

Towards an inclusive and agile implementation roadmap for a digital quality infrastructure

Jens Niederhausen¹

¹ *Physikalisch-Technische Bundesanstalt, Abbestr. 2-12, 10587 Berlin, jens.niederhausen@ptb.de*

Abstract – How do we best transition from an outdated QI with many manual processes and analogue *quality documents* to an efficient and interconnected QI that fully leverages digital and automatized processes and granular *quality data*? This paper aims to identify digital transition strategies that can account for the realistic boundary conditions that exist in today's diverse QI landscape, particularly the different digital maturity levels across institutions and nations as well as elaborate regulatory frameworks. Informed by related initiatives, the paper presents promising approaches to map out transition roadmaps for individual starting conditions and transition velocities.

I. INTRODUCTION

The digital transformation of the quality infrastructure (QI) holds great promise for a complete revolution of how quality is assured. However, like other cases of digital transformation, this disruptive change requires a re-assessment of established processes and additionally includes changes to and implications for products, services, and business models [1]. Notably, it has been found that 70% of all digital transformation initiatives do not reach their stated goals, which was attributed to a lack of coordination and systematic reporting [2]. Thus, for an established system that works productively and effectively, it should be carefully considered how and when to initiate change, even when the disadvantages of the status quo are already obvious. Successful initiatives have been correlated with the combination of digital proactiveness, change commitment, and organizational flexibility [3]. In addition, a *performance infrastructure* that consists of suitable people, processes, and tools working in concert, was found to “help[s] create effective executive-level alignment, communication, and coordination during a transformation.” [4]

The QI transformation is different from that of a single organization, since it relies on the coordinated change of several elements of a larger system that is not under the control of a central body (see Fig. 1). The paper explores two specific aspects that seem particularly relevant for the timely and efficient adaptation of digital solutions in the distributed and de-central system that is the QI:

i) inclusiveness: If new solutions are incompatible with legacy processes or emerging solutions employed by other

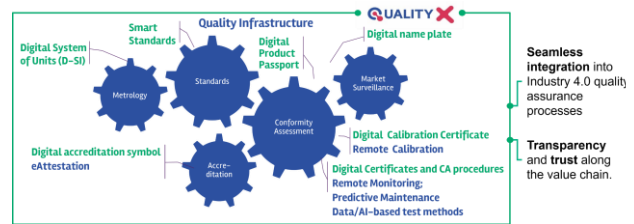


Fig. 1. The Digital QI Ecosystem Quality-X as envisioned by the initiative QI-Digital [15][16]

actors, they pose technical barriers and interrupt ongoing activities. This must be avoided as much as possible. Technologically, backward compatible and interoperable technological implementations of digital QI tools and processes allow individual actors to initiate change independent of their stakeholder network. Organizationally, a *performance infrastructure* can ensure that all relevant actors are up to speed, guaranteeing a coordinated digitalization roadmap where no stakeholder is left behind or slows the other ones down.

ii) agility: the transition of a complex system like the QI is not completely deterministic. The solution that seems most promising at one point in time will not necessarily prevail in the marketplace of ideas. Agile approaches are most suitable to deal with such a scenario. This is related to *organizational flexibility* and can be supported by a suitable *performance infrastructure*.

II. METHODS

This paper proposes a three-step approach. The first step is to analyze the *current QI* with respect to its essential elements and their digital maturity (see Fig. 2 and Ref. [5]), focusing on the following QI tools and processes:

- (Meta) data formats
- Norms and standards
- Result reports of conformity assessments
- Proof of accreditation and other endorsements
- Reports and documents relevant for customs and market surveillance authorities
- Corresponding processes and procedures

The second step consists in compiling a vision of the *future QI*. This is done by collecting i) the political and technological goals that the QI must address based on its mission as well as expectations from industry and society

ii) technical solutions that are being pursued or considered for the QI's further development.

The final step consists in mapping pathways between the current and future QI, prioritizing those pathways that allow reaching the optimal digital QI ecosystem with minimal disruptions and detours during the transition period (i.e., the time during which several different digital maturity levels co-exist). This entails choosing and timing the integration of the available technical solutions in a way that maximizes the degree to which the QI goals are achieved at all times.

Note that all three steps are rather substantial tasks by themselves in view of the diverse and complex QI stakeholder network. It is thus not within the scope of this article to provide a comprehensive assessment of either. Rather, sections III A to C present a non-exhaustive compilation based on the author's own experience and network. In addition, Section III D describes the *innovation ecosystem* of the QI-Digital initiative as an example for a *performance infrastructure* for the QI's multi-stakeholder network

III. RESULTS AND DISCUSSION

A. Current Status of the QI

Currently the QI is still completely document based. These documents include reports and certifications (from accreditation, calibration, testing, inspection, certification, market surveillance, customs, reverification) as well as norms and standards. On the one hand, the format and terminology of these documents as well as the corresponding QI processes differ significantly between different jurisdictions (municipalities, federal states, countries, regions) as well as domains (e.g., different measurement categories or certification systems), severely hindering their efficient integration into a wider digital transformation. On the other hand, laws, multilateral certification systems, as well as mutual recognition agreements ensure broad validity of these documents. This combination translates into an urgent need for harmonized formats, terminologies, and processes within rather rigid legal and administrative frameworks.

Despite these complications, the digital transformation of QI formats and documents has been ongoing for almost a decade and digital solutions for the representation of units [6], calibration certificates [7][8], and the accreditation symbol of the German Accreditation body DAkkS [9] are already available, while SMART Standards [10], a digital certificate of conformity [11], and the digital product passport (DPP) [12] are in the pilot phase. Notably, the DPP is the only element that consequently enforces the digital format. The other cases by and large allow analogue options for the foreseeable future.

Solutions for the digital mapping of processes have also been forthcoming for several years now. Mostly, these focus on user portals that allow registered QI actors to

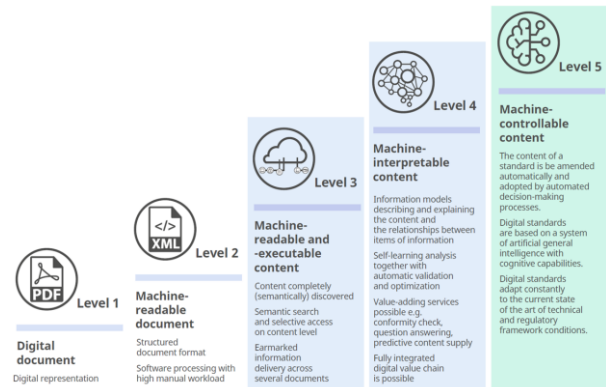


Fig. 2. Extended utility model developed by IDiS [5] that allows assessing digital maturity.

manage their profile, purchase norms and standards, as well as submit requests and retrieve answers for conformity assessments and accreditations. In terms of knowledge sources, certification scheme owners (e.g. IECEx) and accreditation bodies (e.g. DAkkS) provide information on the nature and status of their issued certificates via graphical user interfaces that are connected to their central databases. Market surveillance and customs share information on investigated products (test results, product identification data, economic operator information, accident information, information on measures taken by surveillance authorities etc.) between authorities via central systems (e.g. ICSMS in the EU).

API-based services are much rawer, and often limited to free content like concepts, definitions, and terminologies (e.g., the BIPM SI Digital Framework [13]).

B. Features of the future QI

The International QI Network (INetQI) defines the QI as “The system comprising the organizations (public and private) together with the policies, relevant legal and regulatory framework, and practices needed to support and enhance the quality, safety and environmental soundness of goods, services and processes.

The quality infrastructure is required for the effective operation of domestic markets, and its international recognition is important to enable access to foreign markets. It is a critical element in promoting and sustaining economic development, as well as environmental and social wellbeing.” [14]

From this, the following societal, economic, and environmental requirements for the QI can be derived

- Trustworthy and transparent
- Inclusive and internationally recognized
- Supporting innovation and competitiveness

Due to its role as key element of a functioning economy

and facilitator of international market access, the QI system must also meet high standards regarding

- Safety, security, and data sovereignty
- Reliability, resilience, and adaptability
- Efficiency, sustainability, and cost-effectiveness

The German initiative QI-Digital has formulated its vision as “[a] quality infrastructure for the digitalized and sustainable future that enables modern and efficient quality assurance right through to global value creation networks,” echoing some of the aspects listed above.

To meet the above goals to the highest degree possible and to enable modern QI procedures like co-calibration, virtual measurement instruments [17], remote monitoring, predictive maintenance, and AI-based methods, the following technological characteristics of the future QI’s digital ecosystem (see Fig. 1) are conducive:

- interconnected and decentralized
- data-based (vs. document-based)
- FAIR (i.e. findable, accessible, interoperable, reusable)

These features enable additional data-driven services and thus enhance the overall value of the digital QI ecosystem for the economy, science, and society.

The future digital QI ecosystem can build on technologies that constitute the foundation of modern data ecosystems. The adaptation of the following concepts can thus significantly contribute to an optimized achievement of the above-stated QI requirements.

- Digital twins
- Dataspaces
- (Self-sovereign) digital IDs
- Digital wallets
- Electronic attestation of attributes
- Semantic-web approaches [18]

The large spectrum of measurement procedures, certification systems, product categories, and product life cycle stages result in diverse QI processes and tools. Mapping the requirements to technical solutions already available or under development and precisely identifying possible gaps is a task for the respective domain experts and beyond the scope of this work, which instead aims to highlight the necessary support structure for trans-domain-harmonization and -coordination discussed in Section D.

C. Inclusive and agile approaches

Fig. 2 shows the extended utility model [5] that can help analyze and steer the digital transformation of the QI elements. While the scale goes all the way up to level 5, achieving an end-to-end level 1 QI process is already a major improvement in terms of efficiency, since it prevents media-discontinuities and enables mapping complete process chains to the digital realm. Unified data formats

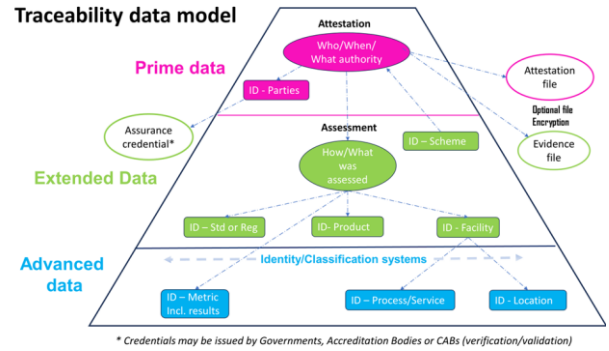


Fig. 3. Conceptual model developed by UN/CEFACT [22].

and open application programming interfaces (APIs) are paramount for reducing manual workload and maximizing efficiency gains. In terms of guaranteeing inclusiveness, handling documents in several different ways should be facilitated by the chosen file type. For example, a PDF file can be read and processed by a human while the machine-interpretable version of that document (e.g., as XML) can be contained as metadata of the PDF file. Extensible documents like XML allow adding metrological and semantic metadata without compromising backward compatibility. This increases the degree of machine-interpretability and enables automatization and the integration of artificial intelligence. E.g. the digital calibration certificate (DCC) offers a long-time stable version 3.0 and more recent versions that enable advanced features [8].

Currently, paper documents are still pervasive and, in many cases, required to meet legal requirements on identity authentication and accessibility. Electronic identities and signatures are increasingly adapted (e.g. enabled by the eIDAS regulation in the EU), however, given that almost three million people have never used the internet in Germany alone, processes will still have to account for communication via traditional mail and paper documents for all acts that include the public.

When exclusively dealing with economic actors, purely digital solutions can be enforced more readily. One prominent example is the EU’s digital product passport (DPP), which will become mandatory for the first product category in 2027.

The CIRPASS 2 consortium developed “a ‘basic’ DPP system that has been stripped down to its most fundamental elements and that is easily applicable to extremely low-cost products with mandatory ‘simplest DPP’ requirements and focuses on short-term DPP deployments for fast adoption of DPPs by industry”[19]. This approach ensures long-term inclusiveness and prompt uptake of the DPP. Advanced users can still benefit from more advanced implementations that make use of dataspace to greatly simplify the automatic integration of data from down the value chain as well as the electronic attestation of attributes, for example, by means of



Fig. 4. The QI-Digital Mission (above) and Innovation Ecosystem (below) with its fields of action and a list of relevant technologies and measures as well as the stated vision of a data-based quality assurance enabled by a digitally transformed QI. [15]

verifiable credentials [20].

A related example concerns product conformity certificates. A UN/CEFACT project group has specified the high-level process for the digital exchange of product conformity certificates along the value chain based on 8 principles that address authentication, unique IDs, standard vocabularies, verifiable endorsements, as well as certificate status and validity. The business requirements specification proposes a *traceability data model* (see Fig. 3) and points out that “the approach should be suitable for parties operating at various levels of digital maturity”. [21][22].

Digital certificates based on data models that encode the full certificate content in a machine-interpretable way like the D-CoC [11] are a natural extension of the traceability data model. So are the use of verifiable credentials and the implementation in DPP initiatives like the EU DPP and the UNTP [23].

D. The QI-Digital Innovation Ecosystem and Roadmap

The proposed three-step approach consists in matching requirements with technical solutions as well as configuring and timing the implementation such that the QI disruption is minimized. Given the complexity of the QI, each step is a major undertaking that must account for a large stakeholder network and a plethora of processes and tools.

Within the last four years or so, QI-Digital has developed and tested its *Innovation Ecosystem*, effectively a

performance infrastructure for consultation, alignment, and coordinated implementation with the QI community (see Fig. 4). It consists of four major elements:

- 1) The digital tools and procedures and their integration into an interconnected and interoperable data ecosystem.
- 2) Pilot projects that provide infrastructure and technical platforms for R&D in realistic test environments
- 3) An analysis of the regulatory framework and administrative practices to identify and overcome obstacles for the implementation of the digital QI ecosystem.
- 4) Measures for sustainable transfer of developed solutions and proactive incorporation of industry needs via comprehensive stakeholder engagement.

While elements 1) – 3) are necessary for a full transformation, it is element 4) that decides about its ultimate success. Only if all stakeholder needs are accounted for and solutions are rolled out effectively, broad acceptance and coordinated and wide-spread adoption can be ensured. It is through these transfer and coordination measures that stakeholder engagement and agile development on a system level is operationalized.

QI-Digital consists of the central actors of the German QI from metrology, standardization and accreditation. Conformity assessment bodies and market surveillance authorities are represented via the advisory council, which also features representatives from industry, academia, and society as members, as well as representatives from relevant ministries as permanent guests.

The advisory council gives all QI stakeholders a say in the transformation process and thus legitimizes the initiative. Sub-groups give strategic advice and contribute to position papers and the analysis of the regulatory framework. In addition, the council has proven indispensable as a steppingstone for the comprehensive engagement of several communities, most notably calibration and testing labs and market surveillance bodies.

One important finding is that one-shot activities by and far do not create significant impact. It usually takes multiple steps to arrive at a meaningful result. For example, big events like the yearly QI-Digital Forum create awareness for an upcoming stakeholder consultation. The respective community then meets several times to assess their status and prioritize their needs. The final step consists of dedicated trainings and workshops, which close knowledge gaps and set up implementation projects.

IV. CONCLUSIONS

The goal of the presented approach is to assist QI actors in their individual digitalization journey, increasing their confidence and motivating them to adapt digital solutions more readily. While the sketched approach in principle

allows systematic analysis and optimization of digital transformation undertakings with respect to inclusiveness and agility, this is beyond the scope of this paper. Instead, the presented examples consider some key strategies as a first step towards a more comprehensive derivation of best practices and guiding principles that are yet to follow.

PTB is part of QI-Digital [15], which has compiled and maintains a *Roadmap for the Digital Transformation of the Quality Infrastructure*, where more details on the development status of the digital QI tools and proposes steps for their further development and scalable roll-out can be found. The interested reader is invited to engage in a dialogue with QI-Digital to jointly shape the QI digital transformation process.

REFERENCES

- [1] C. Matt, et al., Digital Transformation Strategies, Bus. Inf. Syst. Eng. 2015, 57(5):339–343
- [2] S. ZoBell, Why digital transformations fail: Closing the \$900 billion hole in enterprise strategy. Forbes. 2018,
- [3] D. K. Nguyen, et al., Leveraging synergy to drive digital transformation: A systems-theoretic perspective, Information & Management 2023, 60(7):103836, DOI: 10.1016/j.im.2023.103836.
- [4] M. Bucy, et al., The ‘how’ of transformation, McKinsey&Company 2016.
- [5] DIN/DKE, “IdiS.Whitepaper: Scenarios for digitizing standardization and standards”, 2021.
- [6] D. 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”, Zenodo, DOI: 10.5281/zenodo.3816686.
- [7] S. Hackel, et al., “The Digital Calibration Certificate (DCC) for an End-to-End Digital Quality Infrastructure for Industry 4.0.”, Sci. 2023, 5(1):11, DOI: 10.3390/sci5010011.
- [8] PTB, “Digital Calibration Certificate”, URL: <https://www.ptb.de/dcc/>, accessed May 2025
- [9] DAkkS, The digital accreditation symbol, URL: <https://www.dakks.de/en/the-digital-accreditation-symbol.html>, accessed May 2025
- [10] ISO, “IEC/ISO SMART”, URL: <https://www.iso.org/smart>, accessed March 2025
- [11] The D-CoC Team, Digital Certificate of Conformity - Version 1.0, 2023, URL: <https://www.ptb.de/dcoc/>.
- [12] CIRPASS 2 Project, URL: <https://cirpass2.eu/>, accessed May 2025.
- [13] Bureau International des Poids et Mesures, “Si Digital Framework, Digital References for FAIR measurement data, beta testing version”, <https://si-digital-framework.org/>, accessed March 2025.
- [14] International Network on Quality Infrastructure, “Quality Infrastructure Definition”, URL: <https://www.inetqi.net/documentation/quality-infrastructure-definition/> accessed May 2025
- [15] QI-Digital Initiative, URL: <https://www.qi-digital.de>, accessed March 2025.
- [16] QI-Digital Initiative, “Quality-X: A federated digital Ecosystem for the future quality infrastructure”, 2023. URL: <https://www.qi-digital.de/en/publications>, accessed May 2025.
- [17] PTB, “Competence Centre VirtMet”, digital.ptb.de/en/virtmet, accessed May 2025.
- [18] C. Brown, et al., “An Introduction to Linked Data and the Semantic Web”, First International IMEKO TC6 Conference on Metrology and Digital Transformation, Berlin, Germany, 19-21 September 2022, DOI: 10.21014/tc6-2022.037.
- [19] T. Tammet, et al., „The simplest DPP System Proposal – A thought experiment“. CIRPASS-2 Consortium, May 2025. DOI: 10.5281/zenodo.15367064.
- [20] H. van Nieuwenhuijze, et al., "D4.1 Reference Architecture", CIRPASS-2 Consortium. Mai 2025. DOI: 10.5281/zenodo.15467720.
- [21] UN/CEFACT, “White Paper on Digital Product Conformity Certificate Exchange”, 2023, <https://unece.org/trade/documents/2023/10/white-paper-digital-product-conformity-certificate-exchange>, accessed May 2025.
- [22] UN/CEFACT, “Business Requirements Specification on Digital Product Conformity Certificate Exchange - High Level Process”, <https://unece.org/trade/documents/2024/07/session-documents/brs-digital-product-conformity-certificate-exchange-high>, accessed May 2025.
- [23] UNECE, “UN Transparency Protocol” URL: <https://uncefact.github.io/spec-untpl/>, accessed May 2025.