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The Digital Reference Material Document: From Paper Certificates to Interoperable Data Objects in Digital Quality Infrastructure

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***Abstract* – Reference materials (RMs) are essential for traceable and reliable measurements in science and industry, yet their certificate/document remain largely paper-based. The Digital Reference Material Document (DRMD) project at BAM introduces a transformative approach by converting traditional RM certificates/documents into machine-interpretable, XML-based digital assets. Building on the Digital Calibration Certificate framework, DRMDs encode ISO 33401 requirements and integrate semantic standards like D-SI and material identifiers. These digital documents support automated data exchange, integration into laboratory systems, and interoperability e.g. via asset administration shells and data spaces. The paper presents the DRMD schema concept, and outlines the path toward international harmonization and large-scale deployment, positioning DRMDs as a cornerstone of a digital quality infrastructure.**

I. INTRODUCTION

Reference materials (RM) are indispensable when it comes to ensuring the accuracy and reliability of measurement results and thus generating trust in analytical and other quality-assuring services. Inaccurate measurement values or those that are misinterpreted or incorrectly processed or transferred can lead to wrong decisions and thus to considerable follow-up costs or even hazards. Certified RMs ensure the traceability of measurement results to the SI [3], national measurement standards or recognized reference values and are frequently used for calibration and method validation, and the determination of measurement uncertainties. For accredited testing and calibration laboratories, the use of (certified) RMs for ensuring traceability of the results is considered essential as per ISO 17025.

Certified RMs come with a certificate that provides the value of the specified property, its associated uncertainty, and a statement of metrological traceability, and represent a central element of the daily routine of many laboratories for quality assurance. Non-certified RMs come with a so-called RM document, which does not necessarily provide a traceability statement [16]. Both RM certificates and documents come in paper or PDF format, the handling of the information is causing manual efforts, e.g. for data entry and processing. Providing these certificates and documents in a machine-readable way can contribute to significantly optimized process efficiency and accuracy.

The Digital Reference Material Document (DRMD) [18] transforms the traditional certificate and document defined in ISO 33401 into machine-interpretable XML objects. DRMDs function as digital assets that may integrate into laboratory information systems and populate digital twins via asset administration shell [2].

This paper shows how the Digital Reference Material Document fits within the emerging digital quality infrastructure, and supplements human-readable PDF certificates with a machine-interpretable asset. It presents the v0.2.0 XML schema, and open-source tooling and plans for integration into RM databases such as COMAR [17], then shows how DRMDs plug into digital twins and dataspace exchanges. We close by outlining the path to international harmonisation and large-scale deployment.

II. BACKGROUND

A. *Digital Quality Infrastructure*

The system of quality assurance and infrastructure that has been practiced for decades is still largely document- and paper-based and involves a great deal of manual bureaucratic effort. The central actors of the quality infrastructure (QI) in Germany have established the QI-Digital initiative [21] to jointly develop solutions to transform the system holistically into a data-based quality assurance system that meets the requirements of an increasingly digital economy. Among the variety of quality related documents that will be transformed into an appropriate digital representation are e.g. calibration or conformity certificates, test reports – and the RM certificate/document. Their efficient integration into calibration and quality assurance processes requires standardization regarding semantics and ontologies, as well as solutions for trustworthy verification [9].

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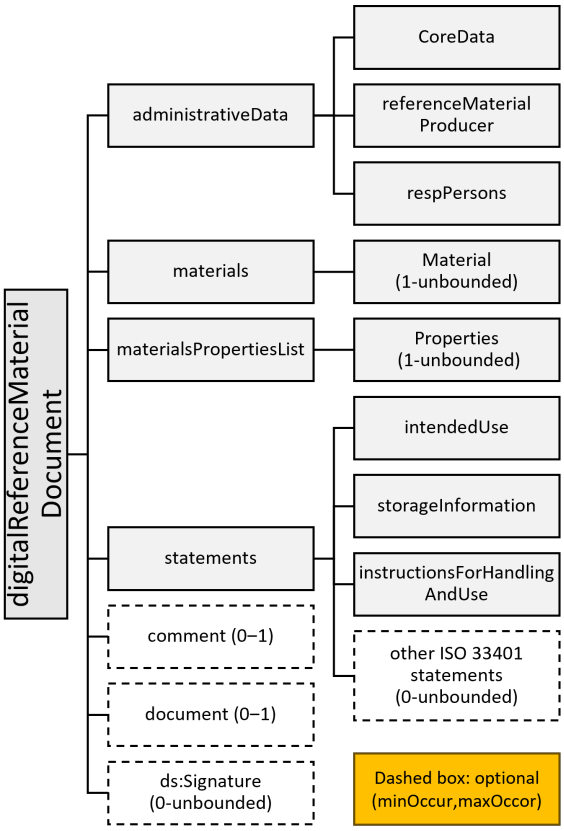

Fig. 1. Snapshot of the DRMD schema structure [18]

B. (Digital) Reference Material Documents

Today, (analogue) RM certificates and documents are usually created manually by the manufacturers, and then published or distributed with the reference material as a PDF copy to the customer, who then enters the relevant data manually into the instrument software.

In the context of the digital transformation of reference materials, the National Research Council Canada (NRC) as well as the National Institute of Standards and Technology (NIST, U.S.) are modelling databases that store the information contained in the RM certificates and documents of their institute [5, 19]. The resulting data architecture accommodates a broad spectrum of information – including quantified property values, multipart and serialised materials, various dependencies, and explicit traceability statements – thereby providing a machine-interpretable foundation for reference material metadata [4]. In Germany, the Federal Institute of Material Research and Testing (Bundesanstalt für Materialforschung und -prüfung, BAM) is driving the development of the Digital Reference Material Document (DRMD).

The DRMD encodes all ISO 33401 certificate requirement – property values, uncertainties, and metrological-traceability statements – in a machine-readable structure that can be ingested directly by laboratory software and other digital quality infrastructure services, eliminating manual re-keying and transcription errors. DRMDs offer significant process improvements. They will allow a laboratory that buys a RM to validate a procedure or to calibrate its device with it – or to calibrate many devices in a routine laboratory – to load the DRMD into the device software, making all RM information (analytes, content, minimum sample size, existing accreditation, etc.) available in machine-readable form. This way, the calibration/analysis can be carried out automatically - without a technician having to type all the contents of the analytes in the sample into the software by hand.

Thus, standardized data formats simplify the exchange of information between systems, make quality control more robust lowers administrative costs, and minimises error prone procedures.

C. Technical Implementation

The DRMD will be based on an XML schema built on the successful Digital Calibration Certificate (DCC) [9, 13, 18] as developed by PTB and others. The current DRMD schema introduces six clearly separated containers (cf. Fig. 1):

- **administrativeData**: includes core metadata: unique identifiers, period of validity and RM producers, etc.
- **materials**: list of material objects; each material embeds description, minimum sample size and *materialClass* tags that may reference external taxonomies.
- **materialsPropertiesList**: includes measurement results, which uses the incorporated D-SI XML scheme (Digital System of Units) to express property values and their uncertainties and *unitsProperties* can be linked to existing taxonomies.
- **statements**: intended use, storage instructions, commutability and other ISO 33401 clauses.
- **comment**: optional free remarks
- **document**: optional binary documents
- **signature**: multiple XML-DSig blocks for integrity and accreditation proofs.

The DRMD toolkit contains (i) the XSD, (ii) XSLT style sheets that render human-readable HTML, (iii) validated XML examples for best practices. The following tools are currently in development to ease development and usage of a proposed DRMD scheme:

- To accelerate market diffusion and adoption of DRMDs, BAM has developed a prototype for an online tool that allows producers of RMs to create their own schema conforming DRMDs.

- An AI powered generator tool to accelerate the transformation of existing PDF certificates into DRMDs is under development. The prototype for this LLM-based generation is showing initial success and will help generating DRMDs for inclusion into RM databases .

BAM hosts an international database that RM producers can use to list their materials (currently more than 2000). Several DRMDs have already been uploaded to COMAR to demonstrate their feasibility. Integrating DRMDs broadly in this database, supported by the abovementioned tools, will accelerate their diffusion.

III. DIGITAL ECOSYSTEM FOR DRMD

The transformation from analogue to digital processes in QI goes far beyond the mere digitization of existing processes. While manual work, paper-based documentation and siloed data storage are still commonplace today, QI needs to evolve into a networked system with automated processes and seamless digital documentation. This integration not only enables more efficient and secure data management, but also creates the basis for anticipatory, use-oriented quality assurance processes.

To leverage the potential of a digital QI, its digital tools, and procedures as well as relevant actors need to be seamlessly integrated into an interoperable, cross-system and coherent digital ecosystem. As the complexity of distributed systems is determined by its interfaces, latest developments towards industrial international data spaces [6] as well as the standardized documentation and access of data, e.g. with the help of the Asset Administration Shell [2], enable such an ecosystem.

For quality documents such as the DRMD these developments represent technical foundations for an efficient and trustworthy information modelling and sharing.

A. DRMD and Asset Administration Shell

The Asset Administration Shell (AAS) was developed as part of the German *Industrie 4.0* [12] initiative to create a standardized digital representation of physical assets. The motivation behind AAS is to enable interoperability among various components in industrial systems, facilitating seamless integration and communication between physical and digital entities.

The AAS acts as a digital twin of physical assets, providing a comprehensive digital model that includes all relevant information and functionalities as well as unified access to it. Thereby, it supports the entire lifecycle of an asset, from creation to disposal, by continuously updating information. Its modular structure consists of submodels that describe specific aspects of an asset, such as energy consumption, maintenance schedules, and documentation. Implementing the AAS offers several advantages: It enhances efficiency by providing precise insights for monitoring and control, and thus enables well-informed decision-making. The AAS optimizes processes by replacing heterogeneous data landscapes with unified, interoperable data structures, increasing transparency and operational efficiency. The International Digital Twin Association (IDTA) provides comprehensive guidelines, submodel templates, and specifications that ensure interoperability and consistency across digital twins. By promoting standardized data structures and semantic definitions, IDTA facilitates seamless integration and communication between various industrial systems, enhancing the efficiency and effectiveness of digital transformation initiatives.

As data schemes display partial overlap of specific data elements, a modular approach is selected for the development of AAS submodel templates. Generic data points are subject to harmonization and transferred from namespaces, with the objective of facilitating their modular application across diverse instances. Synergies may evolve from e.g., general and administrative data, the representation of measurement results, and SI units. Existing AAS submodel templates [14, 15] are also evaluated for the purpose of reusing parts. The DCC data schema is the most mature submodel template available and therefore serves as foundation for further digital QI developments, such as the DRMD and the D-CoC [22]. These will be progressively integrated with the aim of establishing a modular D-X scheme that accommodates multiple QI certificates and documents.

Ultimately, these AAS sub-modeled quality documents could easily be used and managed as information basis for digital product passports or other documents along product life cycles [8].

B. DRMD and Data Spaces

Data spaces [20] are collaborative ecosystems designed to facilitate secure and controlled data sharing among various stakeholders. Originating as an alternative to restrictive bilateral data sharing agreements, data spaces aim to retain data with their owner while granting controlled access to authorized parties. Key features include a secure infrastructure that protects data privacy and complies with regulations such as general data protection regulation (GDPR) [23]. They enable the integration of data from multiple sources based on agreed standards and technology building blocks, enabling interoperability. Robust governance processes are in place to ensure data accuracy, reliability, and trustworthiness. Additionally, data spaces allow data providers to set clear rules about how their data can be used, ensuring data sovereignty and trust. Data spaces are well-suited to foster cooperation among partners and unlock new data sources. Governance frameworks improve the quality and reliability of shared resources. Data spaces align with ethical principles by ensuring data sovereignty,

trust, and fair value exchange. They also support AI applications by providing the massive amounts of high-quality data needed, addressing immediate data needs, and supporting long-term AI development.

The incorporation of foundational components such as digital identities and credentials to conformity assessment entities, in conjunction with SMART standards in data formats that facilitate machine-executable comparison of process parameters with established norms, has the potential to enhance the efficiency of digital QI.

C. DRMD and Digital Trust

Ensuring the integrity of digital documents and data structures is essential to build trust equivalent to traditional paper-based formats. Electronic signatures achieve this by applying a hash function to the content, which is then signed using a verified digital identity. Asymmetric cryptographic techniques are key to safeguarding documents from tampering or unauthorized access, securing information during both transmission and storage. Legal recognition of electronic signatures in many jurisdictions grants them the same validity as handwritten signatures, supporting regulatory compliance and legal processes. Additionally, electronic signatures improve workflow efficiency by reducing the need for physical documents, saving time and lowering costs related to printing, shipping, and storage. They also support remote work and global collaboration through easy document access and signing. Various technical solutions have been developed to support digitally signed certificates.

Public Key Infrastructure (PKI) is a system that uses public and private cryptographic keys to create and verify digital signatures. Certificate Authorities (CAs) issue digital certificates to authenticate signers' identities. PKI ensures document integrity, authenticity, and non-repudiation. In Germany, the national accreditation body *DAkkS* offers a taylored PKI as digital accreditation symbol, i.e., an electronic company seal issued through D-Trust, providing a verified digital identity, exclusively for accredited bodies [7]. These electronic seals can be applied to PDF or XML files with the unique feature of digitally verifying the respective accreditation status of the issuing body on the receiver side of the document.

Verifiable credentials (VCs) [1] are open standards by the World Wide Web Consortium (W3C) which allow third-party verification of digital certificates using decentralized identifiers (DIDs) and cryptographic proofs. VCs are particularly useful for identity verification and access control. Within digital signature frameworks, verifiable presentations enable secure and private sharing of VCs. Privacy-preserving techniques, such as zero-knowledge proof, facilitate the selective disclosure of data, thereby ensuring that only the necessary attributes are revealed for verification purposes.

Trust anchors are foundational in both PKI and VCs, ensuring the credibility of certificates and credentials. In PKI, trust anchors are typically root certificates from trusted CAs. These validate the certificate chain but present challenges in management, particularly in issuance and revocation. In VCs, trust anchors are often DIDs, offering decentralized trust with stronger privacy—but also introducing complexity in management. Secure and recognized DID management is essential for broad VC adoption. The European Blockchain Services Infrastructure (EBSI) [11], an EU initiative, uses blockchain to strengthen digital trust and identity. It addresses challenges in trust anchors via verifiable data registries (VDR) and identity management through a decentralized, transparent, open-source framework that supports VCs and DIDs.

The European Business Wallet (EUBW) aims to simplify regulatory compliance and strengthens digital trust in business-to-business (B2B) and business-to-government (B2G) interactions by providing a unified identity and trust framework. It helps businesses manage identity verification across borders, reducing fraud and ensuring compliance with EU regulations. The implementation of trustworthy identity anchors and the credential issuing within public organisations is of particular importance, especially in the safety certifying testing, inspection and certification (TIC) domain.

In summary, it is imperative to employ digital trust in the context of conformity assessment documentation to ensure the secure exchange of documents. As is currently being discussed in industry and politics at the European level, open standards with flexible trust levels accredited by varying bodies are recommended for open ecosystems. These standards are crucial to supporting interoperable, scalable architectures to be adopted by stakeholders in industry and governmental institutions.

IV. CONCLUSION AND OUTLOOK

The drafting of a data scheme for the Digital Reference Material Document (DRMD) at BAM is progressing in alignment with the more mature Digital Calibration Certificate (DCC). The XML schema evaluates existing approaches to data structures and definitions, integrating generic work such as the Digital System of Units (D-SI). While data modeling is ongoing, the next challenges include ensuring data integrity, verifying the identity and credentials of the issuing body, and enabling sovereign sharing in open ecosystems. These challenges are similar to those faced by other digital conformity documents.

The current data structures will be part of a novel modular D-X schema [10]. To facilitate quick industrial adoption, we continue our collaboration within the IDTA Working Group "Digital Quality Documents" to co-create modular submodel templates for AAS. This collaboration is essential for developing a robust and adaptable framework.

Our efforts include testbed and prototyping activities with stakeholders to support market diffusion. Integration into digital QI process chains and digital ecosystems of the industry and international value chains is a priority. Additionally, international harmonization and cooperation with other national institutes are pivotal.

Previous work has shown promising results, with market maturity on the horizon and a large share of reference materials covered. The deployment of thousands of reference materials using the DRMD will lead to more efficient processes in laboratories and industry applications. Together with other digital QI tools, such as the digital calibration certificate and request, and embedded within the digital ecosystem (including AAS and data spaces), the DRMD holds significant potential. This alignment and further development will be pursued through close collaboration within the QI-Digital initiative and with international partners. The ongoing efforts aim to create a comprehensive and harmonized digital framework that supports the efficient and secure exchange of digital reference material documents, ultimately benefiting the broader industry and scientific communities.

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