# FINAL PUBLISHABLE REPORT

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# 1 Overview

The goal of this project was to develop the basis for a secure, unambiguous and unified exchange of data in communication networks, where metrological data is used. To address this ambitious goal the SmartCom project developed a formal framework for the transmission of metrology data based on the SI (International System of Units), which is applicable to all metrology domains in the Internet of Things (IoT). The project also developed for the first time ever a concept that summarises the minimum requirements for the use of digital calibration certificates (DCCs). Further to this the project developed online validation services for the measurement data formats involved in the DCC concept as well as a secure online conformity assessment procedure for cloud system applications for legal metrology (UniTerm). The project then demonstrated the use of its outputs via 2 demonstrators; one on the use of DCCs and the other on the use of UniTerm in order to promote their uptake by end users.

# 2 Need

The Internet of Things (IoT) network provides the capability to communicate data within a network and data hubs. However, the value of that data depends on its ability to be interpreted correctly. For metrological data, the effective use of the data is only possible, if the unit of measurement and uncertainty associated with the numerical value, expressed in a standard format, are also available.

Cloud storage and services provide state-of-the-art capabilities to store data, but on their own provide little or no information on the origin of the data or how to interpret it correctly. Therefore, an essential component of a digitally-enabled metrology landscape for the IoT must be one that can meet the requirements of (i) calibration, (ii) traceability and (iii) legal metrology. Hence it needs the automatic and secure communication of all relevant elements of the data and metadata, in order to enable it's unambiguous and correct interpretation. However, the interoperability of metrology data is severely impaired if essential information is lost or corrupted and prior to the start of this protocols that addressed this did not exist.

The confusion, ambiguity and incorrect interpretation caused by missing metadata, diversity of units, etc., represents a significant risk for future investments in IoT technologies. If the IoT is to bring benefits to society, it must be based on well-engineered principles, including those derived from the metrological concepts of traceability, uncertainty and interoperability. Therefore, in order to avoid future losses of information and the consequential negative impact on decision-making, the exchange of metrological information (measurement results and associated information) must be securely and unambiguous defined for all measurement tasks.

# 3 Objectives

The overall goal of the project was to provide the methodological and technical foundation for an unambiguous, universal, safe and uniform communication of metrological data in the IoT. The specific objectives of the project were:

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

# 4 Results

<u>Objective 1:</u> *To define the requirements for a uniform, unambiguous and safe exchange format for measurement data and metrological information in an IoT network. The exchange format shall be based on the definition of SI units and meet central requirements from standards, guidelines and legal metrology.*

> "The Internet of Things (IoT) is the network of physical objects that contain embedded technology to communicate and sense or interact with their internal states or the external environment. "
>
> Gartner IT Glossary

The use of IoT tools is now the core-technology for establishling data infrastructures for many fundamental developments in digital transformation e.g., Smart Cities, Smart Homes, Autonomous Driving, eHealth and Industry 4.0 environments (where data from multiple sensors is used to monitor, steer and improve processes in an automated manner). Unseen by most users, the exchange of measured data is needed for nearly all IoT applications. For example, temperature data is needed in laboratories, manufacturing and with heating. To make use of such measurement data and ensure that any inference based on this data is reliable and safe, the metrological requirements for the data must be carefully implemented in IoT networks. However, in practise, metrological requirements had received only limited consideration prior to the start of this project. Furthermore, even basic demands like providing a measurement value together with the associated unit of measurement were missing. Where metrological aspects of measurement were considered, the various implementations/solutions showed significant differences which will hamper future interoperability and use of the data by software and machines. These issues needed urgently resolving as well as a harmonised format for measurement data so that data from different companies and developers can be used together to achieve the benefits of the IoT (see Figure 1).

To address these issues the project consortium (i.e., PTB, CMI, NPL, UM, Aalto, Ostfalia-HAW, Taltech, UNICAS, Hexagon, KRISS, Mitutoyo, NIM, Sartorius and Zeiss) worked together to define universal, unambiguous and safe metadata formats ("atoms") for metrological data that were such easy-to-understand and simple so that they could be implemented in applications where machines communicate and operate on the basis of measurement data.

For the successful development of the requirements for a uniform, unambiguous and safe exchange format for measurement data and metrological information in an IoT network it was important to consider requirements from different domains and users within the field of metrology and computer science. At an early stage of the project the partners CMI, Hexagon, NPL, PTB, UM and UNICAS began a broad review on different international approved standards and guidelines in order to decide on the essential components and data types for the metadata format with a wide range of applicability. For metrology the review included the fundamental definitions for metrological data provided in:

1. the SI brochure (Documentation of the international definition of the International System of Units of measurement) as this is widely accepted and approved by the 60 member states and 42 associated states in the Metre Convention),
2. the International Vocabulary in Metrology (VIM; International approved documents with core definitions of the terms e.g., measurement and quantity)
3. and the Guide to the Expression of Uncertainty in measurement (GUM, the International agreed guideline for the definition and reporting of measurement uncertainty).

These 3 guidelines are also recognised and supported by international standardisation bodies such as ISO and IEC. Other standards that were considered were:

- ISO 80000 Quantities and units series (the International System of Quantities),
- ISO 8601 Date and time format (the international standard for Coordinated Universal Time (UTC) in digital systems),
- IEEE 754 IEEE Standard for Floating-Point Arithmetic (the international standard of the basic number types for computer hardware and software),

- National Institute of Standards and Technology (NIST) Special Publication 811 (The NIST guide for the use of the International System of Units)
- Request for Comments (RFC) 362 (the UTF-8 encoding scheme for characters of any language)
- and the Committee on Data of the International Science Council (CODATA) values of fundamental constants (internationally agreed values of physical constants upon which all measurements are defined today).

A majority of the guidelines from the measurement domain refer to a use of data by humans. Thus, the project partners carefully discussed what was needed for the inclusion of data that used by machines without human inference.

The outcome from this work has been the first ever definition for machine-usable data that (i) has been aligned with all the necessary guidance from the metrological domain, (ii) takes into consideration machine needs such as avoiding redundancy and unnecessary variants of data representation and (iii) supports high arithmetic security (numerical precision) for when using the data. During the project, the Digital SI (D-SI) has been used in a variety of situations such as:

- the format for DCC,
- TraCIM validation. The TraCIM ("Traceability for Computationally-Intensive Metrology") platform is a service run at PTB based on the outcome of a previous EMRP project NEW06
- and in the project's 2 demonstrators (Objective 5).

Partner PTB used the knowledge gained from these applications to make improvements to the metadata-model (as necessary). PTB also adapted the unit definition in the metadata-model following a re-definition of the SI system in 2019.

The project produced a brochure describing the new machine-useable data representation based on metrological standards and regulations such as GUM, VIM and the SI-brochure entitled "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". The brochure was made publicly available in English (https://doi.org/10.5281/zenodo.3816686) and Chinese (https://doi.org/10.5281/zenodo.4003413).

The brochure covers real, complex and vector quantities as well as formats for fundamental constants. The description of the metadata format is accompanied by a realisation of it in Extensible Markup Language (XML), making it easily usable. In addition, a shorter and more end-user focussed 'catchy' version of the digital SI format was developed and is provided as a digital brochure.

Using the XML realisations, fundamental physical constants from CODATA have been implemented in a machine-readable format and have been made available to end users online by PTB on Zenodo https://doi.org/10.5281/zenodo.3688428. The latest number of unique downloads of the machine-readable format is 34.

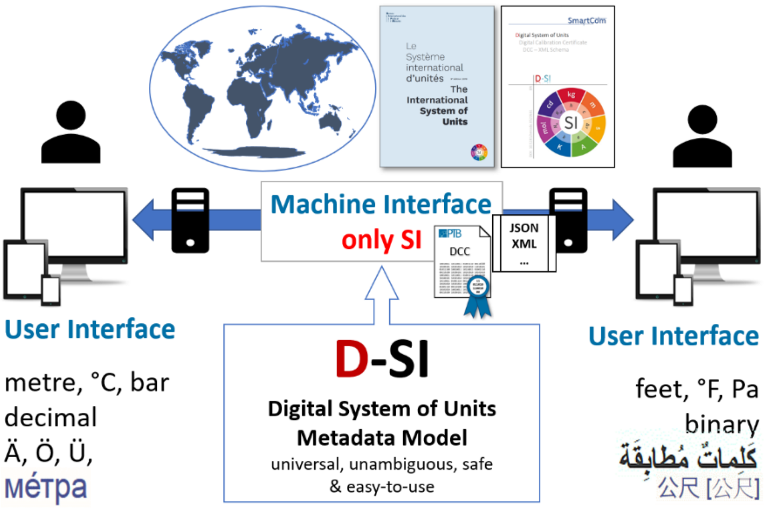


Figure 1 Metrological data exchange – the challenge of digitally exchanging data with, e.g., different units

**Summary**

In summary the project achieved objective 1; To define the requirements for a uniform, unambiguous and safe exchange format for measurement data and metrological information in an IoT network. The exchange format was based on the definition of SI units and met central requirements from standards, guidelines and legal metrology. The project achieved this by collecting essential needs for metrological data and its digital representation from internationally agreed standards such as VIM, GUM, the BIPM SI Brochure, ISO 80000, ISO 8601, NIST SP 811, IEEE 754, RFC 362 (UTF-8) and CODATA's fundamental physical constants. These needs were fused to create uniform, unambiguous and safe metadata models for real, complex and vector quantities.

A comprehensive description of the metadata model is provided by the brochure "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". The brochure has been made publicly available in English (https://doi.org/10.5281/zenodo.3816686) and Chinese (https://doi.org/10.5281/zenodo.4003413).

The description of the metadata model is accompanied by a realisation of it in XML data exchange format, making it easily usable. In addition, a short and end-user focussed 'catchy' version of the digital SI format was developed and is provided as a digital brochure. Based on the XML realisations, fundamental physical constants from CODATA have been implemented in a machine-readable format and have been made available online by PTB.

*<u>Objective 2:</u> To develop and establish secure DCC. This should include exchange formats for administrative information, data transfer, cryptographic requirements, authentication and digital signatures.*

**<u>The need for DCCs:</u>**

In order to be able to develop and establish secure DCC, you must first understand the necessity for a digital and machine-readable version of a well-established analogue system. Currently, calibration processes performed by National Measurement Institutes (NMIs), Designated Institutes (DIs) and calibration laboratories lead to paper-based certificates. These paper-based certificates are physically signed by authorised staff at the respective institution, typically printed on special paper, and conform to standards as prescribed by ISO 17025, indicating the accreditation status of the relevant calibration organisation. The certificate is posted to the customer and the calibration information on the certificate is then manually transcribed into the processing system that uses the device or artefact that has been calibrated. The content of the calibration certificates is based on the SI system of units (see Objective 1), which provides the framework for comparable measurements. The comparability is based on the traceability to the SI system and ensured by an unbroken chain of calibrations (based on primary (i.e., NMI/DI), secondary and tertiary standards).

For example, in Germany, the PTB has the legal mandate to represent the SI units using (primary) national standards and performs approx. 5000 calibrations per year. The second level of accredited calibration laboratories in Germany, provide approx. ten times more calibrations than PTB per year and the third level of calibrations (in-house calibration laboratories) carry out approx. ten times more calibrations than the accredited laboratories. Last in this calibration chain are the company division calibrations with approx. 100 times more than the afore mentioned in-house calibrations i.e., approx. 50,000,000 per year (5000 x 10 x 10 x 100). This shows the huge amount of calibration certificate issued each year, and the essential role they play in the quality management process.

Another factor to consider in the traceability chain is human error; the manual transcription of the data for each calibration is a potential source of error as well as being inefficient in terms of time and costs. Automatic creation of DCC directly from the data acquisition software used in the calibration process would therefore help to eliminate such (manual) data transfer errors and save time and costs.

Some calibration service providers (e.g., NPL in the UK and Metrosert in Estonia) have started generating calibration certificates in the form of digitally signed PDF documents as a first step towards digitisation. This allows calibration certificates to be sent electronically and securely to the customer. However, PDF documents, are not machine readable therefore, a person is still required to physically view the certificate on screen and to transcribe the data to the relevant system. Thus, this PDF method suffers from the same human error time and cost issues as when working with analogue calibration certificates.

The lack of machine-readability of the PDFs has a further negative implication on storage, e.g., for specialised databases and potentially (in case of on-board digital storage capability) in the devices themselves. To address all these issues calibration data in a machine-readable format is needed. Such DCCs would enable a range of data mining and statistical analysis tasks to be performed on the data, with significant advantages for quality assurance.

**<u>Challenges and rules for the secure use of DCCs:</u>**

The cryptographic requirements for the development and establishment secure of DCCs are very complex. Currently no international standard exists for secure transmission, digital stamps and signatures and/or the withdrawal of data.

The implementation of such internationally harmonised approaches also faces challenges in terms of the acceptance of cryptographic security between different organisations, different countries and the sheer number of different stakeholders involved. When looking at the diversity of requirements in strongly regulated areas such as legal metrology it seems highly likely that a fully harmonised international approach may not be achievable. However, even partial harmonisation of approaches such as for the communication of data for a particular measurement device (e.g., weighing instruments based on minimum mandatory requirements), would be provide significant benefits for international metrology.

As a first step towards developing and establishing secure DCCs, the project partners PTB, Taltech and Aalto agreed a minimum set of requirements for the secure use of DCCs and the determination of relevant cryptographical methods. Amongst others, these requirements include:

- preservation of readability,
- integrity and authenticity,
- stable data formats,
- electronic signatures,
- mutual recognition across borders,
- compliance with privacy policy,
- interoperability,
- preservation of controllability of data,
- verification/ validation of data,
- usability
- and the ability for withdrawal.

To be able to implement these requirements the partners first had to consider two aspects: 1) additional data structures in DCCs supporting the use as a digital document and 2) an external infrastructure for the exchange and verification of DCCs.

Following this, a more detailed outline of rules and recommendations for a secure exchange of digital data in metrology was developed by partners Aalto, Taltech, NPL and PTB. This included the transmission of digital metrology data over public networks as this requires a robust security strategy relevant not only to legal metrology information but to all metrological data. Prior to the start of this project, there was no single solution for the creation of digital signatures that were legally binding worldwide, or even for a large proportion of countries. For example, there are significant differences between European (the electronic IDentification, Authentication and trust Services (eIDAS) EU regulation) and Asian regulation (the Fast Identity Online (FIDO) standard) Further to this, current legal metrology standards relating to software operating in devices are limited to autonomously operating instruments that communicate over Local Area Networks (LANs) to simple peripheral type equipment rather than over Wide Area Networks (WANs) such as the internet. Therefore, a further recommendation from the SmartCom project was that standards that cover the security of digitised metrology information transmitted over public networks need to be developed by adapting or integrating existing standards from other domains such as web-based IT security.

A possible approach identified by the SmartCom project was to adapt the security model used by Microsoft, Apple and other organisations operating on WANs, which is reliant on a hieracarchy of secure authorisation (based on Root Certificate Authorities and a Public Key Infrastructure). This hiearachy of secure authorisation very closely resembles the hierachy of traceability to fundamental measurement standards which is core to metrology. The security approach recommended by the SmartCom project requires further work and is relevant not only to DCCs but for the communications of all metrological data, e.g., the communication of measurement data within sensor networks in the IoT network.

**<u>The SmartCom concept of DCCs based on ISO 17025:</u>**

Despite the challenges for their establishment and secure use, the use of DCC is of huge importance for future metrology. The SmartCom project's vision was to replace paper-based certificate systems with fully digital processes leading to DCCs in the form of XML based files which can then be communicated securely and instantly to customers. The design components for DCCs are one of the main outcomes of the SmartCom project and the project was careful to ensure that the design components were full aligned with ISO 17025. The project's design for the DCC in the form of an XML file should be fully machine readable, so that it can be read and interpreted by software, and the calibration data can be automatically transcribed to relevant systems without the need for manual transcription. This then avoids any risk associated with human error and the manual transcription of the calibration data into the target system. For compatibility with current practice, SmartCom's design for the DCCs also provides an on-screen viewable copy of the calibration certificate.

The overall goal of the project's DCC design was to build the foundations for uniform digital communications based on existing metrological standards and the core component of this a digitised version of the SI system of units, or D-SI (see Objective 1). One of the first steps for the DCC design was to decide what the metrological data included in digital certificates must consist of i.e., a numerical value and a corresponding unit as a minimum and once this was decided the partners worked on the development of the DCC content.

In alignment with ISO 17025 the partners PTB, NPL, Hexagon, Zeiss, Mitutoyo, Sartorius agreed to split the DCC design into 4 different layers, see Figure 2:

1. The administrative (shell) layer represents regulated (administrative) data. It contains the required information of core interest (i.e., mandatory), for example, for the unambiguous identification and collection of administrative information for the DCC.
2. The calibration results layer contains a regulated area of the measurement results, following the rules for the D-SI format; as well as an unregulated area for individual additional information e. g. individual calibration information.
3. A layer with individual information, for general, optional, and additional comments, calculation tables and graphics of any individual data formats, typically requested by the recipient of the certificate.
4. An optional attachment layer in which human viewable file can be stored (e.g., pdf format), typically a conventional analogue calibration certificate. This layer will not be machine readable.

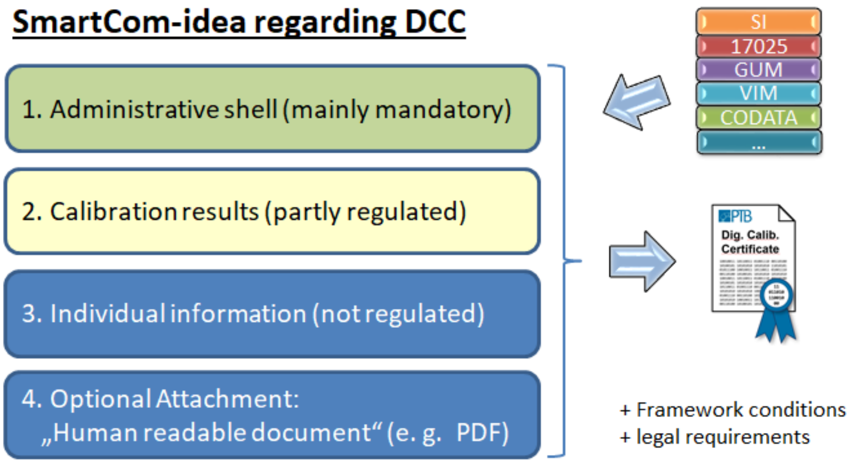


Figure 2 General DCC structure.

This initial DCC design process was followed by discussions on the content of the different DCC layers. This was done to ensure that the DCC design covered the needs of different stakeholders (e.g., industry, NMIs), and all partners (i.e., PTB, CMI, NPL, UM, Aalto, Ostfalia-HAW, Taltech, UNICAS, Hexagon, KRISS, Mitutoyo, NIM, Sartorius and Zeiss) and the project's stakeholder committee were involved in this process. In particular, the DCC's administrative data layer and the calibration results layer were discussed in detail e.g., for applicability with different parameters, and correspondence with existing analogue calibration certificates.

Following this, a basic outline of the DCC content was prepared by PTB and then distributed amongst the other project partners, see Figure 3. This DCC outline contained possible new parameters such as information about the Software used for issuing the calibration certificates and additional structures to enable the inclusion of parameters relevant for securing the document. The partners, then voted on whether they found the parameters useful or not and why. They also were given the opportunity to suggest new parameters for discussion. The final set of basic DCC parameters was determined in an iterative process of discussions, new proposals, change requests and votes, which the partners Aalto, CMI, Mettler-Toledo, Mitutoyo, NIM, NPL, UM and UNICAS taking the lead in the process. The final set of parameters distinguishes between mandatory parameters, which must be given for every issued DCC and optional parameters, for certain domains or types.

| Parameter | Description | yes/no/conditional | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | Partner 1 | Partner 2 | Partner 3 | Partner 4 | Partner 5 | Partner 6 | Partner XY |
| **usedSoftware** | | | | | | | | |
| name | Name of software used for creating an editing the DCC | n | | n | n | n | | n |
| release | Release status of used software | n | | n | n | n | | n |
| **coreData** | | | | | | | | |
| uniqueID | Unique identification of calibration certificate | y | y | y | y | y | | y |
| beginPerformance | Date at which calibration activities started | y | y | n | n | n | n | y |
| **item** | | | | | | | | |
| name | Unambiguous name/ label of calibration item | y | y | y | y | y | y | y |
| description | Detailed description of calibration item | y | y | n | c | y | | c |

Figure 3 Overview of the parameters, required for DCC.

Using the 4 different layers (or branches) for the DCC, in its practical XML implementation, the parameters were then arranged in a tree structure, see Figure 4. This structure gave a clear overview of the DCC content.

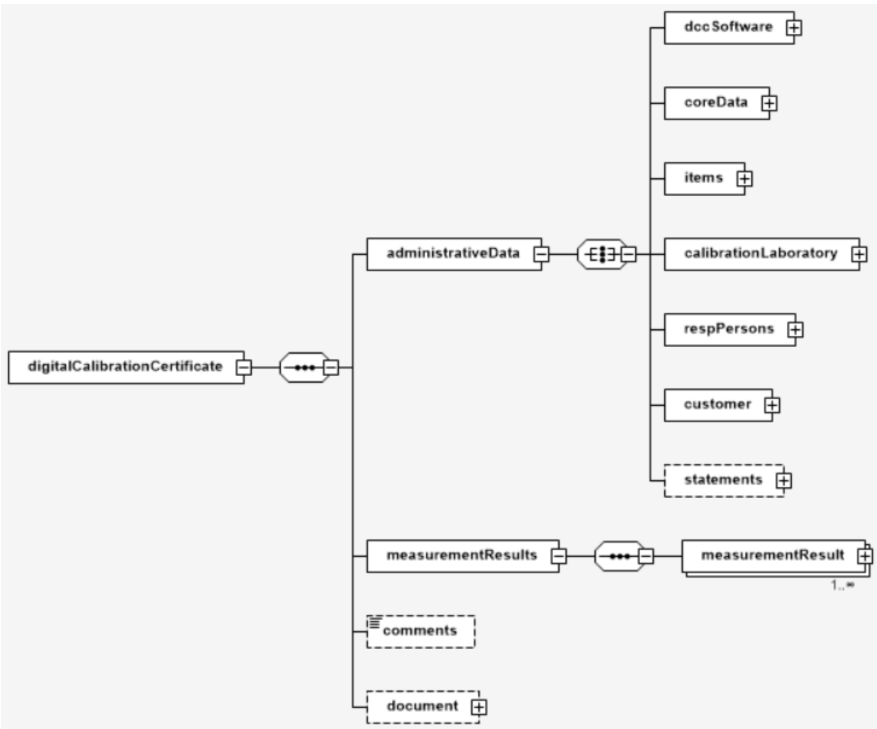


Figure 4 DCC parameters arranged in the tree structure.

**Summary:**

In summary the project achieved objective 2; To develop and establish secure DCC. Including the design of exchange formats for administrative information, data transfer, cryptographic requirements, authentication and digital signatures. The project achieved this by developing a process for the content and security aspects for the use of DCCs. Whilst the SmartCom project has highlighted the need for digital and machine-readable calibration certificates, as well as establishing a process for the secure use of DCCs in metrology further work is needed in order for DCCs to be used in a domain specific basis. A short summary of the DCC structure developed by the project ("*Document describing a universal and flexible structure for digital calibration certificates (DCC)*") can be found at https://doi.org/10.5281/zenodo.3696567

The project also produced valuable information on possible security solutions for DCC use, as well as recommendations on which approaches would best suit metrological needs. However, their implementation is beyond the scope of the current project. Further details on the rules for the secure use of DCC are given in "*Document specifying rules for the secure use of DCC covering legal aspects of metrology*" at https://doi.org/10.5281/zenodo.3664211

*<u>Objective 3:</u> To develop an online validation for services system for the types of data format as addressed under objectives 1 and 2.*

Online validation is a tool currently used in metrology. For example, test data for the validation of Gaussian or Chebyshev calculations or for the determination of the comparability of measurement results already exist and are available as part of the TraCIM ("Traceability for Computationally-Intensive Metrology") platform. TraCIM is a service run at PTB based on the outcome of a previous EMRP project NEW06. The validation of software versions by use of check sums is also well established and described, for example, in WELMEC (European Cooperation in legal metrology) Guide 7.2 Measuring Instruments Directive 2004/22/EC.

Prior to the start of this project the TraCIM platform was only able to validate the correct outcomes from calculation software and WELMEC Guide 7.2 was only able to validate whether software source code had been modified. The SmartCom has gone beyond this by developing a novel module for the validation of SI-based data formats and DCC. The new module can be operated within the existing TraCIM platform and its validation system.

The new module for the validation of SI-based data formats and DCC was developed by PTB and Ostfalia-HAW with support from partners NPL and UM who provided example test data sets for the D-SI XML format. Further to this all other partners i.e., CMI, Aalto, Taltech, UNICAS, Hexagon, KRISS, Mettler-Toledo, Mitutoyo, NIM, Sartorius and Zeiss provide support by running and testing the new module as pilot users. In addition, a Researcher Mobility Grant (RMG), a guest scientist from UM visited PTB and helped to develop a procedure for the verification of the SmartCom module for the validation of SI-based data formats and DCC (as part of the updated TraCIM platform).

The project's updates to the TraCIM platform now provide it with the ability to validate SI-based data formats and DCC including data implemented in XML, see Figure 5. The required XML implementations for the data formats were developed as part of Objectives 1 & 2. Compared to existing tools for XML testing from the domain of computer science, the updated TraCIM platform now allows the full validation of XML data using metrology testing principles (i.e quality management and testing procedures to NMI standard).

A publicly accessible server provides a demonstration of the updated TraCIM platform and new validation module and interested parties can access it following confirmation by PTB (smartcom@ptb.de).

The updated TraCIM platform and a new module for the validation of SI-based data formats and DCC was also presented to the project GEMIMEG II ("Safe and robust calibrated measurement systems for the digital transfer") who this project is collaborating with. As well as to stakeholders at the international DCC conference (PTB 2020), the project's stakeholder advisory board and at the final stakeholder workshop of the SmartCom project.

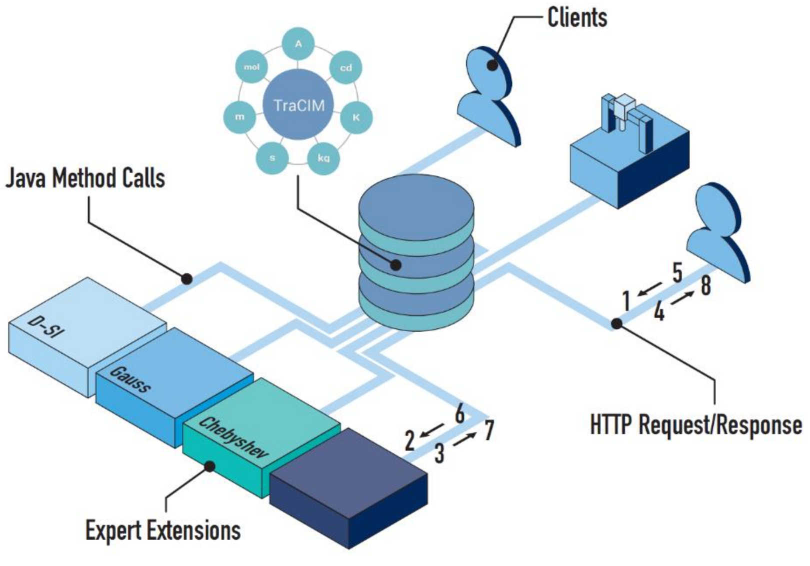


Figure 5 Concept of TraCIM validation system.

**Summary**

In summary the project achieved objective 3; To develop an online validation for services system for the types of data format as addressed under objectives 1 & 2. The project achieved this by updating the existing TraCim service ("Traceability for Computationally-Intensive Metrology", a validation service based on the use of check sums). The service has now been expanded by two new novel modules for the validation of SI-based data formats and DCCs.

The updated TraCIM system provides stakeholders with the ability to validate data implemented in XML and uses the requirements for the XML data determined in objectives 1 & 2. Interested parties can access it following confirmation by PTB (smartcom@ptb.de).

*<u>Objective 4:</u> To develop a reliable, easy to use, validated and secure online conformity assessment procedure designed for cloud system applications for legal metrology. The online conformity assessment procedure should also be applicable for calibration services and provide compliance with current international and European standards.*

The current legal requirements for technology supporting legal metrology do not cover the communication of legal documents related to e.g. measurement instruments over an intranet or internet. With the advent of the IoT and Industry 4.0, future legal metrology activities will be able to operate within and over such networks as well as connecting to cloud-based computer services. These services could also include remote access interfaces to legal metrology instruments with the potential to calibrate and update devices without the need to physically "visit" the instrument.

The lifecycle of an instrument can differ depending on the type of measuring instrument (e.g., water meter, electricity meter, weighing instrument, etc.) and its market. Thus, although the main steps within the lifecycle of a measuring instruments can be considered the same (as shown in Figure *6*). some steps are unnecessary or may be incomplete depending on the type of measuring instrument.

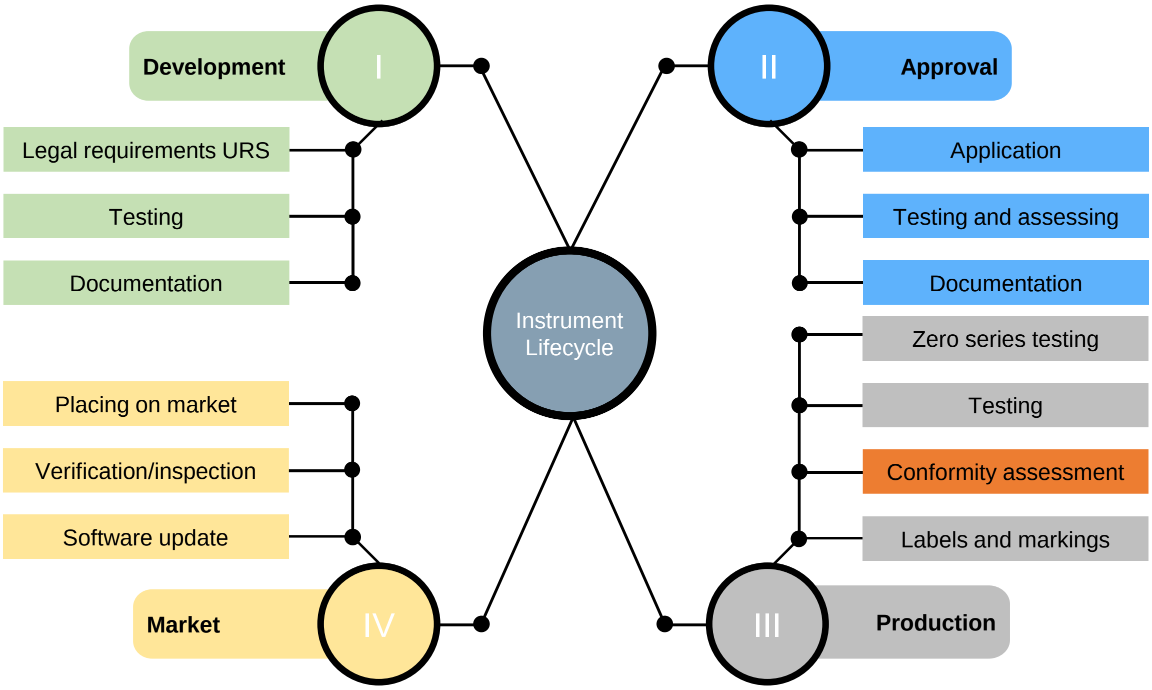


Figure 6 Lifecycle of an instrument.

Discussions between PTB and partners from the weighing industry Mettler-Toledo and Sartorius lead to the decision that the EU Document of Conformity (EU DoC) following the EU Non-automatic weighing instruments (NAWI) Directive 2014/31/EU was the most relevant process for conversion into an XML based, digital format, processed through a cloud service. As a first step towards the development of "online" legal metrology, the SmartCom project considered a typical example of legal metrology information that must be communicated safely and securely between relevant stakeholders before placing a new measurement instrument on the EU market i.e., the EU DoC requirements for the formal acceptance of a new product in the EU.

The project's example of EU DoC creation and exchange was then used to develop a prototype concept for the exchange of metrological data. The elaborated workflow for the secure metrological data exchange process consists of the following steps, see Figure *7*:

- Unified **user interface** installed on internet connected **manufacturer** device (UniTerm).
- **Security concept** for the transmission of metrological information outside the restricted environment.
- **Data transmission** using REpresentational State Transfer (REST), a well-established architectural style using the Hypertext Transfer Protocol (HTTP) protocol.

- **Data storage** and exchange using nodes.
- **XML-based validation schema**, including frameworks of the EU DoC.
- Unified **user interface** installed on **user** internet connected device (UniTerm).

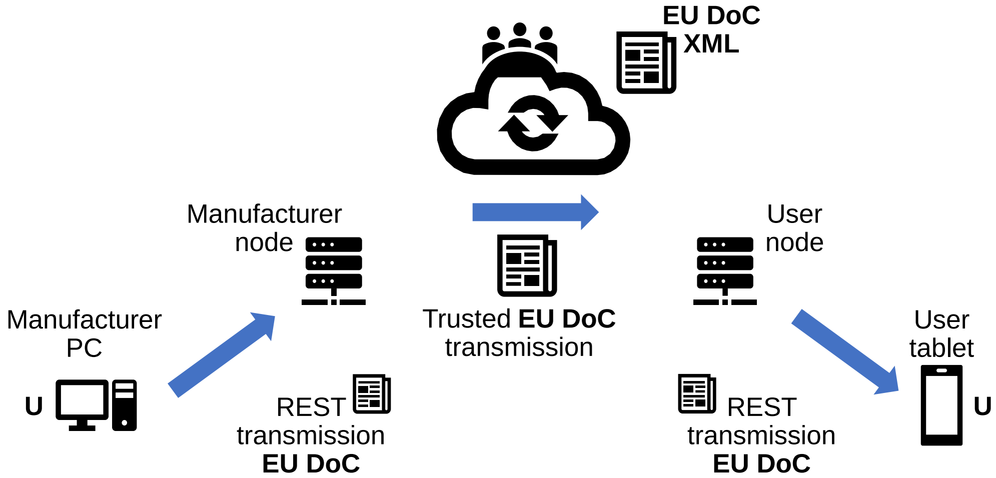


Figure 7 Concept of the online metrological data exchange. Legend: EU DoC; U (SmartCom UniTerm) - e.g. browser application for: viewing EU DoC, applying electronic signature to EU DoC and validating signature DoC.

The SmartCom **unified user interface**, UniTerm, was developed to enable metrological data exchange in the form of the EU DoC for use by stakeholders. In the user interface for UniTerm, the manufacturer fills in the form with the information on the object to be declared and requiring validation. In the next step, the XML file is generated in UniTerm and sent for validation and storage to AnGeWaNt's Document of Conformity (DoC) Service. The UniTerm interface was connected to a central service hub located on the service-oriented architecture (SOA) platform of the German Federal Ministry of Education and Research (BMBF) and the European Social Fund (ESF) project AnGeWaNt entitled Work on calibrated scales for hybrid weighing services on commercial vehicles (https://www.angewant.de/messwesen/), where the validation, storage and distribution of the data is managed. The SOA of the AnGeWaNt project was chosen due to its modular structure, enabling a rapid service prototyping. Additionally, to increase flexibility and ease later expandability, the platform employs standardized and harmonized interfaces across all services. Validation of metrological data in AnGeWaNt's DoC service was based on the validation of the XML file against schema, developed by Ostfalia-HAW and adopted by PTB. Figure 8 shows the basic XML structure of the example. Element *doc:declarationOfConformity* defines the root element of this structure. The prefix "doc" shows all elements that belong to this structure.

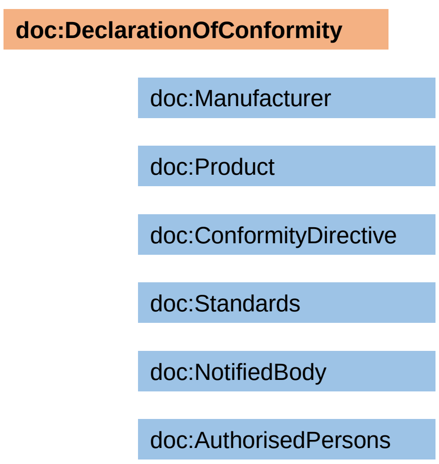


Figure 8 Basic structure of EU DoC XML schema.

The XML example presented in the SmartCom project only uses a subset of the full data that would normally be needed for a universally applicable EU DoC format. The example was developed according to the following three assumptions:

I. It is based on a practical EU DoC example from the weighing industry.

II. It addresses content required by the NAWI Directive Annex IV i.e., that needs to be machine-readable.

III. Where appropriate, it reuses data elements from DCCs to increase the implementation value.

Please note: the example developed is a proof of concept only. It is used to demonstrate metrological data transfer between the instrument's stakeholders and should only be used as a prototype of real application.

The **security concept** of UniTerm was developed by Aalto based on public key cryptography. The idea behind public key cryptography is to use cryptographic keys and specific algorithms to create and validate digital signatures and encrypt files. Cryptographic keys can be symmetric or asymmetric but as digital signatures were also used only asymmetric keys were considered in this project.

An asymmetric cryptographic key pair consists of a private key that is to be kept private and secure and a public key that could be publicly available, e.g., used to verify the signatures generated with the corresponding private key. The private and public key are mathematically connected to each and created with specific algorithms that ensure that the key pair is unique, see Figure 9 for illustration.

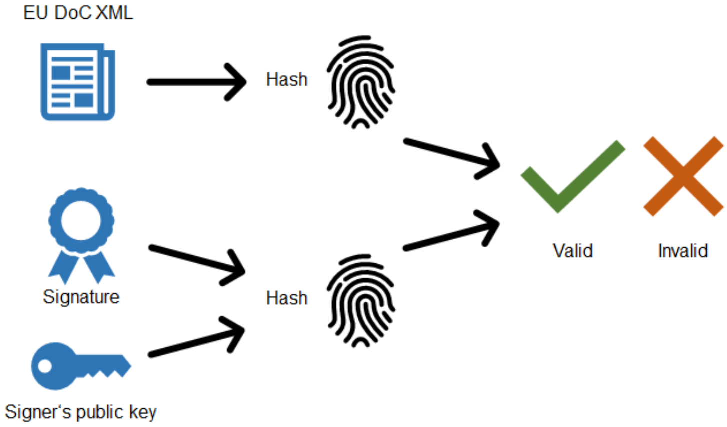


Figure 9 Schematic representation of a public key cryptography.

Partner, Taltech studied the legal regulations applied to the digital signing of the EU DoC, which are defined in EU Decision No 768/2008/EC. and applies to any other document that requires a signature. Within Europe eIDAS EU Regulation 910/2014 is the legal framework that forms the basis for a digital signature to be accepted across the EU by public entities and companies offering public services.

It should be noted that the EU defines the term electronic signature more broadly than the term digital signature, hence not all electronic signatures are legally binding. From a legal perspective, a single digital signature can be valid for several documents as long as the signee takes responsibility for the issued signature and is aware of what is being signed.

Currently, declarations of conformity can be issued as a scanned hand-written signature being inserted into the PDF. However, Qualified Electronic Signatures (QES) based on certificates from a Trust Service Provider (TSP) can be used without human intervention and are legally equivalent to hand-written signatures.

**Summary**

In summary the project achieved objective 4; To develop a reliable, easy to use, validated and secure online conformity assessment procedure designed for cloud system applications for legal metrology. This procedure was based on a secure, XML based UniTerm type interface using the REST protocol, connected to a networked or internet cloud type hub. The security concept of UniTerm was developed by Aalto based on public key cryptography. The online conformity assessment procedure was applicable for calibration services and provided compliance with current international and European standards. The project achieved this and produced a document that covered the core components of the UniTerm design. It was published as a "Guideline describing the concept of UniTerm and how to establish secure communication interfaces in legal metrology" at https://doi.org/10.5281/zenodo.5121620

*<u>Objective 5:</u> To build and validate demonstrators involving running applications from industrial stakeholders, to facilitate the take up of the technology and measurement infrastructure developed in the project.*

Two demonstrators were built and validated to facilitate the uptake up of the project's results (Objectives 1-4).

**DCC Demonstrator**

The first demonstrator showcased Objectives 1 & 2 and the use of DCC, Digital SI (D-SI) and appropriate cryptographical methods such as digital signatures and Distributed Ledger Technology (DLT), a.k.a. a blockchain, for the secure exchange of measurement data and relevant metadata. The DCC demonstrator used a system for the secure exchange of mass and position data of containers in harbours as a part of a logistics chain. Partner, Aalto's smart overhead crane and its digital twin were used as a platform to build a secure data chain including DCCs of critical component logistics from the manufacturer to end users at harbour site and to the respective authorities. The demonstrator was then validated with support from the project's industrial partners Zeiss, Hexagon, Mettler-Toledo and Sartorius.

The DCC demonstrator's approach for ensuring the security and trustworthiness of the data included two aspects. Firstly, the correct representation and traceability of the measurement data, and the reliability of the devices used to collect the data were ensured using the D-SI and DCCs for presenting the measurement and calibration data. The validation of the metrological data was performed with manual run of TraCIM system, using Objective 3. Secondly, the integrity and authenticity of the data was ensured using digital signatures whilst the database was protected against subsequent adding, removing, or replacing of data files by using the blockchain implementation.

As part of the development of the DCC demonstrator, Aalto carried out a study on the legal requirements for the exchange of measurement data using a smart harbour overhead crane. In particular, the requirements of the Safety of life at the sea (SOLAS) convention were considered. SOLAS requires that the verified gross mass of each individual container must be provided to the carrier ship operators by the harbour operators to ensure that the stowage plans of the ships are prepared based on reliable information to optimise the stability and safety of the vessels. However, the exactness of the data can be limited as the calibration information for the instruments used and other relevant metadata might not be included with the measurements or can be presented in varying formats. In addition, any processes involving manual operation includes the risk of human error. Therefore, the aim of the DCC demonstrator was to create a system for the secure exchange of measurement data of the weight and position data of containers in a machine-readable and metrologically correct format. In order to prevent the risk of human errors, mixing of units and tampering of the information.

Based on Aalto's study and outcomes of Objectives 1 & 2, Aalto developed a concept for the DCC demonstrator system, see Figure *10*. At a later stage of the development process, the system was reviewed by project partners Zeiss, Hexagon, Mettler-Toledo and Sartorius. The concept was based on a server running application programming interfaces (API) for the different functions needed for data collection, security, and exchange. The server communicated with the smart crane's OPC Unified Architecture (UA) interface via a Raspberry PI computer that provided a Secure Shell (SSH) tunnel for security.

In summary, the data exchange process in the DCC demonstrator system goes was:

- First the measurement data obtained from the OPC UA interface is converted included into an XML file based on the D-SI data model with relevant metadata.
- The file is then digitally signed as presented in the UniTerm security concept (Objective 4).
- When the file has been signed, it is sent to the blockchain, which in this case is IOTA, where a transaction is made to store the information into the blockchain. IOTA is the distributed ledger system developed to handle transactions between connected devices in IoT.
- The information sent to IOTA includes a reference to the DCC of the measurement instruments so that the state of the instruments at time when the measurement was conducted cannot be repudiated afterwards.
- After the above steps have been done the data is saved into a Structured Query Language (SQL) database from which the data can be inspected in a user interface.

- The user interface is where the user can validate the signature of the data file and blockchain transaction and inspect the DCCs of the measurement devices used.

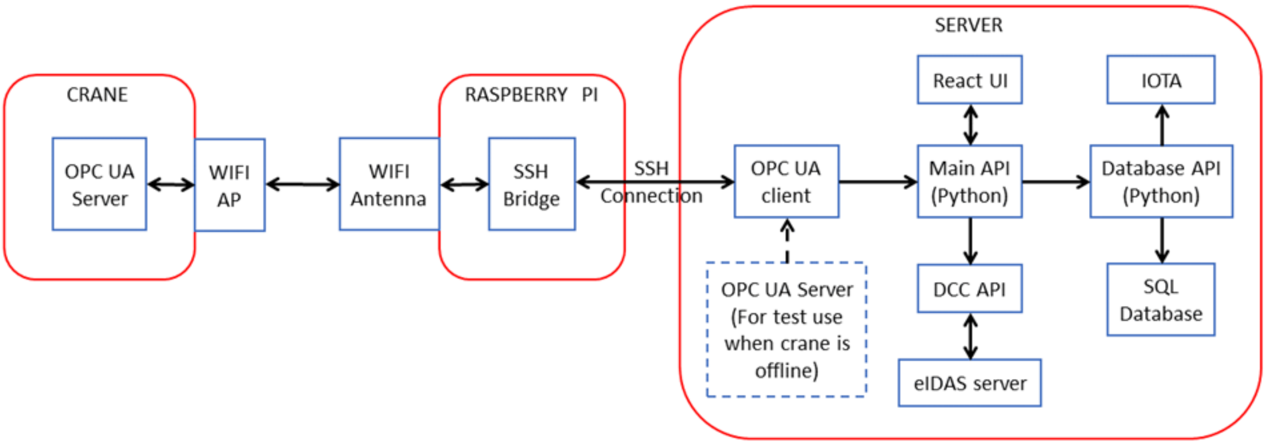


Figure 10 Concept for the smart crane DCC demonstrator for secure data exchanged in the logistics value chain.

Aalto also provided proposals for the technologies and software to be used in the development of the DCC demonstrator, which were reviewed and agreed with partners CMI, NPL, PTB and KRISS to ensure their metrological viability and compatibility with the outcomes of Objectives 1 & 2. Based on the technology and software selections, Aalto then developed the DCC demonstrator system. Aalto presented the system to the entire consortium for review during project meetings.

The DCC demonstrator system was successfully validated by the industrial partners Zeiss, Hexagon, Mitutoyo, Sartorius and Mettler-Toledo. The combination of using DCCs, D-SI, cryptographical methods and a blockchain provided the secure exchange of metrological data both in an industrial end-user application. The codebase of the DCC demonstrator was published as open source in a gitlab repository (https://gitlab.com/aalto-smartcom/ceracrane). Further details use are given in “Report on the validation of a demonstrator for the exchange of dimensional measurements in an end user application, with a secure logistic data chain including DCCs” available at https://zenodo.org/record/5522855.

**UniTerm demonstrator**

The project’s second demonstrator showcased the use of the UniTerm application developed in Objective 4. The UniTerm demonstrator showed how the legal weighing industry can use UniTerm in future technologies such as cloud applications, distributed systems and smart technologies, in order to support the launch of innovative products faster. The demonstrator was developed and validated by partners PTB, Taltech, Sartorius, Mettler-Toledo and Ostfalia-HAW.

Figure 11 shows a top-level Use Case Diagram for the web-based process whereby an instrument manufacturer is requesting the validation of an EU DoC for a new instrument to be brought to market.

It is the manufacturer who instigates the process for the creation of the EU DoC to then be validated by: (a) creating an EU DoC, and (b) uploading the EU DoC to an EU DoC Service.

At the other end of the process the user can securely access the EU DoC document, using their ID.

Please note that behind the automated interactions shown in Figure 11 there will be other systems and actors involved, however they have not been included for the purpose of the system being described here.

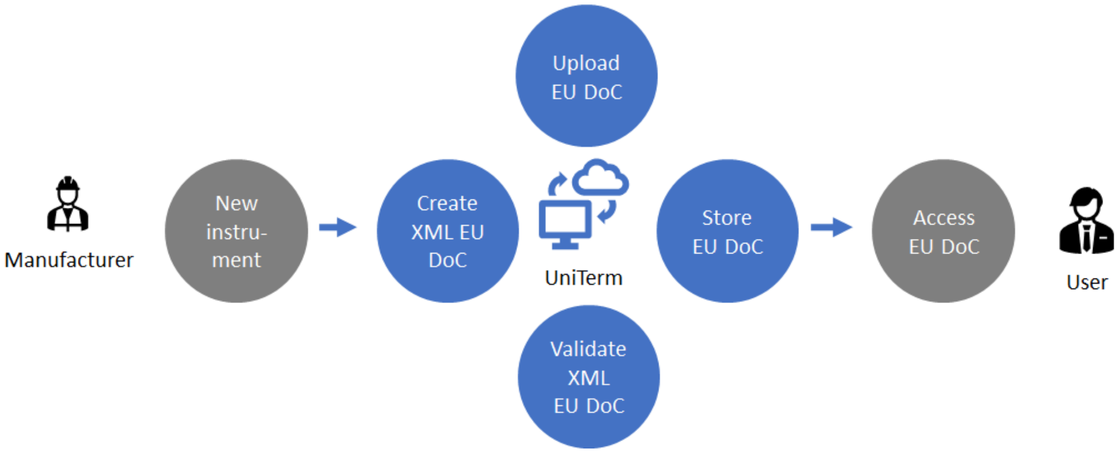


Figure 11 UniTerm Use Case Diagram.

The graphical user interface (GUI) of UniTerm provides different functionality that helps instrument manufacturers and their users to work with the digital EU DoC. The UniTerm demonstrator software can be run locally on a computer or via an internet connected device, as the GUI is executed within a web-browser. The GUI has a button to manually create a new EU DoC which subsequently is converted into a machine-readable XML file.

The process is supported by automated notifications to help prevent incomplete or wrong content by users. A simple Drag-and-Drop mechanism for pre-prepared XML files is provided as well. The up- and download of the digital EU DoC to the cloud platform is controlled using a unique ID and uploaded XML files are validated against an XML Schema Definition (XSD).

The process for applying UniTerm with the Digital EU DoC is shown in Figure *12*. The figure schematically represents the sequence of events, required to create and validate an EU DoC by the manufacturer as well as access to the existing documents by the user. Process map components presented in blue denote the implemented functionality of UniTerm. Orange-coloured fields refer to EU DoC and archive services, using the SOA platform of the AnGeWaNt project (Objective 4). The grey-coloured fields describe functionalities, which could be implemented in a future version of UniTerm.

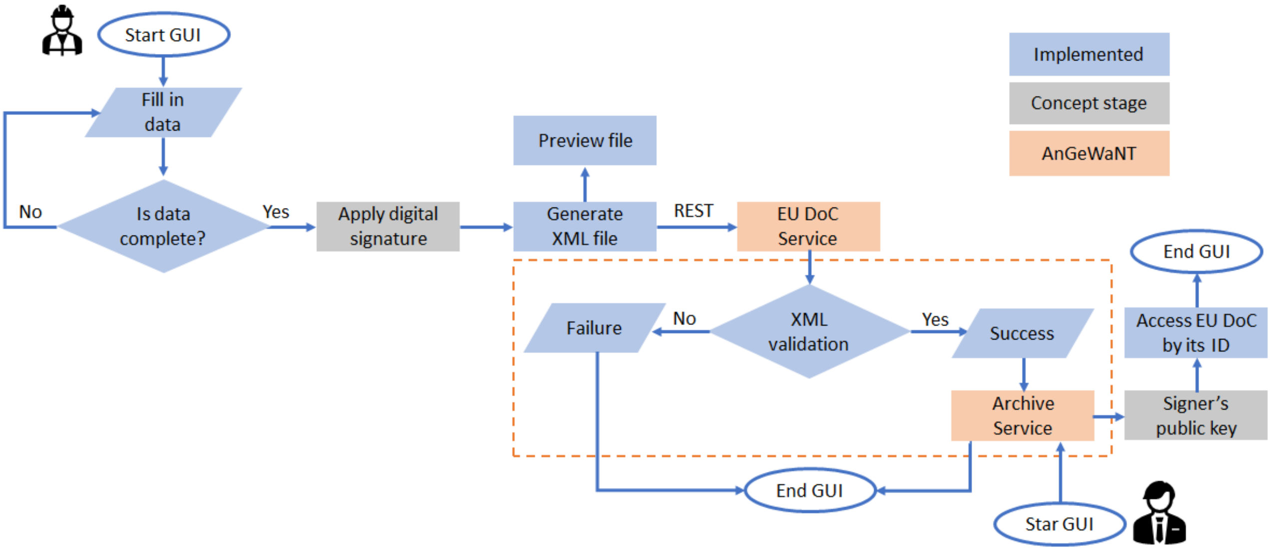


Figure 12 Process map of the UniTerm.

The UniTerm demonstrator was successfully validated by partners Sartorius and Mettler-Toledo. Further details are provided in “Report on the validation of a demonstrator for the use of UniTerm in the legal weighing industry” at https://zenodo.org/record/5527050.

As part of future work, the industrial partners made the following suggestions to improve UniTerm:

- Inclusion of input automatisation as manufacturers frequently issue large numbers of EU DoC documents on a daily basis, which makes manual data input ineffective.
- Integration of UniTerm with the instrument manufacturing system. Direct information transfer from the manufacturing system, containing all the required instrument information, will support the generation of the EU DoC XML file. Allowing the human-readable version of the EU DoC to be downloaded so it can be shared with National authorities, who, do not currently support a digitalised conformity assessment process.
- The extension of UniTerm to include the option to update or correct existing EU DoC.
- Several smaller recommendations were also made regarding more user-friendly interoperability for UniTerm such as more informative error messages and better UniTerm field names, etc.

**Summary**

In summary the project achieved objective 5; To build and validate demonstrators involving running applications from industrial stakeholders, to facilitate the take up of the technology and measurement infrastructure developed in the project. It did this with two demonstrators were built and validated to facilitate the uptake up of the project’s results (Objectives 1-4).

The DCC demonstrator used a system for the secure exchange of mass and position data of containers in harbours as a part of a logistics chain. The DCC demonstrator’s approach for ensuring the security and trustworthiness of the data included two aspects. Firstly, the correct representation and traceability of the measurement data, and the reliability of the devices used to collect the data were ensured using the D-SI and DCCs. Secondly, the integrity and authenticity of the data was ensured using digital signatures whilst the database was protected against subsequent adding, removing, or replacing of data files by using IOTA.

Based on a basic version of the EU DoC for the weighing industry, the UniTerm demonstrator showed how, in principle, legal metrology information can be shared and processed in a local, or wide area network environment. A GUI provided the different functionality that instrument manufacturers and their users require in order to work with the digital EU DoC. The UniTerm demonstrator software can be run locally on a computer or any other interned connected device, as the GUI is executed within a web-browser. The up- and download of the digital EU DoC to the could UniTerm platform is controlled using a unique ID and uploaded XML files are validated against an XML XSD.

# 5 Impact

The project has attracted significant interest from metrological organisations, academia and industry and its promotion to the CIPM of D-SI units for the communication of metrological data has led to the foundation of the CIPM Task Group “Digital-SI” which is pursuing the future harmonisation of SI units in digital applications.

The project has produced 5 publications which are either published or approved and waiting for publication and has been presented 17 times at national and international conferences such as CIM 2019, Euspen International Conference 2020, the 2021 CIPM/BIPM workshop on the International System of Units in FAIR Digital Data and the 1st Internationale DCC Conference.

The consortia have also published 4 articles in professional journals from their attendance at the 2020 Global Internet of Things Summit (GIoTS), 2020 IEEE International Workshop on Metrology for Industry 4.0 & IoT and International Conference on Industry 4.0 and Smart Manufacturing.

Further to this, the project has published 4 Good Practice Guides on its developed ‘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’ and ‘D-SI in Short - Digital brochure on establishing the use of units in digitised communication’ (both Objective 1).

Finally, the project outcomes were presented to a broad international audience at a final project workshop in association with EUROLAB on ‘Metrology for Digital Transformation’. The consortia provided the main content for one of three workshop sessions ‘Digital processes in the quality infrastructure: the digital calibration certificate’ and chaired the subsequent Q&A session. The joint EURAMET and EUROLAB workshop was held in September 2021 and attracted over 600 participants worldwide from a wide range of organisations and institutions including: NMIs and DIs; Accreditation organisations; calibration laboratory’s members organisations; OIML and WELMEC.

*Impact on industrial and other user communities*

The project has shown end users from industry how its DCC demonstrator can provide the secure exchange of mass and position data for containers in harbours as a part of a logistics chain. Partner, Aalto's smart overhead crane and its digital twin were used as a platform to build a secure data chain including DCCs of critical component logistics from the manufacturer to end users at harbour site and to the respective authorities. The demonstrator was then validated with support from the project’s industrial partners Zeiss, Hexagon, Mettler-Toledo and Sartorius.

The Finnish company Beamax who provide smart calibration instruments for use in industry, plans to implement a commercial product based on the project’s DCC with high usability for laboratories in the pharmaceuticals industry. The exploitation is progressed and supported with help from parter Aalto. Another example of impact on industrial users is the German start-up company labfolder, which plans to implement an electronic laboratory folder software product for metrology end-users that uses the metadata format (objective 1) and the DCC for representing and exchanging measurement data.

The SmartCom project’s concept of a uniform and globally available communication protocol (objective 1) is highly valuable for industry and calibration services. In demonstration of this the European weighing industry invited the SmartCom project to their annual meeting in 2018 to obtain information on how it’s stakeholders could benefit from the project’s results. In addition, partner PTB was invited to disseminate the SmartCom concepts multiple times to the German Mechanical Engineering Industry Association (VDMA) and the Association of German Engineers (VDI), where the project’s DCC concept was identified as an essential part of future metrological infrastructures.

The project has worked with stakeholders from industry and other end user communities throughout its lifetime in order to ensure that its results are applicable to end users. The project’s stakeholder advisory board (which was joint with EMPIR project 17IND12) has included input from end users such as ABB Forschungszentrum Deutschland, Hottinger Baldwin Messtechnik GmbH, Instituto de Engenharia de Sistemas e Computadores - Microsistemas e Nanotecnologias (INESC-MN), MESAP Innovation Cluster "Smart Products and Manufacturing", University of Sarajevo Faculty of Mechanical Engineering, VDI/VDE Society Measurement and Automatic Control, Myna-Project.org s.r.l., Spektra Schwingungstechnik und Akustik GmbH Dresden and TNO (NL).

The validation system (objective 3) for establishing a long-term available online service will enable industry to get certification on the usage of the D-SI metadata format (objective 1). A prototypical setup of this service has been established on a web server hosted by partner Ostfalia HAW. A full online service from PTB is planned for public release in 2022.

*Impact on the metrology and scientific communities*

The SmartCom project will support and facilitate the metrology and scientific communities in the set-up and use of new services based on the provision of DCCs and automatic extraction of calibration values. The project will also support European NMIs in taking a leading role in providing quality-assured metrology information for Industry 4.0 and the IoT ecosystem.

To disseminate the project to the metrology and scientific communities, it has been presented at CIPM and to regional metrology organisations such as Euro-Asian cooperation of national metrological institutions (COOMET), Inter-American Metrology System (SIM) and Asia Pacific Metrology Programme (APMP).

The SmartCom project's second demonstrator was also used to showcase to the legal metrology community the use of the UniTerm application developed in Objective 4. The UniTerm demonstrator showed how the legal weighing industry can use UniTerm in future technologies such as cloud applications, distributed systems and smart technologies, in order to support the launch of innovative products faster. The demonstrator was validated by partners PTB, Taltech, Sartorius, Mettler-Toledo and Ostfalia-HAW.

Further to this, first versions of the DCCs based on the SmartCom project's definitions are being currently being tested by the GEMIMEG II project (https://www.gemimeg.ptb.de/startseite/). The GEMIMEG II project which is funded by the German government and started in August 2020, is focussed on the establishment of a national quality infrastructure, in which the quality of acquired data and the reliability of the statements and conclusions derived from them are guaranteed.

The SmartCom project has worked closely with the related EMPIR project 17IND12 Metrology for the factory of the future (Met4FoF). This has ensured that related results from both projects can be shared and used effectively and in order to prevent the duplication of work within the metrological community. The successful collaboration between the SmartCom and Met4FoF projects has resulted in the joint definition of demonstrators within the 17IND12 project – one for the use of the OPC-UA communication standard and one for use in MEMS testing. In the latter, a basic version of the DCC for temperature (adopted within the SmartCom project for INRiM's use case) and was used by the 17IND12 Met4FoF project, for the calibration of their MEMS service. Within the automated equipment testing system in the MEMS service, this basic DCC enabled the traceability of units and further development is planned by 17IND12 partner INRiM in collaboration with the GEMIMEG II project.

Finally, the SmartCom project has disseminated it's results to the metrology and scientific communities via training course and workshops, including a DCC workshop and training course on the development of digital calibration certificates within the SmartCom project in 2019, SmartCom DCC Netinar in 2020 and a EURAMET online session: Digital processes in the quality infrastructure: the digital calibration certificate in 2021.

*Impact on relevant standards*

The project's promotion of SI units for digital communication of metrological data at the International Committee for Weights and Measures (CIPM) led to the foundation of the CIPM Task Group "Digital-SI" which is pursuing the future harmonisation of SI units in digital applications. The German Calibration Service (Deutscher Kalibrierdienst, DKD) has also picked up the project's DCC concept and is now in discussions about how to establish their format for the mass and weighing industry.

In addition to this, the SmartCom project has been presented to the Open Platform Communications United Architecture OPC-UA working group and to the FIWARE foundation. FIWARE provides the future open-source eco-system for a majority of IoT applications and is part of the EU's rolling plan for the ICT standardisation.

Furthermore, the project's outcomes were dissemination to CECIP (the European Weighing Industry Association), EURAMET TC-IM 1448, EURAMET TC-IM 1449, EURAMET TC-L, British accreditation body UKAS, and German accreditation body DAkkS, Though EURAMET TC-IM 1448, the project's DCC concept of was also highlighted to the OIML, the international organisation for legal metrology.

Finally, the project's results were presented to ISO TC 213 10 ("Dimensional and geometrical product specifications and verification"), ISO TC 69 ("Applications of statistical methods"). DIN NATG ("standards committee technical bases"), the PSK (Finnish) Standards Association and VDI/VDE GMA 7.21 ("Industrie 4.0"). A presentation on the project was also given at the VDI/VDE GMA 3.31 ("coordinate measuring machines") annual meeting in October 2021.

*Longer-term economic, social and environmental impacts*

A long-term economic benefit for future markets involved in the IoT can be realised by the adoption of secure, unambiguous and uniform communication specifications for the exchange of data in communication networks, where metrological data is used. As developed by this project, such secure, unambiguous and unified communications should result in shorter timespans from product to market, reduced downtimes, fewer rejected parts, improvements in quality control, better organised maintenance, and better conservation of energy and resources. An example of end users who will benefit from the application of such data exchange systems are goods transporters particularly via harbours and containers. Since July 2016 the International Convention for the Safety of Life at Sea (SOLAS) has required the Verified Gross Mass of all containers to be delivered to the vessel carrier (as it is needed for the stowage plan of the vessel to optimise the ship's stability). The project's DCC demonstrator using a smart overhead crane (at partner Aalto) with secure exchange of mass and position data of containers in harbours as a part of a logistics chain, and hence a more equal weight distribution on container ships shows the potential long-term benefits.

Another long-term impact of the project is the increased confidence that organisations will gain by being able to exchange measurement information digitally, safe in the knowledge that the necessary metadata relating to units and uncertainties have also been exchanged using validated protocols. The long-term benefit of this will be a significant decrease in financial and societal risks resulting from the misinterpretation of data.

# 6 List of publications


1. Brown, C. "Semantic web technologies for data curation and provenance", Conference Proceedings, 19th International Congress of Metrology (CIM 2019), Paris, France, 2019, pp. 1-6, doi: 10.1051/metrology/201926002
2. Ačko, B.; Weber, H.; Hutzschenreuter, D.; Smith, I. "Communication and validation of metrological smart data in IoT-networks", APEM Journal 2020, 15 (1), pp. 107-117, doi: 10.14743/apem2020.1.353
3. Mustapää, T.; Nikander, P.; Hutzschenreuter, D.; Viitala, R. "Metrological Challenges in Collaborative Sensing: Applicability of Digital Calibration Certificates," Sensors 2020, 20, 4730, doi: 10.3390/s20174730
4. Hutzschenreuter, D.; Müller, B.; Loewe, J. H.; Klobucar, R. "Validation of SI-based Digital Data of Measurement using the TraCIM System", Journal of Sensors and Sensor Systems 2021, 10 (2), pp. 289-295, https://jsss.copernicus.org/articles/10/289/2021/


This list is also available here: https://www.euramet.org/repository/research-publications-repository-link/

# 7 Contact details


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