QU4LITY

DIGITAL MANUFACTURING PLATFORMS FOR CONNECTED SMART FACTORIES

D2.8 Standards Compliance and Interoperability Specification (Final Version)

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Abstract: This document defines common specifications for standards compliance and interoperability for zero-defect production within the QU4LITY project and gives general recommendations for the use of these standards. The goal of such a specification is to ensure compliance between the providers of QU4LITY technology and the end users in order to ensure effective implementation within the individual pilot projects as well as between the pilot projects.

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Contents

HISTORY

0.1	15/07/2019	Deliverable structure	FHG
0.2	30/08/2019	Initial version	FHG
0.25	15/09/2019	Contribution to questionnaire from pilot leaders and technology providers	FHG
0.3	17/09/2019	Second draft	FHG
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0.53	12/09/2020	Restructure and update of all chapters	FHG
0.54	15/09/2020	Completed all sections. Formatted the document.	FHG
0.55	24/09/2020	Added required sections (executive summary and conclusion)	FHG
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Executive Summary

Building secure, maintainable and efficient solutions in the field Autonomous Quality (AQ) processes and manufacturing demands the compliance and implementation of relevant standards depending on the specific use case and its requirements. Based on the QU4LITY reference architecture (RA) described in D2.11, the global standard landscape for zero-defect manufacturing technologies and standards currently used within the pilots, the document will give a recommendation of the standards to be followed by technology providers and digital platform implementations for different topics such as **safety and security, artificial intelligence, reference architecture, data interoperability** and **quality standards**. Moreover, the document contains a range of **interoperability specifications** as a common guideline, that will drive digital technologies and enables interoperability at the equipment, processes and pilot levels.

This document represents the final version of "Standards Compliance and Interoperability Specification" as defined as deliverable D2.8, based on its pre-version D2.7. The given recommendations and specifications have been iteratively developed in task T2.4 in strong cooperation with other WP2 tasks and are streamlined with standardization contributions in WP9. Additionally, the document is influenced by the **standardization activities** of other EU-funded projects such as BOOST 4.0, BIG IoT and other results from the respective projects of the DMP Cluster and OPEN DEI.

In a first step, the screening of current standards in the field of zero-defect manufacturing took place. At the same time, information about the usage and the planned use of standards by the technology providers was assessed with the help of a questionnaire. The results were evaluated and linked to the project's standardization cluster activities (see section 2 and 3).

After the identification of the standards used by the pilots and the assessment of the current situation in form of standardization gaps and missing specifications, section 4 provides the key compliance requirements and the recommendation of standards over different categories. In section 4.1, a generic method for the assessment of interoperability specification requirements is described that can be used by the project partners as a guild-line to identify relevant standards, protocols and frameworks for a specific use case. In the further subsections, standard recommendations are given on topics such as security, artificial intelligence, reference architecture and quality standards.

1 Introduction

1.1 Motivation

In Zero Defect Manufacturing (ZDM) the information gathered by sensors and other data sources in its various formats and communication networks are used for an extensively automated exchange of information to optimize production and business processes. In such a broad environment, a large number of models, systems and concepts from a wide range of domains play an important part in shaping that structure. In QU4LITY and many other European and global ZDM initiatives, a greatly increased degree of networking and communication is expected from previously largely autonomous systems, leading to the creation of new complex systems based on different subsystems and other autonomous components. A special challenge occurs for standardization of terminology, integration and interoperability frameworks. To address the challenges with respect to the additional level of integration, the existing system landscape would first have to be coherently and completely defined in a globally standardized manner. Since this is not always the case, the classical system architectures in ZDM will have to be extended, integrated and enhanced, and the associated standards coordinated, consolidated and supplemented. The specification of standards compliance and interoperability will create a secure basis for technical procurement, ensure interoperability in applications, protect the environment, plant, equipment and consumers by means of uniform safety rules, provide a future-proof foundation for product development and assist in communication between all involved subsystems by means of standardized terms and definitions within the zero defect manufacturing landscape.

1.2 Goals and objectives

The main purpose of this document is to define a common standardization strategy for zero-defect production within the framework of the QU4LITY project, but also as a general recommendation in the area of ZDM. The goal of such a strategy is to ensure that there is an agreement within the QU4LITY technology providers and end users:

- How technical choices regarding interoperability can be made in order to ensure effective implementations within each pilot as well as across pilots. The choices should address not only interoperability at the communication layer but also in higher layers of the system (e.g. information, business layers) bearing in mind that a unified interface will be a key factor for market adoption of the standardized technology;
- How current standards in the ZDM space can be selected and used within pilots in order to maximize the common integration and interoperability chances. It is expected that when common standards are used on one or several layers of ZDM framework, this will have an immediate benefit in terms of interoperability;

- How missing or overlapping elements in various ZDM standardization areas –the standardization "gaps" and "overlaps" – can be addressed by the QU4LITY project in a coordinated manner in order to ensure that common solutions to resolve these gaps can be developed by one or several pilots.

The definition of a standardization strategy requires that all concerned stakeholders (e.g., the technology providers and pilot participants involved in the standardization activities) have fully defined their requirements, understood the technical ground on which they want to build their implementations, and know the missing elements that they would like to be developed by the standardization community. The standardization strategy is crucial to ensure interoperability in applications, protect the environment, equipment and consumers by means of uniform safety rules by means of standardized terms and definitions and will require that all technology providers and pilot participants have been undertaking the initial work.

This document, as outlined above, will provide a basic set of common elements (e.g. concepts, definitions, perceived requirements, existing standards, identified gaps, etc.) related to quality, safety and equipment compliance standards to ensure that the future standardization strategy - built by the stakeholders - is based on the same foundations.

1.3 Relation to other Activities

Deliverable D2.7 and D2.8 are the documented results of the work conducted in Task 2.4 (Standards Compliance and Interoperability Specifications). This task is one part of work package 2 – namely Autonomous Quality in ZDM: Vision and Specifications – which as devoted to analyze the stakeholder's requirements, the background platforms and technologies including relevant standards and interoperability needs. Within this work package not only digital models that will drive data integration across various systems and layers for autonomous quality in ZDM are specified, but also a detailed description for the QU4LITY Reference Architecture (Q-RA) is given. Therefore, the work in Task 2.4 is strongly related to other tasks in work package 2, especially, to Task 2.6 (Reference Architecture, Open APIs and Blueprints for Autonomous Quality Solutions) and Task 2.3 (Catalogue & Analysis of ZDM Equipment, Processes and Digital Platforms). The latter provides a structured catalogue of digital technologies and will also analyze technological compatibility of the various components. Deliverable D2.8 ("Standards Compliance and Interoperability Specification (Final version) ") which was due by the end of June 2020 will describe and specify completely QU4LITY's standardization and interoperability strategy. The final deliverables will be streamlined with the standardization contributions of the project in WP9.

This deliverable has also relations with other WPs.

On the one hand, it has relation to WP4 where the components to reduce the interoperability gap will be designed and implemented. The following task addresses this challenge:

- **T4.5 ZDM Equipment Interoperability, Federation and Autonomous Interactions**: will design and implement the techniques for intelligent data exchange and interaction between different types of ZDM equipment. These techniques will overcome the communication gaps between machines and platforms.

In WP5 one of the tasks is concerned with the enhancement of digital platforms based on Open APIs and interoperability characteristics. This task is:

- **T5.4 Digital Platforms Open APIs and Process-Level Interoperability:** This task will augment all digital platforms of the project partners with Open APIs, in order to enable their integration and use in various manufacturing applications, but also their enhancement by third parties. QU4LITY technologies that do not provide Open APIs will be enhanced with such APIs. On the other hand, technologies that already offer some Open API will have to be reengineered and refactored in order to ensure that their APIs adhere to the ZDM data standards. In this way, the task will provide a basis for data interoperability of different technologies and processes.

On the other hand, there are a number of work packages and tasks that will collect the results and conclusions obtained when implementing, deploying and testing the digital enhancements (including interoperability enhancements). In WP6, ZDM developments will be validated, verified and certified against standards and benchmarks at the equipment, platform and process levels. In WP7 the enhancements will be tested and validated in real scenarios. The results and conclusions obtained will be included in the deliverables. There are no specific deliverables where the interoperability enhancement will be presented but the different pilots and benchmark trials will include these in their deliverables.

Task 2.4 has been constantly streamlined with other specific contributions of WP9 to consider the standards already in use but also the identified gaps in standardization and interoperability specification.

- **T9.2 Standardization and Clustering:**

  The standardization strategy and work in Task 2.4 is fully aligned to the dissemination and standardization contributions in WP9, which give exhaustive information on the current standardization activities of the Standard Development and Standard Setting organizations, clusters, associations and other relevant stakeholders. More details can be found in Deliverables of the Task 9.2 (Standardization and Clustering) and Task 9.3 (Community and Ecosystem Building).

1.4 Contributions of partners

The main partners contributed to this deliverable are: ATOS and EPFL as project and WP2 leader respectively contributed to a deeper understanding of the T2.4 goals; Mondragon (MON) contributed as reviewer and survey participant to this deliverable. As the leader of T2.4 FHG contributed to a great extend to the writing of this Deliverable and had responsibility for coordination of activities related to standards compliance, development of the overall strategy in T2.4 and coordination and analysis of the interoperability specification in this project. Additionally, to effectively conduct a survey on standards already in use, the partners listed in Table 12 hold the close contact to the technology providers and stakeholders within the project and took the responsibility for gathering the relevant information on standards used for digital components. Therefore, many other partners have contributed in the form of survey participants to this deliverable.

1.5 Outline

Chapter 2 – General approach- describes the general approach and action plan of the Task 2.4 as well as gives a detailed description of the methods and techniques used in the standards-related data collection process.

Chapter 3 - Standards Research and Pilots Screening -devoted to research and analyses with respect to the state of the art in standardization in ZDM. In a first step, relevant publications and standardization documents are investigated and listed with respect to their field of application. In a second step, a survey is conducted to screen the current standardization situation for each pilot and to evaluate the digital technologies provided by the project partners. This chapter also establishes the linkage to T9.2 and gives an overview of standards mapping results, and provides active contributions of T2.4 with respect to identified standardization objectives.

Chapter 4 – Interoperability Specifications – *provides five respective compatibility specifications for applications and use of standards in QU4LITY pilots. The* specifications are technical guidelines that define an explicit set of requirements to be satisfied within pilot's applications as well as provide recommendations for use of relevant standards.

2 General Approach and Methodology

The following section describes the general approach and action plan of the Task 2.4 as well as gives a detailed description of the methods and techniques used in the standards-related data collection process.

2.1 Overall strategy and action plan

The overall strategy of Task 2.4 ensures the smooth coordination of the internal activities. The main content-related output of the Task is the development of compliance specifications, i.e. compliance guidelines, for QU4LITY pilots. Specifically, compliance recommendations in this document are based on analysis of standard-related information and examine pilots' specific interoperability scenarios regarding compliance requirements and current standards.

In relation to the objectives identified in the QU4LITY proposal, there are several important groups of activities to be performed in Task 2.4. Figure 21 (see Annex A) outlines the detailed action plan.

1. **Standards' screening (sections 2.1, 3.1, and 3.2).** This group performs several important activities with the overall purpose of identification and collection of project-related standards.
2. **QU4LITY Reference Architecture Compliance (section 4.4).** This group includes activities focusing on the conformity of Q-RA with current standards, in particular with regard to I4.0, Industrial IoT, Smart Manufacturing (SM) and other standard-relevant fields. Additionally, the activity analyses related EU-funded projects which studied RAs and compliance in the field of manufacturing (ZDM) in close cooperation with QU4LITY DMP Cluster activities (see Deliverable D9.5). The Reference Architecture Compliance Review as well as the Reference Architecture Mapping are a good means to give an overview of the conformity of an overall architecture with prescribed standards. In particular, the assignment to current standards can help to identify possible gaps in the applied standards, ensure the necessary quality control or offer other architectural alternatives.
3. **Interoperability specifications (chapter 4).** This group includes a set of activities that help to define essential technical and operational standards as well as the list of essential requirements that must be met in terms of interoperability among technical systems. QU4LITY interoperability specifications explicitly address the interoperability challenges in various Pilot use cases. Other activities deal with the practical documentation, which should serve as an overall guideline for technology providers and stakeholders around the pilots.
4. **Streamlining with standardization (section 3.3).** The activities of this group are responsible for synchronization and close cooperation with Task 9.2 Standardization and Clustering. The cooperation between these two tasks is bilateral, i.e. each task benefits from the other and is an important source of information. Therefore, the main objective is to exchange essential

information on the current development of standards and to make a qualitative contribution to QU4LITY standardization.

2.2 Alignment with the Project Plan

In alignment to the overall QU4LITY plan, the first draft was initiated by Deliverable D2.7. Deliverable D2.8 started in M9 and contributed to build on the first version with the goal to accomplish compliance interoperability specifications of the QU4LITY and give helpful recommendations for use of standards within the pilots' applications.

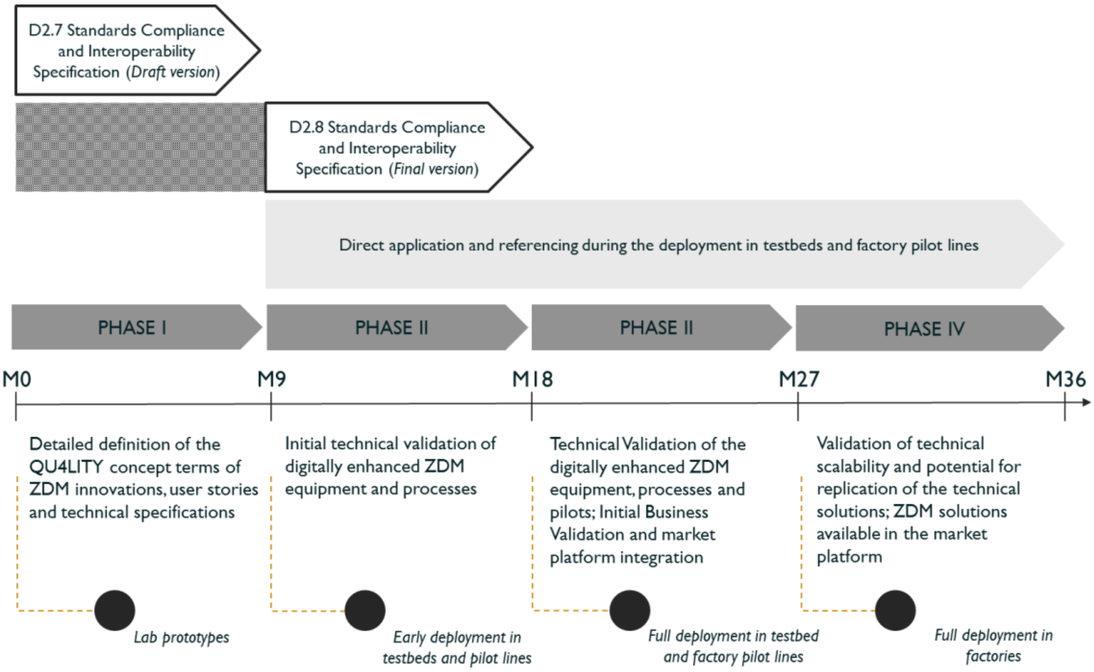


Figure 1: Alignment with the overall project plan

2.1 Description of techniques and templates

In order to carry out a comprehensive standards' screening across the QU4LITY Pilots, two questionnaires were set up addressing each technology owner in the consortium.

2.1.1 Pilots Screening Questionnaire (M1 – M9)

The first questionnaire aims for retrieving the early information about 1) what standards are already in compliance with the technological components provided by each entity, 2) what standards are planned to be followed and 3) what gaps in the standardization process are known to the technology provider. Since Task 2.3 also required input from each pilot partner for D2.5, mainly aspects about technologies missing in the digital technologies list in annex II of the grant agreement, the questions were integrated in a joint questionnaire (see Template in Figure 22 in

Annex B). To facilitate the evaluation, especially for the standards mapping to RAs, all participants were asked to classify their technology and related standards in the categories presented in Figure 23 (Annex B). The categories were taken from the RAMI 4.0 model instead of the QU4LITY RA, because it was not defined yet at the time the questionnaire took place.

A docx-file with these questions was uploaded to the OwnCloud project repository while a request to download the file, fill in the questionnaire and upload it again to the repository was distributed among all QU4LITY partners via mail to the overall mailing list. Since the project consortium is quite large, a tracking of the questionnaire participation for each single pilot took place. Table 12 shows which T2.4 partner was responsible for which pilot tracking. This assignment was based on each partner's amount of PMs in the task and his or her involvement in the pilots, see Figure 24 in Annex B.

2.1.2 Pilots Screening Questionnaire (M9 – M21)

The purpose of the second questionnaire is to 1) gather information what technologies cover which component of the QU4LITY RA and 2) identify interoperability standards and data exchange formats that are used at the interface of these components. Particularly the second aspect requires a coordination between all the partners in a pilot. Hence, this questionnaire had to be discussed in the scope of each pilot rather than contacting the technology provider separately. This is why the questionnaire was included in chapter 4 of the trial handbook send out to each pilot. The pilot contributors were asked to classify their technology in the QU4LITY RA by labelling a block in Figure 7 (e.g. via enumeration) and to fill in a short template shown in Figure 2. The enumerated labels should be used as references in the question about interconnection between components.

- **Indicate an architecture block by a number and name (Indicate component)**
  - **Brief description**:
  - **Connected to components:**
  - **Interoperability-standard (for each connection)**:
  - **Data exchange format (for each connection)**:

Figure 2: Template for the second questionnaire

3 Standards Research and Pilots Screening Results

This chapter presents the results of standards research and pilots screenings activities. The first two sections summarize the outcome of the standards screening throughout the pilots by means of the conducted questionnaires. In the third section, the investigations on relevant standards will be presented which plays an essential role for the work on standards compliance specifications. The overall purpose is to carry out the critical assessment of the interoperability standards applied in order to minimize the risk of technological shortcomings and to identify the gaps to be addressed in the interoperability specifications.

3.1 Pilots Screening Results (M1 - M9)

The following section presents results from the first round of the pilots screening (see respective questionnaire in section 2.1.1).

In total, 22 technology providers participated in the questionnaire covering 12 out of 14 QU4LITY pilots with 38 technologies. These technologies are already in compliance with an overall amount of 19 standards. However, these standards are covered by only ten technologies that are used in ten pilots. Table 1 lists the standards identified in the questionnaire and shows their usage in the pilot by some technology. There, the letter **o** highlighted in green represents a pilot technology already following the particular standard while plans to do so are marked by a yellow highlighted **p**. Only three entities (CEA, IDEKO and SYNESIS) are planning to enhance their intellectual property such that it will follow another standard, while two gaps in the standardization landscape were identified by MGEP and TID, see Table 15 in annex C. Thus, a first conclusion is that a majority of QU4LITY technology providers seems to neglect standards related topics.

Table 1: Mapping of standards from questionnaire to the pilots.

	#1 - PHILIPS	#2 - SIEMENS	#3 - CONTI	#4 - WHR	#5 – MON-1	#5 – MON-2	#6 - KOLEKTOR	#7 - THYSSEN	#8 - AIRBUS	#9 - GHI	#10 - RIASTONE	#11 - PRIMA	#12 - DANOBAT	#13 - FAGOR	#14 GF	other application
API REST						o							o	o		
IEC 61499																o
IEEE 802.1AS for TSN					o											
IEEE 802.1Qbv					p											
IoT-A event information model					o	o								o		
ISA 95							o									
ISO/IEC 15408:2009													o			
ISO/IEC 18045:2008													o			
MIMOSA DB					o	o								o		

	#1 - PHILIPS	#2 - SIEMENS	#3 - CONTI	#4 - WHR	#5 – MON-1	#5 – MON-2	#6 - KOLEKTOR	#7 - THYSSEN	#8 - AIRBUS	#9 - GHI	#10 - RIASTONE	#11 - PRIMA	#12 - DANOBAT	#13 - FAGOR	#14 GF	other application
MQTT						o	o							o		
MTConnect													p		o	
OPC-UA					p	o	o				p	p	o	o	o	
OPC-UA Vision							o									
P1589-IEEE												o				
QIF															o	
RAMI 4.0							o									
UMATI						o							o	o		
W3C DCAT	o	o	o		o	o	o					o	o			
W3C ODRL	o	o	o		o	o	o					o	o			

The complete questionnaire results can be found in Table 15in annex C alphabetically sorted by entity. A shorter summary with a mapping to the RAMI categories can be found in Table 13 in annex C that shows a full coverage of all technological categories by each pilot. Although the questionnaire was dedicated to technology providers involve in at least one pilot, there were five contributions from TID, UNP and NXT naming different fields of application, see Table 14 in annex C.

3.2 Pilots Screening Results (M9 – M21)

In a second round, information about the protocols and interoperability standards Based on the requirements of each pilot, standards, protocols and related frameworks are considered, analysed and selected to finally implement the component as specified.

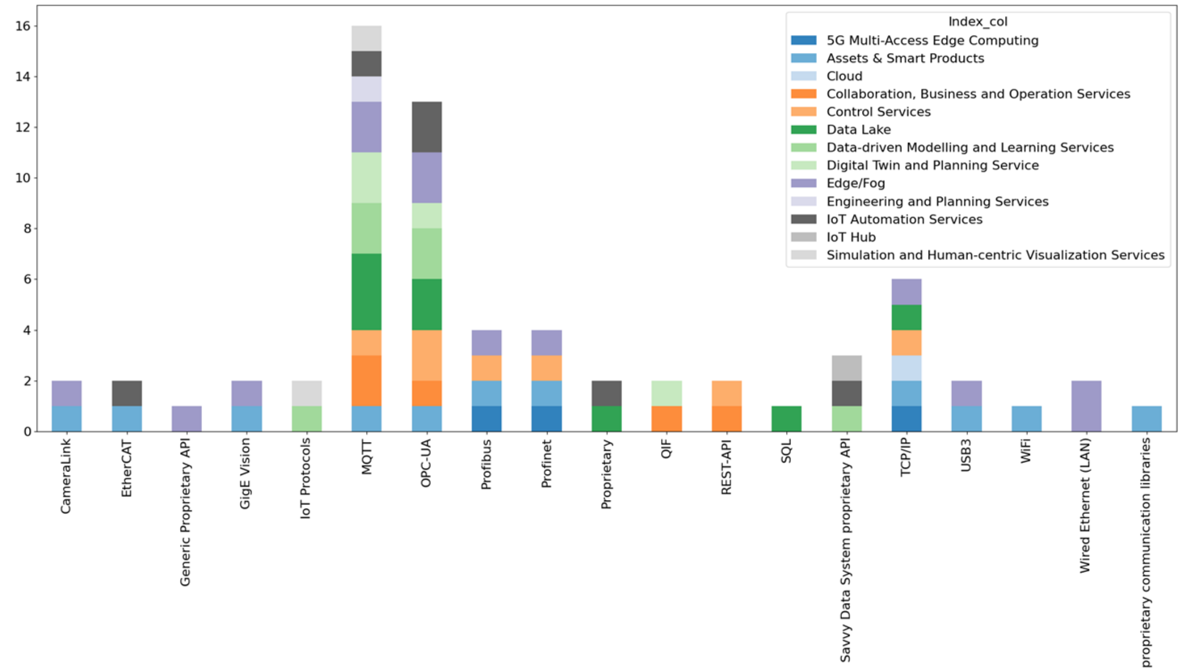


Figure 3: Standards, protocols and frameworks for ZDM currently used by the pilots (data from seven pilots)

Figure 3 shows the frequency of protocols, standards concerning interoperability used by the QU4LITY pilots. In addition, the bar colour indicates the component for which the protocol or standard was applied. In can be seen, that MQTT and OPC-UA are most frequently used, whereas some pilots use proprietary communication protocols and APIs. It is also obvious, that Edge/Fog hardware tend to have very broad interoperability needs ranging from GigE Vision, over Profinet to MQTT and Wi-Fi. Overall, different standards and protocols are needed for different applications and their specific requirements.

3.3 Standards research and Linking to Projects' Standardization and Cluster Activities

One of the first questions that arises when one is asking for standards in ZDM: Which topics need to be covered in order to provide a sufficient fundament of standardization and interoperability? To answer this question, we take a look at current trends in the manufacturing industry during our comprehensive standards research. This section aims at establishing the linkage to projects standardization work, highlighting the standards research results and providing an overview of active contributions of T2.4 to Task T9.2 with respect to projects' standardization activities.

Recent developments in countries with the highest industrial outputs (China, Europe, USA, Japan) have led to a concepts named (China 2020, Industrie 4.0, Industrial Internet of Things) that is often used to describe data-driven, AI-powered, networked "smart factories" as the harbingers of the fourth industrial revolution[1]. I4.0 has been made possible by the spread of new digital solutions used throughout the production process chain. Based on these technical fundamentals, zero-defect production and the associated Smart Factories are being developed with the aim of promoting the manufacture of high-quality industrial products in Europe.

Therefore, the starting point for the standards research in this work uses the latest research results of Task T9.2 about the current activities and stakeholders with respect to the identified standardization landscape (see Deliverable D9.5 and later D9.6). **More the 170 standards** could be collected through different sources, i.e. previous projects' results of the partners, online platforms of the standard developing organizations, associations, and other. Furthermore, to accomplish a profound screening of the pilot's standards were analyzed in terms of their relation to Q-RA and **mapped to Q-RA components**. It means that the components were taken as a respective basis as shown in Figure 5.

The mapping results contain all collected standards that served a **basic input for establishing of compliance specifications**. For more details consult Chapter 4 and Figure 5: Overview of the workflow for collecting data and relevant mapping procedures. The complete listing can is then converted in respective recommendations (tables) in sections 4.1.3, 4.2.3, 4.3.3, 4.4.3, 4.5.3.

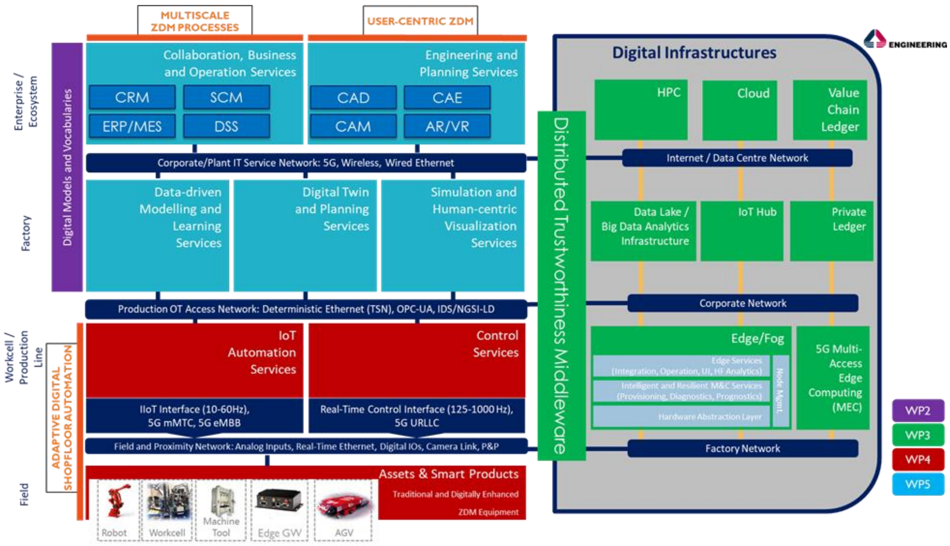


Figure 4: Allocation and collection of specific requirements for Q-RA components.

Task T2.4 coordinated this activity with experts of the Task T9.2 and exchanged latest results of the standards research. Overall, Task 2.4 contributed to standardization activities with the following items:

- a set of ZDM specific requirements to verify standards compliance interoperability framework for industrial applications; as well as interoperability goals and overall context in I4.0;

[1] Industry 4.0 - https://www.plm.automation.siemens.com/global/de/our-story/glossary/industry-4-0/29278

- standards compliance requirements on a ZDM Framework based on standards research regrading RAMI4.0 layers (see Chapter 0) and classification of standards;

Especially we would like to highlight the contribution of standards screening and the mapping results as it was a significant input to QU4LITY's DMP cluster work (see more details on DMP WG1 in Deliverables D.5 – D.8). The screening results will be prepared in Task 9.2 for public use and made available on the EFFRA Innovation Portal[2] linked to section of the Structured Wiki "*Standards, standardization and regulation*".

2 https://portal.effra.eu/wiki

4 Standards Compliance and Interoperability Specifications

The standards compliance and interoperability specifications proposed in the following sections are **guidelines for QU4LITY pilots** on the **most appropriate use of standards** to develop robust QU4LITY solutions that contribute to **compliance** with five respective cross-cutting standardization areas - **security, interoperability, artificial intelligence, quality, reference architecture, frameworks and vocabulary** development (based on [1]). A special focus of the specifications refers to new application requirements of Industry 4.0 and Zero Defect Manufacturing (ZDM).

Figure 5 shows the overall workflow developed in Task T2.4 for the preparation of the specifications, indicates relevant data sources, and outlines important inputs and outputs at all work stages.

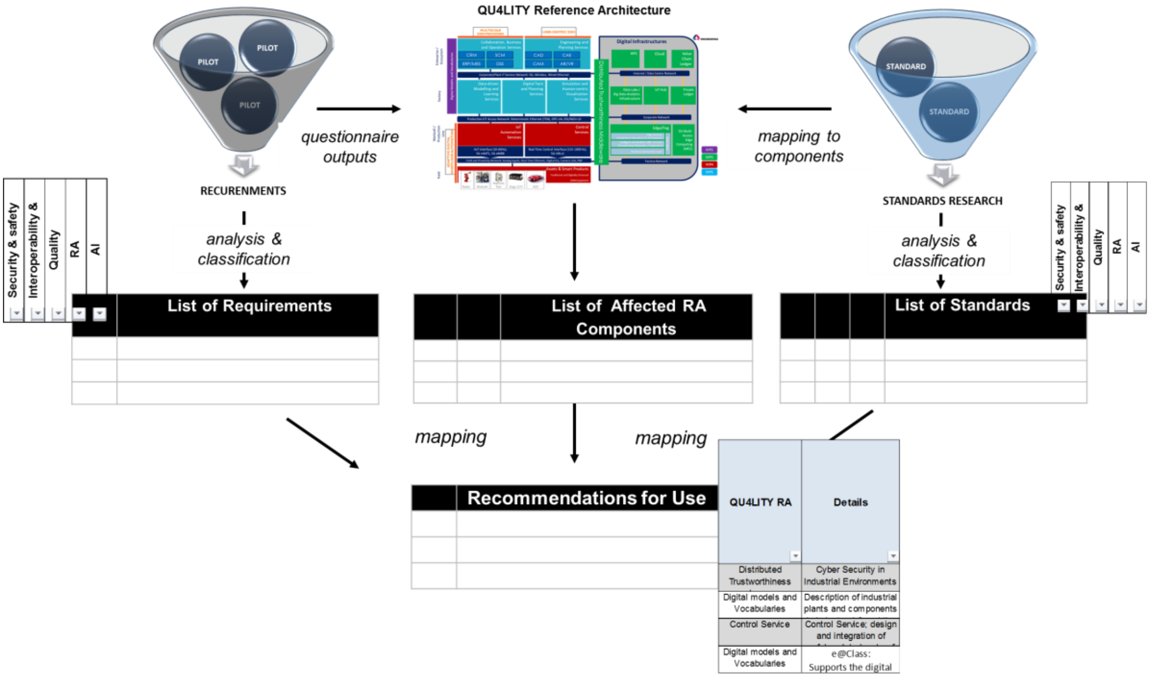


Figure 5: Overview of the workflow for collecting data and relevant mapping procedures.

It should be noted that the requirements collected from the pilots were compiled from the respective current results of WP2 - WP5 (see the relationship between components and work packages of the project depicted in Figure 4) and information provided in the pilots manuals, i.e. *Trial Handbook*.

All specifications aim at providing helpful recommendations for use for affected pilots:

1. Compliance Specification for Interoperability Standards
2. Compliance Specification for Safety and Security Standards
3. Compliance Specification for Artificial Intelligence Standards
4. Compliance Specification for Quality Standards
5. Compliance Specification for Reference Architecture Standards, Reference Architecture Standards, Digital Models and Vocabularies

4.1 Compliance Specification for Interoperability Standards

4.1.1 Definition of Interoperability

Crucial decision making operations that supply predictive and prescriptive purposes are commonly based on deep data analysis. Therefore, interoperability among various systems, application and processes play a key role in ZDM-related scenarios.

In broader context, **interoperability** describes the ability of a system or software application to exchange or make use of data and is an essential requirement for all hard and software elements that participate in the exchange of information in the given framework.

In traditional sense, interoperability usually applies to connectivity. However, due to a cross-linking of multiple systems in various domains in I4.0, interoperability now extends and comprises a much broader framework. Therefore, with regard to common RA components, interoperability combines all three layers (see example for RAMI I4.0 in Figure 18): integration layer, communication layer, and information layer. Although these layers are tightly tangled in a system-to-system interaction model, these three notions have still different goals and application areas in the I4.0 as depicted in Figure 6 [2, 2].

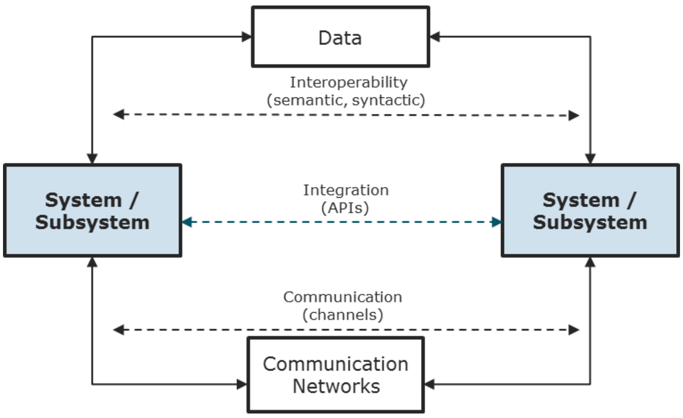


Figure 6: Interoperability vs. integration and connectivity (based on [1])

4.1.2 Key Compliance Requirements

The trend towards a globally networked world, as demonstrated by the enormous growth potential. in the Internet of Things (IoT) and Machine2Machine Communication (M2M), brings its own challenge for standardization and interoperability. No longer is a single standardization body responsible for an entire technology. Complex products and systems are often based on several standards (e.g. from ETSI, IETF, IEEE, ITU-T, ISO) as well as requirements set by Industry forums. In addition, potential interoperability problems can be addressed by the fact that standards are used in contexts not foreseen by the original specifiers.

Even in individual standards, good technical quality is essential, errors, unclear requirements, conflicting options and other factors that could lead to non-interoperability must be reduced to a minimum.

In general, QU4LITY interoperability specifications are applied to direct the work to be accomplished by a QU4LITY Pilot in terms of interoperability. In particular, the specifications define essential technical and operational standards that must be met by technical systems across QU4LITY interoperability scenarios. This should be done in order to meet the key requirements and ensure interoperability in respect of components and interfaces.

General requirements for interoperability specifications are difficult to obtain since each pilot has its own very specific requirements. However, to narrow down the required scope, an overall analysis of the pilot use cases will be given, taking into account that additional application-specific requirements have to be considered.

As an extend to the *OSI* definition, interoperability can be further described with the help of the Degrees of Interoperability (used within the Canadian Department of National Defense and NATO). These organizations were focused on the sharing of information and came up with four degrees of interoperability as follows[3]:

- **Degree 1: Unstructured Data Exchange** involves the exchange of human-interpretable unstructured data, such as the free text found in operational estimates, analysis, and papers.
- **Degree 2: Structured Data Exchange** involves the exchange of human-interpretable structured data intended for manual and/or automated handling, but requires manual compilation, receipt, and/or message dispatch.
- **Degree 3: Seamless Sharing of Data** involves the automated sharing of data amongst systems based on a common exchange model.
- **Degree 4: Seamless Sharing of Information** is an extension of Degree 3 to the universal interpretation of information through data processing based on co-operating applications.

These degrees should be further refined and made technically meaningful for each of the degrees. An example refinement of degree 3 with four sub classifications leads to:

- **3A: Formal Message Exchange**
- **3B: Common Data Exchange**
- **3C: Complete Data Exchange**
- **3D: Real-time Data Exchange**

The intent is to specify the detailed degrees of interoperability to the requisite level of detail so that they are technically meaningful.

[3] According to the TOGAF framework specification, an Open Group Standard

These degrees are very useful for specifying the way that information has to be exchanged between the various systems and provide critical direction to the project partners implementing the systems.

Similar measures can be established to determine service/business and technical interoperability but not only data/information interoperability.

According to the QU4LITY reference architecture (RA), different components can interoperate with each other based on the Degrees of Interoperability defined above. The RA as defined in D2.11 Reference Architecture and Blueprints (Version 1) is shown in Figure 7.

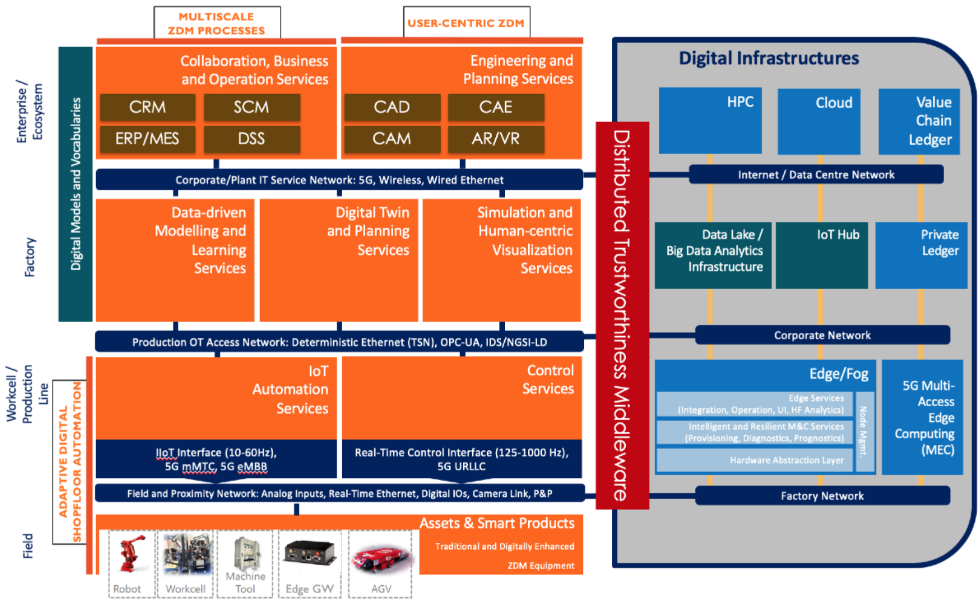


Figure 7: QU4LITY Reference Architecture defined in D2.11

In order to derive general interoperability requirements, the main components on which each QU4LITY pilot is based are defined as:

- *Collaboration, Business and Operation Services*
- *Engineering and Planning Services*
- *Data-driven Modelling and Learning Services*
- *Digital Twin and Planning Services*
- *Simulation and Human-centric Visualization Services*
- *IoT Automation Services*
- *Control Services*
- *Assets & Smart Products*
- *HPC*
- *Cloud*
- *Value Chain Ledger*

- *Data Lake / Big Data Analytics Infrastructure*
- *IoT Hub*
- *Private Ledger*
- *Edge/Fog*
- *5G Multi-Access Edge Computing*

The more detailed description can be found in D2.11.

Each component can potentially be defined with a large number of interoperability standards and communication protocols. However, restrictions are to be expected in relation to the respective pilot, for example due to safety-related aspects, cost pressure for implementation or the necessity to use proprietary standards.

If a mechanism such as the Degrees of Interoperability is used, then a matrix showing the interoperability requirements is a useful tool. Therefore, based on the feedback, which is also part of the Trial handbook-Chapter 4, of seven QU4LITY pilots, an overall components interaction (interoperability) matrix of the pilots was generated (see Figure 8).

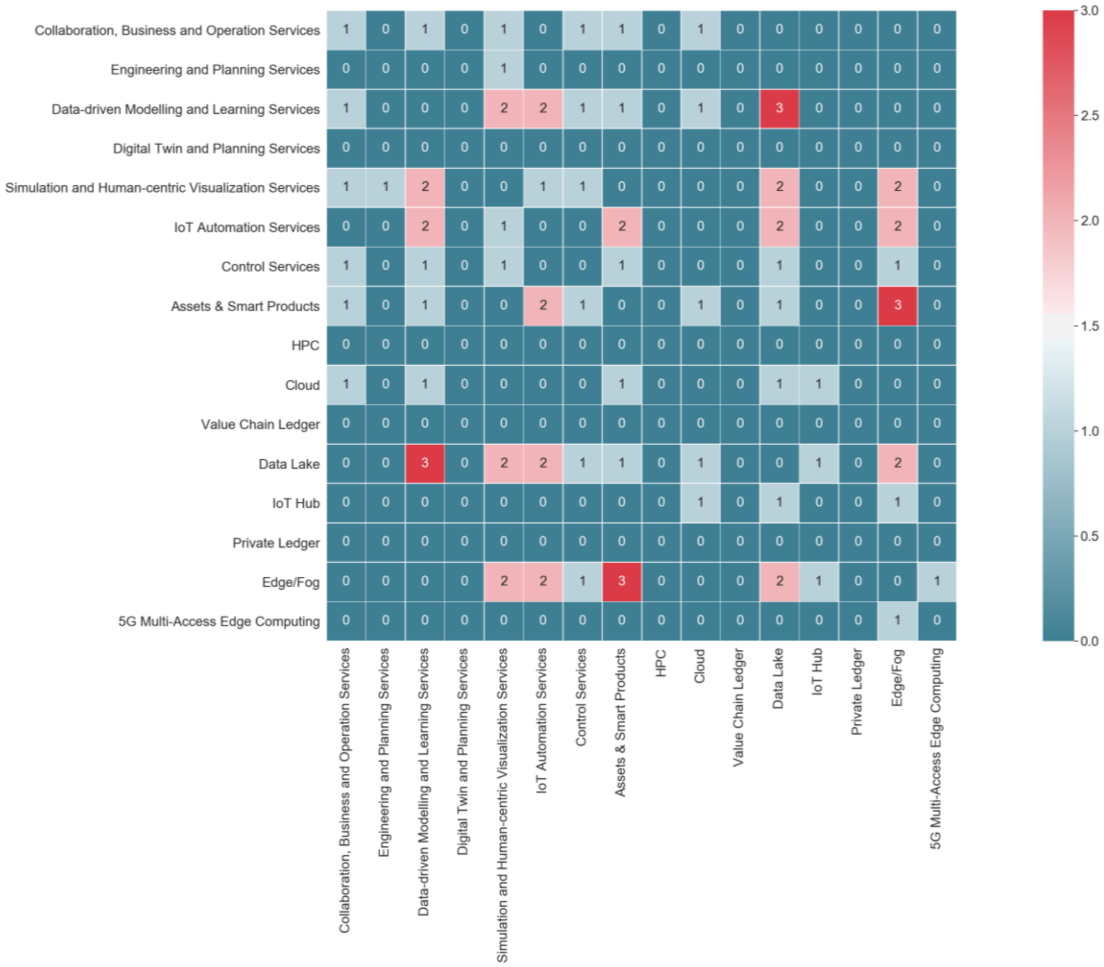


Figure 8: Matrix of interoperability requirements based on data from seven QU4LITY pilots

The matrix gives only a general overview about the interaction of the different components and furthermore assumes the information flow is bi-directional (which leads to a symmetrical matrix). Nevertheless, some components are connected to many different other components (e.g. Edge/Fog devices, Data lakes, Assets & smart products). Other components are not used at all or are not well enough represented by the data the pilots have provided to show any connection (Private ledger).

In a further step, a specific pilot can be described with the help of an interoperability matrix and the degrees of Interoperability. The figure below gives an example of how QU4LITY pilots may describe the requirements with respect to interoperability between several components.

Each interaction between components can be defined differently and are not required to be equal in both directions of the information flow. As an example based on Figure 9, data transfer from Assets & Smart Products (Machine with camera) to Edge/Fog (edge device) requires real-time data transfer of type *3D* but the interaction from Edge/Fog to Smart Products only requires type *3A* interoperability.

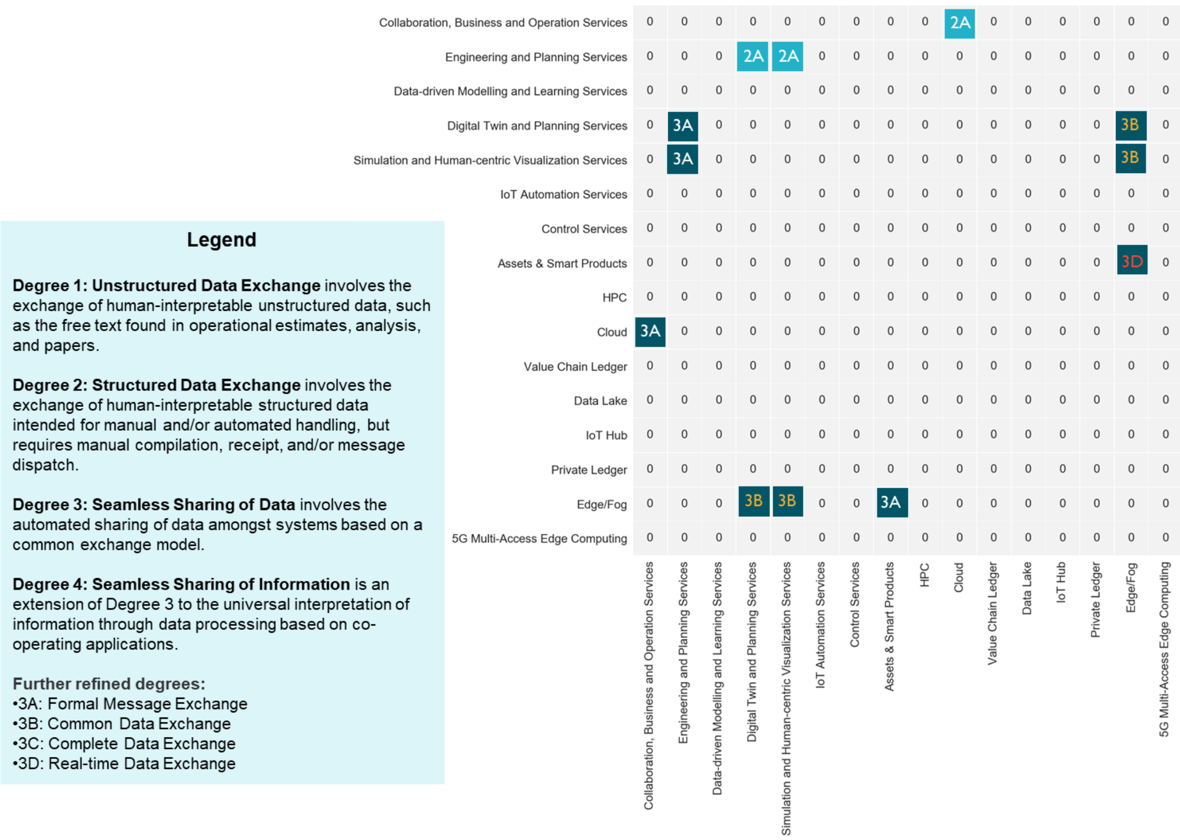


Figure 9: Example of an interoperability requirements matrix for a hypothetical ZDM pilot using different degrees of interoperability

The matrix above can be used within the pilot and/or within the extended enterprise as a way of detailing what information and/or services can be shared. Defining interoperability requirements in a clear unambiguous manner at several levels (business/service, information, and technical) is a useful for planning, defining and maintaining complex architectures. Interoperability specification will become even more important when services will be shared internally and externally in ever more inter-dependent extended manufacturing environments and/or enterprises.

4.1.3 Recommendations for Use

Based on the requirements of each pilot determined in the method described in the previous chapter, standards, protocols and related frameworks can be considered, analyzed and selected to finally implement the component as specified.

In the next step a coarse classification of the presented interoperability protocols and standards in (section 4.1.3) as well as further standards and protocols important for ZDM takes place. Rather than trying to fit all of the ZDM/IoT Protocols on top the OSI Model, the protocols and standards are grouped into the following layers to provide some level of organization:

- *communication protocol*
- *Semantic*
- *Network functionality*
- *Physical functionality*
- *Multi-layer framework*

Based on the above classification, the standards used by the QU4LITY pilot project (green) are shown in Figure 10, together with other standards and protocols that extend the groups.

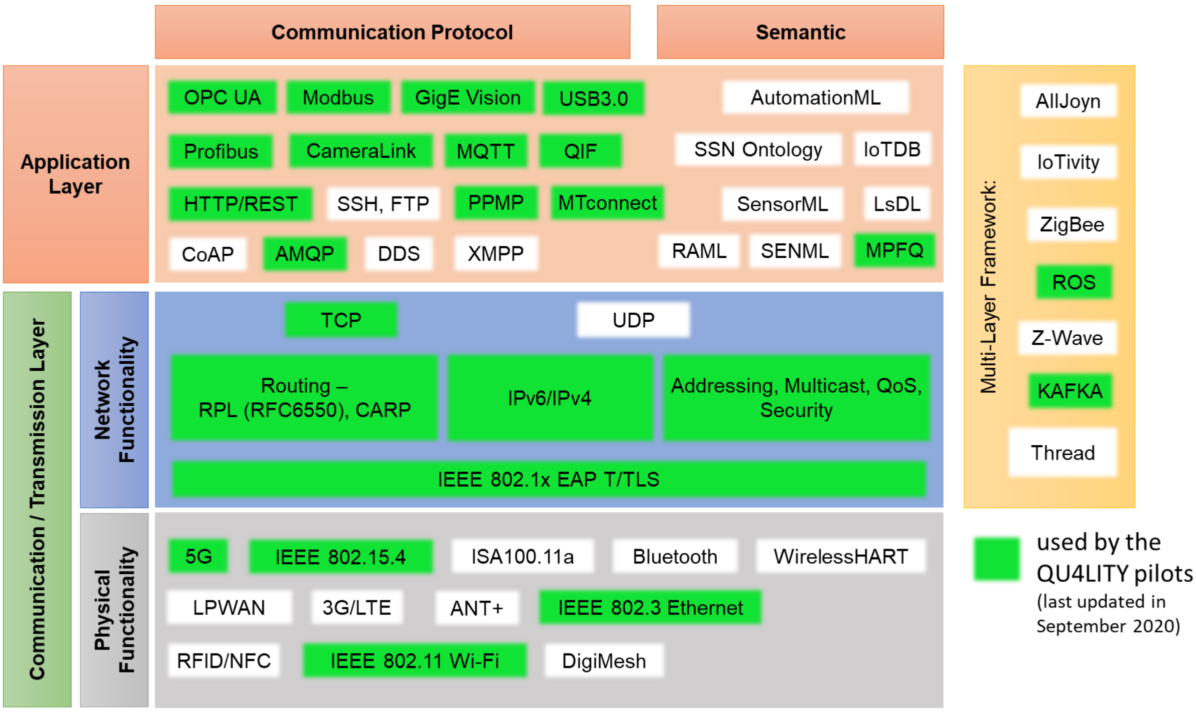


Figure 10: Overview of relevant standards, protocols and frameworks for ZDM

In order to fulfil the interoperability requirements derived from the component interaction matrices, standards from each of the five interoperability groups might be necessary.

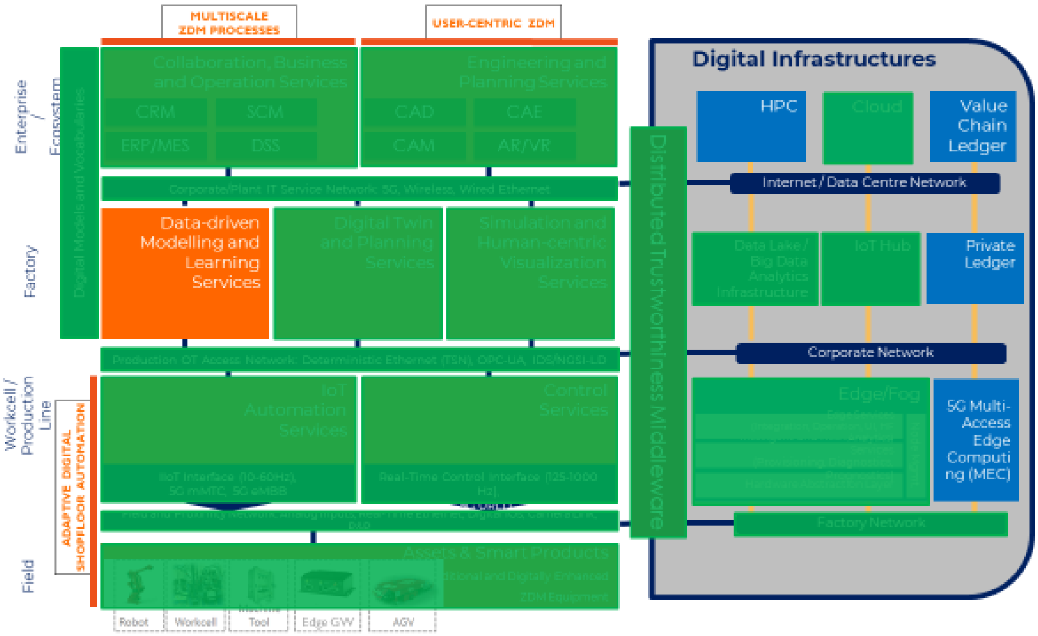


Figure 11: Q-RA compliant components for interoperability

Figure 10 accomplishes Table 2, which represents a list of current standards that can be recommended for use in QU4LITY pilots. Figure 11 depicts which QU4LITY RA components are covered by the following standards list.

Table 2: Recommendations for use in terms of interoperability standards.

Committee	ID[45]	Title	Q-RA	Details
DIN German Institute for Standardization	DIN SPEC 16592:2016, Link	Combining OPC Unified Architecture and Automation Markup Language.	Digital models and Vocabularies	Description of industrial plants and components in Industry 4.0 and the exchange of this description in the application environment
e@Class e.V.	eCl@ss, Link	eCl@ss	Digital models and Vocabularies	supports the digital exchange of product descriptions and service descriptions
IEC/TC 65/SC 65B Measurement and control devices	IEC 61131 series, Link	Programmable controllers - ALL PARTS	Control Service	PLC,HMI (Part 3: PLCOpen XML)
IEC TC3/SC 3D Product properties and classes and their identification	IEC 61360-1:2017, Link	Standard data element types with associated classification scheme - Part 1: Definitions - Principles and methods	Digital models and Vocabularies	CDD, Definition of the properties and associated attributes, interoperability, product properties

[4] Contains references to other specifications from the chapter (S: security & safety, Q: quality; RA: reference architectures, AI: Artificial Intelligence)
[5] under development (*)

Committee	ID[45]	Title	Q-RA	Details
TC 65/SC 65C - Industrial networks	IEC 61784 series, Link	Industrial communication networks - Profiles	Factory Network/ Field and Proximity Network	Profiles for industrial communication networks (Fieldbus/Device level)
TC 65/SC 65C - Industrial networks	IEC 61158 series, Link	Industrial communication networks - Fieldbus specifications	Factory Network/ Field and Proximity Network	Feldbus/Device level (EtherCAT, PROFINET), generic concept of fieldbuses
IEC/TC 65/SC 65E Devices and integration in enterprise systems	IEC 61804 series, Link	Function blocks (FB) for process control and electronic device description language (EDDL)	IoT Automation Services	EDDL: production system engineering; device/process description
ISO/TC 184 Automation systems and integration	IEC 62264-1:2013, Link	IEC 62264-1:2013 Enterprise-control system integration — Part 1: Models and terminology	Collaboration, Business and Operation Service	Describes the manufacturing operations management domain; models
IEC/TC 65/SC 65E Devices and integration in enterprise systems	IEC 62453 series, Link	Field device tool (FDT) interface specification	IoT Automation Services	FDT: production system engineering; Integration between the manufacturing operations and control domain
IEC/TC 65/SC 65E Devices and integration in enterprise systems	IEC 62541 series, Link	OPC unified architecture – Part 1: Overview and concepts	Corporate Network/ Production OT Access Network	OPC UA: an industrial M2M communication protocol for interoperability; information modelling
IEC/TC 65/SC 65E Devices and integration in enterprise systems	IEC 62714 series*, Link	Engineering data exchange format for use in industrial automation systems engineering - Automation Markup Language	Engineering and Planning Services	AutomatonML: industrial automation systems engineering; AML
IEC/TC 65 Industrial-process measurement and control	IEC 62890:2020 *, Link	Industrial-process measurement, control and automation - Life-cycle-management for systems and components	Cross-cutting	Life Cycle Management for systems: Definitions and reference models related to the life-cycle of a product type and the life time of a product instance; used for industrial-process measurement, control and automation.
IEC/TC 65 Industrial-process measurement and control	IEC TS 62832-1:2016, Link, *Ref.: RA*	Industrial-process measurement, control and automation - Digital factory framework - Part 1: General principles	Digital Twin and Planning Services	General principles of the Digital Factory framework
ISO/TC 184/SC 4 Industrial data	ISO 13584 series	Industrial automation systems and integration - Parts library	Digital models and Vocabularies	Models, principles, representation of semantic content
ISO/TC 184/SC 5 Interoperability, integration, and architectures for	ISO 19439:2006, Link, *Ref.: RA*	Enterprise integration — Framework for enterprise modelling	Digital Twin and Planning Services	Enterprise modelling; computer integrated manufacturing

Committee	ID[45]	Title	Q-RA	Details
enterprise systems and automation applications				
W3C	RFD, Link	Resource Description Framework (RFD)	Digital models and Vocabularies	Data interchange on the Web
W3C	RIF, Link	Rule Interchange Format (RIF)	Digital models and Vocabularies	Exchanging rules among rule systems, in particular among Web rule engines.
W3C	SPARQL, Link	SPARQL Query Language for RDF	Digital models and Vocabularies	A query language and protocol for RDF.
W3C	OWL Link	Web Ontology Language (OWL)	Digital models and Vocabularies	Represents rich and complex knowledge about things, groups of things, and relations between things.
IEC/TC 65 Industrial-process measurement and control	IEC PAS 63088:2017, Link, *Rel.:RA*	Smart manufacturing – Reference architecture model industry 4.0 (RAMI4.0)	Digital Twin and Planning Services	RAMI4.0 - Digital twin, process optimization run-time
ISO/IEC JTC 1/SC 41 Internet of Things and related technologies	ISO/IEC 30149, Link, *Rel.: S, RA*	Internet of things (IoT) – Trustworthiness framework	Distributed Trustworthiness Layer	Trustworthiness of IoT system/service
ISO/IEC JTC 1/SC 41 Internet of Things and related technologies	ISO/IEC 30161 Link	Internet of Things (IoT) – Requirements of IoT data exchange platform for various IoT services	IoT Automation Services	Data exchange platform for various IoT services
ISO/IEC JTC 1/SC 41 Internet of Things and related technologies	ISO/IEC 30162*, Link	Internet of Things (IoT) – Compatibility requirements and model for devices within industrial IoT systems	Digital models and Vocabularies	Compatibility requirements and model for IIoT Systems
ISO/IEC JTC 1/SC 41 Internet of Things and related technologies	ISO/IEC TR 30164:2020, Link	Internet of things (IoT) – Edge Computing	Edge/Fog	Edge Computing
ISO/IEC JTC 1/SC 41 Internet of Things and related technologies	ISO/IEC 30165*, Link, *Rel.: RA*	Internet of Things (IoT) – Real-time IoT framework	IoT Hubs	Real-time IoT framework
IEC/TC 65/SC 65E Devices and integration in enterprise systems	IEC 62264 series, Link	Enterprise-control system integration - Part 2: Object and attributes for enterprise-control system integration	Collaboration, Business and Operation Service (CRM, ERP/MES, SCM, DSS)	Enterprise-control system modelling; Integration; APIs
ISO/IEC JTC 1 Information Technology	ISO/IEC 19464:2014, Link	Information technology – Advanced Message Queuing Protocol (AMQP)	Corporate Network/ Production OT Access Network	AMQP

Committee	ID[45]	Title	Q-RA	Details
ISO/IEC JTC 1 Information Technology	ISO/IEC 19845:2015, Link	Information technology – Universal Business Language Version 2.1 (UBL v2.1)	Digital models and Vocabularies	UBL v2.1: a generic XML interchange format for business documents that can be customized to meet the requirements of particular industry; modeling and executing business processes (see also BPL, ebXML)
ISO/IEC JTC 1 Information Technology	ISO/IEC 20922:2016, Link	Information technology – Message Queuing Telemetry Transport (MQTT) v3.1.1	Corporate Network/ Production OT Access Network	MQTT: an extremely lightweight publish/subscribe messaging transport protocol
ISO/IEC JTC 1 Information Technology	ISO/IEC 21778:2017, Link	Information technology – The JSON data interchange syntax	Cross-cutting	JSON
ISO/IEC JTC 1 Information Technology	ISO/IEC 30118 series, Link, *Rel.: S, RA*	Information technology – Open Connectivity Foundation (OCF) Specification – Part 1: Core specification	IoT Hubs	OCF Spec; industrial communication framework for IoT
ISO/TC 184/SC 4 Industrial data	ISO 23247 series*, Link , *Rel.: RA*	Automation systems and integration — Digital Twin framework for manufacturing	Digital Twin and Planning Services	Digital Twin framework for manufacturing (information exchange, digital representation of manufacturing elements, etc.)
ISO/IEC JTC 1/SC 32 Data management and interchange	ISO/IEC 6523-1:1998, Link, *Rel.: S*	Information technology – Structure for the identification of organisations and organisation parts – Part 1: Identification of organisation identification schemes	Digital models and Vocabularies	Unique identification for organizations in a multi-company approach/ exchange
ISO/IEC JTC 1/SC 32 Data management and interchange	ISO/IEC 6523-2:1998, Link, *Rel.: S*	Information technology – Structure for the identification of organisations and organisation parts – Part 2: Registration of organisation identification schemes	Digital models and Vocabularies	Registration of organization identification schemes; Unique identification for organizations in a multi-company approach/ exchange
IEEE Institute of Electrical and Electronics Engineers	IEEE P2413:2019, Link, *Rel.:RA*	Architectural Framework for the Internet of Things (IoT)	Cross-cutting	IEEE Architectural Framework for the Internet of Things (IoT)
ISO/IEC JTC 1/SC 38 Cloud Computing and Distributed Platforms	ISO/IEC 17788:2014, Link	Information technology – Cloud computing – Overview and vocabulary	Cloud	Cloud computing general overview and vocabulary
ISO/IEC JTC 1/SC 42 Artificial Intelligence	ISO/IEC TR 20547-1:2020, Link, *Rel.:AI*	Information technology — Big data reference architecture — Part 1: Framework and application process	Data Lake /Big Data Analytics Infrastructure	Big data framework and application process
ISO/IEC JTC 1/SC 42 Artificial Intelligence	ISO/IEC 20547-	Information technology - Big data reference architecture - Part 3: Reference architecture	Data Lake /Big Data	BDRA: Big data reference architecture

Committee	ID[45]	Title	Q-RA	Details
	3:2020, Link, *Rel.: RA, AI*		Analytics Infrastructure	
ISO/IEC JTC 1/SC 42 Artificial Intelligence	ISO/IEC TR 20547-5:2018, Link, *Rel.: AI*	Information technology - Big data reference architecture - Part 5: Standards roadmap	Data Lake /Big Data Analytics Infrastructure	Big data standards roadmap
DIN German Institute for Standardization	DIN SPEC 2343:2020-09, Link, *Rel.: S, AI*	Transmission of language-based data between artificial intelligences - Specification of parameters and formats	Data-driven Modelling and Learning Service	AI, interoperability, data transmission in ecosystems; to develop interoperable speech-based applications, to verify and trace data of speech-based applications and to enable data access or data protection
ITU	Suppl on Y. Sup.aisr*,Link, *Rel.:AI*	Artificial Intelligence Standard Roadmap	Cross-cutting	AI, road mapping
ISO/IEC JTC 1/SC 41 Internet of Things and related technologies	ISO/IEC 30166:2020, Link , *Rel.: S, Q, RA, AI*	Internet of things (IoT) — Industrial IoT	Cross-cutting	Industrial IoT standards and road mapping
ISO/IEC JTC 1/SC 41 Internet of Things and related technologies	ISO/IEC TR 30164:2020, Link, *Rel.: S, RA*	Internet of things (IoT) — Edge computing		IoT, edge computing
ISO/IEC JTC 1/SC 41 Internet of Things and related technologies	ISO/IEC 30162*, Link	Internet of Things (IoT) — Compatibility requirements and model for devices within industrial IoT systems	Digital models and Vocabularies	IoT, compatibility requirements and model for devices
ISO/IEC JTC 1/SC 41 Internet of Things and related technologies	ISO/IEC 30161*, Link	Internet of Things (IoT) — Requirements of IoT data exchange platform for various IoT services	IoT Automation Services	IoT, requirements of IoT data exchange platform for various IoT services
ISO/IEC JTC 1/SC 41 Internet of Things and related technologies	ISO/IEC 30149 *, Link , *Rel.: S*	Internet of things (IoT) — Trustworthiness framework	Distributed Trustworthiness Layer	IoT, trustworthiness framework
ISO/IEC JTC 1/SC 41 Internet of Things and related technologies	ISO/IEC 30147 *, Link , *Rel.: S*	Information technology — Internet of things — Methodology for trustworthiness of IoT system/service	Distributed Trustworthiness Layer	IoT, methodology for trustworthiness of IoT system/service
ISO/IEC JTC 1/SC 41 Internet of Things and related technologies	ISO/IEC 21823-1:2019, Link, *Rel.: RA*	Internet of things (IoT) — Interoperability for IoT systems — Part 1: Framework	IoT Hubs	IoT, interoperability framework
ISO/IEC JTC 1/SC 41 Internet of Things and related technologies	ISO/IEC 21823-2:2019, Link	Internet of things (IoT) — Interoperability for IoT systems — Part 2: Transport interoperability	IoT Hubs	IoT, information exchange, peer-to-peer connectivity and seamless communication both between different IoT systems

Committee	ID[45]	Title	Q-RA	Details
ISO/IEC JTC 1/SC 41 Internet of Things and related technologies	ISO/IEC 21823-3*, Link	Internet of things (IoT) — Interoperability for IoT systems — Part 3: Semantic interoperability	Digital models and Vocabularies	IoT, semantic interoperability
ITU	Y.csb-arch*, Link , *Rel.: RA*	Cloud Computing -Functional architecture for cloud service brokerage	Cloud	Cloud Computing, functional architecture for cloud service brokerage
ITU	FG Cloud TR Version 1.0 (02/2012), Link, *Rel.: RA*	FG Cloud Technical Report Part 2: Functional requirements and reference architecture	Cloud	Cloud Computing, functional requirements and reference architecture
ISO/IEC JTC 1/SC 38 Cloud Computing and Distributed Platforms	ISO/IEC DIS 19944-1*, Link	Cloud computing – Cloud services and devices: data flow, data categories and data use — Part 1: Fundamentals	Cloud	Cloud computing, Fundamentals for Cloud services and devices: data flow, data categories and data use;
ISO/IEC JTC 1/SC 38 Cloud Computing and Distributed Platforms	ISO/IEC TS 23167, Link	Information technology — Cloud computing — Common technologies and techniques	Cloud	Cloud Computing, description of a set of common technologies and techniques used in conjunction: virtual machines (VMs) and hypervisors; containers and container management systems (CMSs); serverless computing; microservices architecture; etc.
ISO/IEC JTC 1/SC 38 Cloud Computing and Distributed Platforms	ISO (IEC CD 22123-2*, Link	Information technology — Cloud computing — Part 2: Concepts	Cloud	Cloud Computing, Concepts
ITU	ITU-T Y.cccsdaom -reqts*, Link	Cloud computing - Requirements for cloud service development and operation management	Cloud	Cloud Computing, cloud service development and operation management
IEC TC 65 WG24 Asset Administration Shell for Industrial Applications	IEC 63278-1 ED1*, Link, *Rel.: RA*	Asset administration shell for industrial applications – Part 1: Administration shell structure	Digital models and Vocabularies	AAS, interoperability
DIN German Institute for Standardization	DIN SPEC 91406:2019-12, Link	Automatic identification of physical objects and information on physical objects in IT systems, particularly IoT systems	Digital models and Vocabularies	Automatic device Identification, unique ID
ISO/TC 299 Robotics	ISO 10218-2:2011, Link, *Rel.: S*	Robots and robotic devices — Safety requirements for industrial robots — Part 2: Robot systems and integration	Distributed Trustworthiness Layer	Robots and robotic devices; safety requirement; robot systems and integration
ISO/TC 299 Robotics	ISO/TS 15066:2016, Link	Robots and robotic devices — Collaborative robots	Assets & Smart Products	Robots and robotic devices, Collaborative robots

Committee	ID[45]	Title	Q-RA	Details
ISO/TC 184/SC 5 Interoperability, integration, and architectures for enterprise systems and automation applications	ISO 11354-2:2015, Link	Advanced automation technologies and their applications — Requirements for establishing manufacturing enterprise process interoperability — Part 2: Maturity model for assessing enterprise interoperability	Digital models and Vocabularies	Enterprise; manufacturing enterprise process interoperability; interoperability model
ISO/TC 184/SC 5 Interoperability, integration, and architectures for enterprise systems and automation applications	ISO 11354-1:2011, Link	Advanced automation technologies and their applications — Requirements for establishing manufacturing enterprise process interoperability — Part 1: Framework for enterprise interoperability	Engineering and Planning Services	Enterprise; manufacturing enterprise process interoperability; interoperability framework
ISO/TC 184 Automation systems and integration	ISO 23570-1:2005, Link, *Rel.: S*	Industrial automation systems and integration — Distributed installation in industrial applications — Part 1: Sensors and actuators	Distributed Trustworthiness Layer	System integration; sensors and actuators installation
DIN German Institute for Standardization	EN 61069 series, Link, *Rel.: S*	Industrial-process measurement, control and automation - Evaluation of system properties for the purpose of system assessment	Distributed Trustworthiness Layer	Terminology and basic concepts; assessment methodology; assessment of system functionality, performance, dependability, operability, safety. system properties
ISO/IEC JTC 1/SC 41 Internet of Things and related technologies	ISO/IEC30141:2018, Link, *Rel.: RA*	Internet of Things (loT) — Reference Architecture	Cross-cutting	IoT RA
ISO/IEC JTC 1/SC 31 Automatic identification and data capture	ISO/IEC 29161:2016, Link, *Rel.: S*	Information technology — Data structure — Unique identification for the Internet of Things	Digital models and Vocabularies	IoT, unique identification
ISO/TC 199 Safety of machinery	ISO 11161:2007, Link, *Rel.: S*	Safety of machinery — Integrated manufacturing systems — Basic requirements	Distributed Trustworthiness Layer	Safety of machinery, integrated manufacturing systems, basic requirements
ISO/TC 159/SC 3 Anthropometry and biomechanics	ISO 14738:2002, Link	Safety of machinery — Anthropometric requirements for the design of workstations at machinery	Simulation and Human-centric Visualization Services	Human and safety of machinery; anthropometric requirements for the design of workstations at machinery
IEC/ TC 3 - Documentation, graphical symbols and representations of technical information	IEC 60445:2017 RLV, Link	Basic and safety principles for man-machine interface, marking and identification - Identification of equipment terminals, conductor terminations and conductors	Simulation and Human-centric Visualization Services	HMI: Identification of equipment terminals, conductor terminations and conductors

Committee	ID[45]	Title	Q-RA	Details
ISO/TC 199 Safety of machinery	ISO TR 21260, Link, *Rel.: S*	Safety of machinery — Mechanical safety data for physical contacts between moving machinery or moving parts of machinery and persons	Distributed Trustworthiness Layer	Safety of machinery, mechanical safety data for physical contacts between moving machinery or moving parts of machinery and persons
International Data Spaces Association	IDS-RAM:2019, Link, *Rel.: S, RA*	IDSA Reference Architecture Model 3.0	Digital Twin and Planning Services	IDSA RA
Industrial Internet Consortium	IIRA:2019, Link, *Rel.: RA*	The Industrial Internet of Things, Volume G1: Reference Architecture Version 1.9	Digital Twin and Planning Services	IIRA
ISO/TC 184/SC 5 Interoperability, integration, and architectures for enterprise systems and automation applications	ISO 19439:2006, Link	Enterprise integration — Framework for enterprise modelling	Engineering and Planning Services	Enterprise modelling and integration
ISO/TC 184/SC 4 Industrial data	ISO/PAS 17506:2012, Link	COLLADA digital asset schema specification for 3D visualization of industrial data	Digital models and Vocabularies	COLLADA: defines an open standard XML schema for exchanging digital assets among various graphics software applications
ISO/TC 184/SC 5 Interoperability, integration, and architectures for enterprise systems and automation applications	ISO 15746 series, Link, *Rel.: S*	Integration of advanced process control and optimization capabilities for manufacturing systems- SER	Control Service	Information models for advanced process control optimization capabilities for manufacturing systems; framework; models; validation
MESA	B2MML, Link	Business To Manufacturing Markup Language	Digital models and Vocabularies	B2MML: an XML implementation of the ANSI/ISA-95, enterprise control system integration
MTConnect	ANSI/MTC 1.4-2018, Link	MTConnect	Factory Network/ Field and Proximity Network	MT Connect: used to access real-time data from shop floor manufacturing equipment such as machine tools
ISO/TC 184/SC 4 Industrial data	ISO 18828-3:2017, Link	Standardized procedures for production systems engineering — Part 3: Information flows in production planning processes	Engineering and Planning Services	Data modelling; information flows identified for each planning discipline within production planning
ISO/TC 184/SC 4 Industrial data	ISO 15926 series*, Link, *Ref.: Q*	Integration of life-cycle data for process plants including oil and gas production facilities	Digital models and Vocabularies	include support for modelling the lifecycle of product information; adresses integrated asset planning life-

Committee	ID[45]	Title	Q-RA	Details
				cycle, conformance testing, data modelling; (OWL).

4.1.4 Example of prominent standards

Communication protocol standards such as OPC-UA and MQTT that, according to Figure 3 and Figure 10 are already used frequently within the pilot use cases, will be explained more detailed in the following section:

4.1.5 MQTT

MQTT stands for **MQ** Telemetry Transport but previously was known as Message Queuing Telemetry Transport and is a lightweight publish/subscribe messaging protocol designed for M2M (machine to machine) telemetry in low bandwidth environments [3].

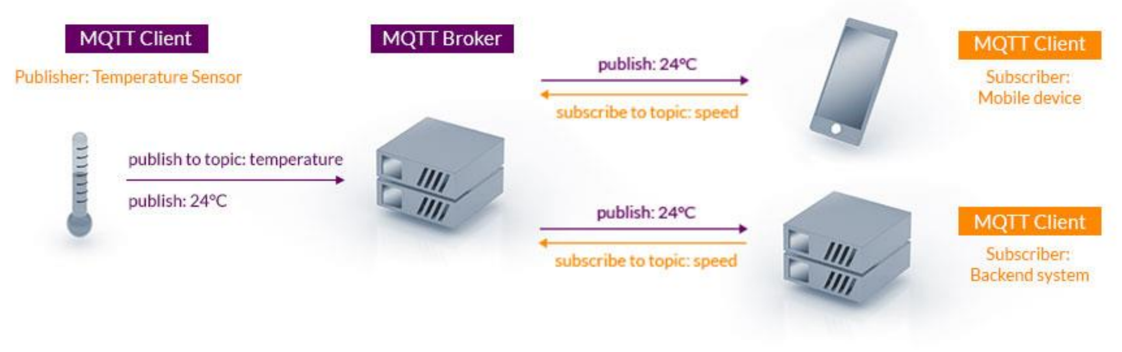


Figure 12: MQTT Publish / Subscribe architecture (Source: [3])

In MQTT a publisher publishes messages on a topic and a subscriber must subscribe to that topic to view the message. Furthermore, MQTT requires the use of a central Broker that (normally) does not store messages. The MQTT protocol has been implemented for many programming languages such as C, C++, Python, Go, Java, Perl and many more. The key features of MQTT are summarized below:

- **Lightweight and Efficient:** MQTT clients are very small, require minimal resources so can be used on small microcontrollers. MQTT message headers are small to optimize network bandwidth.
- **Bi-directional Communications:** MQTT allows for messaging between device to cloud and cloud to device. This makes for easy broadcasting messages to groups of things.
- **Reliable Message Delivery**: MQTT has 3 defined quality of service levels: 0 - at most once, 1- at least once, 2 - exactly once

- **Support for Unreliable Networks**: MQTT’s support for persistent sessions reduces the time to reconnect the client with the broker.
- **Security Enabled:** MQTT makes it easy to encrypt messages using TLS and authenticate clients using modern authentication protocols, such as OAuth.

4.1.5.1 OPC-UA

OPC UA (short for Open Platform Communications United Architecture) is a data exchange standard for industrial communication (machine-to-machine or PC-to-machine communication) [4]. The open interface standard is independent of the manufacturer or system supplier of the application, the programming language in which the respective software was programmed and the operating system on which the application works.

The biggest difference to previous versions is that machine data can not only be transported, but also be **described semantically** in a machine-readable form. OPC UA enables access to data of different kinds in vertical as well as horizontal direction. The spectrum ranges from OPC UA components directly integrated on the devices and controls or machines and systems to so-called gateways and aggregating servers.

Key feature of OPC-UA:

- Manufacturer-independent and platform-neutral
- Integrated security concept (encryption, signing and authentication)
- Consistent and scalable
- Information model and semantic services
- Unrestricted parallel operation to PROFINET
- Real-time capability of OPC UA PubSub in combination with time-sensitive networking (TSN)
- Standardized interface and wide availability
- Secured communication without additional hardware directly in the protocol
- Simple and clear interpretation of the data
- Simple Ethernet-based networking, using the existing Industrial Ethernet infrastructure
- Internationally standardized interfaces for easy machine integration (Companion specifications)
- High performance through fast communication
- When using TSN hardware and OPC UA PubSub, OPC UA data can be transferred deterministically regardless of the network load

4.2 Compliance Specification for Safety and Security Standards

4.2.1 Description and Goals

Industrial plants and production machinery are nowadays strongly networked via IT. As a consequence, production companies often have to deal with external threats and unauthorized intrusion into automation and control systems as well as compromised or unauthorized software operations on production facilities. Thus, Industrial Security describes the protection of production and industrial plants against intentionally or unintentionally caused errors and deals with the security of control networks of production and industrial plants in the field of factory automation and process control. For better understanding Table 3 shows common differences between safety and security.

According to this a large number of critical requirements could be allocated with regards to system and process engineering both at low OT and IT levels as well as information security and data privacy.

Process control and safety systems are usually merged under one system, called Integrated Control and Safety System (ICSS). Industrial safety systems are typically used to protect human, industrial plant, and the production environment in case of the process unexpected behavior. Safety-related standards are, therefore, focused on preventing any damage to people and thing.

Table 3 Common key differences regarding safety and security

	Safety	Security[6]
Obstacle	Hazard	Threat
Refinement	Root cause	Vulnerability
Agent/ Trigger	Environment (unexpected)	Attacker (malicious)
Impact	Damage to people and things, priority high (e.g. availability)	Measured in business terms (e.g. system availability)
Risk Management	Root cause obstacle elimination,reduction,tolerance, etc.	Vulnerability removal or isolation, attack recovery, run-time monitoring, frequent updates, etc.

4.2.2 Key Compliance Requirements

In terms of safety and security pilots identify a large number of common requirements, which could be analyzed and classified according to six major features presented in Table 4.

6

Table 4: Analysis of the key requirements for QU4LITY safety and security requirements

Security Feature	Common Pilots Requirements
Authentication	All communication with the device should be authenticated using strong passwords or use of authentication protocols (PRIMA)
Secure Communication	Communication to/from device, platform, etc. needs to be secured using encrypted communication (PRIMA); system/process latency and response latency (FAGOR)
Protection against cyber attacks	Embedded firewalls provide a critical layer of protection (general)
Security / safety Monitoring and Detection	Detection and reporting of invalid logins or attacks (general), testing and validation (GHI, FAGOR, PRIMA, DANOBAT, WHR); Ensure of cloud module availabilities (GF); verify input data is correct and accurate (MONDRAGON)
Embedded Security Management and Transfer	Integration with a security management system, (general), no process interrupted (FAGOR); secure data transfer (GF, FAGOR)
Data Security and Privacy	Protect from data lost (GHI, FAGOR, reliable data sharing (GHI), data privacy GDPR and compliance (GHI, PRIMA, DANOBAT), secure information correlation (GHI), improvement of machine availability (DANOBAT, GF), avoid unnecessary increase (DANOBAT); reliability and latency on communication between components (FAGOT, GF); Secure data transfer (GF); ensure robust scalability on cloud (GF)

A brief analysis of these requirements shows that practically all corresponding components are affected by the specific implementation of safety and security solutions as shown in Figure 13. This is mainly due to the fact that safety and security are among the cross-sectional standards that cover the entire QU4LITY framework:

- *Distributed Trustworthiness (Framework) Level*, *IoT Hubs,* and *Cloud* components regarding framework and specific requirements, including secure communication between architecture components of an interoperable framework.
- *Collaboration, Business and Operation Services, Digital models and Vocabularies, Data-driven Modelling and Learning Service* regarding secure design specifications and information modelling and secure data transfer service operation.
- *Assets & Smart Product, Control Service* regarding safety of machinery and requirements control systems at the OT level.
- One of the essential requirements is security at all *network levels*, e.g. plant IT service network, production OT access network as well as factory network at field device level regarding real-time communication.

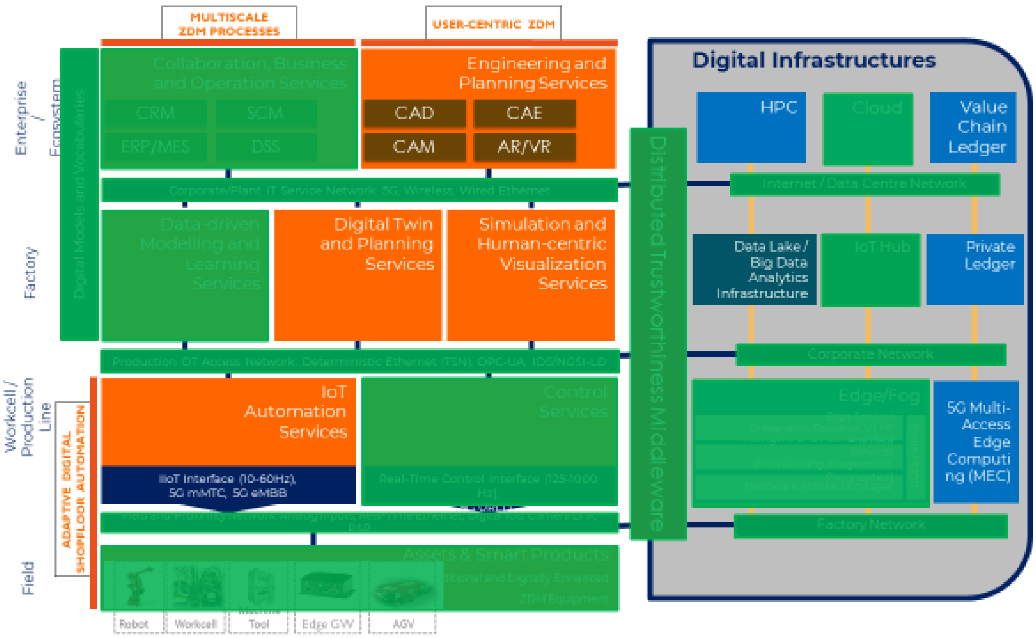


Figure 13: Q-RA compliant components for safety and security.

4.2.3 Recommendations for Use

Table 5 lists recommendations for use on current safety and security standards for pilots needs and provides details on the application possibilities according to the affected areas.

Table 5: Recommendations for use in terms of safety and security standards[7]

Committee	ID[8]	Title	Q-RA	Details
IEC/TC 65 Industrial-process measurement and control	IEC 62443 series, Link	Security for industrial automation and control systems	Distributed Trustworthiness Layer	Cyber Security in Industrial Environments
ISO/TC 199 Safety of machinery	ISO 13849-1:2015, Link	Safety of machinery — Safety-related parts of control systems — Part 1: General principles for design	Control Service	Control Service; design and integration of safety-related parts of control systems
ISO/IEC JTC 1/SC 27 Information security, cybersecurity and privacy	ISO/IEC 27000:2018, Link	Information technology – Security techniques – Information security management systems – Overview and vocabulary	Digital models and Vocabularies	Information security management systems; Vocabulary
IEC TC 65/SC 65A System aspects	IEC 61511-1:2016+AMD1:2017 CSV	Functional safety - Safety instrumented systems for the process industry sector - Part 1: Framework, definitions, system, hardware and	Collaboration, Business and	SIS design: Specification, design, installation, operation and maintenance of a safety instrumented system (SIS); engineering of systems that

[7] Also see standards masked as (S) in Table 2: Recommendations for use in terms of interoperability standards.
[8] under development (*)

Committee	ID[8]	Title	Q-RA	Details
	, Consolidated version, Link	application programming requirements	Operation Services	ensure safety of an industrial process through the use of instrumentation.
TC 44 - Safety of machinery - Electrotechnical aspects	IEC 62061:2015 CSV, Link	Safety of machinery - Functional safety of safety-related electrical, electronic and programmable electronic control systems	Distributed Trustworthiness Layer	Safety of machinery: Functional safety of electrical, electronic PLC systems
ISO/IEC JTC 1/SC 41 Internet of Things and related technologies	ISO/IEC 30147*, Link	Information technology – Internet of things – Methodology for trustworthiness of IoT system/service	Distributed Trustworthiness Layer	Trustworthiness of IoT system/service
ISO/IEC JTC 1/SC 7 Software and systems engineering	ISO/IEC TS 33052:2016, Link	Information technology – Process reference model (PRM) for information security management	Distributed Trustworthiness Layer	Process reference model (PRM) for the domain of information security management; model architecture
ISO/IEC JTC 1/SC 27 Information security, cybersecurity and privacy	ISO/IEC 15408 series, Link	Information technology – Security techniques – Evaluation criteria for IT security	Distributed Trustworthiness Layer	General concepts and principles of IT security evaluation; general model of evaluation
ISO/IEC JTC 1/SC 27 Information security, cybersecurity and privacy	ISO/IEC 27001:2013, Link	Information technology – Security techniques – Information security management systems – Requirements	Collaboration, Business and Operation Services	ISMS: Establishing, implementing, maintaining and continually improving an information security management system within the context of the organization (Information security)
ISO/IEC JTC 1/SC 27 Information security, cybersecurity and privacy	ISO/IEC 27002:2013, Link	Information technology – Security techniques – Code of practice for information security controls	Distributed Trustworthiness Layer	Security techniques: Selection, implementation and management of controls taking into consideration the organization's information security risk environment
ISO/IEC JTC 1/SC 27 Information security, cybersecurity and privacy	ISO/IEC 27005:2018, Link	Information technology - Security techniques – Information security risk management	Distributed Trustworthiness Layer	Risk management: Guidelines for information security risk management (general)
ISO/IEC JTC 1/SC 27 Information security, cybersecurity and privacy	ISO/IEC 27017:2015, Link	Information technology — Security techniques — Code of practice for information security controls based on ISO/IEC 27002 for cloud services	Cloud	Guidelines for information security controls applicable to the provision and use of cloud services
ISO/TC 199 Safety of machinery	ISO 12100:2010, Link	Safety of machinery – General principles for design	Assets & Smart Products	Safety in system design, terminology and

Committee	ID[8]	Title	Q-RA	Details
		– Risk assessment and risk reduction		methodology; risk assessment through life cycle
ISO/TC 199 Safety of machinery	ISO/TR 22100-4:2018, Link	Safety of machinery — Relationship with ISO 12100 — Part 4: Guidance to machinery manufacturers for consideration of related IT-security (cyber security) aspects	Distributed Trustworthiness Layer	Cybersecurity guidance on potential security aspects in relation to safety of machinery when putting a machine into service or placing on the market for the first time
ISO/TC 199 Safety of machinery	ISO 13849-2: 2012, Link	Safety of machinery - Safety-related parts of control systems - Part 2: Validation	Control Service	Control systems; Production System Engineering; safety of machinery; conditions to be followed for the validation by analysis and testing of the specified safety functions
ISO/IEC JTC 1/SC 42 Artificial Intelligence	ISO/IEC TR 24028:2020, Link	Information technology - Artificial intelligence - Overview of trustworthiness in artificial intelligence	Distributed Trustworthiness Layer	Trustworthiness in AI systems, availability, resiliency, reliability, accuracy, safety, security and privacy
DIN German Institute for Standardization	DIN SPEC 92001-2, Link	Artificial Intelligence - Life Cycle Processes and Quality Requirements - Part 2: Robustness	Distributed Trustworthiness Layer	AI, lifecycle quality requirements; robustness, safety and transparency and corruption robustness (i.e. model sensitivities to naturally occurring noise / data outliers)
ISO/IEC JTC 1/SC 42 Artificial Intelligence	ISO/IEC 23894*,Link	Information Technology — Artificial Intelligence — Risk Management	Distributed Trustworthiness Layer	AI, risk management
ISO/IEC JTC 1/SC 42 Artificial Intelligence	ISO/IEC TR 24028, Link	Information technology -- Artificial Intelligence (AI) -- Overview of trustworthiness in Artificial Intelligence	Distributed Trustworthiness Layer	AI, Trustworthiness
ISO/IEC JTC 1/SC 42 Artificial Intelligence	ISO/IEC TR 24029*,Link	Artificial Intelligence (AI) -- Assessment of the robustness of neural networks	Distributed Trustworthiness Layer	AI, assessment of the robustness of neural networks
ISO/IEC JTC 1/SC 42 Artificial Intelligence	ISO/IEC 38507*, Link	Governance of IT -- Governance implications of the use of artificial intelligence by organizations	Distributed Trustworthiness Layer	AI, Governance
ISO/IEC JTC 1/SC 41 Internet of Things and related technologies	ISO/IEC 30149*, Link	Internet of things (IoT) — Trustworthiness framework	Distributed Trustworthiness Layer	IoT, Trustworthiness framework
ITU	Y.ccrm*, Link	Cloud computing - Framework of risk management	Distributed Trustworthiness Layer	Cloud computing, risk management framework

Committee	ID[8]	Title	Q-RA	Details
ISO/TC 299 Robotics	ISO 10218-1:2011, Link	Safety requirements for industrial robots — Part 1: Robots	Distributed Trustworthiness Layer	Robots and robotic devices, Safety requirements for industrial robots
ISO/TC 299 Robotics	ISO 9283:1998, Link	Manipulating industrial robots — Performance criteria and related test methods	Distributed Trustworthiness Layer	Robots, manipulating industrial robots, performance criteria and related test methods
ISO/TC 299 Robotics	ISO/TR 13309:1995, Link	Manipulating industrial robots — Informative guide on test equipment and metrology methods of operation for robot performance evaluation in accordance with ISO 9283	Distributed Trustworthiness Layer	Robots, testing and safety for industrial robots; robot performance evaluation
ISO/IEC JTC 1/SC 31 Automatic identification and data capture	ISO/IEC 29161:2016, Link	Information technology — Data structure — Unique identification for the Internet of Things	Digital models and Vocabularies	IoT, unique identification
ISO/TC 199 Safety of machinery	ISO 11161:2007, Link	Safety of machinery — Integrated manufacturing systems — Basic requirements	Distributed Trustworthiness Layer	Safety of machinery, Integrated manufacturing systems, basic requirements
DIN German Institute for Standardization	EN 61310 series, Link	Safety of machinery - Indication, marking and actuation	Distributed Trustworthiness Layer	Safety of machinery, Indication, marking and actuation; requirements for visual, acoustic and tactile signals, e.g. indication of hazardous situations and health hazards
TC 44 - Safety of machinery - Electrotechnical aspects	IEC 60204:2020 SER, Link	Safety of machinery - Electrical equipment of machines - ALL PARTS	Distributed Trustworthiness Layer	Safety of machinery; electrical equipment of machines
DIN German Institute for Standardization	EN 62745:2017, Link	Safety of machinery - Requirements for cableless control systems of machinery (IEC 62745:2017)	Control Service	Safety of machinery, requirements for cableless control systems of machinery
ISO/TC 199 Safety of machinery	ISO TR 21260*, Link	Safety of machinery — Mechanical safety data for physical contacts between moving machinery or moving parts of machinery and persons	Distributed Trustworthiness Layer	Safety of machinery, mechanical safety data for physical contacts between moving machinery or moving parts of machinery and persons
International Data Spaces Association	IDS-RAM:2019, Link	IDSA Reference Architecture Model 3.0	Digital Twin and Planning Services	IDSA RA
ISO/TC 184/SC 5 Interoperability, integration, and architectures for	ISO 15746 series, Link	Automation systems and integration — Integration of advanced process control and optimization capabilities	Control Service	Information models for advanced process control optimization capabilities for

Committee	ID[8]	Title	Q-RA	Details
enterprise systems and automation applications		for manufacturing systems-SER		manufacturing systems; framework; models; validation
ISO/IEC JTC 1/SC 27	ISO/IEC 18045:2008, Link	Security techniques — Methodology for IT security evaluation	Distributed Trustworthiness Layer	Evaluation, using the criteria and evaluation evidence
ANSI	B11.Tr10—202x*, Link	Functional Safety of Artificial Intelligence for Machinery Applications	Distributed Trustworthiness Layer	Functional safety of artificial intelligence for machinery applications
OASIS	SAML, Link	Security Assertion Markup Language (SAML)	Distributed Trustworthiness Layer	XML-based open standard data format for exchanging authentication and authorization data between parties
IETF OAuth Working Group	OAth2.0, Link	OAuth	Distributed Trustworthiness Layer	open standard for secure authorization
OpenID Foundation	OpenID, Link	OpenID	Distributed Trustworthiness Layer	user authentication
OASIS Standard	XACML 2.0, Link	eXtensible Access Control Markup Language (XACML)	Distributed Trustworthiness Layer	declarative access control policy language implemented in XML, processing model to evaluate authorization requests according to the rules defined in policies.

4.2.4 Example of prominent standards

This section provides more details on some prominent standards for common use.

4.2.4.1 ISO/IEC 27001:2013 Information technology – Security techniques – Information security management systems – Requirements

ISO/IEC 27001:2013 is a security standard that defines common security management procedures and comprehensive security controls in accordance with the best practice guidelines set out in ISO/IEC 27002. In detail, it specifies the requirements for establishing, implementing, operating, monitoring, reviewing, maintaining and improving formalized information security management systems (ISMS) within the context of the organization's overall business risks[9] (Figure 14). The standard also specifies requirements for the implementation of security controls tailored to the needs of individual organizations or their parts. ISO/IEC 27001 is the most comprehensive information security management certification that is

[9] Constantin Militaru, "Human Resources Security Management towards ISO/IEC 27001:2005 accreditation of an Information Security Management System," *undefined*, 2009.

internationally accepted and its generic requirements are intended to be applicable to all organizations, regardless of type, size or nature.

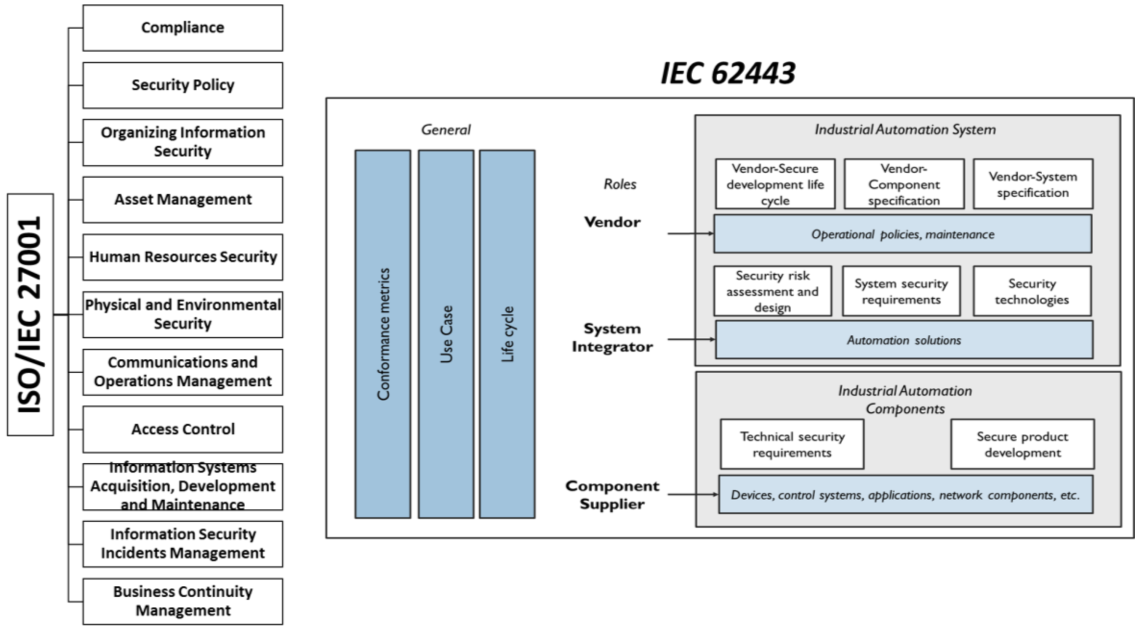


Figure 14: Left: Security control classes of ISO/IEC 27001. Right: security life cycles and roles based on IEC 62443.

4.2.4.2 IEC 62443 SER Security for industrial automation and control systems

IEC 62443(Figure 14)) is a series of documents that deals with the IT security of so-called "Industrial Automation and Control Systems (IACS)[10]". The standard defines use cases, conformity metrics, and other general and specific requirements. All in one, this standard provides a holistic approach for more safety in the industrial field and at the same time takes the various roles into account.

4.3 Compliance Specification for Artificial Intelligence Standards

4.3.1 Description and Goals

Through applying big data and AI techniques, IT systems can take data analytics to the next level and accelerate ZDM solutions to the next level. AI standards are an excellent mean to establish interoperability and compliance between new and old technologies and address AI concerns ultimately acceleration technology adoption by the pilots. Though this section focuses on AI standards, it also investigates on compatibility to ML and Big Data standards as accompanying functionalities in the pilots' applications.

[10] https://www.isa.org/isa99/

One of the prominent standards setters for AI is ISO/IEC SC42 Artificial Intelligence[11] that develops horizontal AI standards enabling smart manufacturing with respect to several standardization areas: foundational standards for AI framework, terms and definitions, which in its turn set a common language and framework compositional rules for the application of AI machine learning and deployment of the next generation smart manufacturing systems. Trustworthy AI is also a key standardization goal that addresses successful deployment of AI systems in smart manufacturing ensuring the required level of security, safety, and trustworthiness. Besides of these topics the committee develops standards that concern ethics and societal consideration, provides required guidance and use cases.

4.3.2 Key Compliance Requirements

AI is a central topic of pilots' solutions. Therefore, a large number of requirements could be identified in this area. Table 6 lists common samples of AI requirements identified in Task 3.3 Deliverable D3.5.

Table 6: Analysis of the key requirements for QU4LITY AI requirements

Pilots	Common Sample AI Requirements
PHILIPS	The quality of products needs to involve learning predictive operations and analysis of data associated with processes signals and dimensional critical-to-quality components;
SIEMENS	Quality management processes need to involve advanced analysis of quality-related datasets and classification of identified failures
CONTINENTAL	The developed system must capture, communicate, store and visualize real-time data (products, quality, equipment, etc.) to perform analysis of quality-related data from multi-stage production lines.
WHIRLPOOL	Main focus on big data requirements for integration and consolidation of data from diverse data sources
MONDRAGON	1.Process control on hot stamping equipment must be enhanced through extraction of knowledge from sources that cause defects; 2. Multiple data source decision support system need to be established to perform the quality data analysis for machinery.
KOLEKTOR	Nearly real-time (predictive) data analytics need to be involved in order to anticipate and timely remove the cause of the process failures
THYSSENKRUP	The quality management process based on a better correlation between process and control must be improved (incl. req. is collecting of data from various points on the production line)
AIRBUS	(Big) data from various sources across the value chain need to be collected and analyzed to identify and maintain production quality targets.
GHI	Data-driven monitoring of the industrial furnace operating parameters need to be involved to identify sources/cause of quality issues to reduce defective parts.
RIASTONE	A data driven DSS for quality management decisions need to be advanced with automated processes and data analytics to raise early detection warning signals of product defects.

[11] https://www.iso.org/committee/6794475.html

PRIMA	A system for advanced collecting, tracking and analysis of data need to be implemented to enhance process robustness in additive manufacturing.
DANOBAT	(Big) data collection of sensor data and analytics need to be realized to execute prediction of the machine's remaining useful life (problems in the operation of the machine).
FAGOR	Critical machinery operational parameters need to be collected to perform conjunction analyses with the production processes and related parameters
GF	The robotized machining cell need to be advanced through the aggregation and integration of information from multi-stage processes in a common data space.

In terms of AI the following components could be identified within the RA specification during the requirements analysis:

- *Digital models and Vocabularies* regarding addressing information modelling issues and interoperability of the information layer between big data and AI related applications and other components;
- *Distributed Trustworthiness* Layer regarding trustworthy AI solution and addressing sensitive data analytics processes;
- *Data-driven Modelling and Learning Service* including respective use cases involving data-driven modelling and learning services to perform analytical observations and predictions;
- *Data Lake /Big Data Analytics Infrastructure* regarding the collection of sensor data or machinery data and e.g. performing advanced operations in terms of failure detection and prediction;
- *Cross-cutting* issues address standards in terms of AI use cases and AI framework compliance.

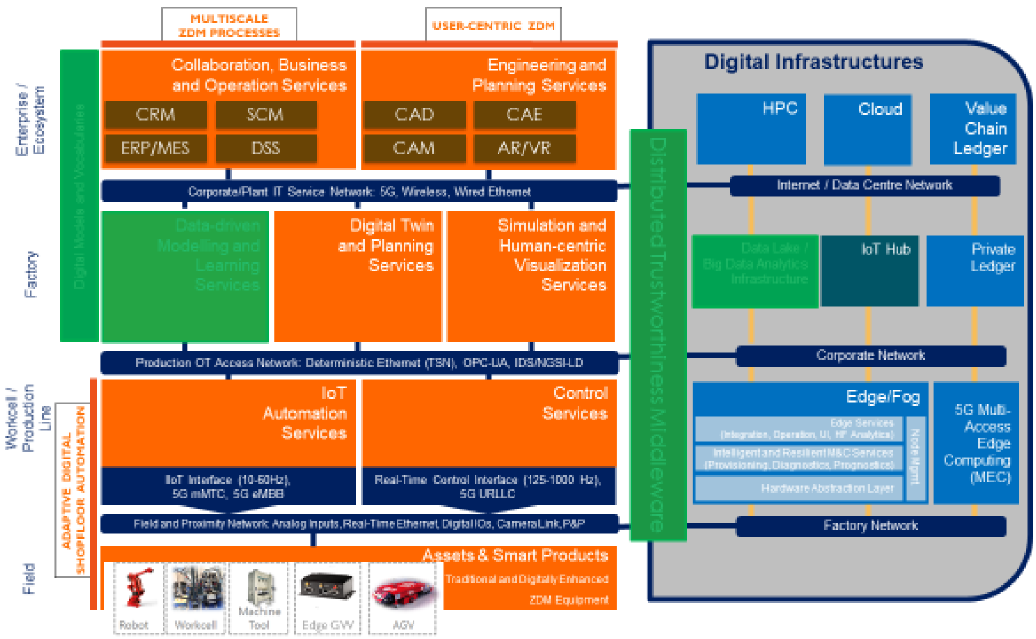


Figure 15: Q-RA compliant components for safety and security.

4.3.3 Recommendations for Use

The recommendations for use in this section refer to several corresponding AI standards, as shown in the Table 7. Although AI standardization is not yet fully developed, there are many standards in development that should be mentioned with regard to future development and orientation for pilots.

Table 7: Recommendations for use concerning AI standards[12]

Committee	ID[13]	Title	Q- RA	Details
ISO/IEC JTC 1/SC 42 Artificial Intelligence	ISO/IEC 20546:2019, Link	Big data - Overview and vocabulary	Digital models and Vocabularies	Big data vocabulary
ISO/IEC JTC 1/SC 42 Artificial Intelligence	ISO/IEC TR 20547-2:2018, Link	Big data reference architecture - Part 2: Use cases and derived requirements	Cross-cutting	Big data use cases with application domains and technical considerations derived from the contributed use cases
ISO/IEC JTC 1/SC 42 Artificial Intelligence	ISO/IEC TR 20547-1:2020, Link	Big data reference architecture — Part 1: Framework and application process	Data Lake /Big Data Analytics Infrastructure	Big data framework and application process
ISO/IEC JTC 1/SC 42 Artificial Intelligence	ISO/IEC 20547-3:2020, Link	Big data reference architecture - Part 3: Reference architecture	Data Lake /Big Data Analytics Infrastructure	BDRA: Big data reference architecture
ISO/IEC JTC 1/SC 42 Artificial Intelligence	ISO/IEC TR 20547-5:2018, Link	Big data reference architecture - Part 5: Standards roadmap	Data Lake /Big Data Analytics Infrastructure	Big data standards roadmap
ISO/IEC JTC 1/SC 42 Artificial Intelligence	ISO/IEC TR 24028:2020, Link	Artificial intelligence - Overview of trustworthiness in artificial intelligence	Distributed Trustworthiness Layer	Trustworthiness in AI systems, availability, resiliency, reliability, accuracy, safety, security and privacy
DIN German Institute for Standardization	DIN SPEC 92001-1:2019-04, Link	Life Cycle Processes and Quality Requirements – Part 1: Quality Metamodel	Digital models and Vocabularies	AI, lifecycle quality requirements; quality model
DIN German Institute for Standardization	DIN SPEC 92001-2, Link	Artificial Intelligence - Life Cycle Processes and Quality Requirements - Part 2: Robustness	Distributed Trustworthiness Layer	AI; lifecycle quality requirements; robustness, safety and transparency (i.e. AI attacks with mathematically optimized

[12] Also see standards masked as (S) in Table 2: Recommendations for use in terms of interoperability standards.
[13] under development (*)

Committee	ID[13]	Title	Q- RA	Details
				perturbations leading to model failure)
DIN German Institute for Standardization	DIN SPEC 13266:2020-04, Link	Guideline for the development of deep learning image recognition systems	Data-driven Modelling and Learning Service	AI; deep learning recognition models
DIN German Institute for Standardization	DIN SPEC 2343:2020-09, Link	Transmission of language-based data between artificial intelligences - Specification of parameters and formats	Data-driven Modelling and Learning Service	AI; interoperability; data transmission in ecosystems; to develop interoperable speech-based applications, to verify and trace data of speech-based applications and to enable data access or data protection
ITU	Suppl on Y. Sup.aisr*, Link	Artificial Intelligence Standard Roadmap	Cross-cutting	AI; road mapping
ISO/IEC JTC 1/SC 42 Artificial Intelligence	ISO/IEC TR 24030*, Link	Artificial Intelligence (AI) — Use cases	Cross-cutting	AI, use cases
ISO/IEC JTC 1/SC 42 Artificial Intelligence	ISO/IEC 22989*, Link	Artificial Intelligence Concepts and Terminology	Data-driven Modelling and Learning Service	AI; foundational, concepts and terminology
ISO/IEC JTC 1/SC 42 Artificial Intelligence	§ISO/IEC 23053*, Link	Framework for Artificial Intelligence (AI) Systems Using Machine Learning (ML)	Data-driven Modelling and Learning Service	AI, framework for AI systems using ML
ISO/IEC JTC 1/SC 42 Artificial Intelligence	ISO/IEC TR 24027*, Link	Artificial Intelligence (AI) — Bias in AI systems and AI aided decision making	Data-driven Modelling and Learning Service	AI: bias in AI systems and AI aided decision making
ISO/IEC JTC 1/SC 42 Artificial Intelligence	ISO/IEC TR 24028*, Link	Artificial Intelligence (AI) -- Overview of trustworthiness in Artificial Intelligence	Distributed Trustworthiness Layer	AI; trustworthiness
ISO/IEC JTC 1/SC 42 Artificial Intelligence	ISO/IEC TR 24029*, Link	Artificial Intelligence (AI) -- Assessment of the robustness of neural networks	Distributed Trustworthiness Layer	AI; assessment of the robustness of neural networks
ISO/IEC JTC 1/SC 42 Artificial Intelligence	ISO/IEC 38507*, Link	Governance implications of the use of artificial intelligence by organizations	Distributed Trustworthiness Layer	AI; governance of IT

Committee	ID[13]	Title	Q- RA	Details
ISO/IEC JTC 1/SC 42 Artificial Intelligence	ISO/IEC 24668*, Link	Artificial intelligence — Process management framework for Big data analytics	Data Lake /Big Data Analytics Infrastructure	AI, Process management framework for Big data analytics
ISO/IEC JTC 1/SC 41 Internet of Things and related technologies	ISO/IEC 30166:2020, Link	Internet of things (IoT) — Industrial IoT	Cross-cutting	Industrial IoT standards and road mapping
ANSI	B11.Tr10—202x*, Link	Functional Safety of Artificial Intelligence for Machinery Applications	Distributed Trustworthiness Layer	Functional safety of AI for machinery applications

4.3.4 Example of prominent standards

Among prominent standards we would like to highlight the following activities:

4.3.4.1 ISO/IEC 22989 Artificial Intelligence Concepts and Terminology and ISO/IEC 23053 Framework for Artificial Intelligence (AI) Systems Using Machine Learning (ML)

ISO/IEC 22989 and ISO/IEC 23053 are two of the fundamental AI standards that examine on different AI application domains and define and describe the respective AI-related use cases using specific terminology and other concepts developed in the common standards of ISO/IEC JTC1 SC42. Both standards are currently being developed at a CD stage, but have made very promising progress towards becoming far-reaching standards for establishing a common AI language and interoperability framework for AI applications.

4.3.4.2 DIN SPEC 92001-1:2019-04 Artificial Intelligence - Life Cycle Processes and Quality Requirements - Part 1: Quality Meta Model

At the national level of standardization, it is worth to highlight the DIN SPEC 9001 goal of this DIN SPEC series is to enable a safe and transparent development and deployment of AI modules. For this purpose, the DIN SPEC describes a set of quality requirements, which are structured by an AI quality meta model (see Figure 16), that is mainly based on three essential quality characteristics - performance & functionality, robustness and comprehensibility.

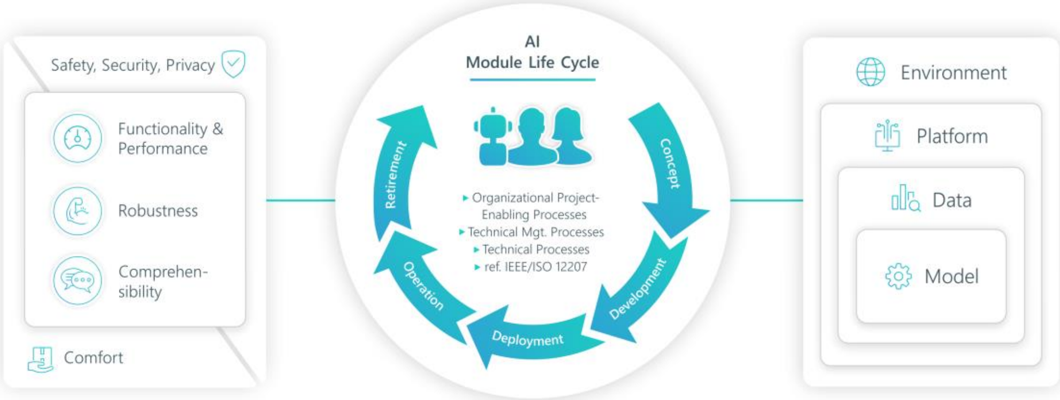


Figure 16: The quality metamodel described in DIN SPEC 92001-1 [5] (Picture: © DIN [6])

This document also deals with risk assessment and provides an appropriate software life cycle approach. The DIN SPEC series applies to all life cycle phases - conception, development, deployment, operation and decommissioning - of an AI module and takes into account a variety of different life cycle processes. Since AI technologies are used for a wide variety of tasks, this DIN SPEC series is aimed at companies in all industries.

4.4 Compliance Specification for Reference Architecture Standards, Digital Models and Vocabularies

4.4.1 Description and Goals

With the increasing maturity of production technology in manufacturing, the need to link software applications and technical systems vertically, i.e. across multiple levels of the automation pyramid, has significantly increased. Additionally, the questions concerning the conformity and interoperability of technical systems and their ability to exchange data within an enterprise IT architecture are gaining immensely in importance. Exactly, this is where the idea of Reference Architectures (RA) and Reference Architecture Models (RAM) comes in for a production company.

A general common system architecture approach usually applies pure IT rules and structures for descriptive purpose. However, the goal of I4.0 is the creation of methodologies that cover all relevant information from the physical world and transfer this to the virtual information world that is supplemented by computer-aided automation (creation of digital image as a "mirror" to a physical world). With regard to this RAs/RAMs offer simple and generally proven solutions that support a company in setting up its entire production on the basis of a jointly agreed standard solution and thus quickly migrate to an advanced level [7].

Furthermore, reference architectures are specification documents that usually provide some common guidelines on e.g. how efficiently apply a migration process, what requirements should apply, and how to convert existing IT architectures to interoperable frameworks. There are a large number of standard-based reference architectures and models for industrial use. Although there are partially very different representations of I4.0 -related concepts and frameworks in the documentation, the majority of those share very common understandings and present overlapping of concepts.

The compliance of RAs/RAMs are therefore essential for QU4LITY in order to ensure seamless integration of technical systems and related processes over the main life cycles.

4.4.2 Key Compliance Requirements

In order to examine the conformity with the most common relative standards in the given area, a detailed requirement analysis was first carried out with regard to the development of the reference architectures[14]. Several key requirements for the compliance specification could be identified as shown in Table 8:

Table 8: Analysis of the key requirements for reference architecture, digital models and vocabularies

Feature	Common Requirements
Conformity	DIN SPEC 91345:2016 RAMI4.0 [8] and its internationally updated version IEC PAS 63088:2017(E) [9] must serve as a standard conformity objective for verification of compliance requirements. These standards are very common in the field of I4.0 and describe "[…] a reference architecture model in the form of a cubic layer model, which shows technical objects (assets) in the form of layers, and allows them to be described, tracked over their entire lifetime (or "vita") and assigned to technical and/or organizational hierarchies […]". Terms and definitions must be conform with current standards.
Complexity and Readability	The proposed Reference Architecture must avoid complex views and multiple internal dependencies between different architectural elements in order to decrease the complexity and readability of the architecture.
Consistency	The conformity objectives should not be limited to RAMI 4.0. Several works aim to create a framework for Industrial Reference Architectures and their descriptions. Except for above described standards, the most common standard in this area is ISO/IEC/IEEE 42010 [10]. Several standards have set the ISO/IEC/IEEE 42010 as an architectural backbone in their work, e.g. ISO/IEC 30141 [11]. ISO/IEC/IEEE 42010 provides a common architecture description based on so-called *architecture views* that handle various abstract architectures following one specific topic. However, the presentation in multiple views with inter-connective and other internal dependencies between different specific topics significantly increases the complexity and readability of the architecture. Nevertheless, the missing architecture views must be verified in accordance with the most common Reference Architecture Standards for possible gaps. With regard to the ZDM-specific vocabulary, the current standards must be reviewed and continually updated.
Harmonization	The Quality Reference Architecture should encounter the recent standardization activities towards harmonization of reference architectures. Taking into account the

[14] See QU4LITY Tasks T2.4 and T9.2

	recent standardization activities that aim to establish a wide-ranging harmonization among various reference architectures, including also those applied in the industrial area, it is recommended to investigate the possible interfaces and application requirements. ZDM terms must be harmonized and coordinated at the international / European layers.
Informational capacity	A standardized reference architecture must fulfil the common design specifications and include several objectives, i.e. specify the main system level goals, provide an architecture description, describe the high level interactions between elements and the system environment, specify general element requirements, and element descriptions. ZDM vocabulary must be aligned with the relative Q-RA components.
Industrial Application	The related key ZDM domains of the Quality Reference Architecture must comply to the RAMI4.0 respective layers.
Integrity	The QU4LITY Reference Architecture must integrate the common ZDM-related standards in such a way that it still conforms with the standard compliance objective, i.e. RAMI 4.0 and do not violate or disagree with other requirements.

Based on the above listed requirements several components could be identified within the Q-RA, as shown in Figure 17, that are primarily affected in terms of common compliance with standards.

- *Digital Models and Vocabularies* regarding common digital models, terms and definitions;
- *Digital Twin and Planning Services*, *Data-driven Modelling and Learning Services* regarding information modelling across different RA layers;
- *IoT Hubs, Cloud, Distributed Trustworthiness Layer, Data Lake /Big Data Analytics Infrastructure*, and other *cross-cutting standards* regarding various framework specifications and composition principles.

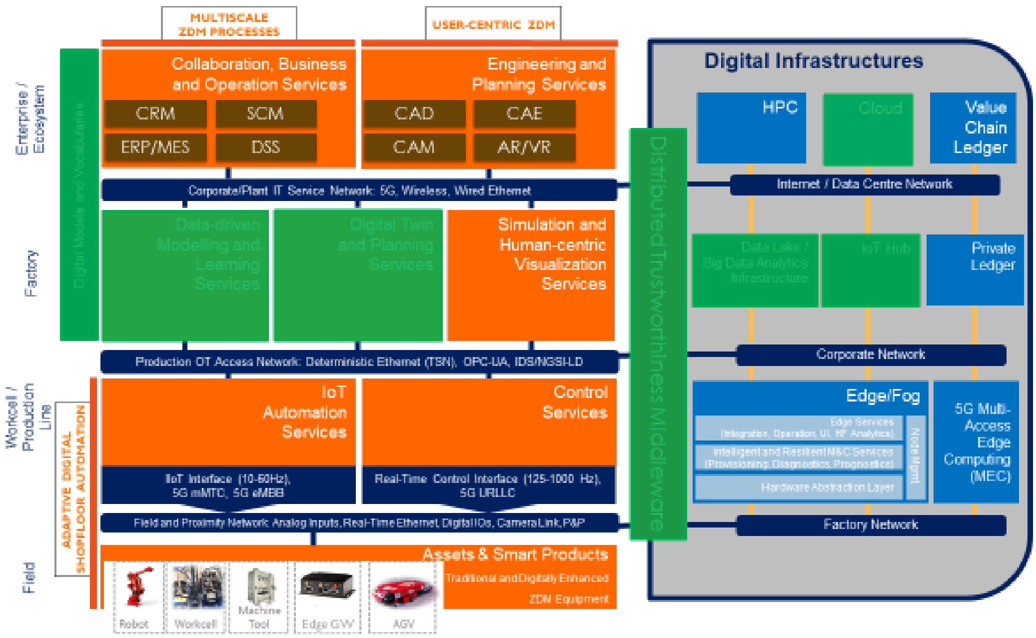


Figure 17: Q-RA compliant components for reference architecture, digital models and vocabularies.

4.4.3 Recommendations for Use

The following section contains a list of recommendations for pilots regarding the potential use of reference architecture standards, terms and definitions and other information modelling standards in their applications. Table 9 depicts mapping results and provides details about specific standards application fields.

Table 9: Recommendations for use in terms of RA standards and vocabularies[15]

Committee	ID[16]	Title	Q-RA	Details
IEC/TC 65 Industrial-process measurement and control	IEC TS 62832-1:2016, Link	Industrial-process measurement, control and automation - Digital factory framework - Part 1: General principles	Digital Twin and Planning Services	General principles of the Digital Factory framework
ISO/TC 184/SC 5 Interoperability, integration, and architectures for enterprise systems and automation applications	ISO 19439:2006, Link	Enterprise integration — Framework for enterprise modelling	Digital Twin and Planning Services	Enterprise modelling; computer integrated manufacturing
IEC/TC 65 Industrial-process measurement and control	IEC PAS 63088:2017, Link	Smart manufacturing – Reference architecture model industry 4.0 (RAMI4.0)	Digital Twin and Planning Services	RAMI4.0 - Digital twin, process optimization run-time
ISO/IEC JTC 1/SC 41 Internet of Things and related technologies	ISO/IEC 30149*, Link	Internet of things (IoT) – Trustworthiness framework	Distributed Trustworthiness Layer	Trustworthiness of IoT system/service
ISO/IEC JTC 1/SC 41 Internet of Things and related technologies	ISO/IEC 30165*, Link	Internet of Things (IoT) – Real-time IoT framework	IoT Hubs	Real-time IoT framework
ISO/IEC JTC 1 Information Technology	ISO/IEC 30118 series, Link	Information technology – Open Connectivity Foundation (OCF) Specification – Part 1: Core specification	IoT Hubs	OCF Spec; industrial communication framework for IoT
ISO/TC 184/SC 4 Industrial data	ISO 23247 series*, Link	Automation systems and integration — Digital Twin framework for manufacturing	Digital Twin and Planning Services	Digital Twin framework for manufacturing (Information exchange, digital representation of manufacturing elements.)

[15] Also see standards marked as (RA) in Table 2: Recommendations for use in terms of interoperability standards.
[16] under development (*)

ISO/TC 184 Automation systems and integration	ISO 22549-1:2019, Link	Assessment on convergence of informatization and industrialization for industrial enterprises – Part 1: Framework and reference model	Digital Twin and Planning Services	Industrial enterprise: Maturity model and evaluation methodology; enterprise quality control
ISO/IEC JTC 1/SC 7 Software and systems engineering	ISO/IEC TS 33052:2016, Link	Process reference model (PRM) for information security management	Distributed Trustworthiness Layer	Process reference model (PRM) for the domain of information security management; model architecture
IEEE Institute of Electrical and Electronics Engineers	IEEE P2413:2019, Link	Architectural Framework for the Internet of Things (IoT)	Cross-cutting	IEEE architectural framework for the IoT
ISO/IEC JTC 1/SC 42 Artificial Intelligence	§ISO/IEC 23053*, Link	Framework for Artificial Intelligence (AI) Systems Using Machine Learning (ML)	Data-driven Modelling and Learning Service	AI, framework for AI systems using ML
ISO/IEC JTC 1/SC 41 Internet of Things and related technologies	ISO/IEC 30166:2020, Link	Internet of things (IoT) — Industrial IoT	Cross-cutting	Industrial IoT standards and road mapping
ISO/IEC JTC 1/SC 41 Internet of Things and related technologies	ISO/IEC 21823-1:2019, Link	Internet of things (IoT) — Interoperability for IoT systems — Part 1: Framework	IoT Hubs	IoT, interoperability framework
ISO/IEC JTC 1/SC 42 Artificial Intelligence	ISO/IEC 20547-3:2020, **Link**	Data Lake /Big Data Analytics Infrastructure	Data Lake /Big Data Analytics Infrastructure	Data Lake /Big Data Analytics Infrastructure
ITU	Y.csb-arch*, Link	Cloud Computing - Functional architecture for cloud service brokerage	Cloud	Cloud Computing, functional architecture for cloud service brokerage
ITU	FG Cloud TR Version 1.0 (02/2012), Link	FG Cloud Technical Report Part 2: Functional requirements and reference architecture	Cloud	Cloud Computing, functional requirements and RA
IEC TC 65 WG24 Asset Administration Shell for Industrial Applications	IEC 63278-1*, Link	Asset administration shell for industrial applications – Part 1: Administration shell structure	Digital models and Vocabularies	AAS, interoperability
ISO/IEC JTC 1/SC 41 Internet of Things and related technologies	ISO/IEC30141:2018, Link	Internet of Things (IoT) — Reference Architecture	Cross-cutting	IoT RA

International Data Spaces Association	IDS-RAM:2019, Link	IDSA Reference Architecture Model 3.0	Digital Twin and Planning Services	IDSA RA
Industrial Internet Consortium	IIRA:2019, Link	The Industrial Internet of Things Volume G1: Reference Architecture Version 1.9	Digital Twin and Planning Services	IIRA
ISO/TC 184/SC 5 Interoperability, integration, and architectures for enterprise systems and automation applications	ISO 22400-2:2014, Link	Automation systems and integration — Key performance indicators (KPIs) for manufacturing operations management — Part 2: Definitions and descriptions	Digital models and Vocabularies	KPIs used in manufacturing operations management
ISO/TC 176/SC 2 Quality systems	ISO 9000 GLOSSARY, Link	Glossary – Guidance on selected words used in the ISO 9000 family of standards	Digital models and Vocabularies	Quality; guidance for configuration management; technical and administrative direction over the life cycle of a product and service.

4.4.4 Example of prominent standards

A wide variety of reference architectures and models with a focus on I4.0 are publicly available and have been promoted by the SDOs and standards-related organizations such as ISO, IEC as well as industry groups and initiatives such as IDSA [12], OFC [13]. Due to the great heterogeneity of architectures and models in recent years, the SDOs and the corresponding liaisons and cooperation have been established to achieve interoperability between the already published and current standards and to contribute to harmonization. The following subsections give more details on some prominent standards for common use.

4.4.4.1 Reference Architecture Model for Industrie 4.0 (RAMI 4.0).

The RAMI 4.0 [9] is the next comprehensive example of profound industrial reference architectures and models that extracts the above described list. A short description of RAMI 4.0 layer was already presented in chapter 3.2.2. in Deliverable D2.3. This deliverable will specifically concentrate on interoperability and standards-related issues that service as a background for the reference architecture compliance analysis and conception of interoperability specifications, following in the next chapters.

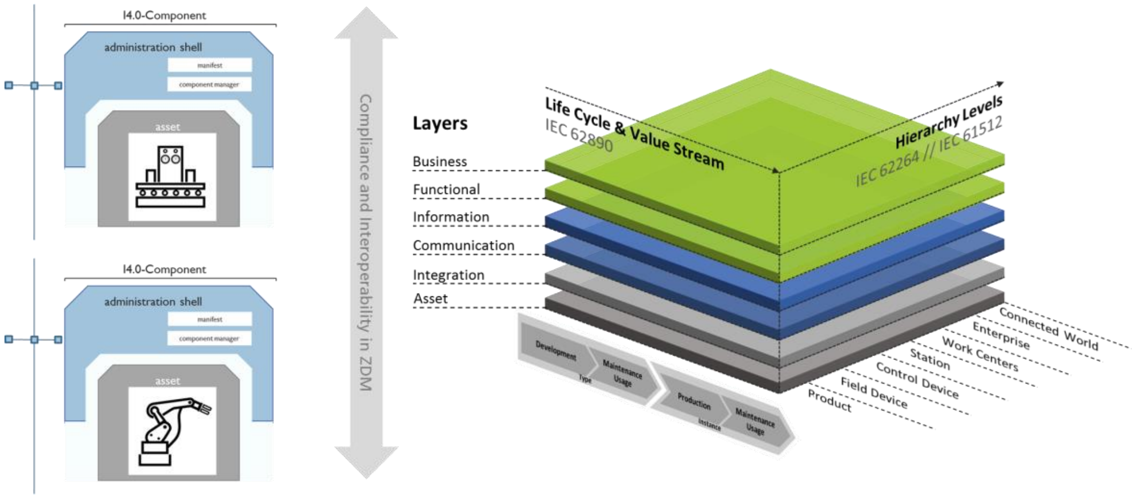


Figure 18: QU4LITY compliance and interoperability in RAMI4.0

In general, RAMI 4.0 brings together the most important aspects of I4.0 and is considered to be one of the central orientation guides for Industry 4.0. as it provides a comprehensive view of the industrial landscape in a broad sense. The RAMI 4.0 standard builds strongly on the concepts of the Industry 4.0 Component (I4.0 Component) and its Asset Administration Shell (AAS) [14].

The *I4.0 Component* describes the properties of CPPS that are networked in the production environment with other assets or virtually represented processes [15]. An asset is usually described as a physical or virtual object that has a value for an organization. In fact, the I4.0-compliant communication is realized in RAMI4.0 on the basis of the I4.0 Component.

The *AAS* as well as an asset is a part of an I4.0-Component and is considered to be one of the important interoperability components in I4.0. The main task of the AAS is to expose the data and functionality of assets that are relevant in a life-cycle. Assets can be combined in much larger constellations, starting form a simple sensor or a field device on the shop floor until a connected factory that includes all possible systems involved in the completely manufacturing life cycle [15]. The German Plattform Industrie 4.0 and IEC TC 65/WG 23 are very active in standardization of AAS and bring interoperability notion of Smart Manufacturing to the next level.

4.4.4.2 Further standards and specifications

Further prominent standards and detailed specifications of the relevant I4.0 RA and RAM are described in details in the Deliverable D2.11 *Reference Architecture and Blueprints.* Furthermore, Deliverable D9.6 *Standardization and Clustering* gives more information on current standardization activities with regard objectives of this section.

4.5 Compliance Specification for Quality Standards

4.5.1 Description and Goals

Quality standards are defined as documents that contain requirements, specifications, guidelines or features that can be used consistently to ensure that materials, products, processes and services are suitable for their purpose [16]. Commonly, the quality processes (in standards) intend to control work and lead to certain level of excellence or quality. For QU4LITY needs a specific type of quality standards, i.e. industry standards, have been screened.

Quality standards deliver measurable benefits when applied within the infrastructure of production companies because they provide continuity; encapsulate best practices and help to avoid mistakes; save cost, define safety requirements intended to reduce the risk of accidents regarding human and work. But the most important benefit is that quality standards also contribute to interoperability, providing a necessary framework for the effective worldwide trading of products and services.

4.5.2 Key Compliance Requirements

With respect to the quality objective pilots identify a number of requirements (based on Deliverable D2.2 *Analysis of User Stories and Stakeholders' Requirements*, final version) that could be classified according to the following quality features as shown in Table 10:

Table 10: Analyses of the key requirements regarding the quality factors

Pilot	Common Sample Quality Requirements
PHILIPS	Automated quality inspections on critical points in the production line resulting in all products within tolerances so that the quality manager can limit activities to norm setting, monitoring and advice.
SIEMENS	Overview of quality affecting processes and components so that the quality manager can take care of root causes and indicate counter measures to ensure zero defect manufacturing with lowest.
CONTINENTAL	Integration with warehouse and individual production lines to support production area's including quality control and process settings.
WHIRLPOOL	Real-time correlation of data; identification of the critical factors affecting quality parameters for each product and aggregated by a model; re-balancing of production based on the warnings regarding quality problems on the product and / or the process.
MONDRAGON	Error propagation by using of warnings (retrieving production line status) that can activate actions on the machine and send information to the operator who can take decisions or can recommend maintenance
KOLEKTOR	Automated quality inspections on critical points in production lines; Reals-time detection and possibly prediction of failures based on advanced analytics and AI; Prescriptive functionality on the injection moulding line that reduces the number of defects during the moulding process so that a product manager can reduce scrap and manual quality inspections and reduce costs.

THYSSENKRUP	Understanding of error sources to avoid errors in machines and productions lines; capturing data and quality files through data acquisition system distributed on various points in the production line
AIRBUS	Allow autonomous quality control loops and easy reconfiguration of manufacturing processes in a constructed high-level advanced industrial system (supplier, factories, machines and processes) to ensure the right quality level as a target for ZDM.
GHI	Increase quality control as well as efficiency of the processes; Data analysis and correlation between quality control and furnace operation parameters for a fast detection of root cause of quality problem in order to optimize the production process but also to reduce the number of defective parts manufactured. Automated quality inspections and insights of cross-analysis quality data and other parameters.
RIASTONE	Achieve product quality improvements through automated quality inspections on critical pints in the production line in all products to report OPE efficiency; raise early detection warning signals of production factors that will originate product defects.
PRIMA	Automated quality inspections on critical points in the part production so that I can easily check the results
DANOBAT	Receive real data (quality data and quality functions on the machine) regarding the performance of the machines to be able to develop new digitally enhanced functionalities to improve the value added to the client and help to achieve a zero-defect manufacturing
FAGOR	Remote monitoring and collection if real data of a press machine to detect early malfunctions and predict breakdowns on the machine.
GF	Automated quality control that exploits data from CMM machines and machine reports in order to check potential defects and allow automated correction or updates in case they arise during the production process

The analysis of these and other related requirements helps to identify the following affected components in the Q-RA as shown in Figure 19: Q-RA compliant components in terms of quality.:

- *Digital Models and Vocabularies, Data-driven Modelling and Learning Services* regarding the modelling of information, advanced cognitive services and human support decisions.
- *Digital Twin and Planning Services, Collaboration, Business and Operation Service, IoT Automation Services* with regard to usage of advanced IT services at the business level, leading in a global sense to a broader framework, digital twin production.
- *Distributed Trustworthiness* secure data transport at the edge and the lower OT level of assets.

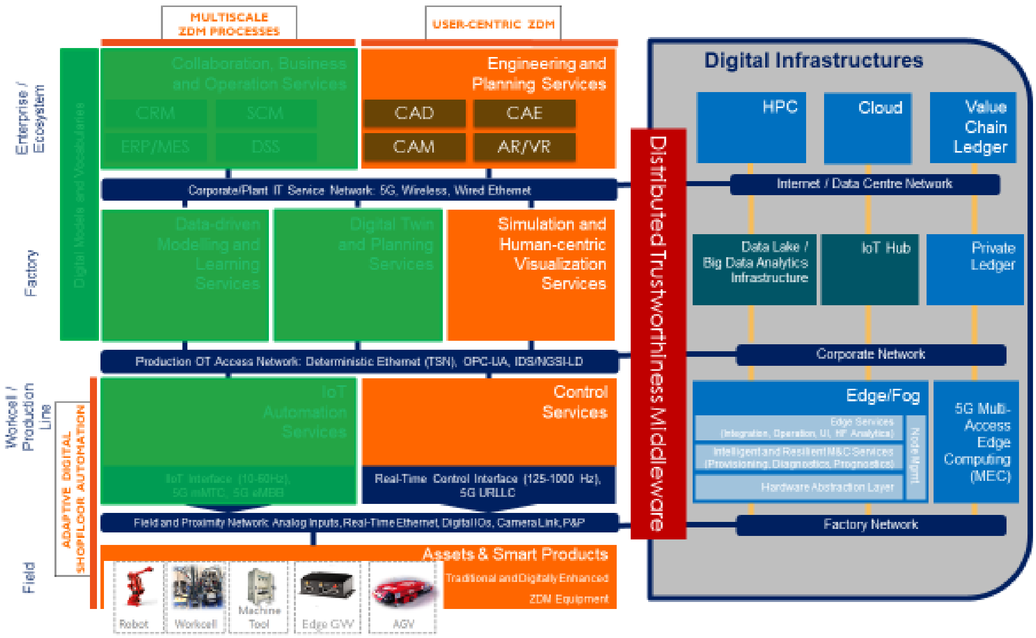


Figure 19: Q-RA compliant components in terms of quality.

4.5.3 Recommendations for Use

Table 11 lists some recommendations on identified quality-related standards:

Table 11: Recommendations for use in terms of quality-related standards[17]

Committee	ID[18]	Title	Q-RA	Details
CEN/TC 319 Maintenance	EN 13306:2018, Link	Maintenance – Maintenance terminology	Digital models and Vocabularies	Maintenance: services. company organization, management and quality, administration. transport. (Vocabulary)
CEN/TC 319 Maintenance	EN 16646:2014, Link,	Maintenance – Maintenance within physical asset management	IoT Automation Services	Management: physical assets; services: performance monitoring and control of assets
ISO/TC 184 Automation systems and integration	ISO 22549-1:2019*, Link	Automation systems and integration – Assessment on convergence of informatization and industrialization for industrial enterprises – Part 1: Framework and reference model	Digital Twin and Planning Services	Industrial enterprise: maturity model and evaluation methodology; enterprise quality control
ISO/TC 184 Automation	ISO 22549-2:2019*,Link	Automation systems and integration –Assessment on convergence of	Data-driven Modelling	Industrial enterprise: maturity model and evaluation methodology;

[17] Also see standards masked as (Q) in Table 2: Recommendations for use in terms of interoperability standards.
[18] Under developmet (*)

Committee	ID[18]	Title	Q-RA	Details
systems and integration		informatization and industrialization for industrial enterprises — Part 2: Maturity model and evaluation methodology	and Learning Service	enterprise quality control
DIN German Institute for Standardization	DIN SPEC 92001-1:2019-04, Link	Artificial Intelligence – Life Cycle Processes and Quality Requirements – Part 1: Quality Metamodel	Digital models and Vocabularies	AI, lifecycle quality requirements; quality model
ISO/IEC JTC 1/SC 41 Internet of Things and related technologies	ISO/IEC 30166:2020, Link	Internet of things (IoT) — Industrial IoT	Cross-cutting	Industrial IoT standards and road mapping
ISO/TC 176/SC 2 Quality systems	ISO 9000:2015 FAMILY, Link	Quality management systems	Collaboration, Business and Operation Service	Quality; to use quality management systems to ensure their products and services consistently meet customer's requirement
ISO/TC 184/SC 4 Industrial data	ISO 23952:2020, Link	Quality information framework (QIF) — An integrated model for manufacturing quality information	Digital models and Vocabularies	Quality modelling and support of quality workflow scenarios

4.5.4 Example of prominent standards

Some of the prominent standards regarding quality that are worth to consult are:

4.5.4.1 ISO 9000 family - Quality management

The ISO 9000 family [17] is the well-known quality management standard for companies and organizations of any size (Figure 20). One of the fundamental standards is ISO 9001, that sets out the criteria for a quality management system. All the requirements of ISO 9001:2015 are generic and are intended to be applicable to any organization, regardless of its type or size, or the products and services it provides.

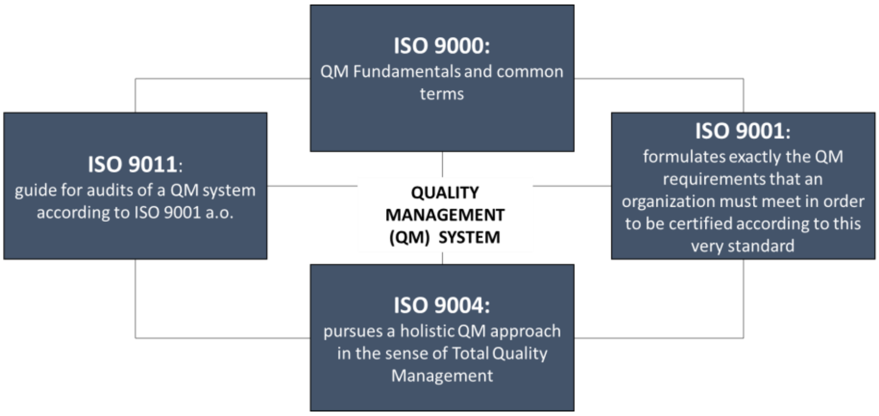


Figure 20: The ISO 9000 family of quality management standards

4.5.4.2 ISO 10303 series - Automation systems and integration - Product data representation and exchange

The product lifecycle standards in the context of the smart manufacturing addresses respective phases as Design, Process Planning, Production Engineering, Manufacturing, Use and Service, and End-of –Life and Recycling and aims to enhance modeling accuracy and contribute directly to manufacturing system agility and product quality. ISO 10303 is an ISO standard that aims at provisioning of mechanisms capable of describing product data throughout the life cycle of a product, independent from any particular system. The nature of this description supports interoperability and serve as a basis for implementing and sharing product databases and archiving. Thus, e.g. the ISO 10303-216:2003 specifies the scope and information requirements for the exchange of ship moulded form definitions, geometric representations, and related hydrostatic properties. Or ISO 10303-45:2018 that specifies the integrated resource constructs for material and other engineering properties.

Conclusions

The document provides a recommendation of standards to be used by technical experts and developers in the field of zero-defect manufacturing (ZDM). Methodologies and standards have been specified for the following ZDM topics:

- Interoperability specification and requirements
- Safety and Security
- Artificial Intelligence
- Reference Architectures, Digital Models and Vocabularies
- Quality standards

On the basis of the QU4LITY reference architecture (RA) and developments in other projects concerning ZDM, the assessment of interoperability requirements between different RA components has been shown and a list of recommended standards, protocols and frameworks for certain interoperability sub-categories has been developed.

Overall, this deliverable represents the groundwork for the technical implementation of technologies and digital platforms that will be performed as part of the work in WP3, WP4 and WP5. It also drives the implementation the experimental facilities defined in WP6 and pilot use cases in the scope of WP7. It gives an example of standards in use for different areas and use cases but also shows new and recently developed standards and frameworks that can increase the efficiency, maintainability and interoperability of technical solutions in ZDM applications. Therefore, the document can be considered as a valuable guideline for all partners involved in technical design, system development and validation.

5 Annexes

5.1 Annex A - Detailed Action Plan

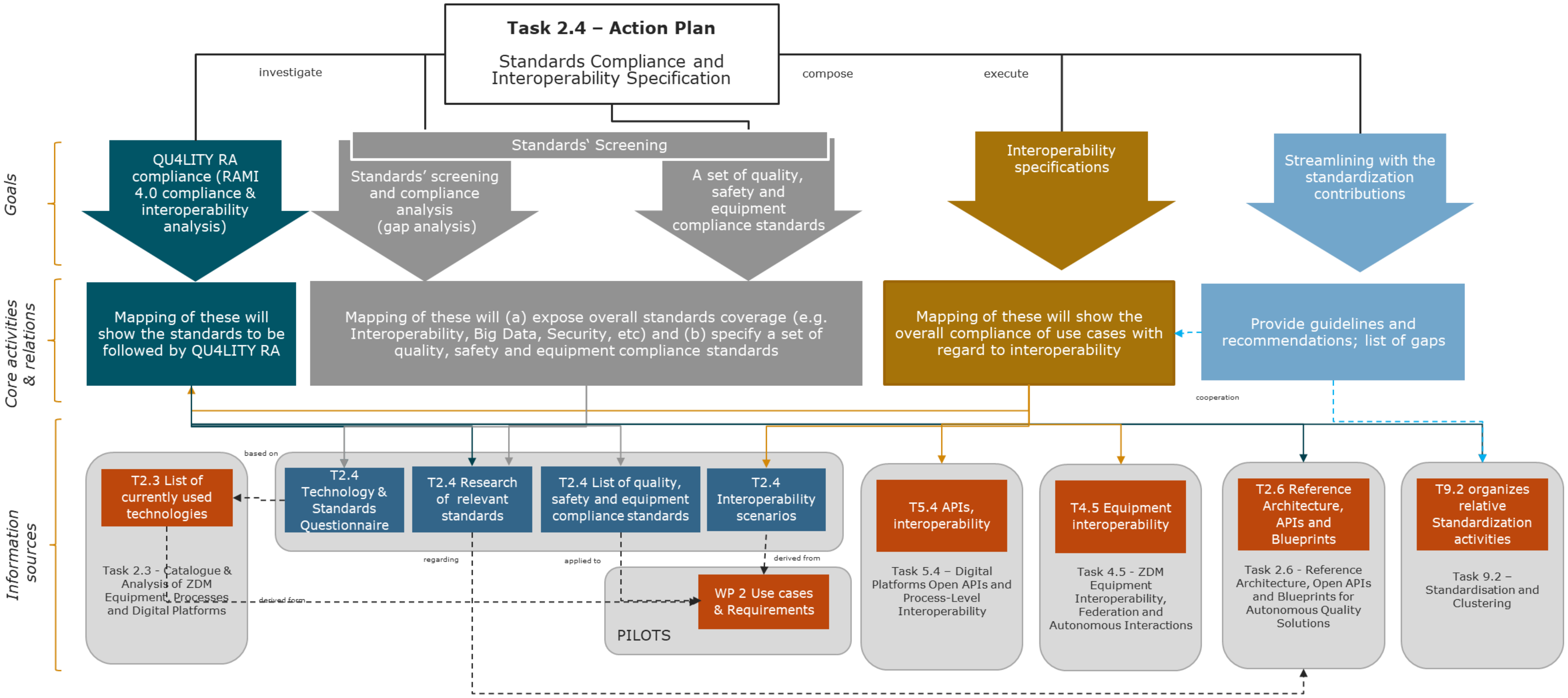


Figure 21: Detailed action plan

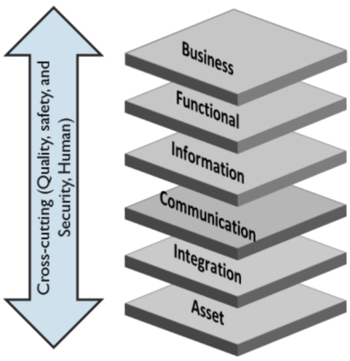
5.2 Annex B – Details on first questionnaire (M1 – M9)

Characterization	Hardware/Software	
	Component type	
	Technological category	
	Internal Components	
	Component License (is it open source?)	
Additional Information	Website	
	Documentation	
	Stores	
	Libraries	
	Notes (not publicly shown)	
Relevant Standards	Standards already in compliance	
	Standards planned to be introduced	
	Known Standardization gaps	

Figure 22: Template of the Questionnaire

8. Reference Architecture: standards related Reference Architectures and Reference Models, such as IoT RA, IIRA, RAMI4.0, Fog/Egde RA, etc.

7 .Cross-cutting standards (Quality, Safety & Security, Human): standards related to cross-cutting technologies at all six levels (Asset, Integration, Communication, Information, Function, Business) such as security and safety



Source: after DIN/DKE German Standardization Roadmap Industrie 4.0

6. Business: standards related to business applications such as ERP, CRM, MES, Analytics and KI, Machine Learning applications, planning and scheduling, and other applications supporting business processes that trigger operations on assets.

5. Functional: standards related to operational domain that provide a certain function and has the goal to optimize operations across assets (asset management applications, diagnostics, deployment, data storage, cloud/edge functionalities, etc.)

4. Information: standards supporting interoperability between assets, devices and business applications, including standards regarding vocabulary, data models, data distribution, asset description, ontology, etc.

3. Communication: standards related to communication technologies, such as communication protocols (OPC-UA/TCP/IP), API/Interfaces, network technologies, etc.

2. Integration: standards related to technologies between the physical and virtual world, such as technology adaptors, virtual controllers and applications responsible for integration of assets

1. Asset: standards related to automation systems, equipment and devices, including sensors, production machines, HMI devices, etc.

Figure 23: Standards categories for the Questionnaire

Table 12: List of assigned T2.4 partners to the QU4LITY pilots.

Pilot	**Assigned T2.4 partner**	**Pilot**	**Assigned T2.4 partner**
Philips	PHILIPS	Airbus	EPFL
Siemens	SIEMENS	GHI	SQS
Continental	CONTI	Riastone	SYN
Whirlpool	ENG	Prima	PRIMA
Mondragon	MGEP	Danobat	IDEKO
Kolektor	KOL	Fagor	FAGORA
ThyssenKrupp	FHG-IGD	GF	EPFL

The responsibility of the pilot monitoring was delegated to a majority of T2.4 partners based on their amount of PMs in this task and their involvement in the pilots. Both information are shown in Figure 24: The upper row are T2.4 partners that are at the same time pilot case owners while the lower row are plain QU4LITY partners. Only the ThyssenKrupp pilot is not covered by the T2.4 partners. Unless a T2.4 partner is already the pilot case owner, the partner involved in a pilot with the most effort was dedicated to that pilot in order to identify all technology providers in this pilot, contact them and track their participation in the questionnaire. The final assignment is shown in Table 12.

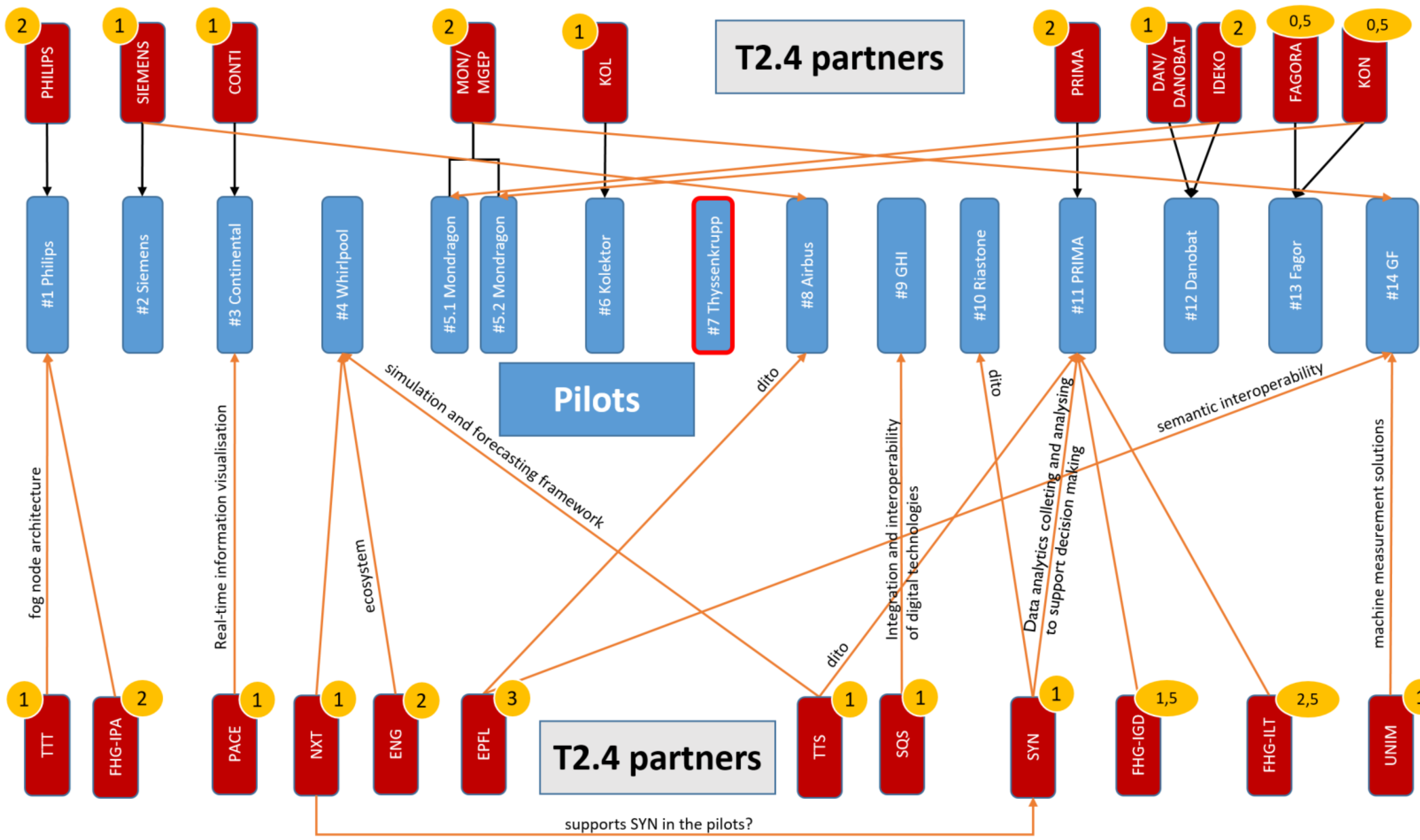


Figure 24: PMs of T2.4 partners and their pilot involvement

5.3 Annex C – Detailed pilots screening results (M1 – M9)

The following table summarizes the technologies grouped by each pilot and their classification in the RAMI layers, where

- **o** represents compliance to some standard
- **x** means the technology is in no compliance to any standard
- **p** stands for plans to introduce some standard to this technology
- **b** means the technology already obeys some standard, but will be enhanced to follow additional ones
- the last column collects all self-chosen categories, see Table 15 for more details.

The AIRBUS pilot #8 and the GHI pilot #9 were left out since none of the pilot partners participated in the questionnaire.

Table 13: Summary of the first pilots screening with coverage of RAMI layers.

QU4LITY pilot	Technology provider	Technology name	1 - Asset	2 - Integration	3 - Communication	4 - Information	5 - Functional	6 - Business	7 - Cross-cutting standards	8 - Reference Architecture	Others
#1 - PHILIPS	FHG-ISST/ IDSA	Industrial Data Space								**o**	
	SINTEF	HolMS, Holonic Manufacturing System									**x**
		Best Practices for Zero Defect Manufacturing (ZDM) in Industry									**o**
	TNO	PLASEN									**x**
		Learning visual quality control									**x**

QU4LITY pilot	Technology provider	Technology name	1 - Asset	2 - Integration	3 - Communication	4 - Information	5 - Functional	6 - Business	7 - Cross-cutting standards	8 - Reference Architecture	Others
#2 - SIEMENS	FHG-ISST/ IDSA	Industrial Data Space								**o**	
#3 - CONTI	ATB	Context Extractor & Device Centric Context Model				**x**					
		CPS Selection Tool				**x**					
	ATB/ IKERLAN	Safire Analytics Framework				**x**					
	PACE	Pacelab WEAVR		**x**		**x**					
	ATOS	MASAI		**x**	**x**					**x**	
	FHG-ISST/ IDSA	Industrial Data Space								**o**	
	SINTEF	HolMS, Holonic Manufacturing System									**x**
		Best Practices for Zero Defect Manufacturing (ZDM) in Industry									**o**
#4 - WHR	IMECH	Decision Support System for ZDM			**x**			**x**			
#5 – MONDRAGON-1	MGEP	Mantis Proactive Maintenance Service Platform			**o**		**o**	**o**			
	FHG-ISST/ IDSA	Industrial Data Space								**o**	

QU4LITY pilot	Technology provider	Technology name	1 - Asset	2 - Integration	3 - Communication	4 - Information	5 - Functional	6 - Business	7 - Cross-cutting standards	8 - Reference Architecture	Others
	ATLAS	Prediction of defects based on assets deterioration rate				x					
		Decision Support System and Strategies for ZDM				x					
	LKS	LKS Big Data Platform					x				
	SINTEF	Best Practices for Zero Defect Manufacturing (ZDM) in Industry									o
	CEA	SDN-based software framework for flexible (re-)configuration and management of industrial (IoT) networks			o						
#5 – MONDRAGON-2	VTT	VTT OpenVA – Visual Analytics platform					x				
	FHG-ISST/ IDSA	Industrial Data Space								o	
	MGEP	Mantis Proactive Maintenance Service Platform			o		o	o			
	LKS	Datafabric IOT Gateway						x			
		Datafabric Authenticator						x			
#6 - KOLEKTOR	KOL	KiS – Kolektor Imaging Software 4.0	o	o	o	o	o	o	o	o	
		Sinapro.IIoT MES/MOM	o	o	o	o	o	o	o	o	

QU4LITY pilot	Technology provider	Technology name	1 - Asset	2 - Integration	3 - Communication	4 - Information	5 - Functional	6 - Business	7 - Cross-cutting standards	8 - Reference Architecture	Others
	FHG-ISST/ IDSA	Industrial Data Space								o	
	CEA	Acoustic moulding tool monitoring	x								
#7 - THYSSEN	CEA	Acoustic steering column part monitoring	x								
#10 - RIASTONE	SYN	Smart decision support tools					p	p			
#11 - PRIMA	VTT	AR information visualization and Human Error Avoidance				o					
	FHG-ISST/ IDSA	Industrial Data Space								o	
	TTS	Additive manufacturing simulator						x			
	ATLAS	Decision Support System and Strategies for ZDM				x					
	SYN	Data analytics tool for Additive Manufacturing			p	p	p	p			
	FHG-IGD	Design4AM – Interactive Visualization solution				x					
#12 - DANOBAT	IDEKO	Danobat Data System – Savvy Data System			b		b	b			
	FHG-ISST/ IDSA	Industrial Data Space								o	

QU4LITY pilot	Technology provider	Technology name	1 - Asset	2 - Integration	3 - Communication	4 - Information	5 - Functional	6 - Business	7 - Cross-cutting standards	8 - Reference Architecture	Others
	ATLAS	Prediction of defects based on assets deterioration rate				x					
		Decision Support System and Strategies for ZDM				x					
	SINTEF	Best Practices for Zero Defect Manufacturing (ZDM) in Industry									o
#13 - FAGOR	ATB/ IKERLAN	Safire Analytics Framework				x					
	IKERLAN	IKCLOUD			x		x	x			
		IKSEC securization guidelines							x		
	MGEP	Mantis Proactive Maintenance Service Platform			o		o	o			
	VTT	VTT OpenVA – Visual Analytics platform					x				
#14 GF	UNIM	M3MH		o	o	o	o				
	GF	rConnect			o	o					
		Azure Cloud/ML environment									x
		MPP – Multi-process preparation platform									x
		T.R.U.E.									x
		Workshop Manager – WSM									x

Only three entities are planning to enhance their intellectual property such that it will follow another standard:

- IDEKO wants to introduce MTConnect to the 'Danobat Data System – Savvy Data System'
- SYNESIS wants to be in compliance with the OPC-UA and MQTT standard for their two technologies 'Smart decision support tools' and 'Data analytics tool for Additive Manufacturing'.
- CEA plans to follow the standards IEEE 802.1Qbv and OPC UA in their technology 'SDN-based software framework for flexible (re-)configuration and management of industrial (IoT) networks'

The call for identifying known gaps in the standardization landscape was answered by

- MGEP for the 'Mantis Proactive Maintenance Service Platform':
  "With the converters we want to explore the possibilities for interoperability among platforms. Converters can be customized to interoperability needs."
- TID (Telefonica) for the 'Edge Computing Node (CTPD)':
  "Compliance with ETSI MEC. Onlife Edge is not compliant since ETSI standard does not fulfil Telefonica requirements, hence some modification have been included in the product comparing standard."

Although the questionnaire was dedicated to technology providers involve in at least one pilot, there were five contributions from TID, UNP and NXT naming different fields of application, see Table 14.

Table 14: Technologies without a specific application in a pilot.

Technologies without naming a specific pilot		1 - Asset	2 - Integration	3 - Communication	4 - Information	5 - Functional	6 - Business	7 - Cross-cutting	8 - Reference	Others
Technology provider	Technology name									
TID	Edge Computing Node (CTPD) Used in: AIC experimentation facility									**x**
UNP	Fog Node for Non-Intrusive Part Profile Monitoring Used in: -									**x**
NXT	nxtSTUDIO Used in: Use case in WP4 with ASTI		**b**	**b**						
	nxtIECRT Used in: Use case in WP4 with ASTI			**b**						
	nxtHMI Used in: Use case in WP4 with ASTI		**b**							

Table 15: Complete results from first standard screening questionnaire

Entity	Technology name	Pilots	Category (see Figure 22)	Used standards	Planned standards	Known gaps
ATB	Context Extractor & Device Centric Context Model	CONTI	4	-	-	-
	CPS Selection Tool	CONTI	4	-	-	-
	Safire Analytics Framework	CONTI, FAGOR	4	-	-	-
ATLAS	Prediction of defects based on assets deterioration rate	MON-1, DAN	4	-	-	-
	Decision Support System and Strategies for ZDM	MON-1, DAN, PRIMA	4	-	-	-
ATOS	MASAI	CONTI	2, 3, 8	-	-	-
CEA	Acoustic steering column part monitoring	THYSSEN	1	-	-	-
	Acoustic moulding tool monitoring	KOL	1	-	-	-
	SDN-based software framework for flexible (re-)configuration and management of industrial (IoT) networks	MON-1	3	IETF, IEEE, IEEE 802.1AS for TSN	IEEE 802.1Qbv, OPC UA	-
FHG-IGD	Design4AM – Interactive Visualization solution	PRIMA	4	-	-	-
FHG-ISST IDSA	Industrial Data Space	CONTI, DAN, KOL, MON-1 MON-2, PHILIPS, PRIMA, SIEMENS	8	W3C DCAT W3C ODRL	-	-
GF	rConnect	GF	3, 4	OPC-UA, MTconnect	-	-
	Azure Cloud/ML environment	GF	Machine Learning	-	-	-
	MPP – Multi-process preparation platform	GF	CAM EDM DS Process Planning	-	-	-
	T.R.U.E.	GF	CAM EDM DS Process Planning	-	-	-

Entity	Technology name	Pilots	Category (see Figure 22)	Used standards	Planned standards	Known gaps
	Workshop Manager – WSM	GF	Automated Cell Manufacturing order Process Planning	-	-	-
IDEKO	Danobat Data System – Savvy Data System	DAN	3, 5, 6	OPC-UA, UMATI API REST, ISO/IEC 15408:2009, ISO/IEC 18045:2008	MTConnect	
IKERLAN	IKCLOUD	FAGOR	3, 5, 6	API-REST, OPC-UA, MQTT, RAMI 4.0	-	-
	IKSEC securization guidelines	FAGOR	7	-	-	-
IMECH	Decision Support System for ZDM	WHR	3, 6	-	-	-
KOL	KiS – Kolektor Imaging Software 4.0	KOL	1, 2, 3, 4, 5, 6, 7, 8	OPC-UA Vision, RAMI 4.0	-	-
	Sinapro.IIoT MES/MOM	KOL	1, 2, 3, 4, 5, 6, 7, 8	OPC-UA, OPC-UA, Vision, MQTT, RAMI 4.0, ISA95	-	-
LKS	LKS Big Data Platform	MON-1	5	-	-	-
	Datafabric IOT Gateway	MON-2	6	-	-	-
	Datafabric Authenticator	MON-2	6	-	-	-
MGEP	Mantis Proactive Maintenance Service Platform	FAGOR, MON	3, 5, 6	MIMOSA DB IoT-A event information model	-	With the converters we want to explore the possibilities for interoperability among platforms. Converters can be customized to interoperability needs.
NXT	nxtSTUDIO	Use case in WP4 with ASTI	2, 3	IEC 61499	-	-
	nxtIECRT	Use case in WP4 with ASTI	3	IEC 61499	-	-

Entity	Technology name	Pilots	Category (see Figure 22)	Used standards	Planned standards	Known gaps
	nxtHMI	Use case in WP4 with ASTI	2	IEC 61499	-	-
PACE	Pacelab WEAVR	CONTI	2, 4	-	-	-
SINTEF	HolMS, Holonic Manufacturing System	PHILIPS, ONTI	Control software	No	No	No
	Best Practices for Zero Defect Manufacturing (ZDM) in Industry	PHILIPS, CONTI, DAN, MON-1	-	ISO/IEC	No	-
SYN	Smart decision support tools	RIASTONE	5, 6	-	OPC-UA, MQTT	-
	Data analytics tool for Additive Manufacturing	PRIMA	3, 4, 5, 6	-	OPC-UA, MQTT	-
TID	Edge Computing Node (CTPD)	AIC experimentation facility	-	-	-	Compliance with ETSI MEC. Onlife Edge is not compliant since ETSI standard does not fulfil Telefonica requirements, hence some modification have been included in the product comparing standard.
TNO	PLASEN	PHILIPS	Algorithm	-	-	-
	Learning visual quality control	PHILIPS	Algorithm	-	-	-
TTS	Additive manufacturing simulator	PRIMA	6	-	-	-
UNIM	M3MH	GF	2, 3, 4, 5	QIF	-	-
UNP	Fog Node for Non-Intrusive Part Profile Monitoring	-	Supervised Machine Learning, Pattern Classification, Predictive Modelling, Fog Computing,Discrete Signal Monitoring	-	-	-
VTT	AR information visualization and Human Error Avoidance	PRIMA	4	P1589 - IEEE	-	-

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List of abbreviations

Abbreviations	Explanations
AAS	Asset Administration Shell
AIOTI	Alliance for Internet of Things Innovation
AI	Artificial Intelligence
API	Application Programming Interface
AQ	Autonomous Quality
CEN	European Committee for Standardization
CENELEC	European Committee for Electrotechnical Standardization
CD	Committee Draft
CPS	Cyber Physical System
CPPS	Cyber Physical Production System
DIN	Deutsches Institut für Normung
DKE/VDE	German Commission for Electrical, Electronic & Information Technologies of DIN and VDE
H2M	Human-to-Machine
I4.0	Industry 4.0
ICPS	Industrial Cyber-Physical System
IEC	International Electrotechnical Commission
IIC	Industrial Internet Consortium
IIoT	Industrial Internet of Things
IIRA	Industrial Internet Reference Architecture
IoT	Internet of Things
IoT RA	Internet of Things Reference
ISO	International Organization for Standardization
JTC	Joint Technical Committee
JWG	Joint Working Group
KPI	Key Performance Indicator
M2M	Machine-to-Machine
MQTT	Message Queue Telemetry Transport
NIST	National Institute of Standards and Technology
OASIS	Organization for the Advancement of Structured Information Standards
OCC	Open Cloud Consortium
OCF	Open Connectivity Foundation
OMG	Object Management Group
OPC UA	OPC Unified Architecture
Q-RA	QU4LITY Reference Architecture
RAMI 4.0	Reference Architecture Model Industrie 4.0
REST	Representational State Transfer
SDOs	Standards Developing Organisations
SM	Smart Manufacturing
TR	Technical Report

W3C	World Wide Web Consortium
WG	Working Group
ZDM	*Zero Defect Manufacturing*
ZVEI	Zentralverband Elektrotechnik- und Elektronikindustrie

References

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