ongoing, process, the demand for a more modular approach to digital quality documents has become obvious. The paper introduces the DX schema, which is the conceptual basis for the future DCC version 4 and other digital certificates, reports, and documents related to metrology, conformity assessment and a process oriented digital quality infrastructure. In addition the paper introduces some examples of digital certificates and reports which will potentially benefit from the DX.

I. INTRODUCTION

The concept of DX schema has its origins in several projects for digitalization in metrology, including the GEMIMEG, GEMIMEG-II [1], and ISAN [2] projects. In the GEMIMEG and GEMIMEG-II projects, participants identified the need for digital documents within the industrial supply chain, such as Digital Calibration Certificate (DCC), Digital Calibration Request (DCR), and Digital Calibration Answer (DCA). In the ISAN project, a digital accident report (D-AR) was developed by a team at Physikalisch-Technische Bundesanstalt (PTB). The D-AR was designed to transfer data from a sensor system to a rescue center.

Both developments share the commonality of being based on metrological measurements, which are provided by DCC or Digital Test Report (DTR), respectively. Unfortunately, the current structure of the DCC is not modular enough to generate other reports or certificates. This limitation led to the development of a digital document schema, the DX schema. The DX schema incorporates more generic types that are common to the certificates, re-

ports or requirement exchange documents and thus should be defined in a unified way. The DX schema refers to the variable "X", symbolizing its ability and aspiration to serve as structured basis to digitalize all other schemas related to metrology, which means that it is the foundational or basic but modular schema to derive other exchange documents.

Through extensive discussions and reconsideration, it was concluded that DX should offer greater flexibility and compatibility with various ISO standards. While the DCC was designed for ISO 17025 [3], the DX schema aims to support additional ISO standards.

In this paper, the concept of the DX schema and its relevant ISO standards are presented in Section II. Section III presents the DX ontology alongside the corresponding DX XML implementation, and proposes a workflow for co-development of ontology. Based on DX, three examples of digital quality documents are given in Section IV, including DCC, digital calibration request, and digital test certificate. Finally, Section V outlines the DX roadmap, such as the DX Wiki and DX-related software tools.

II. DX AND INTERNATIONAL STANDARDS

The fundamental concept of the DX is to provide a versatile generic and modular structure characterized by recurring types. The DX can be viewed as a systematic and structured collection of various types of documents, such as administrative data, metrological data, statements and findings from the examiner, and concluding conformity statements. In order to ensure flexibility, compatibility, and compliance with independent digital certificates and reports, individual components (i.e. types) must consider all relevant norms, standards, nomenclatures, and technical regulations.

The DX schema inherits the representation of measurement data from the Digital System of Units (D-SI) [4] for the representation of measurement data, which ensures seamless integration and consistency within existing sys-

tems. The D-SI also traces back to the BIPM reference point of metrological units, which incorporates the fully traceable history of all seven SI metrological base units and the 21 derived units.

The ISO 17000 series of standards are related to conformity assessment, which provides guidance and requirements for a variety of activities, such as operation, calibration, testing, certification, validation, and accreditation. The DCC is defined by ISO/IEC 17025, while other digital certificates and reports are defined by various other ISO standards. The DX will be designed in accordance with the ISO 17000 series and developed using the following specific documents.

- ISO/IEC 17000:2020 Conformity assessment – Vocabulary and general principles [5].
- ISO/IEC 17025:2017 General requirements for the competence of testing and calibration laboratories [3].
- ISO 17034:2016 General requirements for the competence of reference material producers [6].
- ISO/IEC 17043:2023 Conformity assessment – General requirements for the competence of proficiency testing providers [7].
- ISO/IEC 17065:2012 Conformity assessment – Requirements for bodies certifying products, processes and services [8].

Moreover, the DX will also be designed based on the fundamental metrological norms and standards. The most important of these are:

- SI Brochure of the BIPM [9],
- International Vocabulary for Metrology (VIM) [10],
- Guide to the Expression of Uncertainty in Measurement (GUM) [11].

The aim is to use the modular DX schema to represent various digital certificates and reports related to metrology, including the Digital Calibration Certificate (DCC), Digital Calibration Request (DCR), Digital Test Certificate (DTC), Digital Test Report (DTR), Digital Reference Material Certificate (DRMC), Digital Certificate of Conformity (DCoC), and others. Each certificate or report must be developed according to one or more specific ISO standards. Based on the DX, the relevant ISO standards for each document are shown in Fig. 1. The details of selected certificates and reports, i.e. DCC, DCR and DTC, are provided in Section IV.

In the future, the development of the DX should consider not only the ISO 17000 series of standards but also additional series of ISO standards and guidelines. For example, ISO 9000 series of standards are related to quality

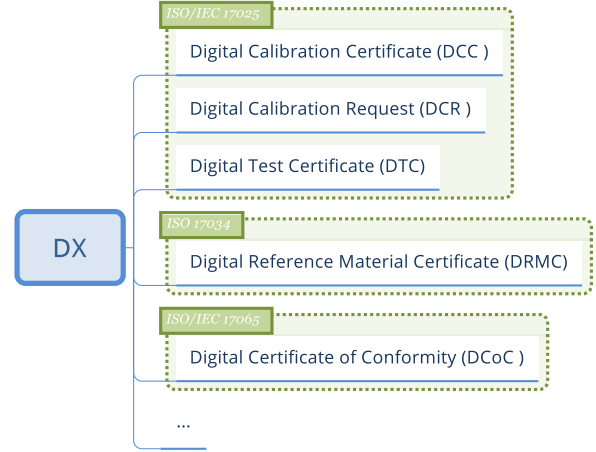


Fig. 1. DX based schema and the relevant ISO standards.

management. As already mentioned in Section I, the DX can also be used for many other ISO or IEC based standards to create appropriate reports or certificates, like the D-AR. The modular structure helps to cover a broad range of content with dedicated modular types related to the specific content of a respective standard. To incorporate a new standard, the rules of DX have to be followed in order to enable full cross-functionality and to leverage all synergies.

III. SEMANTICS AND ONTOLOGY OF DX

The semantics and ontologies are the basis of the digital language used in digital documents (see [12] and [13]). Simply speaking, semantics defines the word and the ontology the relation between different terms of the semantics. This enables a shared and unambiguous understanding of key concepts across communities, systems, and domains. In the context of the ISO 17000 series - which includes standards for calibration laboratories (ISO 17025), reference material producers (ISO 17034), and other conformity assessment bodies - the development of machine-interpretable data structures is critical. The DX schema initiative aims to support this need by providing a generalized XML implementation for digital documents across these standards. However, to unlock the full potential of semantic interoperability and machine reasoning, we propose the parallel development of a DX semantics and ontology.

A. The role of ontologies in metrology

Ontologies provide a formal, machine-understandable specification of domain knowledge. In metrology, they help to ensure that fundamental terms such as quantity, unit, uncertainty, or measurement result are consistently understood and used - not just by humans, but also by software systems. Concise and precise semantic definitions for every term used are essential for building trustworthy,

interoperable digital systems that can reason over measurement data, link documents across standards, and enable advanced search and analytics.

Recent efforts in the metrology domain underscore the importance of ontologies:

- The SI Reference Point [14], developed under the auspices of the BIPM, provides persistent identifiers (PIDs) and semantic definitions for SI units, prefixes, and defining constants, along with a semantic model for compound units. It forms a semantic backbone for referencing standard quantities in a machine-readable way.
- Another significant ontology development in metrology is the D-SI Ontology [15], developed by PTB. It provides a semantic model for quantity values and uncertainties and was derived from the D-SI XML schema definition, ensuring alignment between schema and ontology for improved interoperability. The D-SI Ontology reuses the semantic model of units provided by the SI Reference Point to ensure consistency and compatibility in the representation of units across different systems.

The latter initiative demonstrates the value of coupling XML schema definitions with corresponding ontologies, especially when aiming for long-term sustainability and interoperability in digital infrastructure.

B. Why Develop the DX Ontology Alongside the DX XML Schema Definition

We strongly recommend that the DX schema be developed in tandem with a corresponding DX Ontology. This co-development approach offers multiple benefits, particularly in ensuring semantic alignment and long-term interoperability. Designing the ontology alongside the XML schema definition allows for early alignment of concepts, structures, and naming conventions. This integrated approach helps to prevent inconsistencies and mismatches that often arise when ontologies are developed retroactively or without consideration for the underlying schema.

Moreover, the DX Ontology can be intentionally standardized and structured to reuse and extend existing ontological models, such as the SI Reference Point, the D-SI Ontology, or QUDT (Quantities, Units, Dimensions and Types). The latter is a set of "ontologies modeling physical quantities, units of measure, and their dimensions in various measurement systems" [16]. This promotes modularity and supports a wide range of use cases across the ISO 17000 series of standards, enabling the schema to serve as a foundation for interoperable and future-proof data models.

A common DX schema with standardized and defined semantics and ontology could also serve as a basis to har-

monize and align technical terms for identical content in standards on their iteration when transforming to smart digital standards to leverage synergies even across standards.

A further advantage of ontology-based modeling is the support it provides for smart documents and reasoning. The use of the Web Ontology Language (OWL) [17] enables powerful querying and inferencing capabilities, allowing systems to answer complex competency questions. Examples include identifying which documents include calibration results for a specific measurement standard, determining which laboratories are accredited for a particular calibration method, or detecting when reported uncertainties exceed acceptable thresholds.

The DX Ontology also facilitates improved data integration and linking. By representing documents in a structured, machine-readable format and using standardized terms from an ontology to describe their structure and content, it becomes possible to connect information across different systems and to enrich DX-based data with external resources - such as accreditation registries, instrument databases, or calibration hierarchies.

In terms of validation and data quality assurance, ontologies provide a richer set of tools than XML schema alone. While the schema ensures that documents follow the correct structure, the DX Ontology - especially when combined with SHACL (a rule-based language for validating data) [18] - can also define and enforce rules about the meaning and consistency of the content. This allows for validating more nuanced conditions, such as whether a quantity value includes both a numeric value and a corresponding unit, or whether a measurement result correctly references a defined measurand.

Finally, the combination of DX XML and ontology design directly supports the FAIR principles (Findability, Accessibility, Interoperability, and Reusability) [19]. Embedding semantics into the structure of digital documents ensures that metrological data is not only machine-readable, but also machine-understandable - laying the groundwork for its integration into future digital ecosystems.

C. Proposed Workflow for Co-developing the DX Semantics, Ontology and implementation in XML

To ensure a coherent and effective integration of schema and ontology, we propose the following workflow:

1. Requirements Gathering

Identify the key document types, data structures, and use cases to be supported by the DX schema.

2. Ontology and XML Schema Co-Design Process

• Develop the DX Ontology

Start by building the DX Ontology to model the

key concepts and relationships relevant to the ISO 170XX series. As part of this process, implement a structured class hierarchy that organizes these concepts according to the domains and document types covered by the standards.

- **Derive the DX XML Schema from the Ontology**

Use the ontology as the semantic foundation for the DX XML Schema. This ensures that the schema is aligned with the ontology's structure and terminology. Use annotations to maintain traceability between schema types and ontology terms, which enables better documentation, validation, and long-term maintainability of both models.

3. Ontology Alignment and Reuse

Where possible, reuse terms and structures from existing ontologies (e.g., SI Reference Point for units, D-SI for measurement values). Align with external vocabularies where needed.

4. Generation of RDF Representations

Use transformation tools or scripts to convert XML documents based on the DX schema into RDF [20] - a graph-based format for representing structured data - in a way that aligns with the DX Ontology.

5. Validation and Reasoning

Develop SHACL shapes based on the ontology to validate RDF data. Use OWL reasoners to check logical consistency and derive implicit knowledge.

6. Publication and Governance

Ensure the ontology is versioned, documented, and published using persistent Universal Resource Identifiers (URIs). Align with best practices in ontology governance and community involvement.

IV. EXAMPLES FOR DX BASED CERTIFICATES AND REPORTS

Designed as a modular XML schema, the DX does not follow a fixed structure, which can be viewed as an extension of D-SI. Meanwhile, digital certificates and reports primarily consists of a tree structure of types from both the DX and the D-SI. Additionally, custom types can be incorporated into the digital certificate or report when needed.

Every type in the DX stands on its own and is only connected to others when required. However, for a digital certificate or report, it is good practice to follow the ring structure (Figure 2) commonly used in DCC. The ring structure categorizes data based on its usage. The first ring defines administrative data, such as laboratory information, software used, etc. The second ring contains the results of measurements. The third ring defines comments related to the measurements. Finally, the fourth ring can include

a document, such as a PDF or HTML file, to provide a human-readable view of the report or certificate.

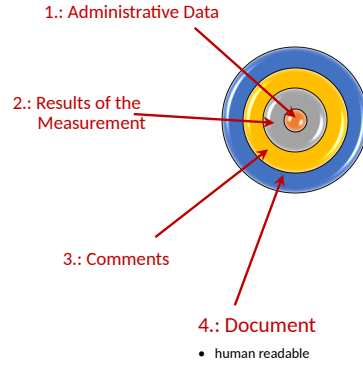


Fig. 2. Ring structure as good practice.

A. Redefinition of coreData

Typically, a DX-based schema should include an element called coreData in the first ring (the administrative data section). In the DCC schema, coreData is an element that contains essential information, such as the language of the certificate and a unique identifier.

The DKD (Deutscher Kalibrierdienst) expert report DKD-E 0-2 summarises common requirements for machine-readable certificates and highlights the need for standardised administrative data across the ISO 17000 series [21]. This report recommends to include administrative requirements for reports on conformity assessments, i.e. type of certificate, certificate number, revision number, number of the first certificate issued, name of issuing organisation, address issuing organisation, and date of issue of the certificate.

With the DX, it would be beneficial to redefine coreData as a universal administrative data element on the DKD expert report. This means coreData could be used consistently across all DX-based schemas in different ISO standards, serving as a standardized container for key administrative-level data.

B. Digital Calibration Certificate version 4

The DCC version 4 has essentially the same tree structure as DCC version 3. The difference, as shown in Figure 3, is that the type of measurementResultList, comment, document, and signature now follow a different namespace. The types of these four elements are inherited from the DX, as they can be commonly used, while the administrative data is specific to DCC version 4 and thus is customised for this schema.

C. Digital Calibration Request (DCR)

The Digital Calibration Request (DCR) was developed as a part of the GEMIMEG-II project, serving as a key dig-

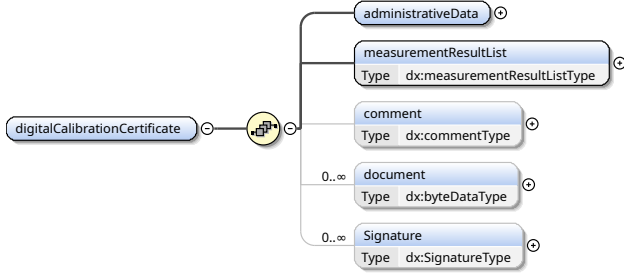


Fig. 3. DCC version 4 schema based on DX.

ital document within a fully digital industrial workflow. It is used to specify and exchange of the calibration requirements between customers and calibration service provider. By receiving a DCR, the calibration service provider can extract the information, including complete and detailed technical specifications for the requested calibration.

The structure of the DCR is slightly different from that of the DCC because, logically, a DCR cannot include the results of a measurement. The DCR provides the measuring points and additional information about the calibration to the calibration laboratory. These details need to be included in the DCR but are not necessarily part of the later DCC. This is accomplished through the element measurementRequest, as shown in Figure 4.

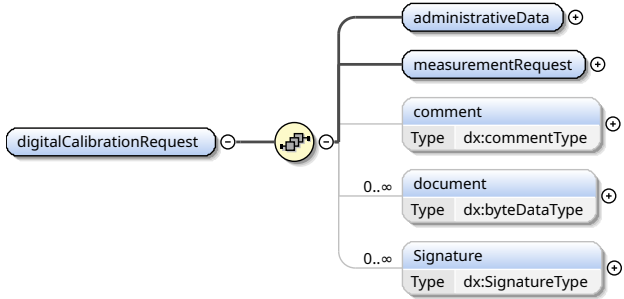


Fig. 4. DCR schema based on DX.

D. Digital Test Certificate (DTC)

ISO/IEC 17025 covers both calibration certificates and test reports (or test certificates), which share common requirements including unique identification and laboratory information (name and address). However, each document type has specific requirements. Calibration certificates must always include measurement uncertainty, while test reports only require this information under certain circumstances. Additionally, test reports contain specific information not found in calibration certificates, such as test conditions and, when applicable, sampling information when the laboratory is responsible for the sampling activity.

Based on the DX schema, PTB is currently developing a Digital Test Certificate (DTC) schema, which

follows a similar ring structure as the DCC as shown in Fig. 2. Like the DCC, the DTC includes elements such as measurementResultList, comments, documents, and signature following the types of DX, while its administrativeData element should be contained in its own schema. Compared to the DCC version 4 structure, the key structural difference is in the element dtc:administrativeData, where the child element dtc:sampling is used under the element dtc:item. dtc:sampling is used to describe specific requirements related to reporting sampling, especially the sampling plan and sampling method.

V. ROAD TO FUTURE

In the future, several projects for the DX are in the pipeline.

A. DX Wiki

A Wikipedia [22] for DX is currently under development. The Wikipedia demonstrates how to use DX to develop custom schemas based on it. Additionally, it provides information about commonly used schemas based on DX, such as DCC version 4, DCR, DTR or DTC.

B. DX Library

There is a need for a DX software library, similar to the library for the DCC, which will allow to sign, validate, evaluate formulas, and perform other operations for certificates or reports based on the DX. These functionalities have already been considered during the development of the DX schema but can only be tested and released at a later stage.

C. DCC version 3 to DCC version 4 Converter

Furthermore, there is a need for a converter from DCC version 3 to DCC version 4. This will make it easy to transform a DCC into the upcoming DX standard.

VI. CONCLUSION

The development of DX represents a significant advancement in metrology, providing a flexible and modular XML schema for generating digital certificates and reports that adhere to various ISO standards mainly for the ISO 17000 series. By expanding the DCC, DX offers improved compatibility with ISO standards beyond the scope of the DCC, making it a versatile foundation for a variety of metrological and quality related documents. The modular structure ensures its adaptability to diverse requirements while maintaining consistency in data representation, ensuring compliance with metrological norms and facilitating integration into existing systems.

The versatility of the DX schema to incorporate and support various certificates, such as the DCC, DCR, and

DTC, demonstrates its potential to streamline processes within the industrial supply chain and testing laboratories. Furthermore, the future development of tools like the DX Wiki, a library for DX, and DCC version 3 to DCC version 4 Converter promises to enhance accessibility and ease of use, ensuring that DX continues to evolve in line with emerging needs and standards. The standardized DX schema as a common basis for metrological and other quality related documents is also a key enabler to transfer DX documents into the digital quality document submodel of the asset administration shell. [12] By that, the DX might become a versatile digital foundation for a large number of quality documents for a versatile digital quality infrastructure. to support full digital and automated interoperability along industrial value chain with numerous stakeholders.

ACKNOWLEDGMENTS

Sincere gratitude is extended to the GEMIMEG-II project, funded by the German Federal Ministry for Economic Affairs and Climate Action (BMWK), and the International Standard Accident Number (ISAN) project, sponsored by the Niedersächsische Vorab Initiative of the Volkswagen Foundation (VolkswagenStiftung). These projects have made significant contributions to the development of the DX schema, and their support is appreciated.

REFERENCES

- [1] T. Engel. GEMIMEG-II – How metrology can go digital... In: *Measurement Science and Technology* 34.10 (July 2023), p. 104002. DOI: 10.1088/1361-6501/ace468. URL: <https://dx.doi.org/10.1088/1361-6501/ace468>.
- [2] ISAN project. Accessed: 2025-03-06. URL: <https://www.tu-braunschweig.de/informatik/research/projects/international-standard-accident-number>.
- [3] General requirements for the competence of testing and calibration laboratories. ISO/IEC 17025:2017.
- [4] Daniel Hutzschenreuter et al. SmartCom Digital System of Units (D-SI) Guide for the use of the metadata-format used in metrology for the easy-to-use, safe, harmonised and unambiguous digital transfer of metrological data - Second Edition. Version D-SI 1.3.0-2. July 2020. DOI: 10.5281/zenodo.3816686. URL: <https://doi.org/10.5281/zenodo.3816686>.
- [5] Conformity assessment – Vocabulary and general principles. ISO/IEC 17000:2020.
- [6] Conformity assessment – Vocabulary and general principles. ISO/IEC 17034:2016.
- [7] Conformity assessment – General requirements for the competence of proficiency testing providers. ISO/IEC 17043:2023.
- [8] Conformity assessment – Requirements for bodies certifying products, processes and services. ISO/IEC 17065:2012.
- [9] The International System of Units (SI). 2014. URL: <https://www.bipm.org/en/publications/si-brochure/> (visited on 03/24/2025).
- [10] International vocabulary of metrology – Basic and general concepts and associated terms (VIM). JCGM, 2012.
- [11] Evaluation of measurement data – Guide to the expression of uncertainty in measurement. JCGM, 2008.
- [12] Engel, Thomas. From a digital calibration certificate to a digital quality infrastructure. In: *EPJ Web Conf.* 323 (2025), p. 01003. DOI: 10.1051/epjconf/202532301003. URL: <https://doi.org/10.1051/epjconf/202532301003>.
- [13] Thomas Engel and Alexandru Popescu. GEMIMEG - Digitalization of calibration processes in metrology. In: *Measurement: Sensors* (2025), p. 101474. ISSN: 2665-9174. DOI: <https://doi.org/10.1016/j.measen.2024.101474>. URL: <https://www.sciencedirect.com/science/article/pii/S2665917424004501>.
- [14] SI Reference Point. URL: <https://si-digital-framework.org/> (visited on 04/15/2025).
- [15] D-SI Ontology. URL: <https://gitlab1.ptb.de/d-ptb/d-si/ontology-d-si> (visited on 04/15/2025).
- [16] QUDT Working Group. QUDT Ontologies: Quantities, Units, Dimensions and Data Types. Accessed: 2025-05-13. 2023. URL: <https://qudt.org/>.
- [17] W3C OWL Working Group. Web Ontology Language (OWL). Accessed: 2025-06-20. 2012. URL: <https://www.w3.org/TR/owl2-overview/>.
- [18] Knublauch, Holger and Kontokostas Dimitris. Shapes Constraint Language (SHACL). Accessed: 2025-06-20. 2017. URL: <https://www.w3.org/TR/shacl/>.
- [19] GO FAIR Initiative. Fair Principles. Accessed: 2025-06-20. 2016. URL: <https://www.go-fair.org/fair-principles/>.
- [20] Cyganiac, Richard and Wood, David and Lanthaler, Markus. Web Ontology Language (OWL). Version 1.1, Accessed: 2025-06-20. 2014. URL: <https://www.w3.org/TR/rdf11-concepts/>.
- [21] T. Krah et al. DKD-E 0-2, Expert report: Common requirements for machine-readable certificates in the ISO 17000 series. 2024.
- [22] DX Schema wiki. URL: <https://www.dx.wiki> (visited on 03/06/2025).