Ref. Ares(2021)2655009 - 20/04/2021

QU4LITY

DIGITAL MANUFACTURING PLATFORMS FOR CONNECTED SMART FACTORIES

D2.12 Reference Architecture and Blueprints (Final Version)

Deliverable Id :	**D2.12**
Deliverable Name :	**Reference Architecture and Blueprints (Final Version)**
Status :	**FINAL**
Dissemination Level :	**PU**
Due date of deliverable :	**31/03/2021**
Actual submission date :	**20/04/2021**
Work Package :	**WP2**
Organization name of lead contractor for this deliverable :	**ENGINEERING Ingegneria Informatica S.p.A.**
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Abstract: A report on the final release of the QU4LITY Reference Architecture (mainly based on the activities going on within task T2.6), including a methodology to instantiate it in different contexts.

Co-funded by the Horizon 2020 Programme of the European Union

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Contents

HISTORY

Version	Date	Modification reason	Modified by
0.1	08/01/2021	First amended ToC	Angelo Marguglio
0.2	03/02/2021	Modified structure for Ch. 5	Manfredi Giuseppe Pistone
0.3	06/03/2021	Updated content for Ch. 4 and 5	Angelo Marguglio
0.4	21/03/2021	Added contributions from TTT, ENG, INTRA, EPFL, ATLAS, SIEM, UNP, JSI, TID	Manfredi Giuseppe Pistone
0.5	22/03/2021	Added contributions from INNO, UNIM, SYN	Manfredi Giuseppe Pistone
0.6	06/04/2021	Added latest contributions and made final improvements, mainly on Ch. 1, 5, 6 and 7	Manfredi Giuseppe Pistone, Angelo Marguglio
0.7	08/04/2021	Final improvements before peer-review	Angelo Marguglio
0.8	13/04/2021	Final improvements after peer-review	Angelo Marguglio
0.9	19/04/2021	Final improvements after Quality Manager review	Manfredi Giuseppe Pistone, Angelo Marguglio
1.0	20/04/2021	Final version ready for publication	Diego Esteban

1 Executive Summary

One of the challenges in implementing Autonomous Quality (AQ) processes and solutions is the development of the **QU4LITY Reference Architecture (Q-RA)** for digital Zero-Defect Manufacturing (ZDM) solutions for smart manufacturing, based on innovative technologies and on relevant sector standards such as RAMI 4.0. Then, building from there, **blueprints** have been derived, providing concrete implementations, together with the other outcomes of WP2 (e.g., a well-documented set of open standards, communication protocols, digital technologies, data models, Open APIs) that QU4LITY-based implementations should conform to. The project has been working on developing a **Reference Implementations (RI)** using such blueprints, in order to validate the QU4LITY vision and solution in the experimental facilities (in WP6) and in all real-life business use cases (in WP7).

This document delivers the final release of the Q-RA and the overall, abstract design of a QU4LITY-based system (the main changes from the initial version have been summarized in Section 2.2). It also reports on the technological choices and standardization framework identified for the QU4LITY RIs (even if the detailed analysis and justifications will be reported in the corresponding deliverables in WP3-4-5).

The Q-RA has not been designed from scratch, being strongly based on the most relevant outcomes of other Research and Innovation activities. To this end, this document presents an analysis of the most recent releases of some relevant, generic reference architectures for digital industries, industrial IoT and edge computing - namely those from the Plattform Industrie 4.0 initiative (RAMI 4.0), the Industrial Internet Consortium (IIRA and OpenFog RA), or the Chinese Industrial Internet Architecture (IIA). On the other hand, several research projects have already been executed by many of the Consortium partners, providing a wide set of background knowledge on the topic and solid suggestions. Following this experience, the Digital Shopfloor Alliance Reference Framework has been adopted as the main input to further enhance it for ZDM scenario, exploiting its adherence to standards and the openness toward the integration of multiple digital enablers.

Firstly, Sections 3 present the context positioning, providing the ground for the next sections. On the other hand, given the extension we would devote to this state of the art, and being this deliverable the second and updated release on this topic, we have preferred to move the detailed context and standards analysis can be found in the appendixes (i.e., Appendix A – "State of the art in Digital Manufacturing Platforms for ZDM" and Appendix B – "Relevant Reference Architectures").

Consistently with this approach, Section 4 presents the Q-RA as a **Four-Tier** design, where the *main* Tiers (Field, Line, Factory and Ecosystem) are hierarchically stacked according to their scope with respect to the physical processes in the factory, and one *Sovereign Digital Infrastructures* providing common services such as connectivity and distributed processing capabilities. Moreover, the Q-RA groups system functionality into three distinct **Functional Domains** (*Adaptive Digital Shopfloor*

Automation, *Multiscale ZDM Cognitive Processes* and *Human-Centric Collaborative Intelligence*), which are orthogonal to the Tiers, and three **Crosscutting Functions** (*Security*, Sovereign *Digital Infrastructures*, and *Digital Models and Vocabularies*) that are domain-agnostic. To better clarify the role of all these elements, they are mapped, whenever possible and relevant, to the corresponding concepts in RAMI 4.0.

The overall design of the QU4LITY-based system that is documented in this deliverable (see Section 4) populates Tiers, Functional Domains and Crosscutting Functions with **Components**: self-consistent software modules that play a well-defined role and interact with each other and with the outside world through interfaces. While this high-level design still does not provide any technical specifications of such modules, leaving this responsibility to development tasks, some of them are already identified as **Digital Enablers** (falling mainly in the scope of WP3, but where also WP2, 4 and 5 will contribute). The Digital Enablers specification is out of scope of this deliverable and will be described in relevant outcomes of the corresponding WPs.

Moreover, as one of the aims of this document is to provide a validation of the Q-RA's design against the project's requirements and reference use cases, which are the outcome of previous deliverables in WP2 (D2.1/D2.2 and D2.3/D2.4), an overview of the project vision is presented in Section 4.1. Then, Q-RA components will be linked to the project work-packages that, according to the project's Description of Action (DoA), will be responsible for their concrete design and implementation (see Sections 4.7).

As the Q-RA is an abstract design, this document also reports about the methodology adopted to provide blueprints for actual implementations, in order to set up a sound development playground for the RI in the other technical work-packages (see Section 5). Generally speaking, the QU4LITY RI will be a toolbox that includes at least one implementation of each of the identified Components. Furthermore, a core subset of the QU4LITY Digital Enablers will be validated in a relevant industrial environment (in WP6 and WP7) and offered through the marketplace realized in WP8.

2 Introduction

2.1 Objectives and Scope

The current deliverable (i.e., D2.12, "Reference Architecture and Blueprints (Final Version)") aims to report on the final results of tasks T2.6 ("Reference Architecture, Open APIs and Blueprints for Autonomous Quality Solutions"). However, relevant information to the ongoing work in other technical work-packages (i.e., WP3, WP4, and WP5), it has been decided to also include a high-level specification of the QU4LITY framework in this version of the deliverable, foreseeing further details in the outcomes of the other WPs.

Task T2.6 follows an incremental-iterative approach, thus initial results were included in "D2.11 - Reference Architecture and Blueprints (Version 1)"and the final results are being reported in this D2.12.

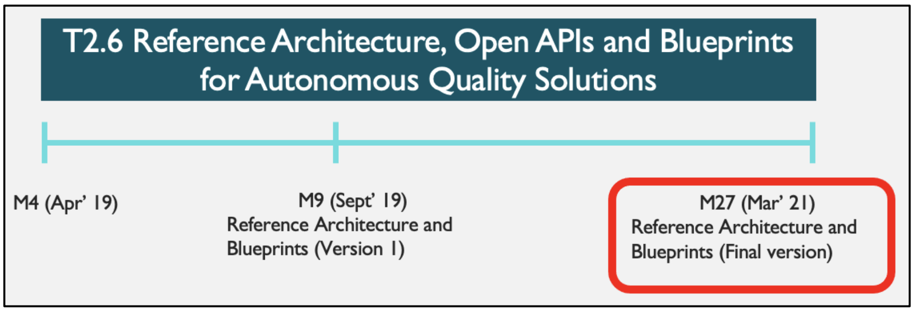

Figure 1 – Task T2.6 timeframe and related deliverables

The purpose of the task T2.6 is to identify the key challenges overcome in the QU4LITY project as well as common and application specific requirements to refine the initially proposed reference implementation and to define the functional architecture.

2.2 Main changes after the first release

Following the first iteration of Task T2.6 and its outcome represented by D2.11, as well as the results of the first half of the project in the rest of the work-packages, and the recommendations received by the review team after the Midterm review, many changes exist in this report D2.12.

Even if most of the content of the first release is still valid, a more in deep revision and fine tuning have been performed to provide stronger basis of the second and final iteration of the project execution. To this end, the following main changes/addendum have been implemented in this report:

- Section 3.1 - Project Background: following the two-iterations approach of the whole WP2, this section has been updated in order to include the final findings of the work done to analyse the context and derive the project vision, taking advantages of the lessons learnt collected in the first cycle of development and validation activities carried out within QU4LITY. In this respect, a brand-new sub-section (notably §3.1.1 - Common ZDM Scenario) has been added to this report to collect the most relevant ZDM scenario addressed by the project and supported by the Q-RA.

- Section 3.2 - QU4LITY Vision and Positioning: the main results of the previous bullet also led to an updated description of the overall QU4LITY Vision represented in this Section.
- Section 4 - QU4LITY Architecture Framework: the core part of this specification is updated to reflect the important changes implemented in the Q-RA, as well as to introduce a more detailed and structured specification of all the components of the Q-RA, eliciting the main relationships with the other components and creating a more intuitive mapping toward the rest of the technical activities within the project. In this framework, a further description of the mapping toward the technical activities withing WP3-4-5 has been introduced in Section 4.7 - Mapping to other QU4LITY technical dimensions.
- Section 6 - All the pilots' technical developments have been deeply studied in order to provide a clear mapping toward the Q-RA and a set of blueprints for all the challenges represented by the different project pilots.
- Appendix A/Appendix B: most of the analysed projects progressed in the timeframe between D2.11 and D2.12, therefore the ongoing analysis and alignment work between QU4LITY and such projects has requested to be revised and reported here (e.g. updating the findings, relevant for QU4LITY, from Z-Fact0r and ZDMP), while new relevant sources have been identified in new endeavours (e.g. the ForeSee Cluster). At the same time the Industrial Internet Reference Architecture (IIRA) has been updated following the latest release (i.e., v1.9) from the Industrial internet Consortium, in order to provide an up-to-date understanding of such a relevant standard. Finally, the Digital Shopfloor Alliance (DSA) initiative, being the main source of inspiration of the Q-RA, has been further analysed and described, especially concerning the adoption of the IEC61499 standard, as emerged by the need expressed in enhancing equipment in WP4.

2.3 Methodology

The fast-growing number of implementations of Digital Manufacturing Platforms and the existing fragmentation on OT/IT systems already available on the shopfloors have triggered various initiatives to define Reference Architectures (RA) for the industry. A RA provides guidance for the development of a system, solution and application architecture and provides common and consistent understanding for the system, as well as its decompositions and interaction patterns. RAs provide a high level of abstraction that is applicable to many actual implementations of the system, coping with different business objectives and technologies adopted.

Conceptualization of a system's architecture, as defined in the ISO/IEC/IEEE 42010 "Systems and software engineering – Architecture" [2] standard, assists the understanding of that system's essence and key properties related to its behaviour and composition. It describes the structure of the system with its entities, as well as the interactions between each entity and environment. RAs are used as generic guidelines that abstract the specific needs and technologies of various implementations and use cases. The RAs provide [3]:

- a common lexicon that facilitates communication

- a common (architectural) vision that focuses and aligns efforts of multiple people and teams
- modularisation to divide the effort and the complementary context that ensures later integration
- guidance and baselines
- articulation of domain and realization concepts

This document presents the Reference Architecture of QU4LITY-based systems, based on the use of multiple, concurrent views. Multiple views allow to address separately the concerns of the various stakeholders of the QU4LITY project, mainly technical partners and business partners, and to handle separately the functional and non-functional requirements separately. The **QU4LITY Reference Architecture (Q-RA)** will be designed using an architecture-centered, scenario-driven, iterative development process.

The Q-RA deals with the design, implementation and deployment of complex Digital Manufacturing Platforms able to realize the Autonomous Quality concept foreseen within the whole project (and described in detail in D2.3/D2.4 and reported in Section 3.2 below). It is the result of assembling a certain number of architectural components, integrating existing digital technologies and organization processes with several outcomes of QU4LITY, in some well-chosen forms to satisfy the major functionality and non-functional requirements of the system described in other project deliverables (mainly D2.1/D2.2 and D7.1/D7.2).

Following the terminology defined in the ISO/IEC/IEEE 42010 [2], an architecture description expresses an architecture of a system of interest. While an *architecture* can be abstract, consisting of concepts and properties, an *Architecture Description* is a work product formalizing an architecture, including one or more architecture views. An *Architecture View* addresses one or more of the *Concerns* held by the system's *Stakeholders*. An architecture view expresses the architecture of the system of interest in accordance with an *Architecture Viewpoint* (or simply, viewpoint). To this end, an *Architecture Framework (AF)* contains the conventions, principles and practices for the description of architectures established within a specific domain of application and/or community of stakeholders. The AF can be described following several dimensions, establishing the conventions for the construction, interpretation and use of architecture of a system from the perspective of specific system concerns.

The following Figure 2 presents a graphical representation of the mentioned entities and their interrelationships.

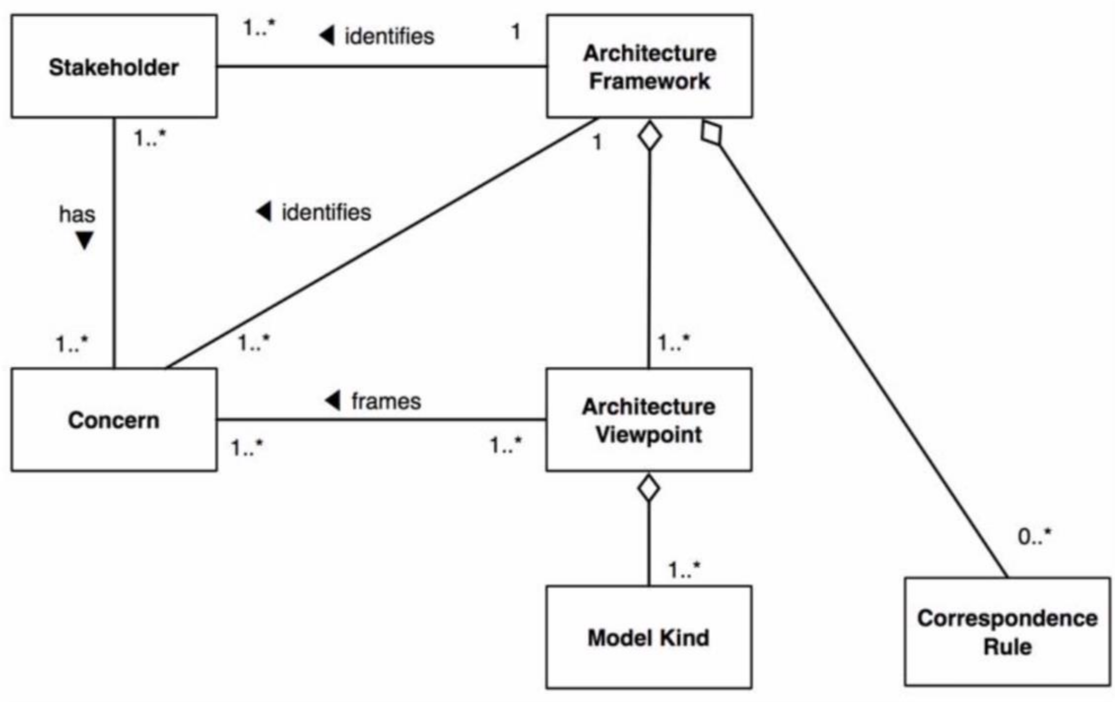

Figure 2 – The Architecture Framework entity model in ISO/IEC/IEEE 42010

In the context of the QU4LITY Architecture Framework (further described in Section 4), the most relevant viewpoints specified are the following: Functional View, Information View, System Deployment View and Networking View.

Apart from adherence to the above methodological approach, the present deliverable has taken into account several existing Reference Architectures in the world-wide community, as well as several mapping and alignment handover still undergoing and aiming to harmonize the different angles used in the different approaches dealing with Reference Architecture for manufacturing, as presented in the Appendix B.

Note however that the Q-RA architecture has considered user and system requirements from D2.1/D2.2, rather than the low-level technical ones that will be further analysed in the scope of WP3, WP4 and WP5. This is because the presented Q-RA focuses on high-level solutions with system wide impact on QU4LITY based systems, rather than on low-level technical details that will be elaborated as part of detailed design and implementation.

2.4 Document Structure

D2.12 is divided in the following main parts:

- **Introduction**: This section identifies the tasks of the project related to the deliverable including information on objectives as well as a short description of the relationship of the current deliverable with the results of other tasks and work-packages. This section, moreover, highlights the changes that have been made since the initial release of deliverable D2.11.

- **Background and Vision**: An analysis of the context relevant to the QU4LITY architectural design, complemented by a description on how this work can be aligned to the overall Autonomous Quality vision pursued by the project.
- **Relevant Reference Architectures**: An analysis of the main initiatives working on standardization of Reference Architectures in the manufacturing sector and alignment task among them.
- **QU4LITY Architecture Framework**: This is the core part of the document including relevant information from each domain composing the QU4LITY overall solution. This description includes (1) the specifications of the domains representing any system based on the high-level QU4LITY requirements; (2) the identification of the QU4LITY Reference Architecture providing an overlooking picture on the different components to be adopted in QU4LITY-based systems; (3) the mapping toward the technical solutions delivered in the project.
- **QU4LITY Blueprints**: The analysis of main business processes to be put in place in the final solution to realize a coherent system from the individual modules, following the common view prescribed by the QU4LITY architecture toward its instantiation in actual implementations in the piloting activities.
- **Conclusions:** This section provides summarized information on the QU4LITY Reference Architecture to pave the way to further technical developments in WP3, WP4 and WP5.
- **Appendix A and B**: These annexes present the detailed and updated analysis of the relevant R&I project working in the ZDM domain, as well as the most relevant international standards inspiring the architectural work of the Q-RA.

An overall view of the document structure can be seen in the figure below.

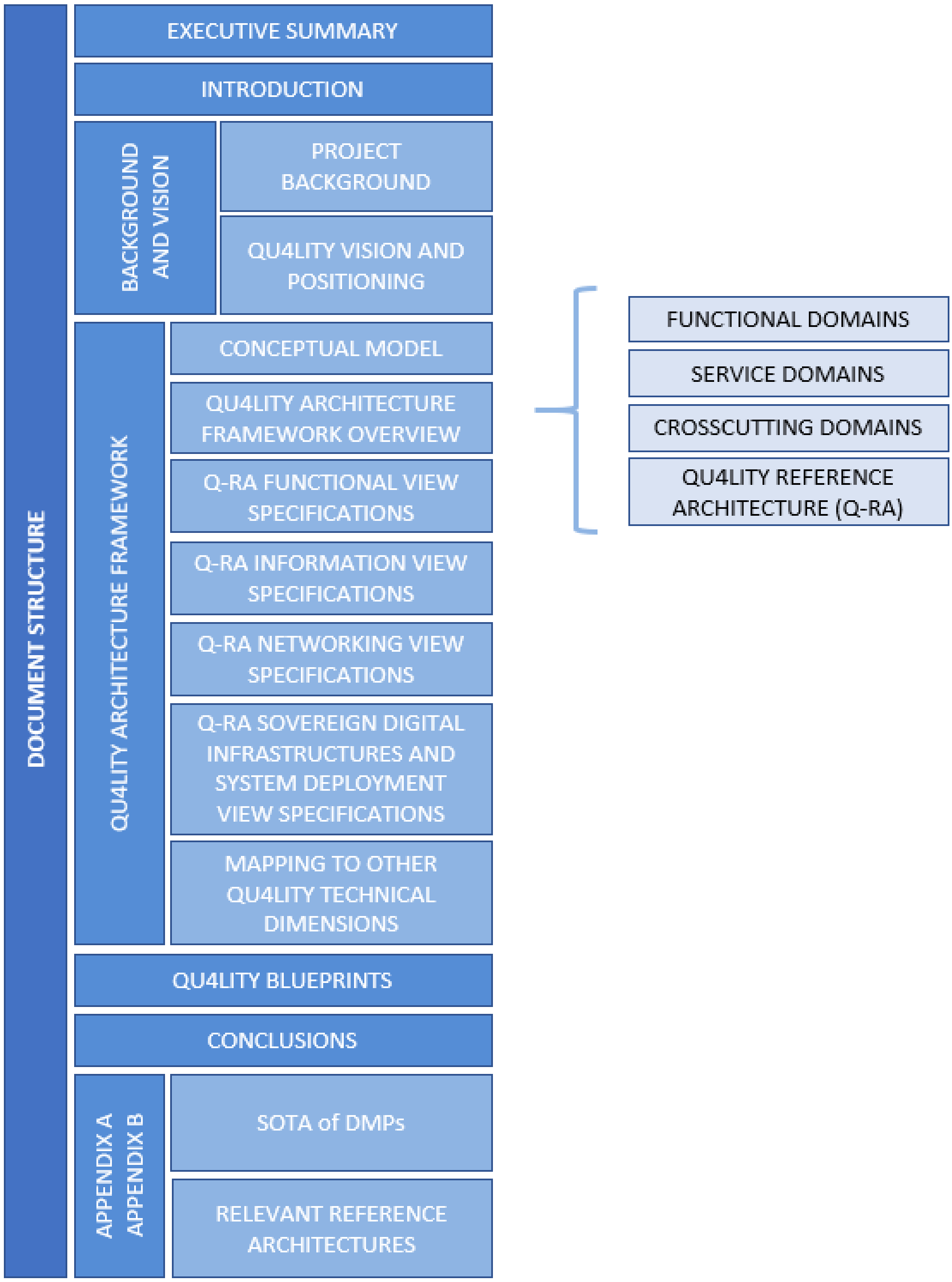

Figure 3 – D2.12 Document Structure

3 Background and Vision

3.1 Project Background

Industry 4.0 started as a digital transformation initiative with a focus on the digital transformation of European factories towards smart digital production systems through intense vertical and horizontal integration. In such a scenario, SMEs are the main target of most of the national (and international) initiatives supporting the Digital Transformation of the European economy, since manufacturing is the second most important sector in terms of small and medium-sized enterprises' (SMEs) employment and value added in Europe [6]. Over 80% of the total number of manufacturing companies is constituted by SMEs, which represent 59% of total employment in this sector.

In an increasingly competitive global market, companies must implement quick and sustainable actions to respond to market changes and new requirements. In terms of market trends, a growing attention is given to product and process quality, therefore traditional businesses need to be enhanced with digital technologies to overcome the current limitations and to implement agile demand-driven approaches.

To SMEs, it still seems difficult to understand the added value of the digital transformation already happening, and its driving forces able to increase their business competitiveness, making them aware and compliant with Industry 4.0 principles. Moreover, as SMEs intend to adopt modern data-driven services, making their advanced manufacturing processes more competitive and robust, they face additional challenges to the implementation of "digital enabled production".

This increased awareness, even supported by a more informed public society, has brought the European industry and relevant standardization consortia to develop the RAMI 4.0 reference model, built on the strong foundations of the manufacturing European industry (e.g., in the automotive sector). Consequently, the rest of the world (mainly USA and Asia) have started huge investments to define their reference model for the digitization of their manufacturing processes. This has resulted in the development of the Industrial Internet Reference Architecture (IIRA) by the US Industrial Internet Consortium (IIC) initiative and the Industrial Value Chain Reference Architecture (IVRA) by the Industrial Value Chain Initiative (IVI) in Asia. These initiatives clearly showed the need to consider in the digitalization of European industry not only the Smart Factory dimension, but also Smart Product and Smart Supply Chain dimensions.

As a side effect, several initiatives kicked off complementary efforts to ensure RAMI 4.0, IVRA and IIRA interoperability, mapping and alignment for global operation of digital manufacturing processes, especially in the context of smart data-driven manufacturing processes.

QU4LITY project aims to create an open, certifiable, and highly standardized, SME-friendly and transformative shared data-driven ZDM product and service model. It will demonstrate how European industry can build unique and highly tailored ZDM strategies and competitive advantages through an orchestrated open platforms ecosystem, ZDM atomized components and digital enablers.

As described in the report: "D2.4 - QU4LITY Vision & Autonomous Quality (AQ) Model", we will see an evolution in the flexibility and modularity of factory processes (autonomous transportation & logistics, plug & produce modular assembly cells, human & robot collaboration, digital factory) that will be linked to an increased ability for manufacturing equipment and manufacturing processes to make autonomous decisions supervised and assisted by the expertise and knowledge of human workers. Those autonomous manufacturing processes will see and deploy different levels of human-AI collaboration. According to Industry 4.0 classification, QU4LITY will address the implementation of processes and manufacturing equipment up to Autonomy Level 4, where processes will run autonomously, and the human is only involved to supervise and intervene in emergency situations. The QU4LITY AQ model will meet the Industry 4.0 ZDM challenges (cost and time effective brownfield ZDM deployment, flexible ZDM strategy design & adaptation, agile operation of zero-defect processes & products, zero break down sustainable manufacturing process operation and human centred manufacturing).

The adoption of the QU4LITY autonomous quality model demands a unified framework that supports an AQ control workflow. In parallel to the development, deployment and set-up of information flows, cognitive services, and self-adaptive manufacturing equipment, the QU4LITY AQ model considers the design and implementation of the IT and OT integrated digital infrastructure leveraging the reliable and high-performance networking, storage, computing & processing required by autonomous ZDM operation. Such IT/OT deployment should adhere to the QU4LITY Reference Architecture (Q-RA).

The following sections will present the state of play of Digital Manufacturing Platforms and their role within the QU4LITY vision, while the Appendix A/Appendix B presents a state of the art of the main reference architectures already available in the manufacturing arena.

3.1.1 Common ZDM Scenarios

ZDM is a holistic quality management approach that ensures both process and product quality by reducing product defects through corrective, preventive, and predictive techniques. It mainly leverages data-driven technologies and guarantees that no defective products leave the production site and reach the customer aiming at higher manufacturing sustainability[1]. ZDM combine techniques from maintenance,

[1] Definition specified in the scope of the CEN/CLC/WS on "Zero Defects in Manufacturing Terminology" (ZDMTerm), where QU4LITY partners participate.

logistics and process control. Hence, such techniques can be found in various ZDM scenarios.

To better clarify the main ZDM scenarios to be addressed in QU4LITY, Task 2.1 has investigated the user stories and their requirements from all QU4LITY stakeholders. The analysis results show that most stakeholders' requirements are related to data management in general and some specific phases (e.g., data collection, data visualization and data mining). It reflects the fact that most pilots realized the importance of their data and wish to exploit the value contained, but they are facing difficulties in handling their data. Some more advanced scenarios are also proposed such as autonomous control, decision support, quality monitoring and prediction, as well as production system optimization etc. These scenarios demonstrate that at least some pilots hope to reach a higher level of intelligence which aligns with the vision of Industry 4.0 and the aims of QU4LITY project.

The most relevant stakeholders of ZDM scenarios include production/plant managers, innovation engineers, operators, maintenance managers, data scientists, quality managers, suppliers and group leaders.

For example, production/plant managers focus mostly on prescriptive functionality, automated quality checks and performance information of machines/equipment. Their main interest is in reducing scrap or excluding the defective products/parts and reduction of cost. The concerns of these stakeholders are all covered by the QU4LITY ZDM vision. The prescriptive functionality corresponds to the QU4LITY objective of predictive maintenance and defect prediction, automated quality checking corresponds to the cognitive and autonomous control, performance information of machines/equipment reflects the digital twin objective, etc.

Another typical scenario is related to innovation engineers such as design engineers, digital innovation experts and R&D engineers etc. Their main concerns include receiving real data about the performance of the process and gaining insights provided by analytics. It emphasizes the importance of industrial data and the potential value contained. It also aligns with the high-level requirements asking for advanced data management solutions are necessary, i.e., data management, data collection and data mining, covering different levels of a production system, like product, machine, control devices, stations, workshops, intra-/inter- enterprise etc.

Operators also play an important role in most ZDM scenarios. Their interests focus on manufacturing line monitoring and start/close procedures for planned interruptions. They also see benefits when they can receive a signal when the process is showing deviations that might lead to errors. Another joint function is the use of Virtual Support, e.g., AR/VR for training or instructions.

The above ZDM scenarios are analysed from different stakeholders' point of view. More details about the interests of different stakeholders are introduced in D2.2 "Analysis of User Stories and Stakeholders' Requirements", but they are also driving the different iterations of the activities around the definition of the Q-RA.

To address the interests of different stakeholders in different ZDM scenarios, it is necessary to integrate various technical enablers and components provided by QUALITY partners from different work packages and tasks. Some generic scenarios are separated into low-level requirements and connected to specific task. Some examples are listed below:

- To extend/update the current list of standards to include the latest standards regarding interoperability for IIoT and digital twin applications, AAS discussions and integration of ontology, data models, and vocabulary. The compliance of the QU4LITY Reference Architecture must be verified against the latest standards, e.g., RAMI 4.0. – T2.4&T2.5 Standards, Data Models & Vocabularies.
- To provide active monitoring of production lines, QU4LITY networking-related digital enablers should provide real-time communication capability otherwise ZDM processing may be impacted. – T3.1 Connectivity & Networking
- Cloud Infrastructure should be CSP (Cloud Service Provider) independent; be able to support both private and public cloud; provide interoperability across Cloud solutions and on-premises storage solutions; support in developing/integrating new connectors and interfaces toward more-exploited data platforms. -- T3.2 HPC &Cloud
- QU4LITY enablers should provide processing and sensor data analysis at both edge and cloud level; provide Machine Learning Techniques for Data Driven Calculation of Asset Lifecycle Parameters (Remaining Useful Life, End of Life) and optimizing Sensor Placement and Deployment for Capturing Quality Parameters; Management, Analytics of Streaming Data (Sensors, IoT Devices) and Visualization of Data for Presenting Abnormalities (Quality Issues, Defects). -- T3.3 AI & Big Data
- QU4LITY edge enablers must provide local data processing, visualization, storage capabilities, (deterministic) communication and data synchronization mechanisms with central data warehouse. -- T3.4 Fog & Edge
- QU4LITY SPT framework must provide authorization/authentication policies with the goal of assuring data confidentiality, data integrity and non-repudiation. -- T3.5 Cybersecurity
- Human-in-the-loop processes need to address different layers from individual production processes to factory levels and must cover humans in Supervision, Investigation, Prescriptive guidance, Predictive support and Collaborative processes. Interfaces for user interaction shall address the specific role a user has. – T5.1 Modelling and Learning Services
- The simulation framework shall enable the use of simulation during both, planning and execution phases of production. It shall cover the use of different simulation types (e.g., material flow, bottleneck identification, process simulation, parts handling) and tools (e.g., Plant Simulation, AnyLogic, Python-based simulators) and operating systems those are executed on. – T5.2 Digital Twin and Planning Services
- ZDM processes must be able to (semi-) automatically adapt themselves to changing conditions of the shop floor. For allowing this, depending on the use

case (pilot), a modular integration of adapted and customized tools, as defined by the pilots, must be possible. Communication Standards and Interface covering (e.g., MQTT, OPC UA, TCP/IP, UDP, ROS, Database Connections), depending on the use case, shall be applied to allow communications of the respective modules. – T5.3 Simulation and Human-centric visualization services

- OpenAPI developments need to consider the different developments of the solutions developed in QU4LITY. Key characteristics to be considered need to cover service-oriented or REST architectural styles and adopted most relevant communication protocols in ZDM processes (e.g., MQTT, AMQP, OPC UA, etc.). – T5.4 Collaboration, Business and Operation Services
- Service Planning and Engineering needs to cover definition and implementation phases. Engineering services shall support engineering a quality system according to the MPFQ Model (Material, Processes, Features/Functions, Quality). Modelling services shall allow the use of proprietary data models. – T5.5 Engineering and Planning Services

The above are some examples of the requirements for QU4LITY ZDM scenarios and the corresponding work packages and tasks for realizing them. More examples and details are summarized, as above mentioned, in D2.2 "Analysis of User Stories and Stakeholders' Requirements".

All these technical enablers and components are integrated and structured with the Q-RA introduced in this deliverable. Every one of these technologies and components can be mapped to a certain section of the Q-RA which will be presented in the following sections.

3.2 QU4LITY Vision and Positioning

In the QU4LITY project, Autonomous Quality (AQ) is intended as a paradigm for ZDM in a connected smart Factory 4.0, which requires the implementation of interrelated control loops for real-time adaptation, flexible composition, smart planning and continuous learning. AQ can be defined as a real-time quality control process supported by Industry 4.0 enabling technologies where, at the maximum level of system autonomy, the decisions (closing loop) are taken by software after a deep data analysis. AQ aims at reducing the human input in the data analysis and process control to achieve the automation of the loops of information through improved use of more complex control systems. The goal is to achieve autonomous decision-making processes to assure the quality of production processes and related output in an autonomous way.

In an industry 4.0 perspective, AQ in all production steps can be a challenging task. To reach zero-defect in different process steps by optimizing both equipment or production processes, a fuzzy area of how to tackle predictive and prescriptive interaction of cyber physical production systems (CPPS) and full automation for production lines needs to be implemented and controlled.

The objective of QU4LITY is to demonstrate, in a realistic, measurable, and replicable way an open, certifiable and highly standardised, SME-friendly and transformative shared data-driven ZDM product and service model for Factory 4.0 leveraging on five competitive advantage: significantly increase operational efficiency, scrap reduction, prescriptive quality management, energy efficiency, defect propagation avoidance and improved smart product customer experience, and foster new digital business models. For this reason, the attention is focused both on the product or parts, processes and machines.

The QU4LITY strategies will use data to drive efficiencies and improve capabilities in three ways. First, connecting workforce, manufacturing assets, facilities and devices to the Internet will enable use cases such as large-scale and small-scale high precision manufacturing, plug & control solutions and smart in-process adaptation.

Second, integration with non-production departments, such as engineering, planning and after-sales service, enables new business insights to drive simulation-based production and work-cell self-reconfiguration and multi-stage manufacturing process optimization avoiding error propagation.

Third, improved data visibility among companies enables implementation of outcome-based service models and collaborative and orchestrated digital twin service operation.

In that light, QU4LITY AQ aims at reducing the human input in the data analysis and process control to achieve the automation of the loops of information through improved use of more complex control systems. The goal is to achieve autonomous decision-making processes to assure the quality of production processes and related output in autonomous way. To realise the AQ paradigm, four types of control loops are required:

- Real-time control loop – it is a control system where the time window to collect and process data to then update the system is tight. If there is not a defined time window, the system stability is in danger.
- Composition & orchestration control loop – the data collected must be integrated to support the decision system, the orchestrator automates sequences of activities by implementing the necessary rules and policies to change the system state in response to an event.
- Deep control loop – the data mining infrastructure will support deep-learning as a means of providing AI capabilities in manufacturing analytics. Existing data analytics infrastructures that are already customized for manufacturing will be used to accelerate the developments.
- Augmented human in the control loop – the availability of new technologies that allow data handling and visualization using mobile/wearable apps (mobile middleware) contribute to keeping the human in the loop while reducing errors.

Although many new technologies are adopted, QU4LITY does not call for abandoning well established and sound quality control methods. On the contrary, QU4LITY calls for extending such methods with a multi-dimensional, multi-stage and systematic framework for cognitive collaborative quality assurance throughout an entire supply chain, i.e., autonomous quality control framework.

4 QU4LITY Architecture Framework

4.1 Conceptual Model

Conceptually, technical specifications of QU4LITY should be based on analysis of standard-related information, such as applied standards, essential interoperability requirements etc., and compliance definitions across different QU4LITY activities. Based on these considerations, it is possible to set up a conceptual model that indicates relations between the defined goals and task-specific actions.

Using the methodology presented in Section 2.3, the following diagram (see Figure 4) presents the main relationships among the main components of this architectural work: the *Architecture Framework*, referring to the *Conceptual Model* presented in the previous section, the *Reference Architecture* (further described in the following sections) including also *Domains* and *Architectural Views*.

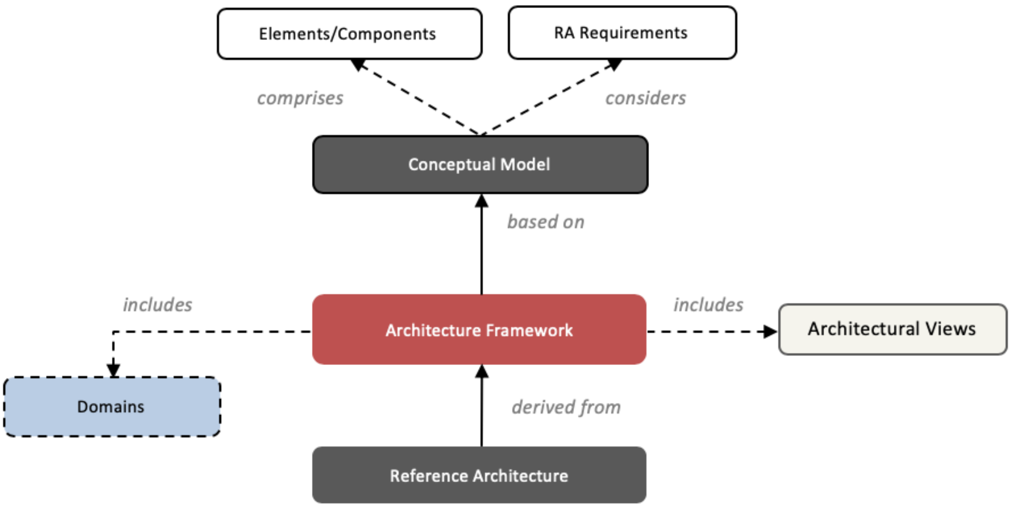

Figure 4 – Q-RA Conceptual Model

Based on the investigation and reviewing of existing standard-related information, a series of concerns and requirements must be considered before the implementation of the Q-RA. Some of the requirements and concerns are listed as follows.

- **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 plays a key role in ZDM-related scenarios. Due to a cross-linking of multiple systems in various domains in Industry 4.0, interoperability now extends and comprises a much broader framework than just simple connectivity. Three interoperability areas can be defined hierarchically:
    - Technical interoperability: it focuses on data transport and exchange of raw data between various points of the network (connectivity).

  - Syntactic interoperability: it is the ability to exchange structured data through common data formats.
  - Semantic interoperability: it is the ability of a system to interpret meaning that is derived from structured data in a contextual manner.
- **Safety and Security**: The increased connectivity and interaction between multiple technical systems in a manufacturing framework leads to various cyber threats and their causes, errors and vulnerabilities are no longer limited within a single system, but can spread further, leading to threats that affect other systems at the same time.
  - Security requirements of classic IT-systems: typically addressed by ISO 27000. Therefore, due to its specific focus on the industrial sector, IEC 62443 also stands out markedly from ISO 27001.
  - Functional safety of a system or industrial automation components: The aim of functional safety is to protect the environment from serious harm caused by a technical system. This includes not only the protection of people from serious harm, but also the protection of the environment and valuable manufacturing goods. ZDM manufacturing systems and their components rely on the automatic protection, which has to respond correctly and in a predictive manner to all system inputs or failures. Therefore, it is important that such automatic protection systems are designed according to the current standards and so that these are able to handle human errors and other hardware failures.
- **Compliance Requirements of the Q-RA**: Based on the analysis of the current architecture standards like RAMI 4.0 and reviewing of the blueprints about common standardization areas and application fields of common reference architecture standards in ZDM Pilots, some common compliance requirements for Q-RA are defined.
  - Conformity with common standards: DIN SPEC RAMI 4.0 and its internationally updated version IEC PAS 63088:2017(E) must serve as a standard conformity objective for verification of compliance requirements.
  - Complexity and high readability: avoid complex views and multiple internal dependencies between different architectural elements.
  - Consistency: verify architecture views in accordance with the most common Reference Architecture Standards for possible gaps.
  - Harmonization: encounter the recent standardization activities towards harmonization of reference architectures
  - Informational capacity: 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.
  - Industrial Application: comply to the RAMI 4.0 respective layers.

- Integrity: 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.

With the progressing of the QU4LITY pilots, more specific requirements and concerns might be defined in addition to the ones mentioned above. Activities from other QU4LITY tasks like comprehensive standard screening across the pilots; and the identification, validation, collection, and comprehensive search for common latest interoperability standards, etc. will provide more specific requirements for the development of the Q-RA during the next step.

4.2 QU4LITY Architecture Framework overview

Starting from the needs described in the previous section, the Q-RA is described in the following sections using several viewpoints, while the diagram depicted below provides an overall architecture representation that includes all the elements.

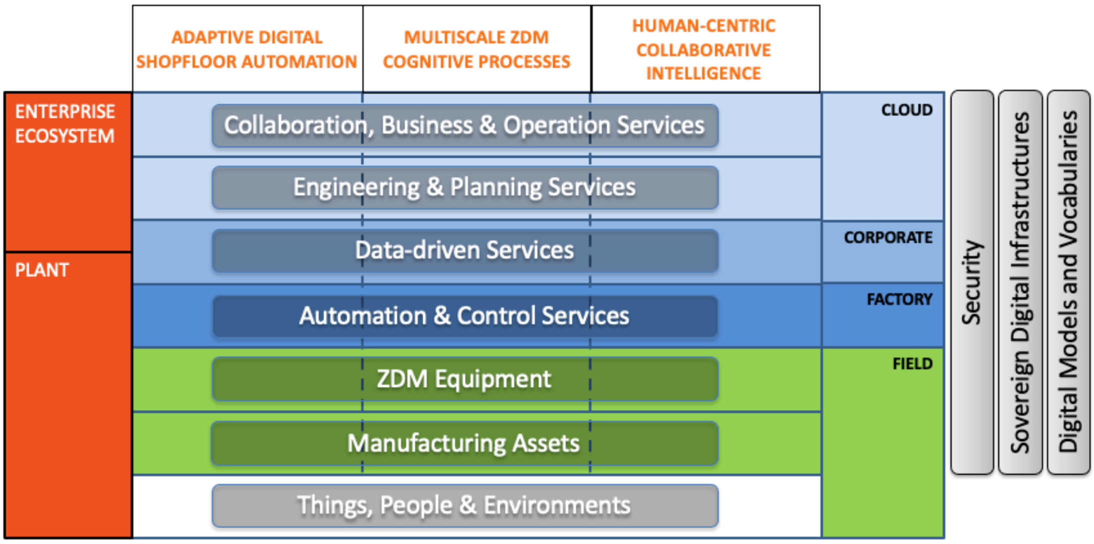

Figure 5 – QU4LITY Architecture Framework overview

According to the Q-RA, the functionality of a ZDM Digital Manufacturing Platform can be decomposed into three high-level **Functional Domains** – *Adaptive Digital Shopfloor Automation*, *Multiscale ZDM Cognitive Processes* and *Human-Centric Collaborative Intelligence* – and three **Crosscutting (XC) Functions** – *Security*, Sovereign *Digital Infrastructures*, and *Digital Models and Vocabularies*.

4.2.1 Functional Domains

Functional Domains and XC Functions are orthogonal to structural Tiers (the implementation of a given functionality may – but is not required to – span multiple Tiers, so that in the overall architecture representation (Figure 5) Functional Domains appear as vertical lanes drawn across horizontal layers. In the picture below, the relationship between Functional Domains, their users and the factory environment are highlighted by arrows showing the flow of data and of control.

The Functional Domains identified in QU4LITY are the following:

- **Adaptive Digital Shopfloor Automation**: This domain includes functionalities supporting *automated monitor and control* of *Assets* and *Smart Products* in the physical world. The traditional and digitally enhanced ZDM equipment, integrated or developed in the project, will find here the natural playground to foster the interactions with the rest of the QU4LITY solutions. The Automation domain requires a bidirectional monitoring/control communication channel with the Field, typically with low bandwidth but very strict timing requirements (tight control loop). In some advanced scenarios, Automation is controlled – to some extent – by the results of more complex ZDM processes and services. The Automation domain is also responsible for decoupling the real word from the digital world, exploiting new auxiliary capabilities provided by the *Sovereign Digital Infrastructures* and *Digital Models and Vocabularies* XC Functions.
- **Multiscale ZDM Cognitive Processes**: This domain includes functionalities for gathering and processing both Data at Rest and Data in Motion for a better understanding of ZDM processes using a data-driven perspective. This typically requires dedicated Digital Infrastructure (provided as part of the Sovereign Digital Infrastructure XC Function) both for supporting data exchanges and processing, as the volume of information that needs to be transferred in a given time unit may be substantial. This domain provides intelligence to its users, but these are not necessarily limited to humans or vertical applications (e.g., virtualization or simulations solutions). Virtualization and Simulation require digital models of plants and processes to be in-sync with the real-world objects they represent. As the real world is subject to change, models should reflect those changes.
- **Human-Centric Collaborative Intelligence**: This domain maps all the services where a human (or even an external system) can interact with the QU4LITY solutions, play any number of roles in an ZDM system — who may conceptualize, design, build and operate ZDM processes.

The following Figure 6 provides a graphical representation of the identified Functional Domains.

Figure 6 – Q-RA Functional Domains

4.2.2 Service Domains

The above-mentioned Functional Domains can be refined using another perspective, given by the Service Domains as shown in Figure 7, namely:

- **Human Domain**: The Human domain accomplish with end-user needs, providing use-to-use and user-friendly interfaces, and supporting the development and access to ZDM Applications built on top of information and services managed by the overall framework. Existing design and engineering tools, as well decision-supporting applications may fit in the scope of this domain.
- **Business Domain**: Information and services intended to support operational management and business maintenance and evolution will be part of this Domain, especially for all the applications related to optimization and collaboration at value-chain level.
- **Virtualization and Simulation Domain**: This domain will offer advanced digital services based on many technologies, such as advanced High-

Performance Computing (HPC), Digital Twin, Virtual/Augmented/Mixed Reality, Big Data and Artificial Intelligence.

- **Automation and Control Domain**: The Automation and Control domain includes functionalities enabling efficient and reliable data exchange and intelligent control over the physical production processes and assets. The introduction of Cyber-Physical Systems (CPS), Industrial Internet of Things (IIoT), and Fog/Cloud technologies in modern shopfloor fuels the evolution towards herp-connected and digitalized factories, where physical assets and digital services can communicate with each other.
- **Physical World Domain**: This layer complies with the interaction among digital services and the physical world. Several devices will be supported, considering both brownfield scenario where new intelligence has to be added in the existing assets, and greenfield scenario where connected and smart ZDM equipment may be used.

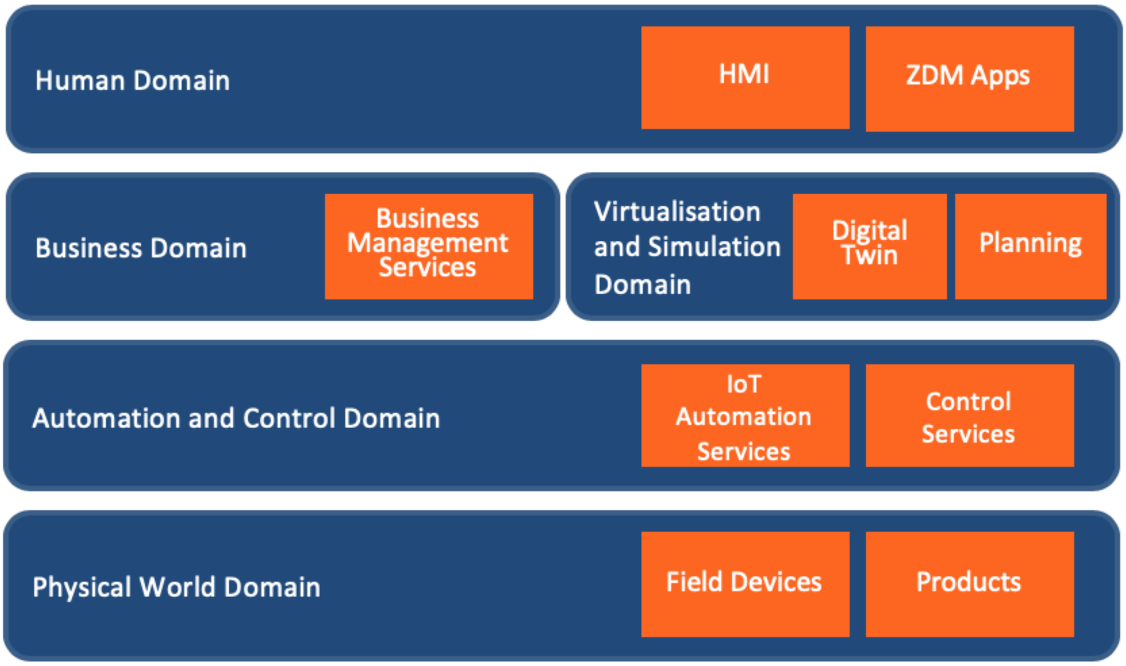

Figure 7 – Q-RA Service Domains

4.2.3 Crosscutting Functions

Crosscutting Functions address, as the name suggests, common specific concerns. Their implementation tends to be pervasive, affecting several Functional Domains and Tiers. They are briefly listed and described in the following:

- **Cybersecurity:** Following the concept of Industry 4.0 and manufacturing the increase of digital services and interconnection of smart factories make cyberthreats one of the most prevalent and critical issues in the day-to-day. This targets technologies, people, physical processes and services. This way, we have identified several cybersecurity technologies that are relevant in this domain, which can provide critical supportive solutions. Among others, the more important issues we target in QU4LITY are data protection, continuous monitoring and remediation, identity & authentication, and security-by-design.

- These solutions are integrated into a cybersecurity framework so organizations could use the solutions that are more relevant to them and integrate them naturally in their systems.
- **Sovereign Digital Infrastructures:** Functions that ensure the connectivity and process capabilities to support the business logic (Q-RA Functional Domains) in the different Tiers and among them, from the Field to the Users, abstracting away the technical details – like device management, transport and communication protocols, Cloud Service Providers and so on.
- **Digital Models and Vocabularies:** Functions for the management of digital models and their synchronization with the real-world entities they represent. Digital modes and vocabularies are a shared asset, as they may be used as the basis for automated configuration, simulation and field abstraction – e.g., semantic interoperability of heterogeneous field systems.

4.2.4 QU4LITY Reference Architecture (Q-RA)

The QU4LITY Reference Architecture (or Q-RA in short) is the conceptual framework that is going to drive the design and the implementation of any QU4LITY based solution. As every RA, its primary goal is to present, in a coherent and homogenous way, the underlying integration principles and digital technologies to be adopted in order to implement our **Autonomous Quality** vision, where real-time quality control processes (supported by Industry 4.0 enabling technologies) provide maximum level of system autonomy based on closed-loop decisions.

To this end, clear communication mechanisms have to be adopted to represent concepts, components, structure and behaviour of the system under analysis both internally for the benefit of the project Consortium and externally for the sake of dissemination and ecosystem-building.

The context and background analyses presented in Chapters 3 and then in Appendix A/Appendix B, together with internal discussions within the Consortium and especially among the technical work-packages (namely WP2-3-4-5), have shaped the high-level design of our Q-RA. In the end, a clear picture of the target system was drawn, and the high-level design was adjusted accordingly.

The final step was to determine how to format such design to be communicated to stakeholders. Thanks to the collaboration with the tasks related to standardization (in WP2 and WP9), we have selected the ISO/IEC/IEEE 42010 standard [2], trying to reduce the overhead of a full-compliance to this standard to guarantee the delivery of the expected outcomes of T2.6 in this time-critical activity of the project.

Following this standard approach, Figure 8 and Figure 10 show that the identified Service Domains (presented in Section 4.2.2) can be mapped toward the four main views (further described in the rest of the section): Functional View, Information View, System Deployment View and Networking View.

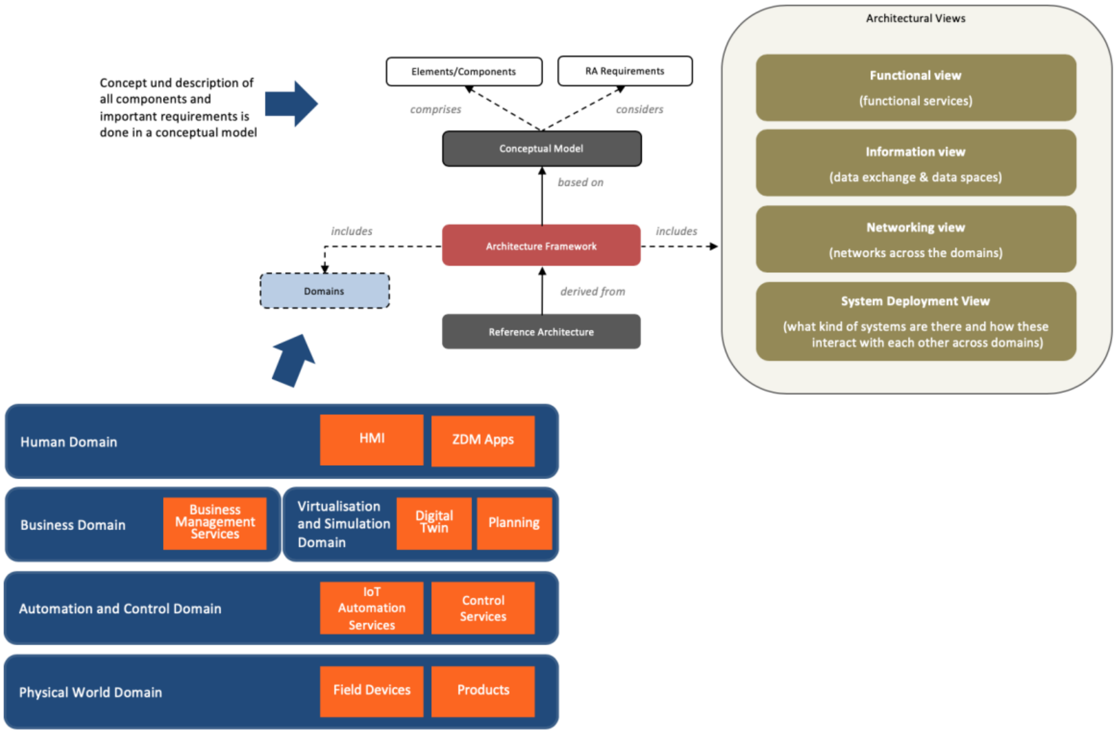

Figure 8 – Q-RA Service Domains vs. QU4LITY Architectural Views

The prime role of the Q-RA, as already stated initially, is to guide the engineering of a QU4LITY-based solution, by the first stakeholders to be addressed, which are the members of the Consortium (considering both the offer and the demand side). In this fluid communication environment shared context, vocabulary and conventions have to be used with a minimum of effort.

The Q-RA is described more in details in the following. The diagram in Figure 9 presents the overall Q-RA, providing a representation that includes all elements, and adopting the following colour notation:

- *Functional Viewpoint* is represented using **Orange** boxes;
- *Information Viewpoint*, representing data and information components, are represented using **Green** boxes;
- *Networking Viewpoint* is represented using **Blue** boxes;
- *System Deployment Viewpoint*, i.e., how the system components can interact or be networked together, is represented by **Light Blue** boxes.

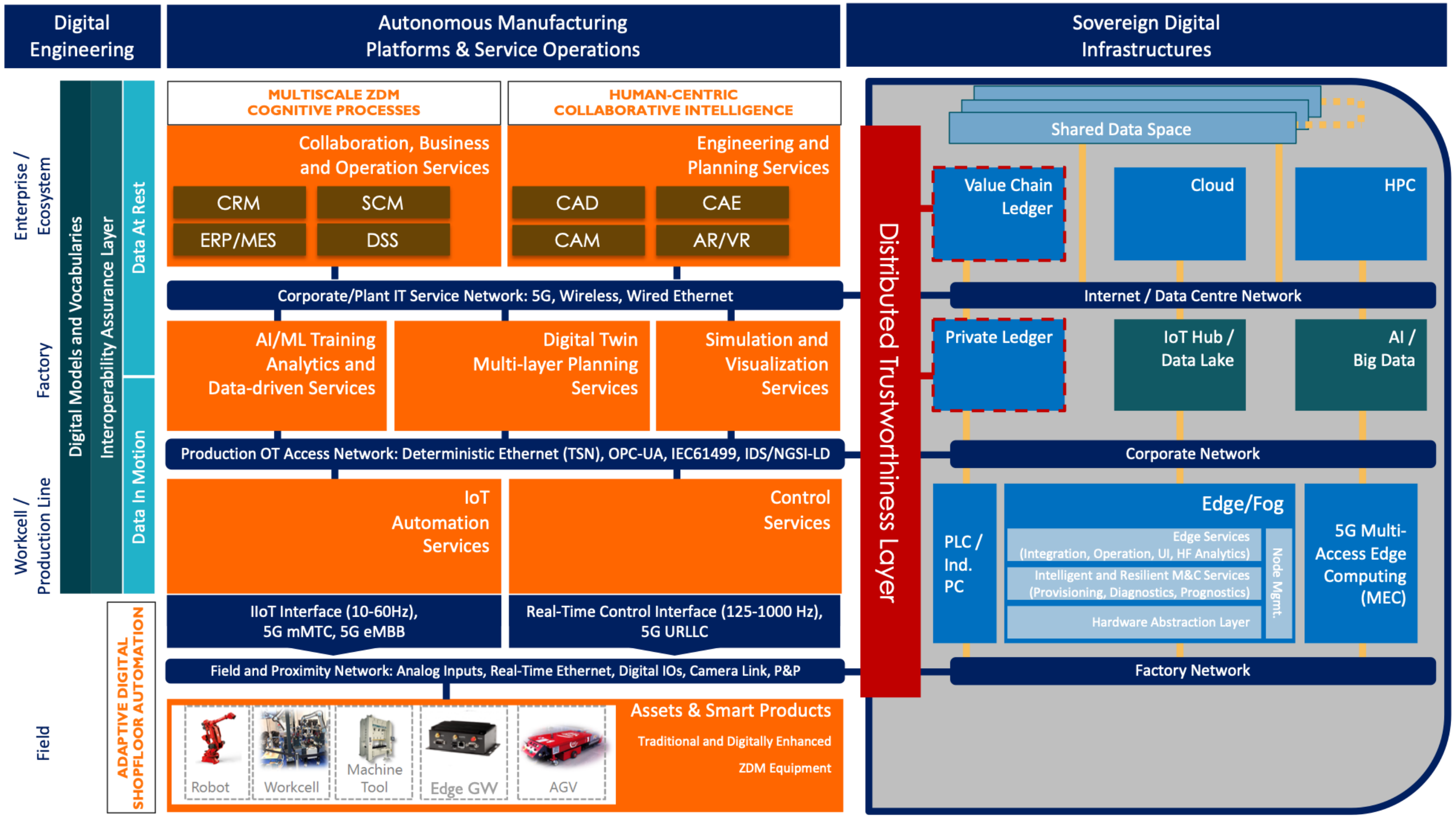

Figure 9 – QU4LITY Reference Architecture (Q-RA) – Final Version

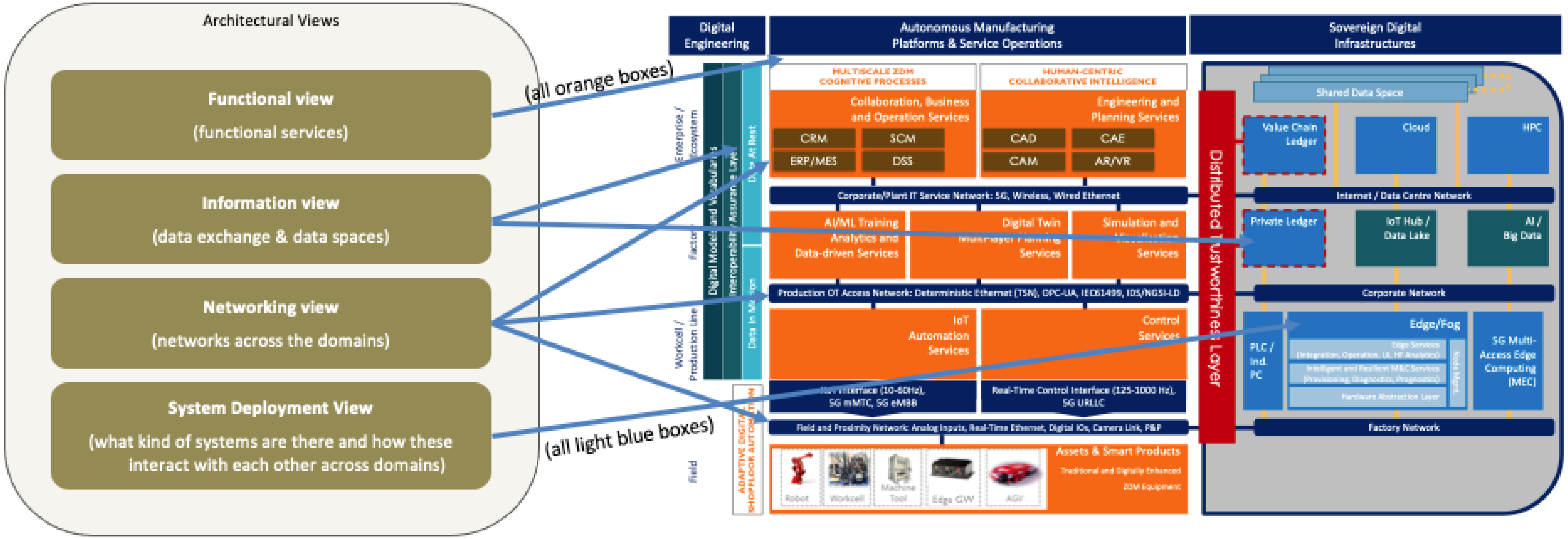

Figure 10 – QU4LITY Architectural Views vs. Q-RA

Figure 10, finally, shows how the different view (i.e., Functional, Information, System Deployment and Networking) can be mapped in the presented Q-RA.

4.2.4.1 Functional View

The **Functional View** is a technology-agnostic view of the functions necessary to form a QU4LITY-based system. This view describes the distribution of and dependencies among functions for support of ZDM processes and activities, marked with **Orange** boxes in Figure 9.

Each functional component may be realized by one or more implementations of actual system components, which may be deployed to form a working system. The functional components are not necessary for some specific applications and therefore, in their actual deployed systems, may not exist.

The main categories of functional components identified so far follow:

- **Workcell/Production Line layer**
  - **IoT Automation Services**: Provide sensing, context & model building capabilities, and access to the data coming from the field devices, identifying data sources and contribute to the data provenance and asset traceability.
  - **Control Services**: Enable the real time control of multiple elements of the production process, thanks to high-performance communication technologies and edge processing capabilities.
- **Factory layer**
  - **AI/ML Training Analytics and Data-driven Services**: Manage complex analytics pipeline and other data-driven processes on heterogeneous data sources, providing access, modelling and processing capabilities over big and dark data generated in modern Industry 4.0 systems.
  - **Digital Twin and Multi-layer Planning Services**: Ease the development, commissioning and operation of Digital Twin (DT), at different scale from a single product to the whole plant. Digital twins make it possible to assess an asset/plant virtually before having it physically (DT working in the past), or they can monitor the actual status of the asset/plant (DT working in the present), or they can be used to simulate a potential future condition applied to a specific asset/plant to plan the optimal use of the twinned asset (DT working in the future). These services can be used both at product and process level.
  - **Simulation and Visualization Services**: Provide complex simulation environment (at both HW and SW level) and tools able to test, know the operation of certain systems or anticipate problems. These simulation services make it easier to know what kind of answers can be offered in certain situations, without any physical risk for humans or machines. The simulated behaviour and observed phenomena need

to be presented to the operators/end users using advanced visualization services easing the digestion of such complex scenario.

- **Enterprise/Ecosystem layer**
  - **Collaboration, Business and Operation Services**: Represent the collection of services implementing applications that realize specific business functionalities for strategic business planning and implementation, internal operation monitoring and management, as well as cross-organization collaboration at value-chain and supply-chain level.
  - **Engineering and Planning Services**: Support several engineering processes as well as planning and optimization functions, in order to provision and optimize manufacturing efficiency and business continuity.

4.2.4.2 Information View

The information is generated by using, monitoring, controlling and analysing connected entities and sub-systems, remaining within a "domain" or being exchanged between "domains".

Both raw and processed information is used by the different ZDM services and applications to fulfil intended task for a given activity in the system.

The main components of the **Information View**, marked with **Green** boxes in Figure 9, are the following:

- **Digital Models and Vocabularies**: Sharing digital models and vocabularies provides the capability to exchange information in the whole system with a common interpretation of information. In this contest, basically two levels of data interoperability are considered: syntactic interoperability is to exchange information in a common data format with a common protocol to structure the data; and semantics interoperability is to interpret the meaning of the symbols in the messages correctly. These interoperability components provide a flexible method of composing services so that the system behaviour can be adapted at run-time to enable advanced ZDM processes.
- **Interoperability Assurance Layer**: interoperability can be defined as the ability of organisations/platforms/components to interact towards mutually beneficial goals, involving the sharing of information and knowledge between them, through the business operation they support. This layer will guide all the interoperability mechanisms to be supported by the Q-RA, by providing a set of common elements (e.g., concepts, definitions, perceived requirements, existing standards, identified gaps, etc.) related to quality, safety and equipment compliance standards.
- **IoT Hub / Data Lake**: The current market offers several IoT Hub services, most of them cloud-based, providing acting as a central communication hub between IoT devices and applications managing them. IoT Hub supports bidirectional communications both from the device to the cloud and vice versa,

providing support to scalable businesses and processes. IoT Hub are often combined with data lake, serving as a centralized repository and providing resilience and scalable storage solutions for both structured and unstructured data.

- **AI / Big Data**: Storage solutions are often paired with AI / Big Data Analytics infrastructures in order to provide the needed processing and management capabilities to realize data analytics — from dashboards and visualizations to big data processing, real-time analytics, and machine learning to guide better decisions.
- **Value Chain Ledger and Private Ledger**: The value of Distributed Ledger Technology (DLT) as a key enabler for ZDM stems from two of its architectural features:
    - Decentralization of control: processes with multiple autonomous actors can be run safely without the supervision of an authority. Smart contracts achieve this objective by replicating their business logic and persistent memory on multiple nodes. No central service is needed to enforce rules or even coordinate the process.
    - Trustworthy tracking of events: despite the lack of a central repository, everything written on a Blockchain by a smart contract cannot be altered or removed without all participants (nodes and clients) noticing, thanks to the cryptographic techniques used to seal both individual transactions and their sequential order. Adding digital identities and signatures to the picture results into a system of record that enforces nonrepudiation.

  Both the Value Chain Ledger and the Private Ledger meet these requirements, their difference being only in scope: the former addressing multi-stakeholder collaborative processes across a manufacturing ecosystem, the latter being for single-stakeholder distributed processes within a factory.
- **Shared Data Space**: Enables the secure and trustworthy sharing of data across industrial systems within the factory and across factories, creating easy link to connect to trusted data-driven ecosystem exploring the benefits of ZDM technologies of even cross-domain.

4.2.4.3 Networking View

Networking and connectivity capabilities support the integration of heterogeneous components, which may belong to different networks or using different communication technologies.

The **Networking View** describes the principal communications networks which are involved and the entities with which they connect. Each of the principal communications networks, marked with **Blue** boxes in Figure 9, can be implemented by means of a range of different network technologies, which are used depending on the characteristics and requirements of the resulting system.

The four principal communications networks are described in the following:

- **Field and Proximity Network**: This network exists within the automation and control services and the physical assets. Its main task is to connect the sensors and actuators to the physical objects of the Field Domain. Field and Proximity Networks use many specialized field protocols, based on low power limited range wireless and wired technologies. Current examples include IPv6 over Low Power Wireless Personal Area Networks (6LoWPAN), ZigBee, Narrow- Band IoT. Individual sensors and actuators may have limited power and limited hardware capabilities, which means that simple, local, and low-power networks are needed to connect them to gateways. These are more powerful and can in turn connect to Production OT Access Networks.
- **Production OT Access Network**: Production OT Access Networks are typically wide area networks connecting devices to the other domains, often using gateways and proxy services. A range of technologies can be used in access networks including wired connections (Broadband / ADSL / Fibre) and wireless connections including Wireless LANs (Wi-Fi), Mobile (cellular) networks and 5G links. Other technologies to be adopted could be deterministic ethernet (TSN) and the International Standard for Distributed Systems IEC61499.
- **Plant / Corporate Service Network**: This network connects elements toward wider components at plant or corporate level. This network can include both Internet elements and also (private) intranet elements. It is typical for intranet networks to be used where the elements of the other domains exist within a single production site. Where communication spans multiple sites, a variety of secure network technologies may be used, including both dedicated connections and Internet connections.
- **Data Centre / Internet Network**: This network connects the segments controlled by corporate policies towards external service providers (e.g., cloud and HPC infrastructures). Such networks can use any of the technologies commonly used to carry internet traffic, including both wired and wireless systems and preferring broadband and ultra-wideband channels.

4.2.4.4 System Deployment View

While the Functional View describes the QU4LITY-based system through its functional components, the system view describes it through its physical components (e.g., sub-systems, devices, networks). The *System Deployment View* describes the following aspects:

- Key physical components and runtime environment (e.g., HPC, Cloud, Edge devices, and so on).
- The distribution of components, and the topology of the interconnectivity of the components.
- The underlying connections and the emerging behaviours and other properties.

The Q-RA can support a variety of **deployment patterns**, supporting both OnPremise and InCloud approaches. Q-RA implementations can be located

OnPremise for most factories, but may also be hosted in the cloud especially for SMEs. Furthermore, multiple distributed computing devices and systems may be attached to Q-RA, both at the edge and on. The Q-RA is designed to be instantiable on a variety of systems to achieve this goal. To this end containerization technologies (e.g., based on Docker) can be adopted as an application run-time environment– see also "D3.13 - Library of Integrated, Interoperable Digital Enablers (Version 1)" document. This allows a separation of the components, allowing an increased independence of each component.

4.3 Q-RA Functional View Specifications

4.3.1 Workcell/Production Line layer

4.3.1.1 IoT Automation Services

ID		Q-RA-1
Responsible task		T4.5 "ZDM Equipment Interoperability, Federation and Autonomous Interactions"
Component name		IoT Automation Services
Component definition		This module provides context and model building capabilities, and, crucially, is able to provide access to the data coming from the Field devices, identifying data sources and contributing to the data traceability.
Details	Functionalities offered	▪ Smart Machine Sensing, ability developed along with the Control Services module, the capability for the machines to be aware of what is happening around, an enhancement which is closely linked to the sensorization of Field devices and process digital twin. This module will, apart from that, enable the application of: ▪ Augmented Decisions Support, which will help humans to make decisions, profiting from the newly

			acquired knowledge by the Big Data Analytics or from Machine Learning. ▪ Smart Process Adaptation, this is, the ability of learning from the product and operational data.
	Needs (add more if needed)	#1	WHAT: I/Os from/to the machine sensors and actuators WITH[2]: Smart Assets & Products
		#2	WHAT: Corrections, received at Workcell level, regarding the most optimal production parameters, as per the Big Data Analytics Models. WITH: AI/ML Training Analytics and Data-driven Services
		#3	WHAT: The existence of infrastructure to store the production data, in order to be able to correlate it with the product quality outcomes. The Data Analysis Services will take the data from here. WITH: IoT Hub / Data Lake
		#4	WHAT: The existence of infrastructure to store the production data, in order to be able to correlate it with the product quality outcomes. The Data Analysis Services will take the data from here. WITH: Shared Data Spaces
	Gives (add more if needed)	#1	WHAT: Interoperability Standards, not only at Workcell and Factory levels (ETHERNET, MODBUS, etc.); but between machines (OPC-UA). This is critical for horizontal integration along the Digital Thread. WITH: Interoperability Assurance Layer

[2] This field indicates the relationship between the current described component "WITH" other components of the Q-RA.

		#2	WHAT: Provides contextual operational data stored in the relevant Infrastructure, for the training of the Models. WITH: AI/ML Training Analytics and Data-driven Services
	Technical foundations		This task has implemented techniques and tools for intelligent data exchange and interaction between different types of ZDM equipment (equipment federation, integration of a machine within a process/factory. Hence, it deals with data interoperability (through the Industrial Data Space of WP5) and machine-to-machine (M2M) interactions between two or more pieces of equipment. The implementation of M2M and data interoperability is actually a foundation to the use of multiple ZDM equipment technologies for the implementation of ZDM processes in WP5 and in the scope of the pilots.
Risks management	Open issues	#1	N/A
	Technological risks	#1	N/A

4.3.1.2 Control Services

ID	Q-RA-2
Responsible task	T4.2 "Enhanced Distributed Communication and Control"
Component name	Control Services
Component definition	QU4LITY Control Services are intended to manage the different equipment (e.g., robots, machines, AGVs, etc.) within the plant or the manufacturing cell, integrating the

			information to remote I/Os via an integrated PLC, facilitating the communication between the Factory and Field layers and adding Edge data processing capabilities to the relevant pieces of equipment.
Details	Functionalities offered		▪ Smart Machine Sensing, the capability for the machines to be aware of what is happening around, an enhancement which is closely linked to the sensorization of Field devices and process digital twin. ▪ Computer vision, mostly related to the manufactured product quality control and product digital twin. Edge-Powered Distributed Control, the ability to process data near-to-the-Field and to make faster, decentralised, decisions on machine operations.
	Needs (add more if needed)	#1	WHAT: I/Os from/to the machine sensors and actuators WITH: Assets & Smart Products
		#2	WHAT: Interoperability Standards among Field and Factory levels (ETHERNET, MODBUS, etc.) WITH: Interoperability Assurance Layer
		#3	WHAT: Physical devices with computing capabilities for agile processing of the amount of data coming from the Field devices WITH: Edge / Fog
	Gives (add more if needed)	#1	WHAT: Provides time-synchronized, traceable, structured data with whom software components herein can elaborate a digital replica of the physical product or equipment.

			WITH: Digital Twin Multi-Layer Planning Services
		#2	WHAT: Provides contextual data for complex simulation environment and to be able to estimate the behaviour of the machine in different circumstances and operational conditions. WITH: Simulation and Visualization Services
	Technical foundations		This module enhances distributed communication and controls system with digital capabilities as a means of increasing their reliability and ease of use in large plants. TSN has been used to support real-time communications between devices and to able to follow the Software-Defined Networking paradigm; while IEC61499-based platforms and Fog/Edge nodes for automation have been implemented. On top of these capabilities, automation functions have been developed in order to facilitate rapid actuation and correction of defects (or their root causes) once defects are detected. Such automation functions are provided at the Field devices level, the Production Control and the Production Scheduling levels, depending on the types of each machine or equipment.
Risks management	Open issues	#1	N/A
	Technological risks	#1	N/A

4.3.2 Factory layer

4.3.2.1 AI/ML Training Analytics and Data-Driven Services

ID			Q-RA-3
Responsible task			T7.3 "Zero Defects Processes Pilots"
Component name			AI/ML Training Analytics and Data-Driven Services
Component definition			Advanced quality classifier
Details	Functionalities offered		1. Get test data 2. Define failure classification Visualize test classification
	Needs (add more if needed)	#1	WHAT: Access to machine client to get test data WITH: Assets & Smart Products
		#2	WHAT: Failure classification by ML trained model WITH: AI/ML Training Analytics and Data-driven Services
		#3	WHAT: Visualization of test classification result WITH: Control Services
	Gives (add more if needed)	#1	WHAT: Test data from test stand WITH: Assets & Smart Products
		#2	WHAT: Failure classification for each product at the test stand WITH: AI/ML Training Analytics and Data-driven Services
		#3	WHAT: Test result WITH: Control Services

	Technical foundations		Data analytics methods used for failure classification and improvement of decision rules
Risks management	Open issues	#1	N/A
	Technological risks	#1	N/A

4.3.2.2 Digital Twin and Multi-layer Planning Services

ID			Q-RA-4
Responsible task			T5.2 "Factory Wide Multiscale ZDM Process Modelling and Multi-domain Simulation"
Component name			Digital Twin Multi-Layer Planning Services
Component definition			Simulation Framework for Quality KPI evaluation
Details	Functionalities offered		1. Load simulation model 2. Check data model 3. Define scenario configuration 4. Evaluate simulation experiment 5. Check KPI results
	Needs (add more if needed)	#1	WHAT: Simulation model WITH: Simulation and Visualization Services
		#2	WHAT: Data model for components and parameterization WITH: Digital Models and Vocabularies
		#3	WHAT: Scenario configuration to define simulation experiment WITH: Simulation and Visualization Services
		#4	WHAT: Run simulation experiment and export results

			WITH: Simulation and Visualization Services
		#5	WHAT: Visualize orchestrated results on UI WITH: Simulation and Visualization Services
	Gives (add more if needed)	#1	WHAT: Simulation model defines the components and its topology WITH: Simulation and Visualization Services
		#2	WHAT: overview on components, parameters, experiments and results WITH: Digital Models and Vocabularies
		#3	WHAT: Definition of several scenarios WITH: Digital Models and Vocabularies
		#4	WHAT: Simulation model evaluation results WITH: Simulation and Visualization Services
		#5	WHAT: Overview on several experiment results WITH: Simulation and Visualization Services
	Technical foundations		Framework for model and tool selection, scenario configuration, model execution, result processing and result visualization.
Risks management	Open issues	#1	N/A
	Technological risks	#1	N/A

4.3.2.3 Simulation and Visualization Services

ID			Q-RA-5
Responsible task			T5.1 "User centric ZDM processes"
Component name			User interface for simulation framework
Component definition			Simulation and Visualization Services
Details	Functionalities offered		1. Result visualization 2. Raw and Structured data visualization
	Needs (add more if needed)	#1	WHAT: Experiments from simulation framework WITH: Simulation and Visualization Services
		#2	WHAT: Raw and Structured Data to be visualized WITH: AI/ML Training Analytics and Data-driven Services
		#3	WHAT: Structured Data to be visualized & Parameters allowed to be changed by a person WITH: Collaboration, Business and Operation Services
		#4	WHAT: Raw data to be visualized WITH: Digital Twin and Multi-layer Planning Services
		#5	WHAT: Structured Data to be visualized WITH: Engineering and Planning Services
		#6	WHAT: Structured Data to be visualized WITH: IoT Automation Services
	Gives (add	#1	WHAT: Compare results from several experiments and choose best solution

	more if needed)		WITH: Simulation and Visualization Services
		#2	WHAT: Parameters changed by a person via an HMI WITH: Collaboration, Business and Operation Services
	Technical foundations		With simulation framework configuration of several scenarios is possible. These scenarios can be evaluated and results can be compared to optimize the ZDM process.
Risks management	Open issues	#1	N/A
	Technological risks	#1	N/A

4.3.3 Enterprise/Ecosystem layer

4.3.3.1 Collaboration, Business and Operation Services

ID		Q-RA-6
Responsible task		T5.6 "Framework and tools integrated service engineering"
Component name		Collaboration, Business and Operation Services
Component definition		This module provides the means for engineering and composing end-to-end ZDM processes covering the full product lifecycle and the all the processes originated in the Company (Design & Engineering, Manufacturing, Logistics and Supply Chain, etc.)
Details	Functionalities offered	The ZDM Integrated Services Engineering is based on the integration of functionalities from the digital manufacturing platforms and technologies, through their OpenAPIs.

			The module comprises tools and techniques for integrating and bringing together functionalities from different digital platforms by using their Open APIs, including machine level platforms (developed in WP4), process level frameworks and H2M2M services (e.g., the framework developed in tasks T5.1 and T5.2), as well as digital enablers (from WP3).
	Needs (add more if needed)	#1	WHAT: the capability of intercommunicating with Data-at-Rest modules from the Factory layer, who in turn should have access to the Data Lakes / Data Spaces, etc., constituting the QU4LITY Infrastructures WITH: Interoperability Assurance Layer
	Gives (add more if needed)	#1	WHAT: integration of the information received by all factories of the Company in the ERP, thus, being able to provide the information which is necessary for the optimisation of the production strategy via AI/ML training at the Cloud (quite possibly helped by HPC Infrastructure) WITH: AI/ML Training Analytics and Data-driven Services
		#2	WHAT: the DSS recommendations, applied to all the production Sites of a Company, once the QU4LITY solutions have been implemented, will enable decision-making, and helped by the adjacent AI/ML training analytics, will enable the improvement of processes, the identification of bottlenecks and the overall improvement of Manufacturing Planning and Execution WITH: Digital Twin Multi-Layer Planning Services
	Technical foundations		This module, along with the adjacent one (Engineering and Planning Services) focuses on the integration of

			the digital twin as enabler/requirement for a Company-wise Digital Services Engineering approach, and makes emphasis on the integration of the "digital replica" of the physical product and operations via the whole implementation of the digital thread. Vertical Integration with the upper layers of the Company is required in order to achieve this.
Risks management	Open issues	#1	N/A
	Technological risks	#1	N/A

4.3.3.2 Engineering and Planning Services

ID			Q-RA-7
Responsible task			T5.1 "Framework for user centric ZDM processes"
Component name			Engineering and Planning Services
Component definition			Tools for supporting the human-machine collaboration
Details	Functionalities offered		Tools from pilot applications for AR/VR, data visualization and data Inspection
	Needs (add more if needed)	#1	WHAT: Commands to start the execution of AR/VR Scenarios WITH: Collaboration, Business and Operation Services
		#2	WHAT: Raw data to be inspected WITH: AI/ML Training Analytics and Data-driven Services
	Gives (add	#1	WHAT: Structured Data to be visualized

	more if needed)		WITH: Simulation and Visualization Services
		#2	WHAT: Structured data to be further processed WITH: AI/ML Training Analytics and Data-driven Services
	Technical foundations		Focus on technology supporting the human operator in the accomplishment of their tasks
Risks management	Open issues	#1	N/A
	Technological risks	#1	N/A

4.4 Q-RA Information View Specifications

4.4.1 Digital Models and Vocabularies

ID		Q-RA-8
Responsible task		T2.5 "Specification and Prototyping of Digital Models, Vocabularies and Digital Twins"
Component name		Digital Models and Vocabularies
Component definition		A range of data models and vocabularies to drive the flow and exchange of digital data across different ZDM equipment and processes.
Details	Functionalities offered	1. Facilitate information flow exchange through ZDM components and digital platforms. 2. Enable data interoperability. 3. Support simulation and implementation. 4. Ensure compliance to existing standards.

			5. Ensure openly accessible (open source) digital models and tools.
	Needs (add more if needed)	#1	WHAT: User stories and stakeholder's requirements for assuring interoperability among components WITH: Interoperability Assurance Layer
		#2	WHAT: Analysis of standards and specifications used or to be used for networking and connectivity to support the design of data models assuring its compliance with standards WITH: Networking and connectivity components (Field and Proximity Network, Production OT Access Network, Plant / Corporate Service Network, Data Centre / Internet Network)
	Gives (add more if needed)	#1	WHAT: Semantic models to enable the interoperability among ZDM components and digital platforms WITH: Interoperability Assurance Layer
		#2	WHAT: Data models and semantic models to support data-driven services and digital twin modelling WITH: AI/ML Training Analytics and Data-driven Services
		#3	WHAT: Data models and semantic models to support data-driven services and digital twin modelling WITH: Digital Twin Multi-layer Planning Services
	Technical foundations		Semantic modelling tools and top-level reference ontologies.

Risks management	Open issues	#1	The adopted top-level ontology is still evolving. The developed domain ontologies and application ontologies need to be updated in future.
		#2	The implementation of the semantic data models is still ongoing. Some experiments are needed to verify it in future.
	Technological risks	#1	The domain ontologies may not fully suitable to all pilots. They need to be adjusted accordingly when applied to more pilots.
		#2	Industrial partners may not be able to update the application ontology after the project finished. We need to prepare detailed instructions about how to update/upgrade ontologies.

4.4.2 Interoperability Assurance Layer

ID		Q-RA-9
Responsible task		T2.4 "Standards Compliance and Interoperability Specifications"
Component name		Interoperability Assurance Layer
Component definition		A 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.
Details	Functionalities offered	1. Create a secure basis for technical procurement, ensure interoperability in applications. 2. Protect the environment, plant, equipment and consumers by means of uniform safety rules.

			3. 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 ZDM landscape.
	Needs (add more if needed)	#1	WHAT: Analysis of standards and specifications used or to be used for networking and connectivity to define specifications and recommendations for compliance with interoperability standards. WITH: Networking and connectivity components (Field and Proximity Network, Production OT Access Network, Plant / Corporate Service Network, Data Centre / Internet Network)
		#2	WHAT: Analysis of safety and security standards used and to be to define specifications and recommendations for compliance with safety and security standards WITH: Distributed Trustworthiness Layer
		#3	WHAT: Analysis of AI standers used and to be used to define specifications and recommendations for compliance with AI standards WITH: AI / Big Data
	Gives (add more if needed)	#1	WHAT: Standard and specification review results to support the design of data models assuring its compliance with standards WITH: Digital Models and Vocabularies

		#2	WHAT: Specifications and recommendations for compliance with interoperability standards WITH: Networking and connectivity components (Field and Proximity Network, Production OT Access Network, Plant / Corporate Service Network, Data Centre / Internet Network)
		#3	WHAT: Specifications and recommendations for compliance with safety and security standards WITH: Distributed Trustworthiness Layer
		#4	WHAT: Specifications and recommendations for compliance with AI standards. WITH: AI / Big Data
	Technical foundations		Analysis of standard-related information and examine pilots' specific interoperability scenarios regarding compliance requirements and current standards.
Risks management	Open issues	#1	Apply analysis results to support digital platforms based on Open APIs and interoperability characteristics collaborating with T5.4.
		#2	Disseminate and align with standardization and clustering activities together with T9.2.
	Technological risks	#1	N/A

4.4.3 IoT Hub/Data Lake

ID			Q-RA-10
Responsible task			T3.3 "AI and Big Data Analytics for ZDM"
Component name			IoT Hub / Data Lake
Component definition			Enables access to and management of Data from Cyber Physical production System (CPPS)
Details	Functionalities offered		1. Connection to CPPS systems and IoT Devices 2. Dynamic Discovery of CPPS Systems and IoT Devices Endpoints 3. Reliable Management of IoT Streaming Data 4. Scalable Storage and Management of Big Data (i.e., data featuring the four Vs). 5. IoT Analytics over Industrial Data
	Needs (add more if needed)	#1	WHAT: Flexible High-Performance Access to Streaming Data WITH: IoT Hub / Data Lake
		#2	WHAT: Management and integration for both streaming data and data at rest WITH: IoT Hub / Data Lake
		#3	WHAT: Integration of Analytics Algorithms including ML Techniques WITH: IoT Hub / Data Lake
		#4	WHAT: Integration of Analytics Algorithms including ML Techniques WITH: AI / Big Data
	Gives (add more if needed)	#1	WHAT: Configurable routing and Data Processing of Industrial IoT Streams (e.g., Streams from CPPS systems) WITH: IoT Hub / Data Lake

		#2	WHAT: Integration of Big Data Databases (i.e., Hadoop) with Data Streaming Frameworks (i.e., Spark) WITH: IoT Hub / Data Lake
		#3	WHAT: Support for different types of modular analytics processors that enable different data analytics schemes WITH: AI / Big Data
	Technical foundations		The IoT Hub and Data Lake Functionalities are provided through Industrial Internet of Things (IIoT) platforms and their integration with Big Data infrastructures (e.g., Apache Hadoop, Apache Spark).
Risks management	Open issues	#1	Multiple IIoT platforms are used in QU4LITY. Their deployment and use are in-line with the Q-RA.
		#2	IoT hubs must fulfil different requirements in terms of data volumes, types of data (e.g., data at rest, streaming data) in-line with the requirements of the industrial use case. To this end, IIoT infrastructures are customized.
	Technological risks	#1	Technical integration complexity risks Mitigation: Design and support of a Module IoT Data Management Architecture
		#2	Lack of support for some ML techniques Mitigation: Support/Integration of Custom Frameworks in addition to out-of-the-box ML libraries

4.4.4 AI, Machine Learning and Big Data Analytics Library

ID			Q-RA-11
Responsible task			T3.3 "AI and Big Data Analytics for ZDM"
Component name			AI, Machine Learning and Big Data Analytics Library
Component definition			Extract ZDM insights and knowledge based on analytics over historical maintenance, process, or logistics data
Details	Functionalities offered		1. Remaining Useful Life (RUL) prediction/estimation 2. Fault detection and fault identification 3. Determination of associations between production variables that lead to certain quality 4. Avoidance of parameters that lead to defects 5. Product anomaly detection and production settings
	Needs (add more if needed)	#1	WHAT: Support for Classical Machine Learning, Deep Learning and Model-Based Reinforcement Techniques WITH: IoT Hub / Data Lake
		#2	WHAT: Support for Classical Machine Learning, Deep Learning and Model-Based Reinforcement Techniques WITH: AI / Big Data
		#3	WHAT: ML System Performance through trial and error WITH: IoT Hub / Data Lake
		#4	WHAT: ML System Performance through trial and error WITH: AI / Big Data
		#5	WHAT: Access to sample datasets for training WITH: IoT Hub / Data Lake

	Gives (add more if needed)	#1	WHAT: Integration of both Machine Learning and Deep Learning Frameworks / Libraries over the IoT Hub and Big Data platforms WITH: IoT Hub / Data Lake
		#2	WHAT: Integration of both Machine Learning and Deep Learning Frameworks / Libraries over the IoT Hub and Big Data platforms WITH: AI / Big Data
		#3	WHAT: Support for the deployment and redeployment of Machine Learning workflows/pipelines including visual AutoML tools WITH: IoT Hub / Data Lake
		#4	WHAT: Support for the deployment and redeployment of Machine Learning workflows/pipelines including visual AutoML tools WITH: AI / Big Data
		#5	WHAT: Data from QU4LITY pilot partners WITH: IoT Hub / Data Lake
	Technical foundations		QU4LITY leverages a variety of known/state-of-the-art Machine Learning techniques, including Deep learning techniques like Long Short-Term Memory and Convolutional Neural Networks (CNN). Moreover, home-grown libraries introduced by the partners (like QARMA4Industry i.e., Quantitative Rule Mining for Industry) are used. Algorithms have been developed over popular state-of-the art data science infrastructures and tools, including Python (Pandas, NymPy, SciPy, scikitlearn, Jupyter Notebooks, Weka)

Risks management	Open issues	#1	The quality of the outcomes depends on the availability of industrial data. Poor data quality or limited data quantify can negatively affect the quality of the outcomes. QU4LITY has instigated the collection of industrial data from the pilot sites early on in the project's workplan.
		#2	Different algorithms are used to address different ZDM and Quality Management use cases. The development of ZDM systems that integrate logistics, maintenance and process control requires integration of multiple ML systems and algorithms. The Q-RA should make provisions for the integration of multiple algorithms of the library in a common system.
	Technological risks	#1	N/A

4.4.5 Shared Data Space

ID			Q-RA-12
Responsible task			T3.3 "AI and Big Data Analytics for ZDM"
Component name			Shared Data Space
Component definition			Enables the secure and trustworthy sharing of data across industrial systems within the factory and across factories.
Details	Functionalities offered		1. Users Authentication and Authorization 2. Secure Message Exchange 3. Dynamic Discovery of End Points 4. Semantic Data Interoperability
	Needs	#1	WHAT: Identity Management, Authentication, Authorization and Secure Data Exchange

	(add more if needed)		WITH: Distributed Trustworthiness Layer
		#2	WHAT: Common Vocabularies and Interoperability Standards among the data provider and data consumer WITH: Digital Models and Vocabularies
		#3	WHAT: Common Vocabularies and Interoperability Standards among the data provider and data consumer WITH: Interoperability Assurance Layer
	Gives (add more if needed)	#1	WHAT: Traceable industrial production parameter and product quality data available in the data space for another partner to be able to use them WITH: AI/ML Training Analytics & Data-driven Services
		#2	WHAT: Traceable industrial production parameter and product quality data available in the data space for another partner to be able to use them WITH: Digital Twin Multi-Layer Planning Services
		#3	WHAT: Traceable industrial production parameter and product quality data available in the data space for another partner to be able to use them WITH: Simulation and Visualization Services
	Technical foundations		Identity Management infrastructure for authentication of participants. Message Bus / Data bus Pattern for message exchange across different endpoints. Industrial Data Space for trusted interactions across supply chain participants.

Risks management	Open issues	#1	Diverse Pilot Requirements in terms of security and data semantics – Use of different Data Exchange infrastructure
		#2	The customization of a Data Space infrastructures (e.g., in terms of users, connectors, security protocols, different endpoints) for different use cases is very challenging and time consuming.
	Technological risks	#1	N/A

4.5 Q-RA Networking View Specifications

4.5.1 Factory Network

ID		Q-RA-13
Responsible task		T3.1 "Scalable, Reliable and High-Speed Connectivity for ZDM"
Component name		Factory Network
Component definition		System responsible for providing critical communication between devices (controllers, actuators, AGVs, etc) and the control systems inside the production line to the site IT subsystems.
Details	Functionalities offered	1. High-speed fieldbus connectivity for time sensitive devices, 2. PLC-to-PLC communication, 3. Ubiquitous field connectivity to production diagnostics, 4. Secured communications to IT subsystems and databases. For these functionalities, 5G for mobile access at production line and TSN ethernet for wired devices at shopfloor are proposed.

	Needs (add more if needed)	#1	WHAT: Low latency and deterministic time slots for real-time communication between devices and IT systems WITH: Real-Time Control Interface (125-1000 Hz), 5G URLLC
		#2	WHAT: High level of security to actuators, valves and other physical equipment since a cyber-attack can cause further damage than only outages or data lose WITH: Field and Proximity Network
	Gives (add more if needed)	#1	WHAT: 5G mobile access for wireless connectivity WITH: Assets & Smart Products
		#2	WHAT: 5G mobile access for wireless connectivity WITH: IIoT Interface (10-60Hz), 5G mMTC, 5G eMBB
		#2	WHAT: TSN wired network for extremely sensitive devices WITH: Field and Proximity Network
	Technical foundations		A factory shopfloor demands granted deterministic allocation of communication channels due to the restricted requirements of delay and bandwidth to operate a production line correctly and safely. 5G access technology promises fully compliant QoS with industrial requirements enabling wireless ubiquitous connectivity at shopfloor and TSN Ethernet standards guarantee open reliable protocols to address the low-level requirements of industrial ZDM applications.
Risks management	Open issues	#1	5G CPE compatibility with TSN modules is under development and several integration solutions have

			been proposed but a clear architecture is not yet decided.
	Technological risks	#1	5G rollout/deployment price.
		#2	TSN standards compatibility with industrial legacy protocols.

4.5.2 Corporate Network

ID			Q-RA-14
Responsible task			T3.1 "Scalable, Reliable and High-Speed Connectivity for ZDM"
Component name			Corporate Network
Component definition			Private network that connects devices in the production line to the corporate infrastructure and services.
Details	Functionalities offered		1. High-speed wired and mobile connectivity to office network, 2. Local breakout features for industrial management services, 3. Security layer including FW and DPI features preventing any undesired access from to time sensitive networks and data lakes in the factory. For instance, it enables Edge/Fog nodes to reach applications running in factory private servers such as Data Lake/Big Data Analytics, IoT Hub or Private Ledger, etc.
	Needs (add more if needed)	#1	WHAT: Separated infrastructure from the sensitive Factory Network with granted security but providing seamless real-time access to controllers and production diagnostics WITH: Distributed Trustworthiness Layer
		#2	WHAT: Separated infrastructure from the sensitive Factory Network with granted security but providing seamless real-time access to controllers and production diagnostics

			WITH: Production OT Access Network
		#3	WHAT: Controlled reliable encrypted access to Internet/Data Centre network for Cloud centralized applications and data sharing with different venues WITH: Cloud
		#4	WHAT: Controlled reliable encrypted access to Internet/Data Centre network for Cloud centralized applications and data sharing with different venues WITH: HPC
	Gives (add more if needed)	#1	WHAT: Provides controlled secured access to local Factory Network from centralized Data Centre Network WITH: Production OT Access Network, Corporate/Plant IT Service Network
		#2	WHAT: Provides controlled secured access to local Factory Network from centralized Data Centre Network WITH: Distributed Trustworthiness Layer
		#3	WHAT: Access to all management services needed for local teams and custom edge services for delay sensitive communications for both Corporate and Factory networks WITH: Engineering and Planning services
		#4	WHAT: Access to all management services needed for local teams and custom edge services for delay sensitive communications for both Corporate and Factory networks WITH: Control Services

		#5	WHAT: Access to all management services needed for local teams and custom edge services for delay sensitive communications for both Corporate and Factory networks WITH: IoT Automation Services
	Technical foundations		Every factory requires a secured network for interconnecting its shopfloors with management and office areas, to connect local host ed services and data lakes, and to interconnect the factory safely with the outer world, such as Internet.
Risks management	Open issues	#1	Multilayer security system to prevent damage in case upper security layers are compromised.
	Technological risks	#1	Security handling Internet access and exposing services out of local factory.

4.5.3 Internet / Data Centre Network

ID			Q-RA-15
Responsible task			T3.1 "Scalable, Reliable and High-Speed Connectivity for ZDM"
Component name			Internet / Data Centre Network
Component definition			System responsible for connecting the factory to the cloud application platforms, High Performance Computing (HPC) applications and Value Chain Ledgers. This may be through Internet or dedicated Data Centre Networks.
Details	Functionalities offered		1. Centralized data collection, 2. Secured access from Internet, 3. Compliance with required data sovereignty.
	Needs	#1	WHAT: Remote workers and management team require access via Internet to Factory Network controllers and status and diagnostics

	(add more if needed)		data. This connectivity is controlled by Corporate Network security systems WITH: Cloud
		#2	WHAT: Remote workers and management team require access via Internet to Factory Network controllers and status and diagnostics data. This connectivity is controlled by Corporate Network security systems WITH: Engineering and Planning Services
		#3	WHAT: Remote workers and management team require access via Internet to Factory Network controllers and status and diagnostics data. This connectivity is controlled by Corporate Network security systems WITH: Distributed Trustworthiness Layer
		#4	WHAT: Access to factory Corporate Network services for centralized interconnection WITH: Collaboration, Business and Operation Services
		#5	WHAT: Access to factory Corporate Network services for centralized interconnection WITH: Cloud
		#6	WHAT: Data sovereignty related to each factory must be granted WITH: Shared Data Space
	Gives (add more if needed)	#1	WHAT: Provides central points for data collection from different factories and a common place to handle alarms and operations WITH: Cloud

		#2	WHAT: Provides central points for data collection from different factories and a common place to handle alarms and operations WITH: IoT Hub / Data Lake
		#3	WHAT: Provides central points for data collection from different factories and a common place to handle alarms and operations WITH: AI / Big Data
		#4	WHAT: Hosts centralized operation services to control venues processes in real-time WITH: Collaboration, Business and Operation Services
		#5	WHAT: Hosts centralized operation services to control venues processes in real-time WITH: Engineering and Planning Services
		#6	WHAT: Hosts centralized operation services to control venues processes in real-time WITH: Cloud
	Technical foundations		Current Cloud services have been widely proved as trusted infrastructure for hosting and processing data from different world-wide sites. This maturity enables several industrial use cases meeting as well as its security and connectivity requirements.
Risks management	Open issues	#1	Data sovereignty depending on factory location.
	Technological risks	#1	Data integrity.
		#2	Cloud dedicated interconnection to cloud providers.

4.6 Q-RA Sovereign Digital Infrastructures and System Deployment View Specifications

4.6.1 Cloud

ID			Q-RA-16
Responsible task			T3.2 "Customization of HPC and Cloud Infrastructures for Digital Quality Management"
Component name			QU4LITY Cloud Infrastructure
Component definition			QU4LITY Cloud Infrastructure provides a seamless solution to exchange data using the QU4LITY Ontology Model (based on R-MPFQ developed in WP2), enabling a semantic enriched data exchange from on-premises data lakes to QU4LITY Cloud Data Storage using a time-based approach.
Details	Functionalities offered		1. REST API layer to ease the interfaces with other processing and visualization components pilot. 2. IEEE754 data encoding/decoding capabilities. 3. ETL capabilities to migrate toward Q-Ontology Relational Model. 4. Interoperability towards different relational database solutions by the adoption of a ORM module. 5. Easy migration pathways towards Cloud-Based Enterprise Management Systems.
	Needs	#1	WHAT: Interoperability Standards across QU4LITY ecosystem WITH: Interoperability Assurance Layer

	(add more if needed)	#2	WHAT: DaR/DiM WITH: IoT Hub / Data Lake
	Gives (add more if needed)	#1	WHAT: Structured Enriched Data through RESTful API WITH: Simulation and Visualization Services
		#2	WHAT: Raw Data through RESTful API WITH: AI/ML Training Analytics and Data-driven Services
	Technical foundations		QU4LITY Cloud Infrastructure has to cope with two key factors: responsiveness and interoperability. To this end, it uses containerization technologies and lightweight and responsive frameworks/modules specifically designed for building fast and scalable network applications, perfect for data-intensive real-time applications that run across distributed devices.
Risks management	Open issues	#1	The landscape of cloud solutions already used by both technological providers and pilots is very wide, therefore QU4LITY will not suggest/provide a turnkey cloud infrastructure solution per se, rather a set of recommended technologies and deployment guidelines, validated in dedicated ZDM scenario coming from the business needs of our experiments.
	Technological risks	#1	N/A

4.6.2 HPC

ID			Q-RA-17
Responsible task			T3.2 "Customization of HPC and Cloud Infrastructures for Digital Quality Management"
Component name			HPC Cluster
Component definition			The HPC infrastructure at JSI offers computational power to train ZDM models that cannot be computed on standard desktop computers and workstations.
Details	Functionalities offered		1. Training of deep neural networks for ZDM processes. 2. Graphical user interface to monitor HPC processes. Infrastructure to develop new models that require the availability of significant computational resources.
	Needs (add more if needed)	#1	WHAT: Generation of synthetic data for training of deep neural networks WITH: Simulation and Visualization Services.
		#2	WHAT: Selection of methods for training ZDM models. WITH: AI/ML Training Analytics and Data-driven Services
		#3	WHAT: Standard data formats for machine learning. WITH: IoT Hub / Data Lake
	Gives (add more if needed)	#1	WHAT: Distribution of ZDM models, e.g. deep neural networks. WITH: HPC
	Technical foundations		HPC grid computing cluster at JSI operates using the Nordugrid Advanced Resource Connector (ARC)

			grid middleware that requires that jobs be predefined in terms of their data, algorithmic and computational requirements before being submitted to the cluster grid for computation. Once a computing job has been submitted, it is placed in a queue that is managed by a SLURM scheduler, and when the job has reached the top of the queue, the grid allocates computational resources for the job, runs the computation and returns the results.
Risks management	Open issues	#1	The availability of resources can be an issue if the HPC infrastructure is overloaded. This is currently managed by assigning job priorities based on fair share principle.
	Technological risks	#1	HPC infrastructures must be frequently upgraded to prevent them from becoming obsolete. One possible way to overcome this issue is to switch to cloud-based HPC infrastructures

4.6.3 Value Chain Ledger

ID		Q-RA-18
Responsible task		T3.6 "Blockchains for Secure Decentralized State Management in ZDM"
Component name		Value Chain Ledger
Component definition		A common work area for multi-stakeholder collaborative processes, typically connected over the Internet.
Details	Functionalities offered	1. Quality Clearing House (QCH) enables a decentralized workflow for quality management in non-hierarchical supply chain scenarios. 2. Secure Messaging Board (SMB) enables the broadcast of

			"trustworthy data objects" (e.g., software, algorithms, parameters) to subscriber channels, with strong guarantees of provenance, integrity and confidentiality. 3. Secure Identity Directory (SID) enables the decentralized management of digital identities and authentication credentials for both human and machine actors.
	Needs (add more if needed)	#1	WHAT: (for QCH) • Quality Assessment Data Model (QADM) • Shipping Unit Manifest (SUM) • Quality Assessment Report (QAR) WITH: Collaboration, Business and Operation Services
		#2	WHAT: (for SMB) Distribution packages for software / firmware WITH: Engineering and Planning Services
		#3	WHAT: (for SID) Public key and descriptor of identity owners WITH: Collaboration, Business and Operation Services (governance of manufacturing ecosystem)
	Gives (add more if needed)	#1	WHAT: (for QCH) • Quality Assessment Data Model (QADM) • Shipping Unit Manifest (SUM) • Quality Assessment Report (QAR) WITH: Collaboration, Business and Operation Services
		#2	WHAT: (for SMB) Distribution packages for software / firmware WITH: Control Services
		#3	WHAT: (for SMB) Distribution packages for software / firmware WITH: Assets & Smart Products

		#4	WHAT: (for SID) Decentralized Identifier (DID) WITH: (any component that relies on DIDs for identity management)
	Technical foundations		The Value Chain Ledger is a toolkit of three ZDM-specific smart contracts (QCH, SMB and SID) that can be deployed on a standard Hyperledger Fabric blockchain platform. As part of the toolkit, client libraries for the Java environment are also provided, to facilitate the integration of legacy systems.
Risks management	Open issues	#1	N/A
	Technological risks	#1	N/A

4.6.4 Private Ledger

ID		Q-RA-19
Responsible task		T3.6 "Blockchains for Secure Decentralized State Management in ZDM"
Component name		Private Ledger
Component definition		A common work area for single-stakeholder distributed processes, usually connected on a corporate network.
Details	Functionalities offered	1. Secure Messaging Board (SMB) enables the broadcast of "trustworthy data objects" (e.g., software, algorithms, parameters) to subscriber channels, with strong guarantees of provenance, integrity and confidentiality. 2. Secure Identity Directory (SID) enables the decentralized management of digital

			identities and authentication credentials for both human and machine actors.
	Needs (add more if needed)	#1	WHAT: (for SMB) Distribution packages for software / firmware WITH: Engineering and Planning Services
		#2	WHAT: (for SID) Public key and descriptor of identity owners WITH: Collaboration, Business and Operation Services
	Gives (add more if needed)	#1	WHAT: (for SMB) Distribution packages for software / firmware WITH: Control Services
		#2	WHAT: (for SMB) Distribution packages for software / firmware WITH: Assets & Smart Products
		#3	WHAT: (for SID) Decentralized Identifier (DID) WITH: (any component that relies on DIDs for identity management)
	Technical foundations		The Private Ledger is an instance of the Value Chain Ledger (see previous section) that is deployed as a private blockchain network instead of a permissioned one. Due to this limitation in scope, the QCH smart contract is not supported on the Private Ledger.
Risks management	Open issues	#1	N/A
	Technological risks	#1	N/A

4.6.5 PLC/Ind. PC

ID			Q-RA-20
Responsible task			T3.4 "Fog/Edge Computing Technologies Adaptation and Cyber-Physical Systems Integration"
Component name			PLC / Industrial PC
Component definition			PLC / Industrial PC points, among others, at the hardware required for the fog/edge solution to be hosted on. Although the aim is to be hardware independent, certain requirements on the hardware needs to be made, referring to processing power, interfaces, etc.
Details	Functionalities offered		1. Enough processing power for the tasks at hand 2. Interfaces to the different other entities, like other edge devices or cloud solutions. These interfaces can be either wired or wireless
	Needs (add more if needed)	#1	WHAT: Connections to other entities (like edge/cloud) WITH: Cloud
		#2	WHAT: Connections to other entities (like edge/cloud) WITH: HPC
		#3	WHAT: Connections to other entities (like edge/cloud) WITH: Edge / Fog
		#4	WHAT: Reliable communication interfaces WITH: 5G Multi-Access Edge Computing (MEC)
	Gives (add	#1	WHAT: Processing capabilities WITH: AI/ML Training Analytics and Data-driven Services

	more if needed)	#2	WHAT: Processing capabilities WITH: Digital Twin Multi-layer Planning Services
		#3	WHAT: Processing capabilities WITH: Simulation and Visualization Services
		#4	WHAT: Processing capabilities WITH: IoT Automation Services
		#5	WHAT: Processing capabilities WITH: Control Services
	Technical foundations		N/A, as no hardware was developed inside QU4LITY
Risks management	Open issues	#1	Hardware solutions are always a tricky part in developing solutions. Many manufacturers are hardware dependent or are dependent from the requests from their customers. Therefore, it is impossible to provide a specific solution. Within QU4LITY, solutions can be proposed, but there are many different solutions available on the market.
	Technological risks	#1	N/A

4.6.6 **Edge/Fog**

ID	Q-RA-21
Responsible task	T3.4 "Fog/Edge Computing Technologies Adaptation and Cyber-Physical Systems Integration"
Component name	Edge/Fog
Component definition	Edge/Fog computing brings data storage and computation closer to the location (i.e., machine, vehicle) where it is needed and where it can

			immediately be processed, without having to send it to the cloud, thereby significantly improving response times, reducing latency and additionally save bandwidth.
Details	Functionalities offered		1. Virtualization to share hardware between multiple applications with a guarantee of bounded interference of the different applications on each other. 2. Integration of legacy systems through the aid of virtualization. 3. Real-time capabilities for industrial applications, capable of directly influencing production processes. 4. Flexible cloud interfaces to foster solutions into already existing infrastructure.
	Needs (add more if needed)	#1	WHAT: Interoperability Standards across QU4LITY ecosystem WITH: Interoperability Assurance Layer
	Gives (add more if needed)	#1	WHAT: Virtualization to host legacy applications WITH: AI/ML Training Analytics and Data-driven Services
		#2	WHAT: Virtualization to host legacy applications WITH: Digital Twin Multi-Layer Planning Services
		#3	WHAT: Virtualization to host legacy applications WITH: Simulation and Visualization Services
		#4	WHAT: Virtualization to host legacy applications WITH: IoT Automation Services

		#5	WHAT: Virtualization to host legacy applications WITH: Control Services
		#6	WHAT: Real-time capabilities WITH: IoT Automation Services
		#7	WHAT: Real-time capabilities WITH: Control Services
		#8	WHAT: Flexible Cloud interfaces WITH: Cloud
		#9	WHAT: Flexible Cloud interfaces WITH: HPC
	Technical foundations		Edge/Fog solutions have to be easily integrated and capable of hosting and interacting with legacy systems, thus supporting interoperability. To support this, virtualization concept is applied to host applications running on different OSs. Additionally, dockers are being used for easy integration concepts. Furthermore, having data on the edge invites for real-time processing, thus real-time support must be provided by the edge nodes to be of optimal use to the machines where the edge is installed.
Risks management	Open issues	#1	There are many different edge solutions already available on the market. Within the QU4LITY project, only a small subset of the available edge solutions is present. QU4LITY will only provide suggestions for edge solutions and how they can be applied within manufacturing factories and machines.
	Technological risks	#1	N/A

4.6.7 5G-Multi Access Edge Computing

ID			Q-RA-22
Responsible task			T3.1 "Scalable, Reliable and High-Speed Connectivity for ZDM"
Component name			5G-Multi Access Edge Computing
Component definition			The QU4LITY 5G-Multi Access Edge Computing platform is a telecommunications platform which enables the deployment of cloud and IT resources, methods and technologies in data centres within a factory while providing 5G mobile access. Deploying computing and storage resources closer to the production lines, enables real time processing, guarantees bandwidth and increases privacy and security while reducing latency.
Details	Functionalities offered		1. Local breakout, 2. Local data storage 3. Connectivity Services via cellular (5G) or non-cellular (Wi-Fi 6), 4. Computing resources, 5. Location Services.
	Needs (add more if needed)	#1	WHAT: Redundant fibre access to shopfloors and Internet/different factory networks for reliable access. WITH: Field and Proximity Network
		#2	WHAT: Data privacy WITH: IoT Hub / Data Lake
		#3	WHAT: Data privacy WITH: AI / Big Data
		#4	WHAT: Data privacy WITH: Cloud
	Gives (add	#1	WHAT: Lifecycle management of edge applications WITH: Edge / Fog

	more if needed)	#2	WHAT: Lifecycle management of edge applications WITH: Control Services
		#3	WHAT: Lifecycle management of edge applications WITH: IoT Automation Services
		#4	WHAT: Local marketplace of industrial applications for ZDM WITH: Fog / Edge
		#5	WHAT: Local marketplace of industrial applications for ZDM WITH: Control Services
		#6	WHAT: Local marketplace of industrial applications for ZDM WITH: IoT Automation Services
		#7	WHAT: Local marketplace of industrial applications for ZDM WITH: Digital Twin Multi-Layer Planning Services
		#8	WHAT: Local marketplace of industrial applications for ZDM WITH: Simulation and Visualization Services
	Technical foundations		QU4LITY 5G-Multi Access Edge Computing must enable 2 main points: provide a private 5G mobile platform with local breakout support to interconnect production lines with ZDM applications, and provide a lifecycle management platform to support development and operations of those services.
Risks management	Open issues	#1	Integration of 5G/Wi-Fi6 devices with the network.

		#2	Support of both containerized applications and legacy VMs efficiently.
	Technological risks	#1	Tenant management within edge platform.

4.6.8 Distributed Trustworthiness Layer

ID		Q-RA-23
Responsible task		T3.5 "QU4LITY Cybersecurity, Privacy and Trust Framework"
Component name		Distributed Trustworthiness Layer
Component definition		The QU4LITY Cybersecurity, Privacy and Trust (SPT) Framework provides different solutions for cybersecurity, privacy and trust in the manufacturing domain. This way, this component provides a set of solutions developed specifically for the needs of this domain that cover data protection and anonymization, privacy and authentication, continuous monitoring and security-by-design. This framework can be extended also with additional solutions in the future so the SPT can provided necessary solutions as the manufacturing platform evolves with new technologies.
Details	Functionalities offered	1. Data protection and anonymization API 2. Continuous monitoring solution (SIEM) with visual capabilities and providing an API for correlation and more complex functionalities 3. Identity and authentication solution using Keycloak as basis. 4. Security-by-design solution with tailored libraries for the manufacturing domain

	Needs (add more if needed)	#1	WHAT: Exchange data with other entities/systems WITH: Private Ledger
		#2	WHAT: Data of the systems WITH: Factory Network
		#3	WHAT: Data of the systems WITH: Corporate Network
		#4	WHAT: Status of the system and events WITH: Cloud
	Gives (add more if needed)	#1	WHAT: Cybersecurity alarms and events WITH: Private Ledger
		#2	WHAT: Service for data anonymization WITH: IoT Hub / Data Lake
		#3	WHAT: Identity and authentication solution WITH: Factory Network
		#4	WHAT: Identity and authentication solution WITH: Corporate Network
		#5	WHAT: Solution and library for security-by-design of manufacturing systems WITH: Shared Data Space
		#6	WHAT: Solution and library for security-by-design of manufacturing systems WITH: Factory Network

	Technical foundations		The QU4LITY SPT identified several cybersecurity issues in the manufacturing domain after analysing the needs and work of different use cases. This way, we identified the cybersecurity needs that were more critical and designed/implemented several solutions that could cover them. Additionally, another main objective for us was to develop the solutions in a way that could be easily integrated/used in this domain, both from the technical perspective (different technologies, systems, etc.) and the human one (how to provide the best cybersecurity information to users that may not be experts in the field).
Risks management	Open issues	#1	Working with manufacturing systems is complex as they are usually composed of several subsystems. This makes the usage of cybersecurity solutions more difficult as we have to determine the best way for them to work and also how to provide information for cascading effects.
	Technological risks	#1	Cybersecurity is constantly evolving and changing, depending on several factors such as technologies used, architecture of the system, etc. Therefore, the QU4LITY SPT must continue evolving in order to include more cybersecurity solutions that can tackle both current threats and future ones. This is a critical characteristic that we use for designing the system.

4.7 Mapping to other QU4LITY technical dimensions

4.7.1 Mapping of the QU4LITY Digital Enablers

QU4LITY is developing a range of digital enablers that will enable the implementation of ZDM systems that comply with the Q-RA. Specifically, these digital enablers will empower the functionalities of the QU4LITY systems at different levels of the three-tier architecture pattern, including several cross-cutting functions that are applicable to all functional domains of the RA. An initial mapping of digital enablers to components and building blocks of the Q-RA follows (see also Table 1 and Figure 11):

- **Scalable, Reliable and High-Speed Connectivity for ZDM (WP3/T3.1)**: Connectivity should be a cross-cutting function in the Q-RA. All elements of a ZDM platform should be able to benefit from high bandwidth access to devices, CPS systems and other data sources. Apart from several wired technologies, the digital enabler will leverage also 4G and 5G technologies in order to ensure seamless connectivity and access to data sources for all components of the Q-RA compliant system.
- **Customization of HPC and Cloud Infrastructures for Digital Quality Management (WP3/T3.2)**: The physical deployment of QU4LITY should benefit from cloud and HPC resources. Cloud resources are essential for the implementation of the three-tier architecture pattern of the Q-RA, as the platform tier is essential cloud based. Likewise, HPC resources in the cloud will enable high performance computations as part of the industrial analytics cross-cutting functions.
- **AI and Big Data Analytics for ZDM (WP3/T3.3)**: This task comprises two distinct sets of digital enablers for Big Data and AI: Big Data infrastructures (such as streaming middleware and data lakes) and data analytics algorithms. The Big Data infrastructures will implement cross-cutting functions associated with data routing and industrial analysis. These functions will be provided by the range of Big Data platforms that will be customized as part of this task.
- **Fog/Edge Computing Technologies Adaptation and Cyber-Physical Systems Integration (WP3/T3.4)**: The Fog/Edge computing enablers of the project map directly to the edge tier of the Q-RA three tier implementation pattern. They are specialized edge nodes that address ZDM and Quality Management requirements.
- **QU4LITY Cybersecurity, Privacy and Trust Framework (WP3/T3.5)**: The digital enabler of this task adheres to the main principles of the IIRA/IISF. They offer functionalities for protecting the various endpoints of Q-RA, including horizontal cross-cutting functionalities.
- **Blockchains for Secure Decentralized State Management in ZDM (WP3/T3.6)**: The QU4LITY blockchain enablers will implement the secure data sharing and state synchronization across multiple systems in the manufacturing value chain. They can be also used in the platform tier for sharing and synchronizing information across multiple instances of edge nodes. The latter concept has been implemented and validated in the context of the industrial automation use cases, as part of the FAR-EDGE project.
- **Digital Services Interoperability, Packaging and Integration (WP3/T3.7)**: This digital enabler will provide interoperability functions that will be implemented/provided at the enterprise and platform tiers of the QU4LITY systems. They will ensure interoperable access and interpretation of quality management and ZDM information by different components, systems

and stakeholders. Hence, interoperability will be a cross cutting functions that links different functional domains of the Q-RA.

The following table provides a map of implementing Digital Enablers to elements/building blocks of the Q-RA.

Table 1 – Mapping between Digital Enablers and building blocks of Q-RA

Q-RA Building Block	**Digital Enablers (WP3)**
IoT Data Hub / Big Data Lake (i.e., IIoT / Big Data Platforms)	• DataCrop • Open VA • FAGOR-FALINK for Quality Management More Information: See Deliverable D3.6
AI, Machine Learning and/Big Data Analytics Library (i.e., ML/AI Systems &Algorithms)	• RUL Estimation • Fault Identification • QARMA4Industry • Anomaly Detection for Quality Control • Image Analyzer for Surface Inspection • Improved Failure Classification More Information: See Deliverable D3.6

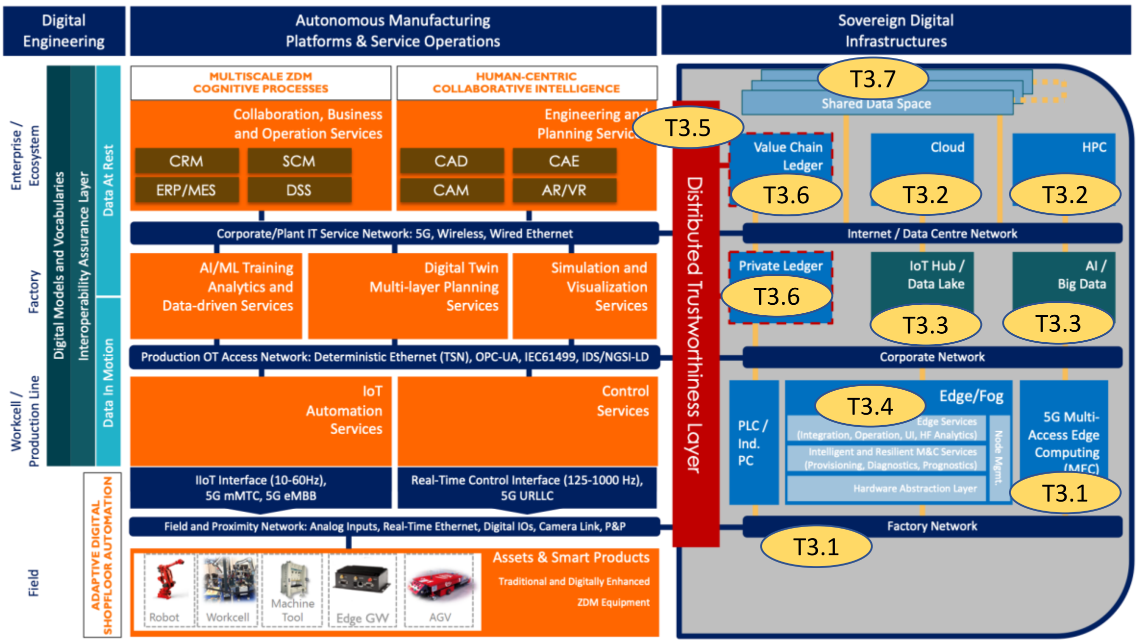

Figure 11 – Mapping of WP3 tasks & enablers to elements of the Q-RA

4.7.2 Mapping of ZDM Equipment Enhancement Task

The digital enablers outlined above provide the means for enhancing the functionality of machines with advanced digitally-enabled quality management and ZDM features. The functional view of the Q-RA includes the main functionalities that will be used for the digital enhancements to the ZDM equipment in the WP4 of the project. In particular, the digital enhancement of ZDM machines will be based on "Data-Driven Modelling", "Control Services", "IoT Automation Services" and "Digital Twins and Planning Services" modules/services of the functional view of the Q-RA. Such models will be used in order to enhance the functionality of existing machinery, as prescribed and performed in WP4 of the project and more specifically tasks:

- "T4.1 Specification of Digital Enhancements and CPS Enablement" is quite transversal to both the Workcell and Field layer modules, and, with the collection of specific requirements, is also related to the interoperability of the equipment with the Factory layer.
- "T4.2 Enhanced Distributed Communication and Control" mainly relates to the Control Services and the communication, both up- and downwards, between the control devices and the Field and Factory layers.
- "T4.3 ZDM Platforms Digital Upgrades Implementation" and its Assessment-related complementary Task T4.4 are basically related to the Field layer, with the installation of all sensors and actuators necessary and the low-level work related to the adaptation, to the specific relevant equipment, of the different components belonging to the Factory modules, such as Data-Driven Modelling and Learning, Digital Twin and Planning and Simulation and Human-centric Visualization Services. This is also done via the integration of this information via the IoT Automation Services modules.
- "T4.5 ZDM Equipment Interoperability, Federation and Autonomous Interactions". The functional view of the QUALITY-RA does not make distinctions regarding the provision of the above listed services over one or more machines since it is a high-level view. The differences between the operation of QU4LITY services over single machine and over multiple scenarios can be made apparent based on the specification of more fine-grained system implementation and deployment views.

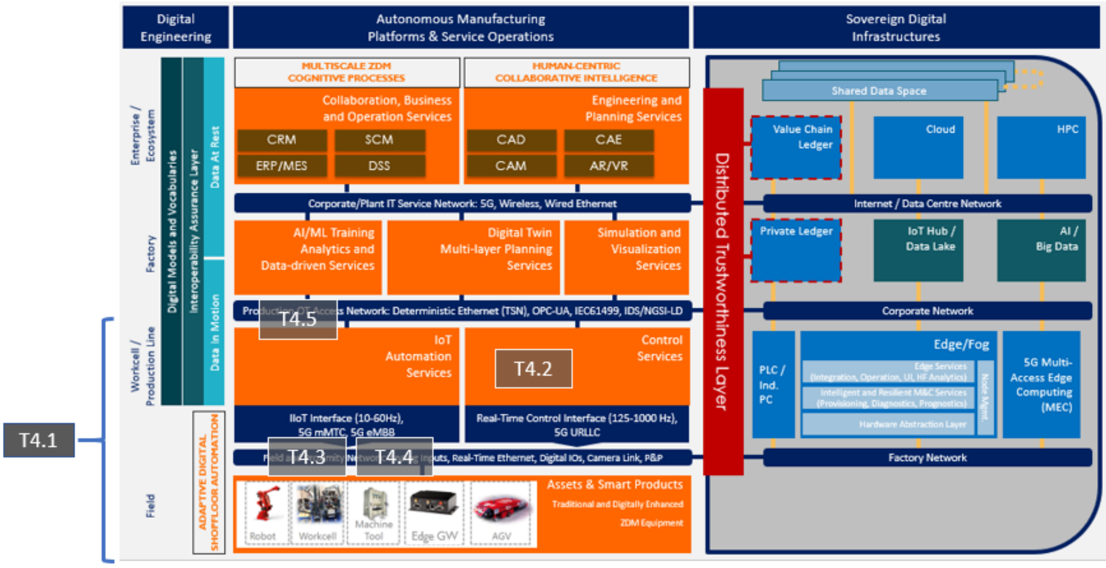

Figure 12 – WP4 tasks mapping with Q-RA

In the next chart we can observe the mapping of WP4 Tasks within the Architecture. It is worth noting that most of them are actually covering multiple modules at the time.

4.7.3 Mapping of Autonomous Quality Services Engineering and Processes

The autonomous quality concept is ultimately implemented in the scope of the engineering of autonomous quality systems and processes. In a typical QU4LITY scenario, autonomous ZDM processes are implemented over a collection of ZDM machines and CPS systems, while involving several of the functional building blocks (e.g., IoT Automation Services, Control Services, Digital Twins and Planning Services) of the Q-RA. In the scope of WP5 of the project, a collection of such functionalities is integrated in order to enable the engineering and deployment of autonomous quality processes. In particular:

- The Adaptive Digital Shopfloor Automation functionalities (WP5/T5.3) combine functionalities from the IoT Automation, Digital Twins & Planning and Control Services of the Q-RA.
- The Factory Wide Multiscale ZDM Process Modelling and Multi-domain Simulation functionalities (WP5/T5.2) integrate functionalities from the Simulation, Digital Twins and Digital Modelling services of the Q-RA. They have a clear functional mapping on the Q-RA and the collaborative multi-scale processes building block of the latter. Note that the collaboration functionalities of the Q-RA leverage other functionalities at lower levels of the RA as outlined earlier.
- The Autonomous Data Management functionalities (WP5/T5.5) combine Data Modelling and Digital Twins & Planning services.

- The User-Centric ZDM processes and Augmented Reality functionalities (WP5/T5.1) leverage the Engineering and Planning services of the Q-RA, which exploit the underlying digital modelling, digital twinning, and digital simulation services. These services provide a foundation for User Centric ZDM processes, based on the proper digital modelling of the ZDM process, which will enable its augmented cyber representation.

As part of WP5 (T5.4) several of the Q-RA functionalities will be enhanced with Open APIs that will facilitate their integration and use in real-life digital automation applications. Note also that the use of joint/common digital models of the ZDM data and processes provides a foundation of interoperability of systems and services that adhere to the QUALITY RA, through enabling them to exchange data and communicate based on common semantics. This will be part of the cross-cutting interoperability enabler, which has been presented in a previous paragraph.

4.7.4 Mapping to the QU4LITY work-packages

The following Figure 13 shows how the different work-packages are expected to contribute, in terms of specification and reference implementation, to the concrete realization of the Q-RA.

The colour schema used in the picture uses the following notation:

- *"WP2 – Autonomous Quality in ZDM: Vision and Specifications"* is represented using **Purple** boxes, representing defined data models and common vocabularies;
- *"WP3 – Interoperable & Trusted Digital Infrastructures for ZDM"* is represented using **Green** boxes, representing all the digital enablers and infrastructures developed or enhanced within the project;
- *"WP4 – ZDM Equipment Digital Enhancement for Autonomous Quality Operations"* is represented using **Red** boxes, representing all the digitally enhanced ZDM equipment;
- *"WP5 – Open Autonomous Quality Services Engineering and Processes"* is represented using **Blue** boxes, representing the HMI technologies and Digital Platforms integrated.

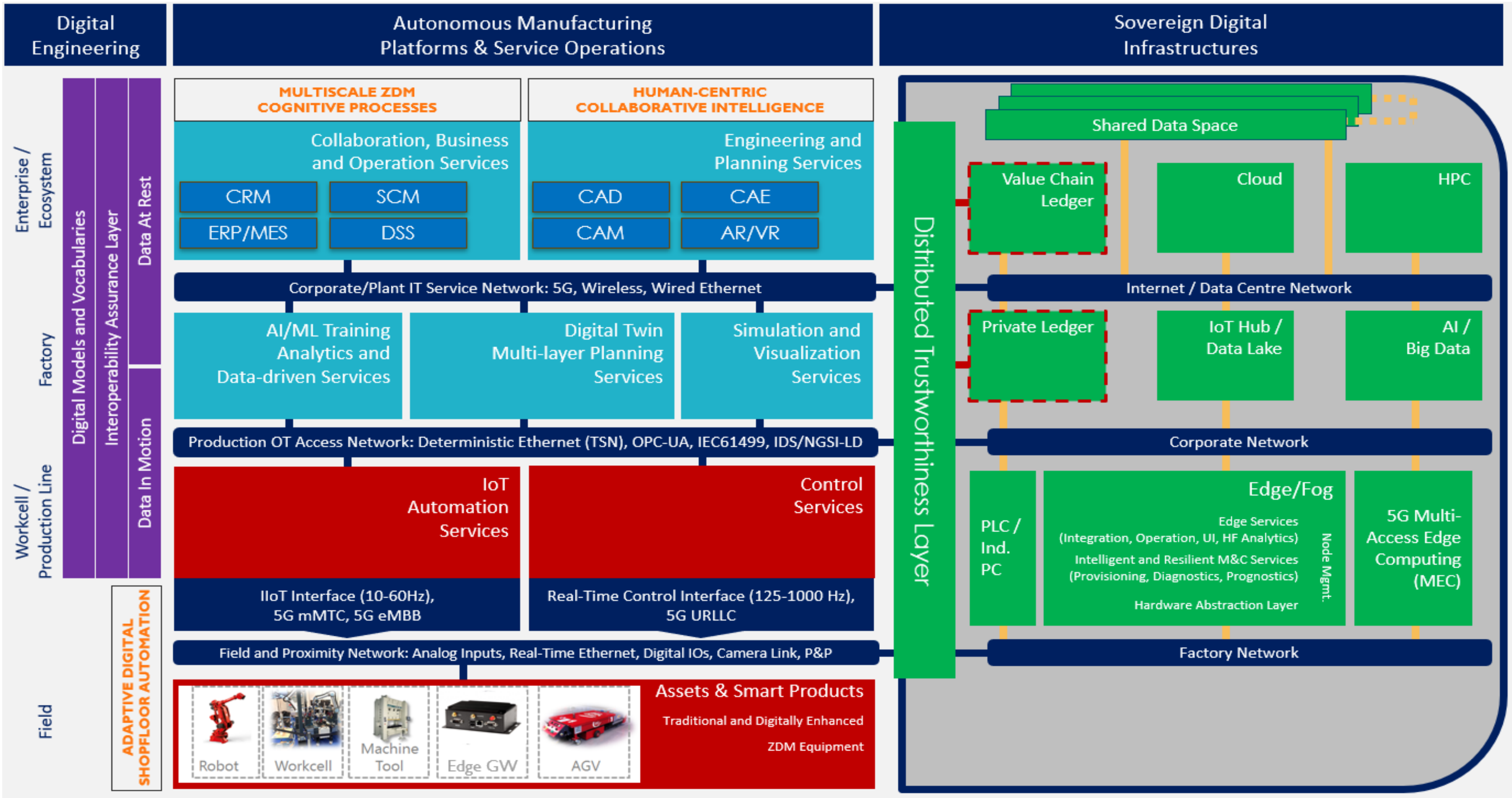

Figure 13 – Q-RA mapping toward the project work-packages

5 QU4LITY Blueprints

5.1 Methodological approach

This chapter will explain the methodology carried out to map the pilots of the projects within the Q-RA. For the project to reach this point, pilot owners should identify which processes are going to be improved, and within each process which components are necessary to achieve the proposed goals (outcome of other project deliverables in WP7, such as D7.1/D7.2, D7.3/D7.4, D7.5/D7.6). In other words, the pilots have defined which services of the **Digital Manufacturing Platform & Service layers** they have applied on their pilot. The mapping in the Q-RA continues further, since it is also necessary to know what has been implemented from a technical perspective, and for each service of the Digital Manufacturing Platform & Service layer the pilots have provided the following information:

- Sovereign Digital Infrastructure
- Infrastructure Operator
- Services
- Services Operator

This information was required to have the knowledge about the digital infrastructure (cloud, PC, data center…) needed by the implemented service, the operator of that infrastructure or service, and the service type description. The following list shows a demonstration of how the RA is completed with the required information.

- Digital Manufacturing Platform & Service: **IoT Automation Services**
- Sovereign Digital Infrastructure: **Edge/Fog**
- Infrastructure Operator: **JSI**
- Services: **Product Visual Classifier & Learning**
- Services Operator: **JSI**

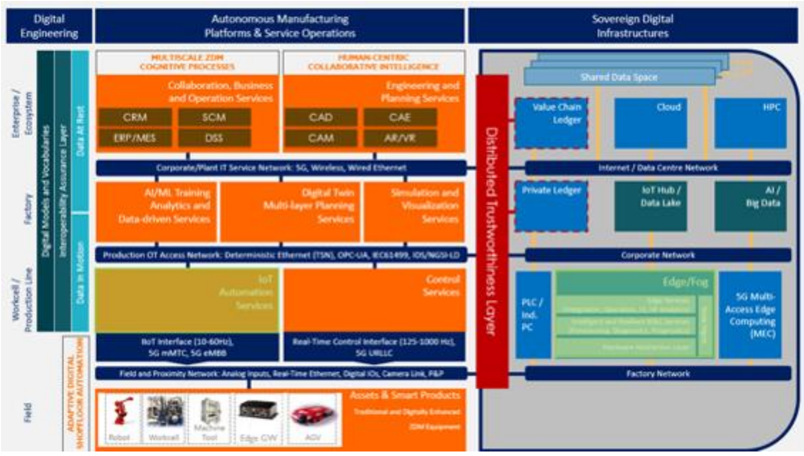

Figure 14 – Mapping Example (Q-RA highlights)

5.2 Mapping of the 14 pilots

5.2.1 PHILIPS: OneBlade shaving unit production line

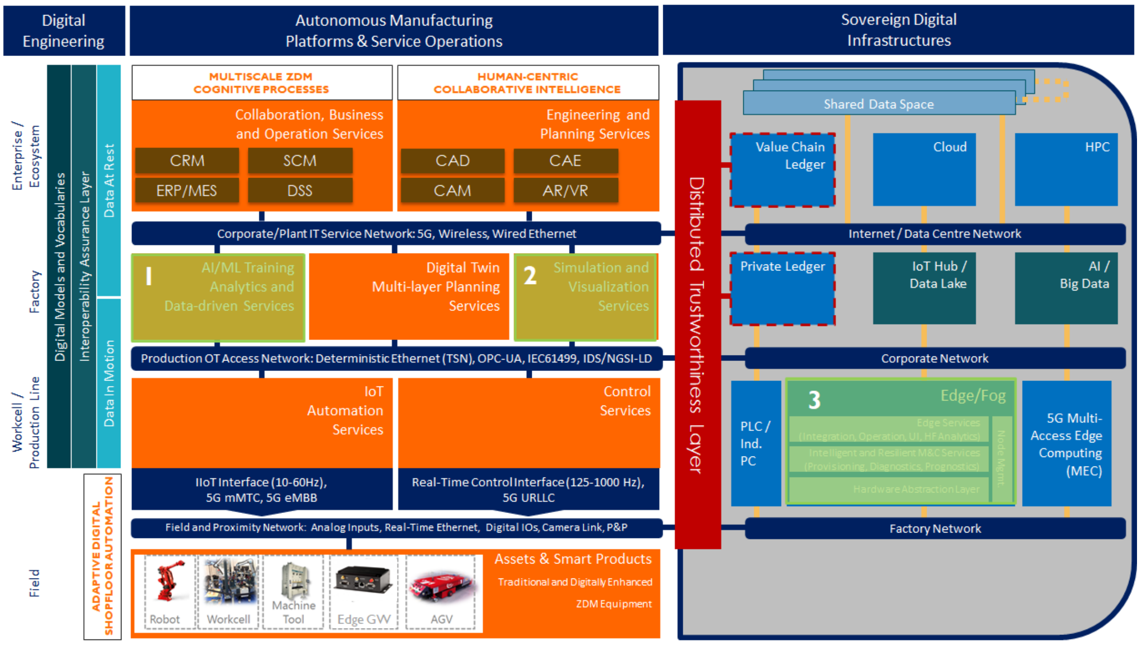

Figure 15 – Mapping of the PHILIPS Pilot within the Q-RA

1. <u>AI/ML Training Analytics and Data-driven Services:</u>

   Brief description: The aim of the pilot is to use data modelling to predict errors in the final product based on parameters in the process. This should raise a warning signal for the operator so he or she can intervene in the process before it runs outside the parameters.

2. <u>Simulation and Visualization Services:</u>

   Brief description: As soon as a deviation in the data is found which will lead to errors in the final product the operator has to be warned and informed about the error and action to take.

3. <u>Edge/Fog:</u>

   Brief description: Edge/fog provides a platform where data can be collected, stored and analysed directly at the machine, without causing delays by transferring it to the cloud. Multiple applications can be hosted on an edge device for analysing the collected data.

5.2.2 SIEMENS: Control Products Quality Improvements

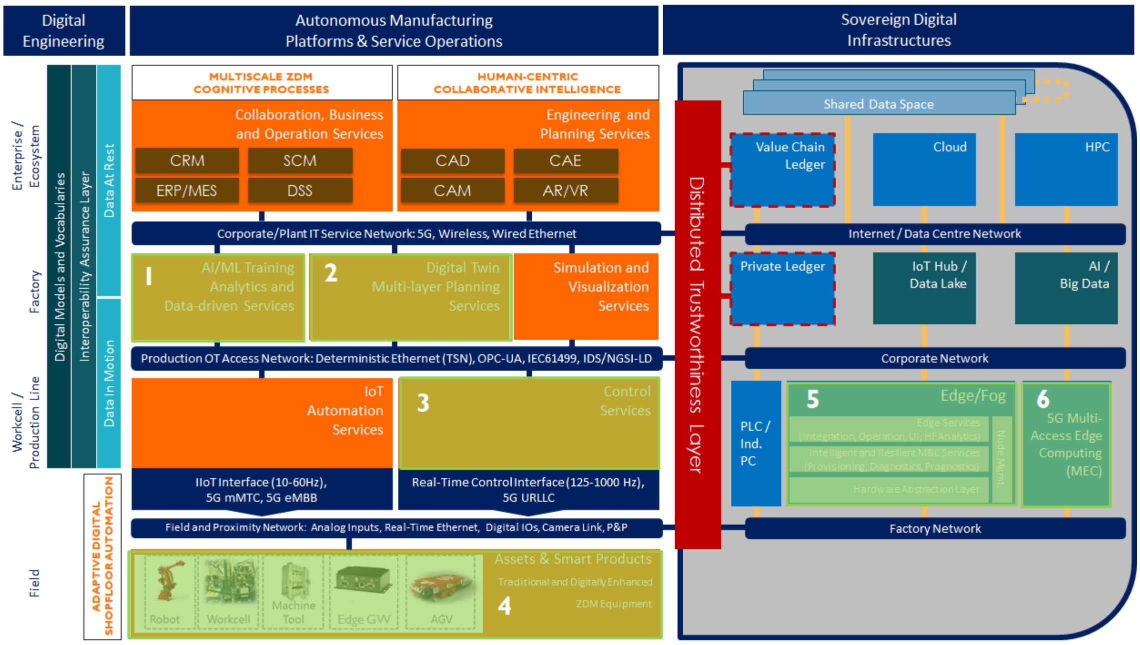

Figure 16 – Mapping of the SIEMENS Pilot within the Q-RA

1. <u>AI/ML Training Analytics and Data-driven Services:</u>

   Brief description: Data analytics methods used for failure classification and improvement of decision rules. Historical test data used for training of the classification algorithm also to be updated by online data in case of changes.

2. <u>Digital Twin Multi-Layer Planning Services:</u>

   Brief description: Test strategies are developed and analysed to improve testing process based on failure propagation module and cost model for test stands and rework

3. <u>Control Services:</u>

   Brief description: Quality control by inspection and function tests with appropriate failure classification

4. Assets & Smart Products:

   Brief description: Test stands with inspection or functional test equipment with raw data for quality analysis

5. Edge/Fog:

   Brief description: Edge device used for quality classification service.

6. 5G Multi-Access Edge Computing (MEC):

   Brief description: The failure propagation module uses correlation between several test stands and therefore several quality classifications on Edge. For test strategy assessment the failure propagation is used.

5.2.3 CONTI: Autonomous Quality in PCB Production for Future Mobility

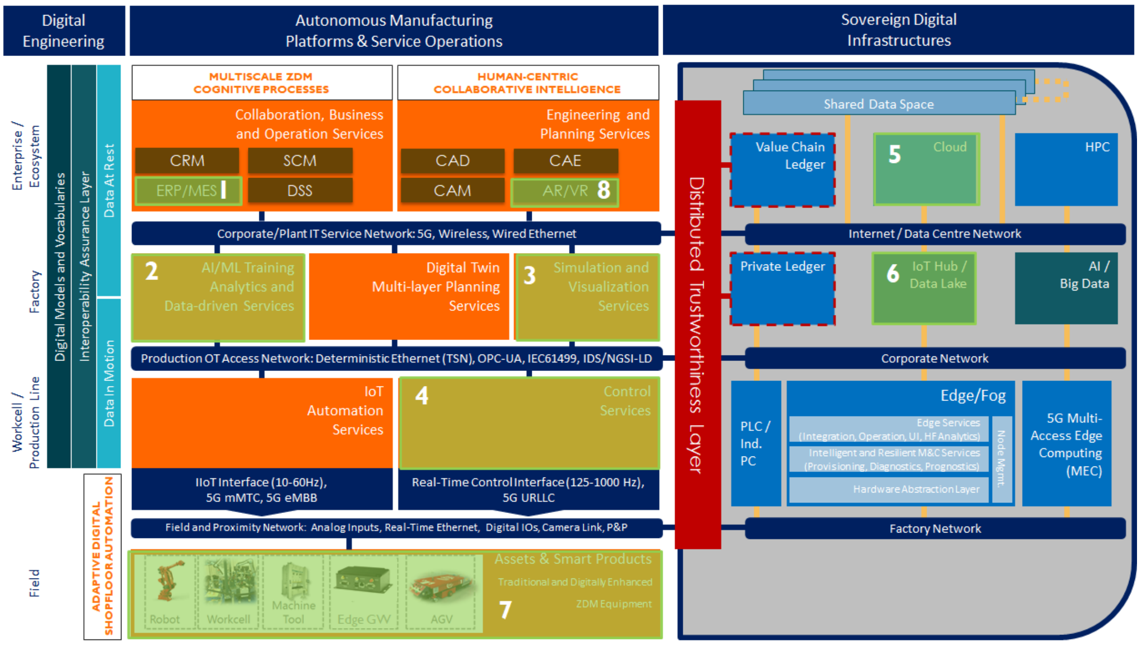

Figure 17 – Mapping of the CONTI Pilot within the Q-RA

1. Collaboration, Business and Operation Services (ERP / MES):

   Brief description: ERP - SAP provides an integrated and continuously updated view of core business processes using a central database maintained by a database management system. ERP systems track business resources—cash, raw materials, production capacity. ERP receives product documentation and holds initial product manufacturing process documentation including Testplans. MES collects events and forwards related notifications to other services like WEAVR to support operators in executing necessary actions.

2. AI/ML Training Analytics and Data-driven Services:

Brief description: Manage complex analytics pipeline and other data-driven processes on heterogeneous data sources, providing access, modelling and processing capabilities over big and structured/unstructured data generated in modern Industry 4.0 systems.

3. Simulation and Visualization Services:

   Brief description: Visualization Services will take care of displaying Data in an easy to access and fast to understand way. Augmented operational support using guided visualizations and annotations via PACELAB WEAVR.

4. Control Services:

   Brief description: Microservices executed on a Kubernetes Cluster.

5. Cloud:

   Brief description: Cloud acts as a host for Manufacturing Data lake. An enhanced and protected area is provided for Manufacturing services.

6. AI/Big Data:

   Brief description: Manufacturing Data Lake holds all Data created by Manufacturing Equipment, Personnel, Sensors and Environment. Structured as well as unstructured data can be managed.

7. Assets & Smart Products:

   Brief description: Smart glasses/HoloLens.

8. Engineering and Planning Services:

   Brief description: WEAVR AR/VR solution from PACE supporting Planning of Processes in manufacturing like maintenance/setup/Repair.

5.2.4 WHR: Dryer Factory Holistic Quality Platform

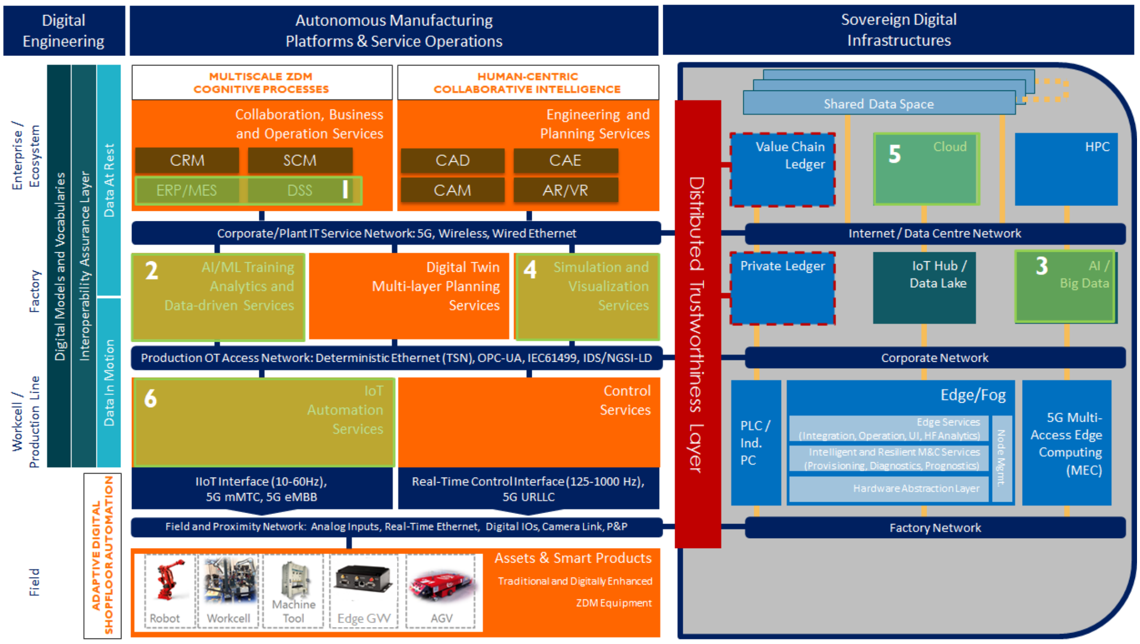

Figure 18 – Mapping of the WHR Pilot within the Q-RA

1. Collaboration, Business and Operation Services (ERP / MES):

   - **Brief description**:

     - MES Standardization

       The production plan from SAP ERP is integrated in the MES and gives to the users the possibility to display the plan information through an ad-hoc user interface. The Production Routing contains the list of all operations which contribute to realize the finished or semi-finished product. At MES level, a deeper granularity managing the routing at workstation level will be introduced. So, in the MES it should be possible to:

       - Detail the real task list
       - Associate Working Instruction
       - Associate Work Centre (resource, if any assigned)
       - Define a Skill for each task list.

     - Advanced Testing

       Acquisition, storage and retrieval for the test results generated by test equipment systems along the plant production lines

     - Data Visibility & Analytics

- QLoss: This measurement describes the frequency of units with defects which may cause a service call in the market
- FPY: (First Pass Yield), it is a measure of finished goods (FG) produced without any reprocessing, the percentage (ranging from 0% to 100%) of reworked and incomplete units with respect to total units.
- AY: (Assembly Yield) Measurement describes the actual utilization of a factory versus the theoretical output.
- OEE: (Overall Equipment Effectiveness) Results of measurements: Availability x Performance x Quality
- Operations with timing execution and operator reference (if available)
- Functional tests results
- Non-conformance's registration
- Repairs (whether have been repaired)
- As-built: list of components assembled
- Product status: if it is on hold in quality, etc

- Automated Material Handling

  Operational Flow:

  - Production scheduling module (pacemaker or the team leader using an UI) decides the shopping lists to be activated for a specific tugger route, retrieving data from BoM and Material master data.
  - Shopping list data will be saved in MES to be used into the proper user interface.
  - The tugger operator will be able to display the selected shopping list based on required time anticipation to perform the material delivery in synchronization to the production progress.
  - When the tugger has been completed all the deliveries required by the shopping list, the operator will be able to set the status Complete over the shopping list and store delivered quantities

2. <u>AI/ML Training Analytics and Data-driven Services:</u>

   Brief description: IMECH will develop the MPFQ quantitative modelling in order to define the correlation indexes between the quality and materials, processes, functions on the basis of the MPFQ model.

3. <u>AI/Big Data:</u>

Brief description: IMECH will define the suitable dedicated server that enables the data analysis service.

4. Simulation and Visualization Services:

   Brief description: TTS will develop the Quality trend cockpit as visualization services to support management level in detecting critical areas.

5. Cloud:

   Brief description: ENG will develop a bridge to close the gap between WHR legacy systems and WHR-pilot specific QU4LITY Infrastructure, providing a seamless solution to exchange data from WHR on premise Data Lake to QU4LITY Cloud Data Storage solution using a time-based approach. QU4LITY Cloud Bridge will offer REST API to interface with other processing and visualization components within WHR pilot taking care of any data decoding/encoding needs (i.e., IEEE754 data encoding). Moreover, ENG, as part of the realization process of the QU4LITY Cloud Bridge, will also take in charge of the transposition of QU4LITY ontology (based on R-MPFQ model defined by EPFL) into a relational DB (for better integration with analytics and visualisation components).

6. IoT Automation Services:

   Brief description: The WH legacy system is composed by following elements: Drum Line, Vacuum and Charge Station, Heat Pump Test Stations, Assembly Line, Functional Test, Aesthetic Check, Final Electrical Test, Quality Gate, Repairing Area, Repairing Gate.

5.2.5 MON: Zero defect and Autonomous Quality in Machinery Building for Capital Goods sector

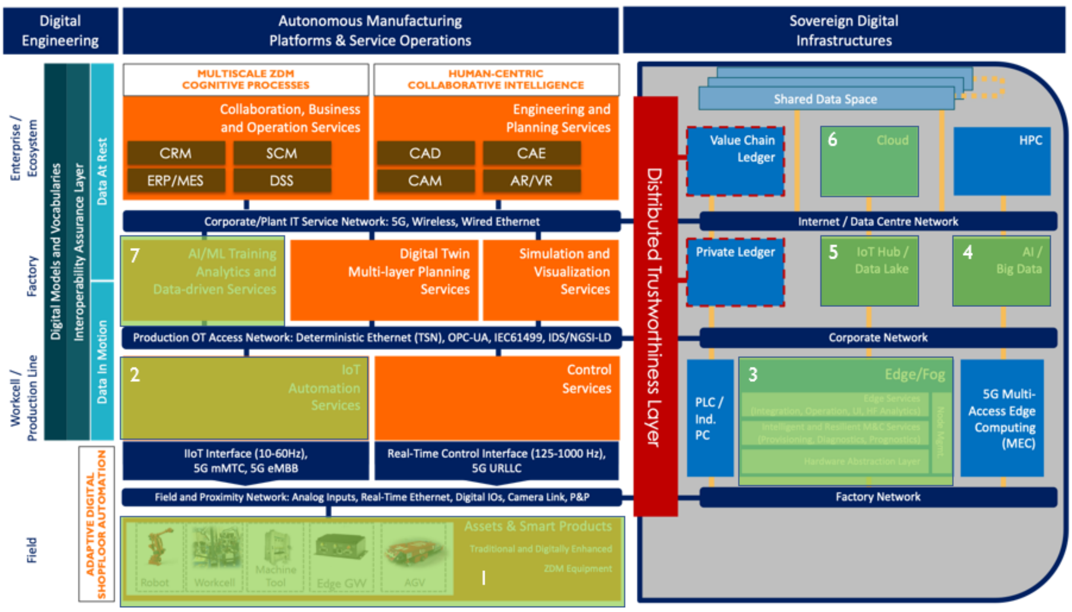

Figure 19 – Mapping of the MON Pilot within the Q-RA

1. Assets & Smart Products:

   Brief description:

   - Fagor Arrasate - Automotive manufacturing processes with hot-Stamping Machinery line with sensors and edge devices for data pre-processing and achieving the aim of ZDM and AQ.
   - DANOBAT - Manufacturing Processes railway Cutting/Grinding Machinery systems with attached sensors, IoT Savvy Box and advanced analytics with the aim of ZDM and AQ.

   There are Several monitored assets in the processes together with physical components

2. IoT Automation Services:

   Brief description: SAVVY BOX by IDEKO and IoT Sensors using DA-IA engine by IKERLAN stablish the IoT automation Service for Manufacturing Processes with Cutting/Grinding Machinery, led by Danobat and Manufacturing Processes with Hot Stamping Machinery led by FARR.

3. Edge/Fog:

   Brief description: DANOBAT and FAGOR ARRASATE together with IDEKO and IKERLAN research centres deploy the sensors and systems to gather data in a first phase from industrial devices in automotive and railway manufacturing line through PLCs at edge layer. Generate datasets

4. AI/Big Data:

   Brief description: Hybrid architecture from Hybrid edge+ cloud system (IDEKO), Savvy Box (IDEKO) and DA-IA engine (IKERLAN) gather data in communication with Digital Enabler (Converter/Message Broker)- MGEP. Furthermore, FHG provides a digital connector for Data Sharing.

5. IoT Hub/Data Lake:

   Brief description: The Danobat Data System is developed on a commercial system Savvy Data System with its own IoT Hub.

6. Cloud:

   Brief description: Data will be sent to cloud level in order to be used by some service providers.

7. AI/ML Training Analytics and Data-driven Services:

   Brief description: FARR-IKERLAN and DANOBAT-IDEKO will extract the key data for the automotive and railway manufacturing line process environment. MGEP will develop big data analytics. ATLANTIS will develop Fault Detection and Identification technologies.

8. Simulation and Visualization Services:

Brief description: FARR-IKERLAN simulates in initial step data for automotive line process. MGEP will develop big data analytics and simulations considering IA algorithms.

5.2.6 KOL: Real-time injection moulding process monitoring-control

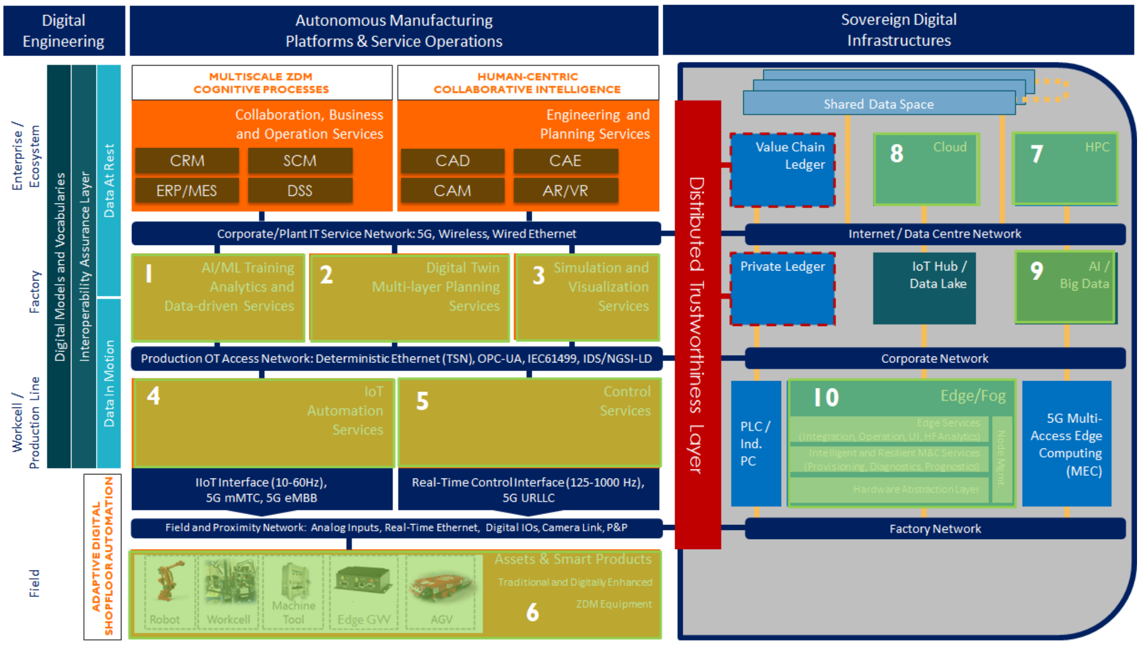

Figure 20 – Mapping of the KOL Pilot within the Q-RA

1. <u>AI/ML Training Analytics and Data-driven Services:</u>

   Brief description: Kolektor Digital Platform (KiS, Sinapro.IIoT) and JSI HPC manage complex analytics pipeline and other data-driven processes on heterogeneous data sources, providing access, modelling and processing capabilities.

2. <u>Digital Twin Multi-Layer Planning Services:</u>

   Brief description: Visual Components will develop process simulation and digital twin to optimize the whole production process. / Discussion required

3. <u>Simulation and Visualization Services:</u>

   Brief description: Visual Components will develop process simulation and the digital twin visualization service. Kolektor Digital Platform (KiS, Sinapro.IIoT) will provide the visualization of various data sources and decision processes.

4. <u>IoT Automation Services</u>

   Brief description: Sinapro.IIoT provide service for data acquisition, data conversion, data storage and provision of tools to perform data analysis from Molding machine (Arburg), Cell1 Test machine, ZDM Equipment.

5. Control Services:

   Brief description: Kolektor Digital Platform (KiS, Sinapro.IIoT) will based on the various data sources, control parameters and predictive models provide the control of the injection moulding process.

6. Assets & Smart Products:

   Brief description: Production machines - Moulding machine (Arburg), Cell1 Test machine, ZDM Equipment, JSI Robot for automated machine vision quality control

7. HPC:

   Brief description: JSI will provide the HPC infrastructure for complex analytics pipeline and other data-driven processes modelling.

8. Cloud:

   Brief description: Data will be sent to cloud level in order to be used by some service providers such as Atlantis, for the app relating to decision support.

9. AI/Big Data:

   Brief description: Manufacturing Data Lake holds all Data created by Manufacturing and Inspection Equipment. It is handled by Sinapro.IIoT.

10. Edge/Fog:

    Brief description: KiS integrates camera sensors to observe the pre and post injection moulding parts. Sinapro.IIoT will gather process parameters at the edge level from injection moulding machine.

5.2.7 THYS: Quality Management of Steering Gear based on Acoustic control

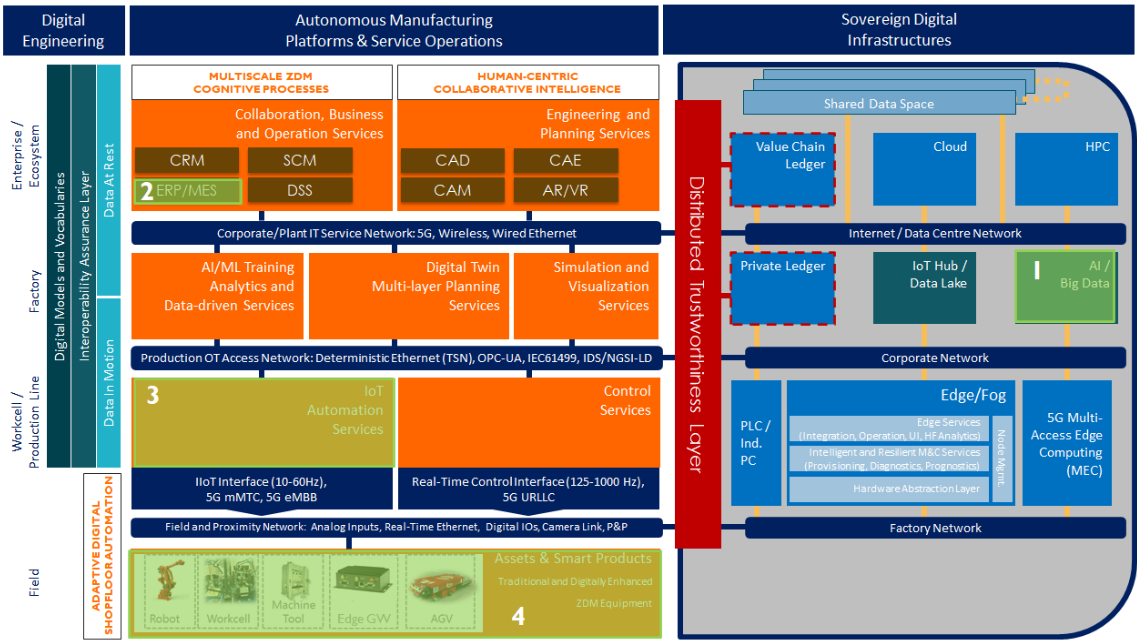

Figure 21 – Mapping of the THYS Pilot within the Q-RA

1. AI/Big Data:

   Brief description: MOM analytic is Thyssenkrupp standard.

2. Collaboration, Business and Operation Services (ERP / MES):

   Brief description: SAP is the ThyssenKrupp standard. The Zpoint software made as MES, it is a software designed for ThyssenKrupp by one of our machine manufacturers.

3. IoT Automation Services:

   Brief description: Beckhoff PLC + Siemens S5/S7

4. Assets & Smart Products:

   Brief description: sensors/actuators of the line. Possibility to integrate other sensors such as accelerometers.

5.2.8 AIRBUS: Trade space framework for Autonomous Quality Manufacturing Systems' Design

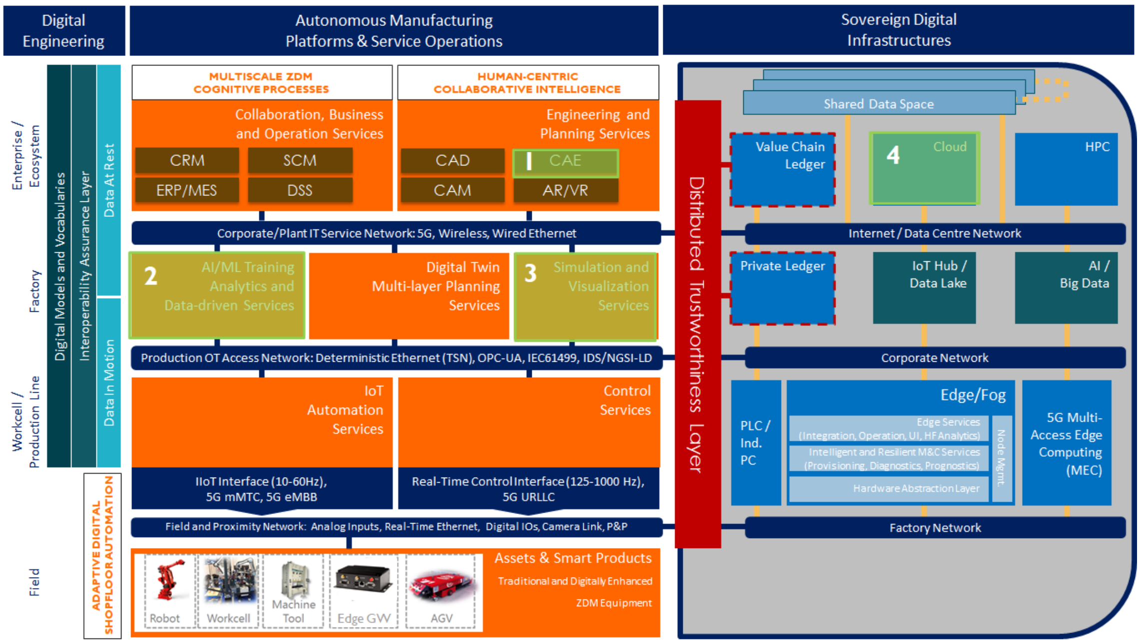

Figure 22 – Mapping of the AIRBUS Pilot within the Q-RA

1. Engineering and Planning Services (CAE):

   Brief description: VisualComponent uses 3D simulation software to simulate both semi-automated and manual assembly processes to compare the differences.

2. AI/ML Training Analytics and Data-driven Services:

   Brief description: Develop a data model to integrate relevant elements that impact process quality. Use ontology-based knowledge management tools analyze the results of different trade-off scenarios.

3. Simulation and Visualization Services:

   Brief description: VisualComponent will use 3D simulation software to simulate both semi-automated and manual assembly processes to compare the differences

4. Cloud:

   Brief description: Data will be sent to cloud level in order to be used by some service providers such as Atlantis, for the app relating to decision support.

5.2.9 GHI: Real-time cognitive hot stamping furnace 4.0

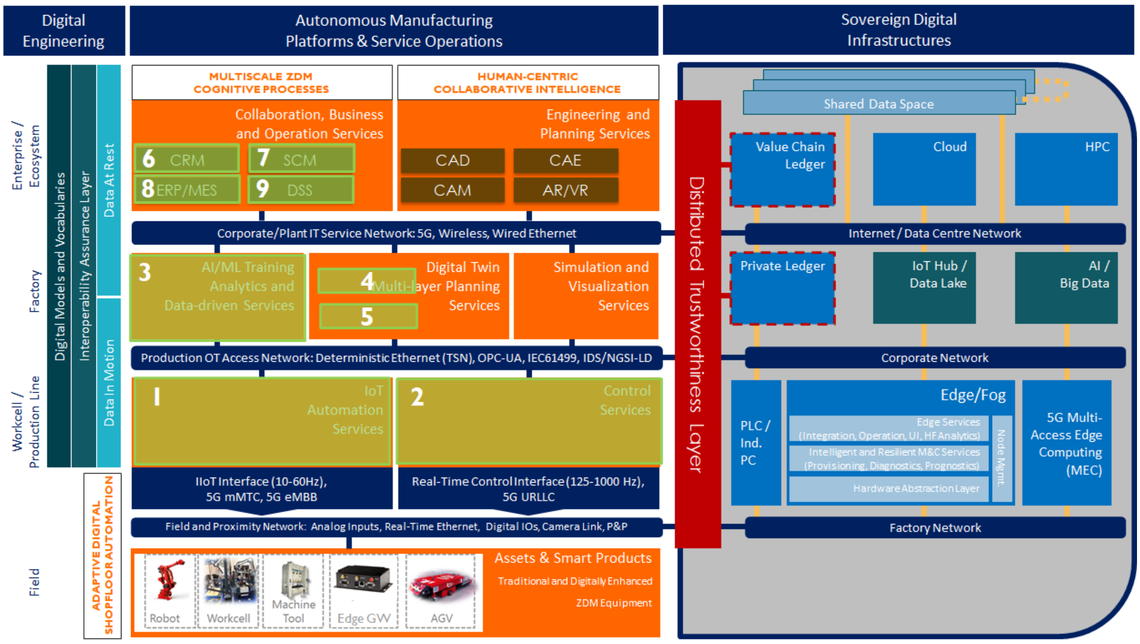

Figure 23 – Mapping of the GHI Pilot within the Q-RA

1. IoT Automation Services:

   Brief description: The Furnace Data Gathering system must be able to process all the data gathered from the IoT elements integrated on the Rolling beam furnace, incorporating a series of connectors that will manage to ingest all the relevant data.

2. Control Services:

   Brief description: The Edge-powered Quality Control component acts as an intermediary for real-time communication and control system between the Coordinate Measuring Machine and M3 Software. In addition to be capable to gather the quality data and control the machine, this component will be also in charge for the secure and contextualized data sharing to the QC data space.

3. AI/ML Training Analytics and Data-driven Services:

   Brief description: The Furnace Data Analysis component consists of a data analysis platform that will allow the furnace to improve its operation through the development of algorithms that allow the optimal austenitizing temperature to be maintained homogeneously on the part.

4. Digital Twin Multi-Layer Planning Services:

   Brief description: The BEYOND Monitor component consists of a service derived from the furnace data analysis platform for the Real-Time visualization and monitoring of its operation, allowing the evaluation of KPIs with visual indicators of inefficiencies and deviations from optimal operation.

5. Digital Twin Multi-Layer Planning Services:

   Brief description: The GD&T parts digitization component consists on the metrological software that carry out the acquisition of 3D point clouds and Quality control information from the parts that will be measured. This means, the digitalization of a physical object in order to obtain quality control information.

6. Collaboration, Business and Operation Services:

   Brief description: The BEYOND Reporting component consists of another service derived from the furnace data analysis platform that generates monthly furnace status reports.

7. Collaboration, Business and Operation Services:

   Brief description: The Quality Control Data Analysis component will carry out advanced analysis of the quality data obtained from the CMM measurements with the objective of detecting deviations trends and defective parts to later find the correlation with the industrial furnace parameters.

8. Collaboration, Business and Operation Services:

   Brief description: A cloud Quality Control Sata Space for a secure and trusted data sharing to enable the correlation between quality control data from hot stamped parts and furnace operational data, endowing the data analysis system from knowledge to optimize the operation of the furnace for a ZDM production system.

9. Collaboration, Business and Operation Services:

   Brief description: A validation service for components according to the standards formulated by IDSA, which regulates the trusted and sovereign sharing of data, as a key tool to promote and enable global information and business transactions between enterprises.

5.2.10 RiaStone: Autonomous Quality ZDM for "Ceramic tableware Single-firing

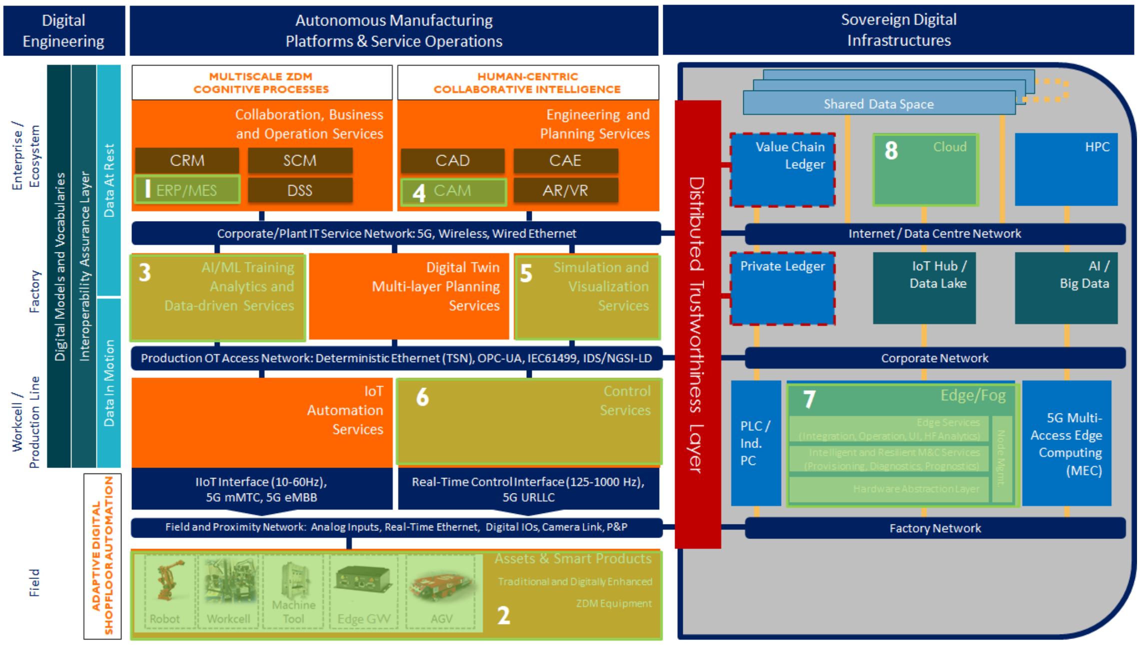

Figure 24 – Mapping of the RiaStone Pilot within the Q-RA

1. Collaboration, Business and Operation Services (MES):

   Brief description: MES provides an integrated and continuously updated view of core business processes using common databases maintained by a database management system.

2. Assets & Smart Products:

   Brief description: SAMA Isostatic Presses and Lipert Automated Glazing Chambers with integrated sensing systems edge devices for data pre-processing.

3. AI/ML Training Analytics and Data-driven Services:

   Brief description: The INOV/INESC ML Imaging Platform will acquire and correlate imaging data with the predefined IKEA quality matrix KPIs.

4. Engineering and Planning Services (CAM):

   Brief description: The INOV/INESC ML Imaging Platform will produce digital outputs that will be used by the Synesis Automatic Production Line Adjustment tool for full AQL Implementation

5. Simulation and Visualization Services:

   Brief description: The Intra Analytics Engine tool will be used with the purpose of supporting management level decisions by visualizing trends of key quality indicators and quantitative measures in a graphical way to be displayed to human stakeholders and increase awareness for critical situations and to detect areas of production or product improvement.

6. Control Services:

   Brief description: The Synesis Automatic Production Line Adjustment tool correlate the data originated at 1 and 2, issuing instructions to the production machinery that will re-adjust production parameters for defects free production,

7. Edge/Fog:

   Brief description: The INOV/INESC ML Imaging Platform integrates camera sensors that will perform submillimetre measurement, and surface evaluation of greenware, Synesis will gather meta-information from the processed images together with machine status and process parameters at the edge level to extract data for AQL processing.

8. Cloud:

   Brief description: Data will be sent to cloud level in order to be used by the Intra Analytics Engine tool will be used with the purpose of supporting management level decisions by visualizing trends of key quality indicators and quantitative measures.

5.2.11 PRIMA: Additive Manufacturing Pilot Adaptive Control Technology

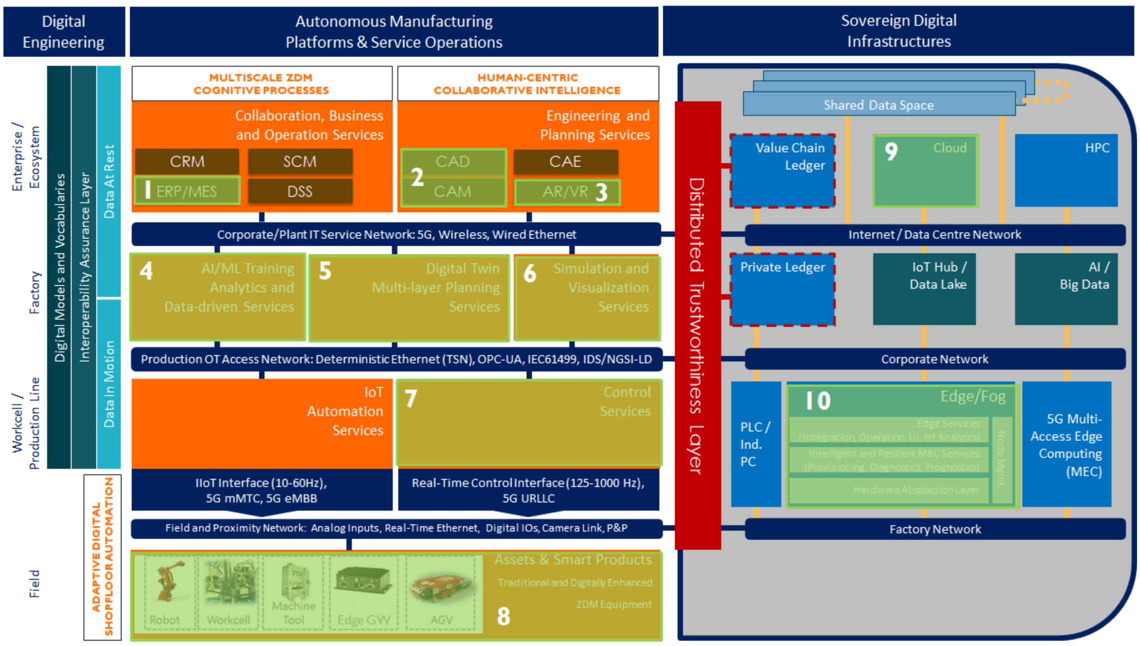

Figure 25 – Mapping of the PRIMA Pilot within the Q-RA

1. Collaboration, Business and Operation Services (DSS):

Brief description: The DSS supports decision taking advantage of data analytics results and domain knowledge, which is translated into rules in its engine.

2. Engineering and Planning Services (CAD / CAM):

   Brief description: Prima uses CAD-Software (Siemens SolidEdge) to create the 3D parts on a 3D Printer. The entire downstream chain includes several software components, such as slicing, to create processing instructions for the machine.

3. Engineering and Planning Services (AR/VR):

   Brief description: With mixed reality operator work tasks (process monitoring and maintenance work) could be planning and evaluated with end-user and designer team. Final workflow could be shown operator via augmented reality with various devices e.g., HoloLens and mobile phones.

4. AI/ML Training Analytics and Data-driven Services:

   Brief description: Data monitored from the machine tool and meta-information generated by different applications running at edge level will be collected and elaborated by the Synesis' data analysis tool to extract useful information to be sent to Atlantis' decision support system.

5. Digital Twin Multi-Layer Planning Services:

   Brief description: TTS will develop an Additive Manufacturing Simulator (AMS) to provide a quick and reliable process time estimation of additive machines based on powder bed system and equipped with multiple and independent laser devices.

6. Simulation and Visualization Services:

   Brief description: Fraunhofer IGD provides interactive volumetric visualization of the sensor data gathered from Fraunhofer ILT's sensor device. The machine operator can give an optional sensor data rating that will be sent to SYNESIS

7. Control Services:

   Brief description: All decisions made at the DSS level will be sent back to the machine control system for any correction and closure of the loop.

8. Assets & Smart Products:

   Brief description: PRIMA 3D Printing machine with attached sensors and edge devices for data preprocessing.

9. Cloud:

   Brief description: Data elaborated at edge level will be sent to cloud level in order to be used by some service providers such as Atlantis, for the app relating to decision support.

10. Edge/Fog:

    Brief description: Different applications runs at Edge level in a digital infrastructure made available partially by Fraunhofer ILT and partially from the PRIMA. Fraunhofer ILT' image processing tool will run on a dedicated node, while TTS' Simulation tool, Synesis' data analysis tool and Fraunhofer IGD's visualization tool will run in an edge device that provides the computational resources needed for the applications.

5.2.12 Danobat: Digital Machine for zero-defects at high precision cutting/grinding

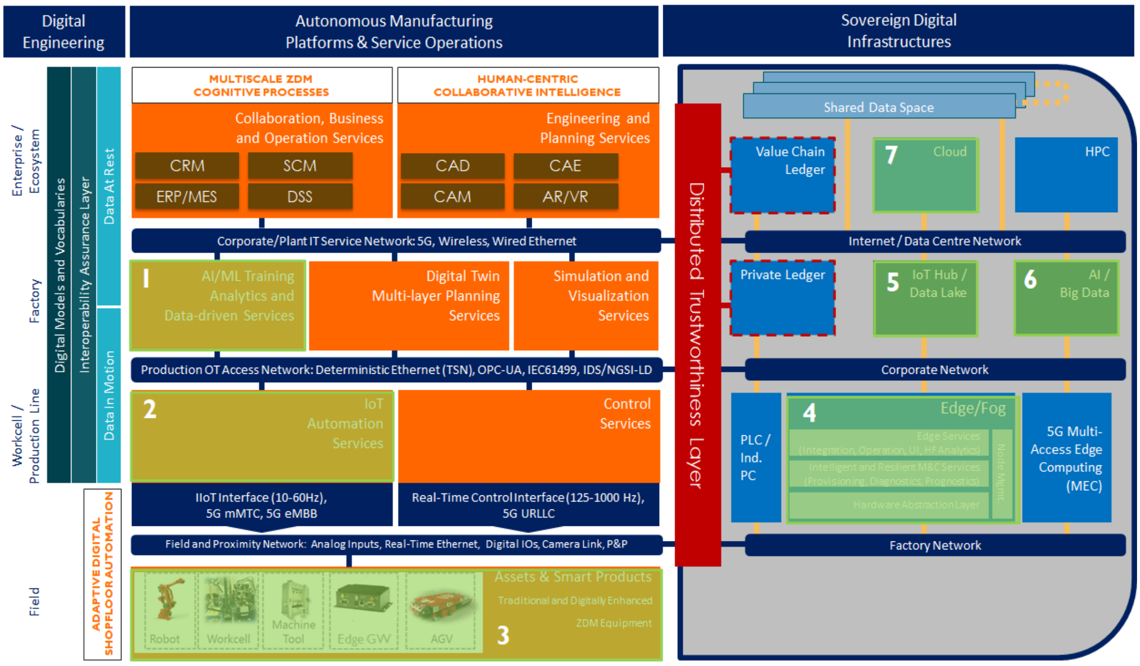

Figure 26 – Mapping of the Danobat Pilot within the Q-RA

1. AI/ML Training Analytics and Data-driven Services:

   Brief description: Manage complex analytics pipeline and other data-driven processes on heterogeneous data sources, providing access, modelling and processing capabilities over big and dark data generated in modern Industry 4.0 systems (D2.11).

2. IoT Automation Services:

   Brief description: SAVVY BOX by IDEKO and IoT Sensors.

3. Assets & Smart Products:

   Brief description: The monitored Asset is the machine which has also several physical components installed as the IoT sensors, the PLC and the PAC programmable automation controller, which are all connected to the edge Box.

4. Edge/Fog:

Brief description: Smart Box with docker application deployment, interoperability module OPC_UA server, CNC write enabler.

5. IoT Hub/Data Lake:

   Brief description: The Danobat Data System is developed on a commercial system Savvy Data System with its own IoT Hub.

6. AI/Big Data:

   Brief description: Infrastructure for Big Data Analytics.

7. Cloud:

   Brief description: The System is deployed in a cloud provided by a supplier.

5.2.13 FAGOR: Zero-Defects Manufacturing Digital Press Machine

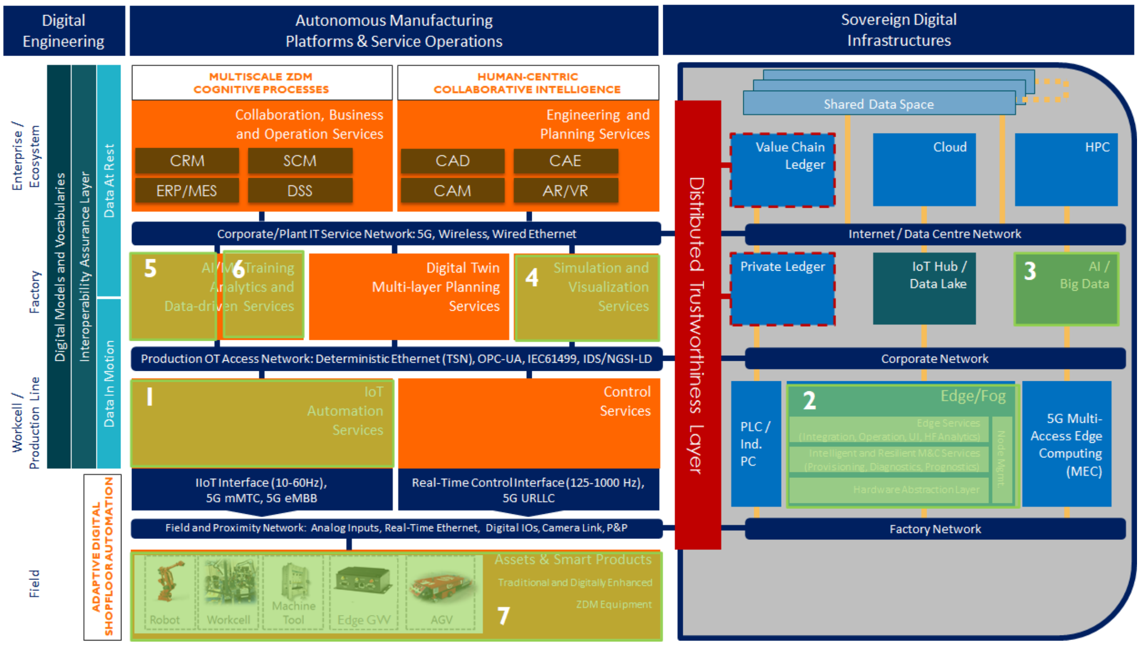

Figure 27 – Mapping of the FAOR Pilot within the Q-RA

1. IoT Automation Services:

   Brief description: IoT Sensors using IKCLOUD+ with DA-IA engine by IKERLAN stablish the IoT automation Service for Manufacturing Processes with Hot Stamping Machinery led by FARR.

2. Edge/Fog:

   Brief description: FAGOR ARRASATE together IKERLAN research centres deploy the sensors and systems to gather data in a first phase from industrial devices in automotive manufacturing line through PLCs at edge layer. Generate datasets. The infrastructure is composed by different parts or components that are implemented/extended in the pilot: FAGOR DAS, FA-LINK, IKCLOUD+, IKSEC+.

3. IoT Hub/Data Lake / AI/Big Data:

   Brief description: IKCLOUD+ and DA-IA engine (IKERLAN) gather data in communication. Data is obtained from FAGOR DAS and FA-LINK.

4. Simulation and Visualization Services:

   Brief description: FARR-IKERLAN will develop simulation automotive manufacturing line process environment. Data models and possible controls and alarms will be accessible by HMI in FA-LINK.

5. AI/ML Training Analytics and Data-driven Services:

   Brief description: FARR-IKERLAN will develop press simulation, like Digital Twin.

6. AI/ML Training Analytics and Data-driven Services:

   Brief description: Manage complex analytics pipeline by IKERLAN. Data-driven processes are received by heterogeneous data sources using FAGOR DAS and FA-LINK and IK-CLOUD+ with DA-IA engine provides support to perform data analytics.

7. Assets & Smart Products:

   Brief description: Fagor Arrasate - Automotive manufacturing processes with hot-Stamping Machinery line with sensors and edge devices for data pre-processing and achieving the aim of ZDM and AQ.

5.2.14 GF: Digital machine and part twins for zero defect manufacturing

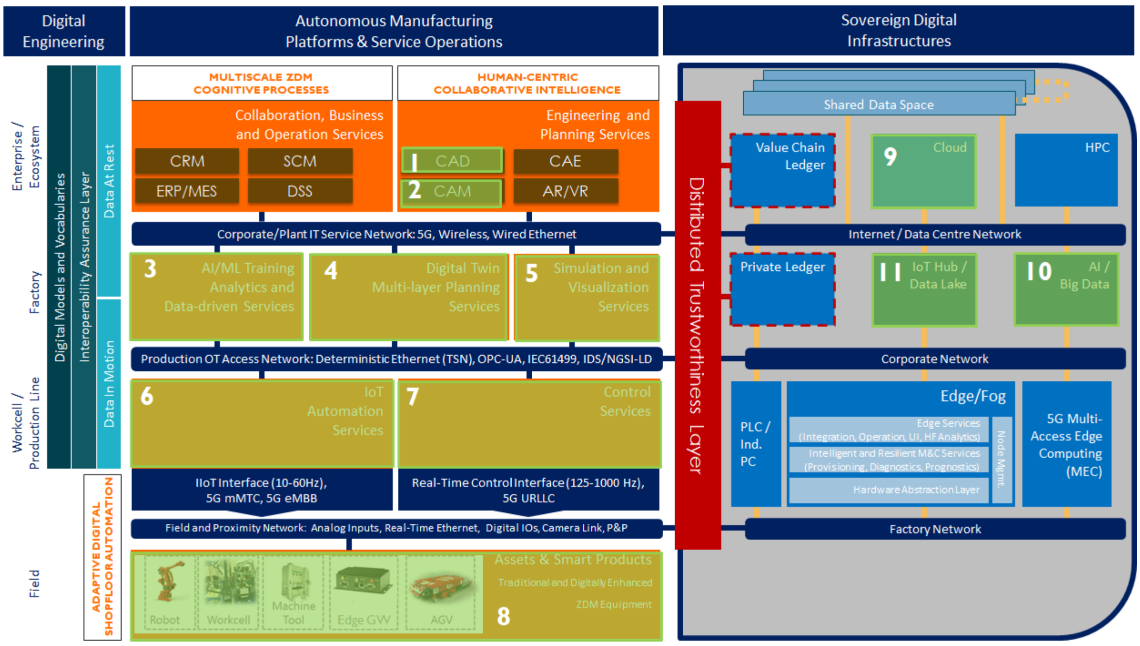

Figure 28 – Mapping of the GF Pilot within the Q-RA

1. Engineering and Planning Services (CAD):

   Brief description: In PowerShape, a GF wizard is implemented for guiding users in electrodes creation. MPP software is an add-in for SolidWorks created by GF for process planning with an integrated CAM DS module.

2. Engineering and Planning Services (CAM):

   Brief description: Different CAM systems for different technologies will be used by GF. PowerMill will be used for generating Milling NC codes, CAM DS integrated in MPP will be used to generate EDM job file and PowerInspect and M3MH will be used to create inspection NC codes. In PowerInspect, a special GF wizard is implemented to guide the user to create the NC code.

3. AI/ML Training Analytics and Data-driven Services:

   Brief description: A cognitive digital twin and analytics framework integrating machining process and component data for multi-stage error compensation and KPI prediction and control.

4. Digital Twin Multi-Layer Planning Services:

   Brief description: A digital twin planning system will be implemented delivering machining codes with simulation tools taking into account given process parameters and machine configuration, in an initial optimized set-up.

5. Simulation and Visualization Services:

   Brief description: A multi-process simulation will be developed for the optimization of the process planning. The system will propose the operator an optimized plan for the time and cost.

6. IoT Automation Services:

   Brief description: Data from machine sensors, monitoring process, components and environment will be collected during machining and aggregated in a common, standardized data space to be associated with data from dimensional measurements.

7. Control Services:

   Brief description: The results of the milled electrode inspection, such as offset values, undersize values and the deviation values, will be stored in GF database. CAM DS will use these results in order to adapt the EDM DS machining job based on the real values of the electrode.

8. Assets & Smart Products:

   Brief description: GF manufacturing cell with GF HPM milling and GF EDM DS machines with integrated sensors and edge devices. The inspection will be performed on a Zeiss CMM. The cell is orchestrated by the 3R systems WSM CellManager.

9. Cloud:

Brief description: Data from machine sensors, monitoring process, components and environment will be collected during machining and aggregated in a common, standardized data space to be associated with data from dimensional measurements.

10. AI/BigData:

    Brief description: Data analytics will be performed first to train the time and cost estimation module for EDM DS, predictive maintenance module and the anomalies detection module, and then, it will be performed on acquired new data in order to keep these modules updated.

11. IoT Hub/Data Lake:

    Brief description: The Digital HUB is the new proprietary GF cloud services infrastructure, based on web technologies and Microsoft Azure environment. The Digital HUB allows to develop, host and deploy web applications providing services based on machine data, as process monitoring, quality prognosis and prediction, and predictive maintenance.

5.3 Coverage of the QU4LITY Pilots

To achieve the goals of QU4LITY, the technologies that this project intends to implement are based on 4 different cornerstones:

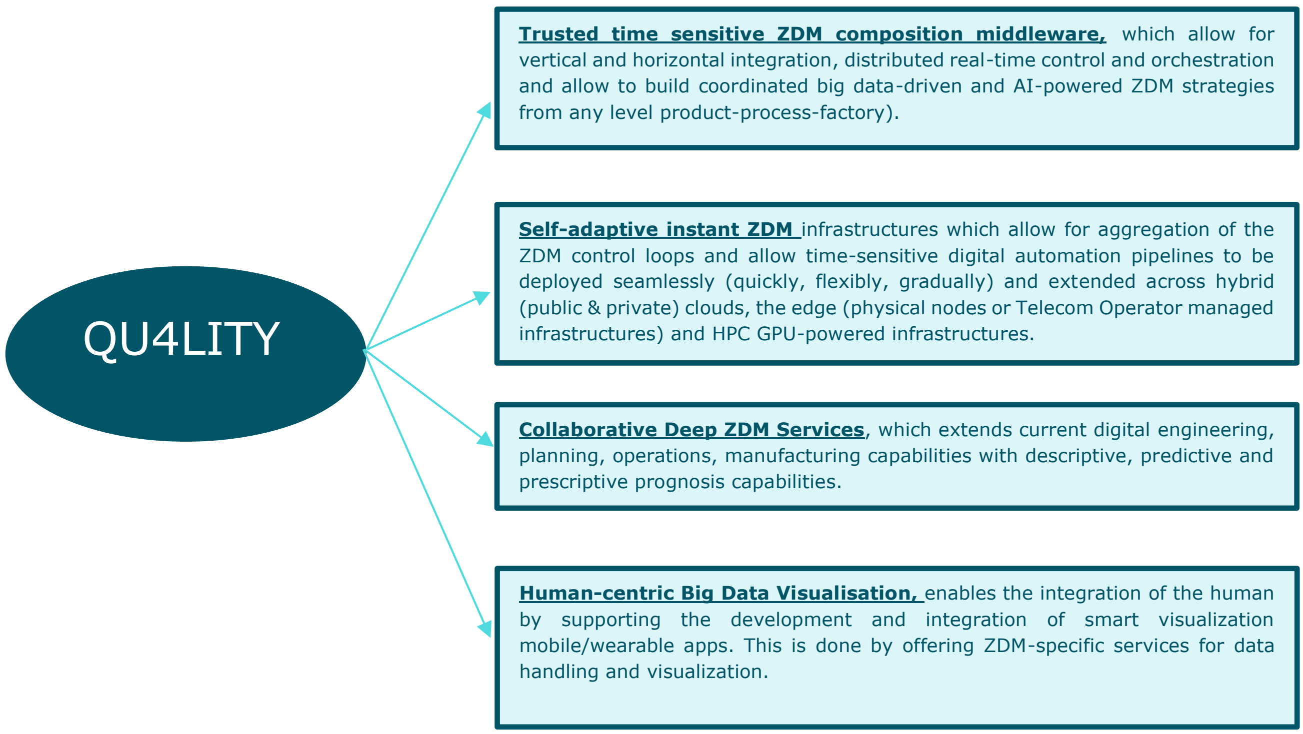

Figure 29 – QU4LITY technology cornerstones

According to the technology described above, the most important blocks/layers for the pilots are those described on chapter "*5.2.4.1 Functional View*".

Workcell/Production Line layer

- Context Perception & Model Building Services
- Control & MES Services

Factory layer

- Digital Twin Planning Services
- Data-Driven Learning Services
- Simulation Services

Enterprise layer

- Assisted Reality & Engineering Services
- Business Management Services

6 Conclusions

This deliverable introduces the final version of the Q-RA, providing the high-level design of a QU4LITY-based system and describing the methodology to derive the Reference Implementations of the modelled components. These results have been driven mainly by earlier work and results from WP2, notably the analysis of requirements and reference use cases, as well as the results of the first development iteration from all the other technical- and business- related work-packages. The main highlights include:

- QU4LITY is not the first effort to specify a Reference Architecture for Digital Industry, but it aims to provide a specific focus on ZDM processes and services.
- The provided RA design is inspired and in-line with recently introduced reference architectures, in Europe and also worldwide, for Digital Manufacturing Platform.
- The Q-RA addresses functionalities in three distinct, yet interrelated and complementary domains: Adaptive Digital Shopfloor Automation, Multiscale ZDM Cognitive Processes and Human-Centric Collaborative Intelligence.
- The Q-RA widens the Quality Management approaches with regard to a more collaborative dimension, moving from factory automation toward collaborative AI-based tools and cross-organization data spaces.
- The Q-RA enables a wide range of ZDM use cases and scenarios, taking as input the main challenges identified in the project experiments, but also looking further at the ZDM scenario coming from the experience of the Consortium.
- All the technical developments and activities are firmly connected to the Q-RA in order to give a holistic view on the problem space (and the QU4LITY way to approach it), identifying the relationships and inter-dependencies among the different components (and the associated project activities).
- The baseline of the QU4LITY-based solutions can leverage frameworks, platforms and tools, including open or closed background assets belonging to project partners.

Overall, this document provides an updated sound basis for development and integration activities that will be performed as part of technical work packages, notably WP3, WP4 and WP5. In particular, the findings of the first iteration, the latest updates in the external ZDM context, and the refined requirements from the ZDM scenario addressed in QU4LITY have been used as a source of inspiration to define the main components and structuring principles of a QU4LITY-based system. Hence, the document will be a valuable input for all partners engaged in technical design and software development and validation in the remaining months of the project, moving toward the end of the second implementation iteration and strengthening the adoption of our technologies in the pilots (WP6 and WP7) and in the market (WP8 and WP9).

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List of abbreviations

Abbreviation	Explanation
AAS	Asset Administration Shell
AEP	Application Enablement Platform
AF	Architecture Framework
AGV	Automated Guided Vehicle
AI	Artificial Intelligence
AQ	Autonomous Quality
AR	Augmented Reality
ARC	Advanced Resource Connector
B2B	Business to Business
CAD	Computer Aided Design
CEO	Chief Executive Officer
CIMS	Computer-Integrated Manufacturing Systems
CNN	Convolutional Neural Network
CPPS	Cyber-Physical Production Systems
CPS	Cyber-Physical Systems
DaR	Data at Rest
DoA	Description of Action
DID	Decentralized Identifier
DiM	Data in Motion
DIN	German Institute for Standardization
DFA	Digital Factory Alliance
DLT	Distributed Ledger Technology
DSA	Digital Shopfloor Alliance
DSS	Decision Support System
DT	Digital Twin
ERP	Enterprise Resource Planning
FP7	Framework Programme 7
FoF	Factories of the Future
GUI	Graphical User Interface
H2M2M	Human-to-Machine-to-Machine
HMI	Human Machine Interface
HPC	High Performance Computing
HW	Hardware
I/O	Input/Output
IaaS	Infrastructure as a Service
IDSA	International Data Spaces Association
IEC	International Electrotechnical Commission
IIC	Industrial Internet Consortium
IIoT	Industrial Internet of Things
IIRA	Industrial Internet Reference Architecture
IIS	Industrial Internet System
IMS	Intelligent Manufacturing System
IoS	Internet of Services
IoT	Internet of Things
ISO	International Organization for Standardization
IT	Information Technology
IVI	Industrial Value Chain Initiative

IVRA	Industrial Value Chain Reference Architecture
KPI	Key Performance Indicator
LCA	Life Cycle Assessment
M2M	Machine-to-Machine
MEC	Multi-Access Edge Computing
ML	Machine Learning
MPFQ	Material, Processes, Features/Functions, Quality
MQTT	Message Queue Telemetry Transport
N/A	Not Available
NDT	Non-destructive Testing
OEM	Original Equipment Manufacturer
ORM	Object Relational Mapping
OPC UA	Open Platform Communications Unified Architecture
OPI	Overall Performance Indicators
OT	Operational Technology
PaaS	Platform as a Service
PLC	Programmable Logic Controller
PPP	Public Private Partnership
Q-RA	QU4LITY Reference Architecture
QADM	Quality Assessment Data Model
QCH	Quality Clearing House
QAR	Quality Assessment Report
R-MPFQ	Resource, Material, Processes, Features/Functions, Quality
RA	Reference Architecture
RAMI 4.0	Reference Architecture Model for Industry 4.0
RAS	Reliability, Availability, and Serviceability
RI	Reference Implementation
RF	Reference Framework
RoI	Return of Investment
ROS	Robot Operating System
RUL	Remaining Useful Life
SDK	Software Development Kit
SID	Secure Identity Directory
SIEM	Security Information and Event Management
SMB	Secure Messaging Board
SME	Small Medium Enterprise
SOA	Service-Oriented Architecture
SPT	Security, Privacy and Trust
SUM	Shipping Unit Manifest
TCP/IP	Transmission Control Protocol / Internet Protocol
ToC	Table of Content
TSN	Time-Sensitive Networking
UDP	User Datagram Protocol
UI	User Interface
VM	Virtual Machine
VR	Virtual Reality
XC	Crosscutting
ZDM	Zero Defect Manufacturing

Partners

Appendix A. State of the art in Digital Manufacturing Platforms for ZDM

Manufacturing industries are continuously facing the challenge of operating their manufacturing processes to deliver the required production rates of high-quality products, while minimizing the use of resources. Zero defects manufacturing (ZDM) is aiming at going beyond traditional six-sigma approaches.

Traditional six-sigma techniques [4] show strong limitations in highly changeable production contexts, characterized by small batch productions, customized, or even one-of-a-kind products and in-line/on-line product inspections. Innovative and integrated quality, production logistics and maintenance design, management and control methods as well as advanced technological enablers have a key role to achieve the overall production quality goal.

The main objectives of ZDM approach are to get zero defects in a production environment (i.e., to get it right at the first time), to achieve waste/scrap reduction, lower production costs, shorter production times, higher productivity and competitiveness, and last but not least, a higher resource and energy efficiency. All those goals should bring a significant competitiveness increase and job creation for the EU manufacturing industry.

Among the challenges that the ZDM approach brings to industries, it is worth to highlight the identification of error sources and types, the identification of most problematic phases within a Life Cycle Assessment (LCA) approach, the clustering of errors (and subsequent solutions) according to the most common levels in an industrial shop-floor activity, and finally, the development and implementation of suitable ZDM tools as solutions for the upstream generation and downstream propagation of production defects.

Regarding the above mentioned zero-defects levels, the ZDM paradigm in an industrial factory approach may be composed by several relevant fields and layers.

- Process level: on one hand, workpiece-fixturing-clamping, components and machine, manufacturing process (in where error sources are located and ZDM tools should be implemented).
- Multi-stage system level: on the other hand, interconnected manufacturing cells and shopfloor/workshop dimension, where data acquisition and processing, data monitoring, process prediction and optimization become more critical.

An integrated approach to quality, safety, maintenance, lead time and productivity is requested. It should be supported by:

Zero-defects manufacturing approaches at process levels (to identify error sources and to avoid error propagation downstream) such as:

- Integrated machine, fixture, tool, workpiece modelling and simulation for quality deterioration, prediction and associated maintenance planning.
- Integration of intelligent, autonomous, self-adaptive, self-powered and cost-effective sensors and actuators for process monitoring, control and quality management.
- Process adaption by self-learning, quality and process data bases modelling of process behaviour.
- Robust automation of processes with input uncertainty.

In-line quality acquisition, before, during and after the process, such as:

- New measurement and inspection and on-line material characterization and NDT (Non-destructive Testing).
- Development and integration of in-line or in-process measurement and inspection techniques (NDT) and the use of modern sensor technologies that can remove the need for end-of-line inspection, without bringing significant in-process cost increases (cost-effective) or time losses (keeping productivity).

Data mining and data analytics through advanced sensing and integrated approach through the manufacturing chain, such as:

- Strategies for optimally combining and harmonizing heterogeneous data such as images, geometry (CAD, triangle meshes or point clouds) as well as numerical raw data, captured during the whole product life cycle (from design to manufacturing) for converting such data into information and knowledge.
- Plug-and-inspect data gathering systems, based on auto-configuration of data exchange protocols and IoT solutions.
- The statistical assessment of the variation of manufacturing quality, geometrical analysis and classification methods and practices for estimating the effect of variation of manufacturing quality.

Digital Manufacturing Platforms play an increasing role in dealing with competitive pressures and incorporating new technologies, applications and services. The challenge is to make full use of new technologies that enable manufacturing businesses, particularly mid-caps, and small and medium-sized enterprises (SMEs) to meet the requirements of evolving supply and value chains. Besides innovation and research actions there are also coordination and support activities to cross-fertilize the industrial platform communities, facilitating the adoption of digital technologies from ongoing and past research projects to real-world use cases and encouraging the transfer of skills and know-how between industry and academia.

These coordination and support activities could be actions consisting of accompanying measures such as standardization, dissemination, awareness-raising and communication, networking, coordination or support services, policy dialogues and mutual learning exercises and studies, including design studies for new infrastructure and may also include complementary activities of strategic planning, networking and coordination between programs in different countries.

In platform building, proposals need to develop next-generation digital platforms, which build on the state of the art, reuse what is available, and integrate different technologies, such as IoT, AI, robotics, cloud and Big Data. Platforms should aim at openness and interoperability between platforms to avoid lock-in, prevent dominant positions on individual players, and comply with standards and regulation. Proposals need to target solutions for SMEs and mid-caps, considering interoperability with emerging and future solutions.

This may require the mapping of reference architecture models for integrating existing sectorial platforms. The interfaces of the platforms need to be described via open specifications and reference implementations need to be developed. A major aim is to offer platform functionalities that can be generically reused in multiple contexts to support various types of applications and services.

The digital manufacturing platform scenario is complex and uncertain, as the main players and roles are still being shaped. Trying to foresee market scenarios, in December 2016, the Economist compared two platforms, the General Electric (GE) Predix and Siemens MindSphere to evaluate the likelihood of finally dominating the industrial Internet. It found that it is unlikely that a single platform will reach complete dominance and highlighted the significance of an open strategy [5].

The findings of the research work show the broad and complex scope of digital manufacturing platforms following the motivation and view of the authors. The relationship between private (IoT platform vendors, manufacturing equipment suppliers and machine tool builders) and public stakeholders (European Commission, Public Private Partnerships, etc.) in the strategy of digitizing the European industry contributes to build a global vision towards addressing future challenges posed by the need to create new business models based on data economy and the growth of digital ecosystems fostered by digital manufacturing platforms.

As a result of digitization advancement, manufacturing system controls must deal with material and machines and integration issues that started to come up in manufacturing, as machines and devices in a manufacturing process were no longer isolated but are part of a system, where all the components could be effectively coordinated. To handle integration issues, computer-integrated manufacturing systems (CIMS) are starting to be widely adopted by companies. In this context, Chen et al. [7] study several perspectives when enabling integrated and intelligent manufacturing.

Increasing opportunities were opened by Internet of Things and CPS technologies, which enabled integration to be made wider and more open, comprising three levels of integration in manufacturing – vertical integration, horizontal integration and end-to-end integration [8].

Intelligent manufacturing platforms are the enablers to implement intelligent manufacturing technologies [7]. The point of view of industries that are preparing to develop cloud computing platforms based on IoT motivated by business is explained. Predix [9], ThingWorx [10] and Siemens [11] software platforms are described as the main references by the authors. In addition, the authors remark that "digital twins" are a significant feature of all such platforms to allow for the prediction of future conditions of productive assets.

There is an approach of Industry 4.0 for manufacturing systems based on the Smart Factory concept [12]. There is a clear focus on enabling technologies for Smart Factory, such as IoT, IoS, Systems Integration and the Cyber-Physical Production System (CPPS). The presented Smart Factory concept relies heavily on distributed computing as a core concept of Industry 4.0, as opposed to the most common manufacturing environments that are centralized. Authors explain the connection between technologies and standards with the role of RAMI 4.0 and its importance in leading the growth of CPPS [13].

The major advances in manufacturing technologies [14] are intelligent manufacturing, IoT enabled manufacturing and cloud manufacturing. Intelligent manufacturing (also known as smart manufacturing) is defined as a broad concept of manufacturing, with the purpose of optimizing production and product transactions by making full use of advanced information and manufacturing technologies.

Intelligent Manufacturing Systems (IMS) are the next-generation manufacturing systems by adopting new models, new forms and new methodologies to transform the traditional manufacturing system into a smart system. Authors remark the importance of service-oriented architecture (SOA) via the Internet to that end, providing collaborative, customizable, flexible and reconfigurable services to end-users. Moreover, the authors highlight the essential role of AI (Artificial Intelligence) in an IMS by providing features such as learning, reasoning and acting in a human-machine cooperation context. IMS shape an ecosystem where manufacturing elements are involved with organizational, managerial and technical implications [15].

Another technological aspect is cloud manufacturing that refers to an advanced manufacturing model under the support of cloud computing, IoT, virtualization and service-oriented technologies. It covers the extended whole life cycle of a product, from its design, simulation, manufacturing, testing and maintenance, aiming to provide on-demand manufacturing services from the cloud [16].

The study in [17] presents an approach to digital platforms and examine the ecosystems that surround them. The authors state that digital platforms have a transformative and disruptive impact on organizations and their business models to the extent that platforms change the power structure and the relationship between participants in the ecosystem. The way service providers and device manufacturers strategize in a platform environment is discussed based on prior ecosystem thinking work [18], taking into account that organizations are not isolated anymore, and value is co-created and co-delivered by multiple contributing entities.

Digital platforms can be on premise, in the cloud or in a hybrid architecture. Nevertheless, the thrust into a productive environment includes the need for agreements on industrial communication interfaces and protocols, common data models, semantic models and the interoperability of data.

RAMI 4.0 is one of the frameworks that will help accomplish this task [19]. RAMI 4.0 is a three-dimensional layer model that compares the life cycles of products, factories, machinery or orders with the hierarchy levels of Industry 4.0. The model divides existing standards into manageable parts, integrates different user perspectives and provides a common understanding of Industry 4.0 technologies, standards and use cases.

The development of digital manufacturing platforms is in an early stage but supported in a mature IoT ground. Due to the broad scope of the concept, it has required the definition and development of a reference implementation, such as RAMI 4.0. In the current platform building context, it is not a matter of making choices for platform adopters but planning an incremental roadmap towards digital transformation. In this sense, the openness of the technological architecture is a must where state-of-the-art technologies regarding IoT, Artificial Intelligence, robotics, cloud or Big Data will be reused and integrated with interfaces described via open specifications. Platforms should aim for openness, avoiding lock-ins, preventing dominant positions of individual players and compliance with standards and regulation.

Moreover, the openness of the digital manufacturing platform is a major issue as an enabler of digital ecosystems to become an AEP (Application Enablement Platform). It is remarkable that the role of the major IaaS (Infrastructure as a Service) providers is becoming more and more vertical or domain oriented. The role of big players, such as Amazon or Microsoft, has been the provision of IoT and IT infrastructures with pay-per-use business models so far. Nowadays, these players are moving towards PaaS (Platform as a Service) services in manufacturing. This movement is being carried out accompanied by reference OEMs of prioritized industrial sectors.

In spite of the relevant advances achieved so far, there is still a lot to do in order to connect to additional services according to the ‘plug-and-play’ philosophy and considering the multi-sided ecosystem of service providers, platform providers and manufacturing companies, mechanisms for the commercial or open-source provision of the digital services through appropriate marketplaces, modularity of existing or in-development platforms of covering different “regions” of the RAMI 4.0 framework, legacy system integration, overcoming semantic barriers, considering requirements of specific manufacturing sectors (process industry, consumer goods, capital equipment, etc.), etc.

The benefits of the fourth industrial revolution must be monetized for companies, to the extent that technology advances become reality. The definition and support of new business models based on data will be the next big challenge in relation to digital platforms. All these issues outline future work in digital manufacturing platforms.

Z-Fact0r

An efficient and effective zero-defect management system should deal with the current trends for customization and demand for zero defect manufacturing by introducing a holistic approach to not only achieve zero-defects, but also maximise quality and performance. To do so five strategies are employed: Z-PREDICT, Z-PREVENT, Z-DETECT, Z-REPAIR and Z-MANAGE, all of which can be applied in the existing manufacturing plants with minimum interventions. Each of the strategies, as the name suggests, serves a different role, which acts synergistically with the others [20].

The methodology relies on two inspection systems – one on the Work-Station level and on the product level, as well as one online data gathering system and one online Defect Management system. In addition to the above, a Knowledge Management system provides intelligence and robustness to switch into the right strategy dynamically through the use of the three sub-systems.

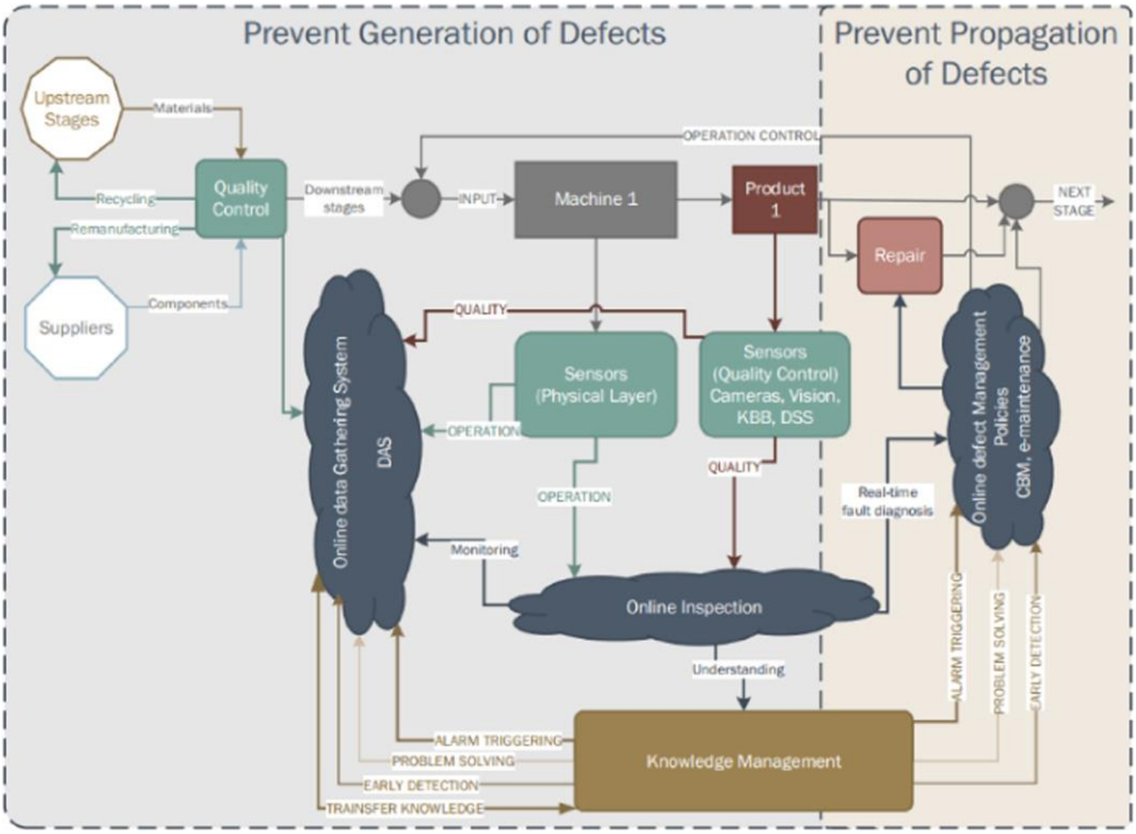

Figure 30 – Zero defect manufacturing system

In the following, an overview of the main deployed sub-systems is presented.

Work-Station Level: A series of sensors and actuators take readings for both the intrinsic and extrinsic machine's key performance parameters. The intrinsic parameters represent each factor that affects the work-station's behaviour on system level, such as structural health, degradation of components, energy consumption, production rate, temperature, etc. The extrinsic parameters involve factors that do affect the machine's performance, but are not in the system level, such as ambient conditions, temperature, humidity, operator's or system's inputs, etc. For each of the deployed use-cases there should be a different set of intrinsic and extrinsic parameters.

Product Level: Optical and visual sensors (lasers and cameras) monitor the quality of each product, according to the requirements for each use-case, based on the specific requirements of the parts from the use cases, it should be decided for each of the processes, the areas to be inspected and the time available for such inspections. It frames the percentage of parts that are measured in each batch. The goal is to ensure that each product conforms to the pre-defined upper and lower acceptable quality limits. To this end, the repeatability is a critical indicator which is monitored using statistics. The goal of this approach is to categorize the products in quality classes, such as class A, class B, etc. All the produced results are stored according to the quality inspection based on the requested quality, expected quality and actual quality. The actions should then be aligned with the ISO 9001:2015 standard aiming at continual improvement to meet customer requirements and the industrial stakeholders.

Data Gathering: The data produced throughout the process along with the inspection of the production line (Workstation and Quality) are logged into servers with time indexes. Wireless or cable transmission of data are achieved through a local area network. To avoid conflicts and loss of data, each of the generated information is stored in the hard drives following a defined filing structure and naming system throughout all the stages.

Knowledge Management: This system receives input from all the rest acting as the "brain" of the zero-defect management approach. The goal of this system is to provide feedback for all the processes executed in the production line. This system comprises an event modelling algorithm to identify the parameters from the overall production line, which affect the Overall Performance Indicators (OPI), such as customer satisfaction, product quality, energy consumption, inventory control and environmental impact. The Decision Support Systems (DSS) and data management algorithms allow the evaluation of each performance and response to defects keeping historical data. The goal of this system is to optimize the overall manufacturing and the involved processes. To do so, the output of the knowledge management system is to provide alarms, which will be filtered after the inherent learning process. Additionally, from the previous acquired knowledge early detection of defects is allowed with increased confidence levels. As a result, the proposed system can solve the problems arising in the production to maximize performance signalling strategies for handling the possible defects.

Manufacturing processes must be environmentally friendly and safe and deliver high quality products adapted to customer requirements, whilst minimizing costs. The increasing interest in sustainable production places a premium on reducing material waste, re-works, rejects and stocks and has led to a demand for the development of zero-defect strategies at system level.

On that vein, the current trend in multi-stage manufacturing is towards more complex, distributed and faster evolving manufacturing facilities. To develop a zero-defect strategy to cope with increasing competition and sustainability related issues, plants should be designed and managed using best practices from emerging key enabling technologies. To that end, it is required to integrate a plethora of novel ICT technologies, state of the art algorithms and models, to support context awareness, inference conclusions, trend and root cause analysis, etc. to support online inspection, monitoring and overall defect lifecycle management, towards zero-defect process operation and enhanced output quality. The final aim is to achieve production system configurations that profitably exploit the quality/productivity trade off at system level whilst reducing complexity.

For that purpose, aligned with the Z-Strategies and the proposed zero-defect management system concept explained earlier, a set of technologies and overall system architecture have been identified as a part of the proposed approach. The first high-level description to lead to the definition of the zero-defect manufacturing platform consisted in identifying and classifying all components that can be called as the tools' landscape and logical architecture.

Based on the proposed approach and defined conceptual view of the system, in Z-Fact0r a novel zero-defect manufacturing platform will be developed and demonstrated in three pilot plans, providing its universal applicability for the achievement of zero defects in manufacturing. Therefore, the zero-defect manufacturing platform will:

- Identify incoming defects and assure the best quality and the maximum production throughput.
- Reduce rejects and re-works by (a) identifying defects in parts caused by faulty machines, (b) by encompassing models and tools to support strategies for Predicting, Preventing, Detecting and Managing defects.
- Introduce autonomous diagnosis capabilities, including root causes analysis, (realized by the ES-DSS) aligned with both the production context (infrastructure, equipment) and the product (quality specifications and actual status).
- Integrate sensorial network with novel self-adjustments mechanisms to leverage semantic interconnection of sensors and online inspection tools, to manage, not only distributed data gathering from the shop floor, but also inter-stage communication and flow of production processes.

To sum up, the main components, their functionality and their interactions are described in the functional view. Accordingly, the main components for Z-Fact0r architecture are (Figure 31):

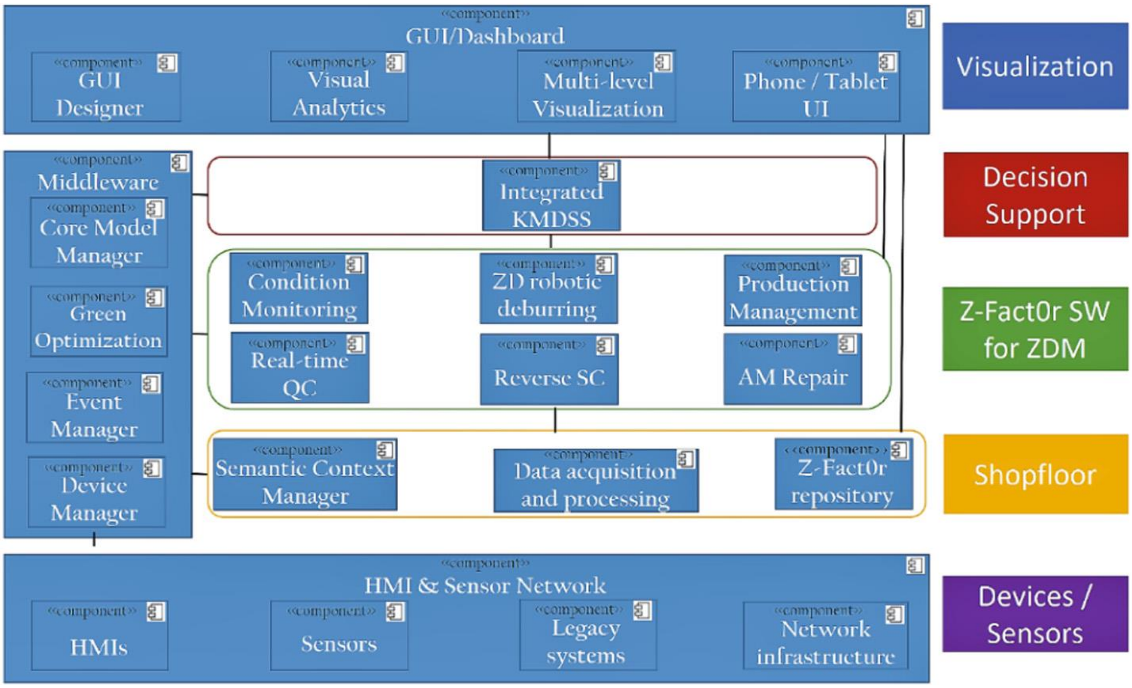

Figure 31 – Z-Fact0r System Architecture

- HMI & Sensor Network, which includes sensors, actuators, HMIs for humans to provide input to machines and thus the overall system, cameras, network infrastructure, legacy systems, etc.
- Shopfloor components which comprise semantic context manager, data acquisition and processing include 3D laser scanning and Z-Fact0r repository.
- Middleware including device manager, event manager, green optimizer and core model manager.
- Z-Fact0r software modules for zero-defect management in manufacturing, which builds the service layer and includes Z-Fact0r specific tools, such as real-time quality control, production management, reverse supply chain, zero-defect robotic deburring and additive/subtractive manufacturing repair.
- Decision Support System (DSS) component, which will supervise and provide feedback for all the processes executed in the production line, evaluating performance parameters and responding to defects, keeping historical data.
- Besides, to facilitate the implementation of the five strategies, Z-Fact0r consortium has considered a policy to support a "reverse supply-chain", in the context of a multi-stage supply-chain attached to a multi-stage production. As a result, the defected products/parts detected in downstream stages (produced during a stage or provided from suppliers in a particular stage) could be returned to upstream stages (internal or external supply-chain tiers) for remanufacturing or recycling.

- Finally, a visualization layer has been foreseen, which includes GUI/Dashboard designer, Visual Analytics Module, multi-level visualization component and phone/table UI, etc.

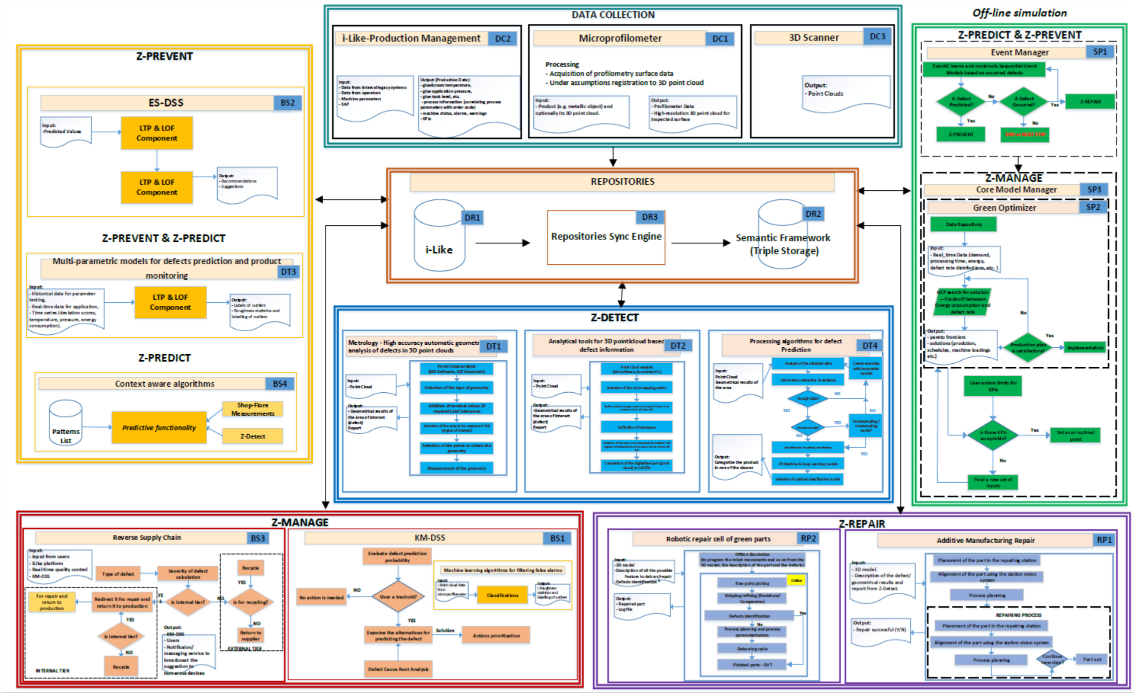

Figure 32 – Z-Fact0r System Architecture - Components and Strategies details

- Z-Fact0r architecture in Figure 32 is based on the blackboard architectural pattern. The computational framework for the design and implementation is supported by the pattern and provides the system with the ability to integrate various components, each one with different scope and functionality. The blackboard also provides the communication APIs between the system sub – components. The Z-Fact0r architecture defines the data flow in the components and the blackboard secures the data persistence. i-Like collects the data from all components and in cooperation with EPFL's semantic framework, they create a middleware based on ontology entities and persistent data queries.
- The blackboard approach provides an efficient way to manage, process, store and retrieve the data signals and their metadata to the respective components. The middleware regulates these transactions in a secure and efficient way, avoiding request conflicts. Each component is independent to the others and each one provides data in the overall system for further exploitation.
- The blackboard pattern is the unifying factor of the system. Its purpose is to integrate the various heterogeneous components into a unified system, which end users depend on for zero defect manufacturing. The distributed sub–components are supported and connected by the blackboard pattern, along with their repositories, which can be queried and the data to be sent in the

middleware as a central data repository. This application of the blackboard pattern helps the integration of the different sub – components and eliminates the need of rewriting the components with enforced conformity.

Z-PREDICT strategy gives estimation for the future states involving the whole production line, e.g., machine status after x number of operations and/or quality of the products for given set of parameters. The system can then predict with high confidence the expected quality as well as the customer satisfaction. The simulation can insert desired values and to predict the outcomes, making the zero-defect management system a 'tailor-made' instrument. Z-PREVENT strategy tunes the system based on historical, current and future (predicted) data to fine-tune the system to preserve the quality levels inside the acceptable limits. Z-DETECT strategy is triggered in the event of a defect. The logged data both from the machine and product level avoids the generation of future defects. In addition, based on the inspection data the system deals with the defects to stop its propagation. Z-REPAIR strategy allows reworking to take place optimally, reducing the direct rework costs, making the outputs acceptable based on the quality standards. Last, the Z-MANAGE strategy acts as the brain of the whole system, receiving all the data and analysing them. The result is filtered alarms, early detection of defects, solutions to generated problems, strategies for repairing (rework or recycling) which all lead to system optimization and zero defects manufacturing.

A holistic framework and ad-hoc strategies have been provided, applicable both to new and existing manufacturing lines to achieve zero-defects manufacturing via a novel ZDM platform that integrates state of the art ICT technologies, AI models and inspection facilities, which elevate manufacturing plants to a superior level of competitiveness and sustainability.

Zero Defects Manufacturing Platform (ZDMP)

Zero Defects Manufacturing Platform (ZDMP) offers an open Industry 4.0 environment, where a new generation of developed zero-defect service applications will be available in a marketplace, contributing to create an ecosystem, where ZDMP stakeholders would be able to interact with each other.

A Zero Defects Manufacturing Platform exists independently between the hardware and the application layers of the technology stack. Its platform will integrate with any connected device and any partner to blend them in with device applications, exposed services, and enable implementation of features and functions into any device and with any application in the same way.

Establishing a complete system for such Industry 4.0 solutions is a huge undertaking for even the most resourceful companies. It requires significant expert know-how, time and capital – and in the end, companies end up plagued by long IT project cycles and low return on investment. Ready-built, open, reference platforms, such as ZDMP, can simplify the development of Zero Defects applications, by easily connecting existing (and new) devices and sensors and enable connections to related information systems and operational assets, delivering more comprehensive business value than a do-it-yourself platform.

Scalability is critical; Platforms need to scale to meet the needs of a company, domain, and easily accommodate continued growth and change in devices, technology, automation and use. Another critical element is the support of existing technologies and standards and not reinventing the wheel.

ZDMP hits many of the challenges with a mission of: To establish a smart Zero Defects environment by deployment and networking of an Intelligent and SME-friendly Platform, Application Studio and Marketplace of developed functionality, applications and services.

Launched in 2019, the 4-year Zero Defects Manufacturing Platform (ZDMP) activity develops platforms for achieving excellence in manufacturing through zero defect processes and products. The 30 partner companies and the European Commission are investing €19 million in the project.

Today, manufacturing industry is undergoing a substantial transformation termed Industry 4.0. It has been enabled through the proliferation on new digital solutions applied across the production process chain. The Zero Defects Manufacturing Platform is a digital platform that will develop both zero defects manufacturing and connected smart factories. The aim of the project is to promote the manufacturing of high-quality industrial products in Europe.

“As the phone evolved into the smart phone, ZDMP will propel the factory to the Smart Factory and the Smart Zero-Defect factory.” says CEO Stuart Campbell, Manager of the ZDMP consortium. “ZDMP will ensure that European industry remains competitive and keeps its leading manufacturing position by producing high quality products at a low cost in the most efficient way.” Campbell continues.

Mr. Harald Schoning, vice president of Software AG, says that “ZDMP will leverage the power of the Industrial Internet of Things and of Artificial Intelligence to create an open, extensible, interoperable and elastic platform that can enable any European manufacturing company of any size to optimize its production and thus strengthen its position in the global market.”.

Tampere University is one of the partner universities in ZDMP. Professor Jose Luis Martinez Lastra from the Faculty of Engineering and Natural Sciences emphasizes the significant impact of Artificial Intelligence and data analytics applications on future manufacturing and Industry 4.0.

“TAU will participate in ZDMP by supporting the formulation of the platform’s architecture; the definition of the distributed and autonomous computing strategies; and will contribute to the creation of the project SDK.” Professor Lastra says.

Professor Lastra leads Tampere University's FAST-Lab, whose research areas include automation, industrial informatics, industrial cyber-physical systems, robotics and artificial intelligence. "The most important application areas of our studies are factory automation, automated health care and intelligent transport. They provide the basis for smart factories, smart health care and smart cities in the future." Lastra points out.

Among other things, the production platform developed in the ZDMP project may be utilized in the automotive industry, machine tools, electronics and construction. The enhanced cooperation between companies can avoid and reduce product and process defects along various supply chains. It will focus on both process and product quality modules for pre-production, production and post-production quality issues, to ensure manufacturers are enabled for zero defects. The participating organizations will contribute €3.2 million for such developing.

The ZDMP Project combines state of the art technological approaches based on commercial grade standard or open-source software with an open development approach and App store. It will focus on both process and product quality modules for pre-production, production and post-production quality issues to ensure manufacturers are enabled for zero defects.

The project is coordinated by Research Centre UNINOVA and concepted and managed by SME Information Catalyst (ICE). In addition to them, other leading partners include Ford, Continental, Software AG, Mondragon Assembly, HSD, FIDIA, Formplast, Consugal, PT Mills, Flexeflina, CEI, AlfaTest, Ceteck, Video Systems, Ascora, Profactor, Softeco, Etxe-Tar, Ikerlan, ITI and Rooter. These are assisted by the Polytechnic University of Valencia, Tampere University and Southampton University as well as the German Standards Organization DIN. Partners Martinrea Honsel, Siveco and ALONG are expected to join the consortium shortly.

The ZDMP project emerged in response to the European Commission H2020 call on Industry 4.0 and Factories of the Future under grand agreement 825631. Visit the website of the Zero Defects Manufacturing Platform project for further information on the partners and funders www.zdmp.eu.

ZDMP aims at providing an extendable platform for supporting factories with a high interoperability level to cope with the concept of connected factories to reach the zero defects goal. In the context, ZDMP will allow end-users to connect their systems (i.e. shopfloor and ERP Systems) to benefit from the features of the platform. These benefits include products and production quality assurance, among others.

As illustrated (Figure 33), the concept of ZDMP can be simplified to a feedback and control system found in areas ranging from human/autonomous driving through to electronics. Steering the system will be the ZDMP apps composed using the projects SDK and different components. Broadly these receive (and present/ actuate) information from sensors/APIs and then process the data.

Influencing this are material and process flaws as well as errors which create defects. This data is processed through process and product analytics services, which in turn feeds back to the apps to complete the cycle reiterating until the system is optimized and Zero Defects product is achieved. ZDMP is that platform and is thus a suite of components that deploys and enables the ecosystem:

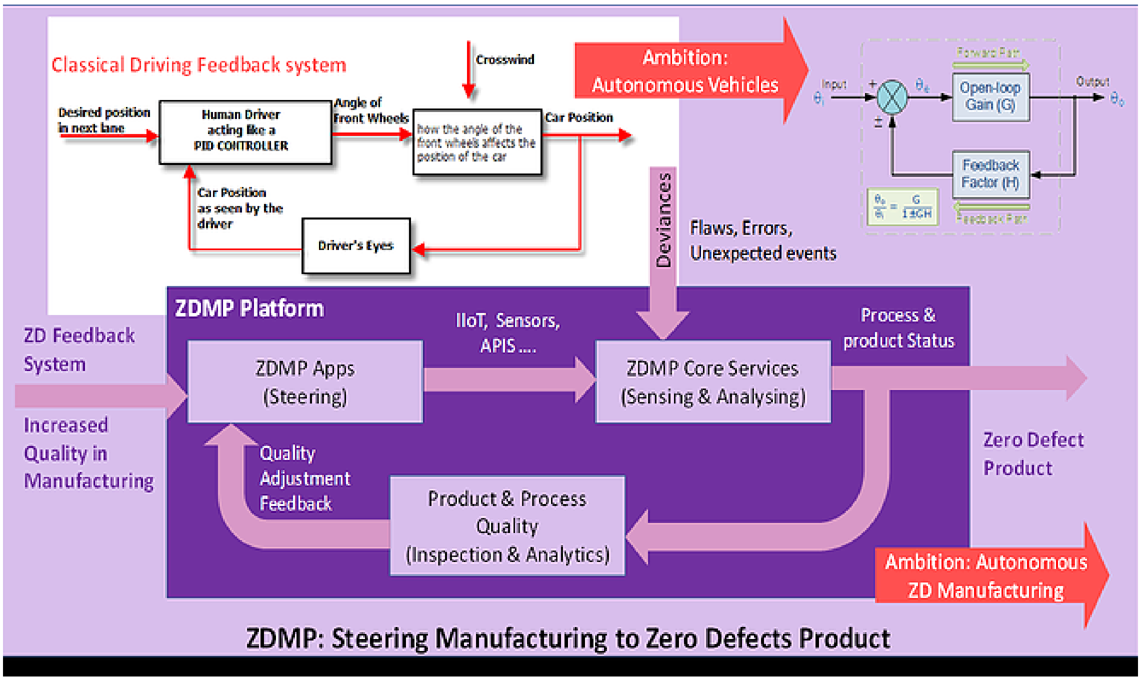

Figure 33 – ZDMP System Architecture

- To build applications that monitor, manage and control connected devices.
- To collect and analyse data from connected devices.
- To enable secure connectivity and privacy between devices and throughout the platform.
- To manage interconnectivity from device/sensors, to machines, to factories, to partners.
- To offer core API services to facilitate use.
- To allow integration with 3rd party systems/services and provide interoperability with other platforms.
- Automate and provide services for the intelligent Zero Defects ecosystem of the platform. In addition, it is important that several non-functional elements are met.
- Relative dependence from the domain of application.
- Sustainability of not just technology but the business model in terms of commerciality.
- Embracing crowd participation and to expose its functions and features to the crowd for them to explore, implement and expand both the solutions available and the ecosystem.

On the other hand, the ZDMP Platform will provide the possibility to extend its features using a dedicated applications store, where end users will add these applications as extensions to the platform according to their needs. Users can also request new applications and software/hardware developers can use the ZDMP SDK (Software Development Kit) to build new Apps for them quickly, using the projects toolkit and platform components.

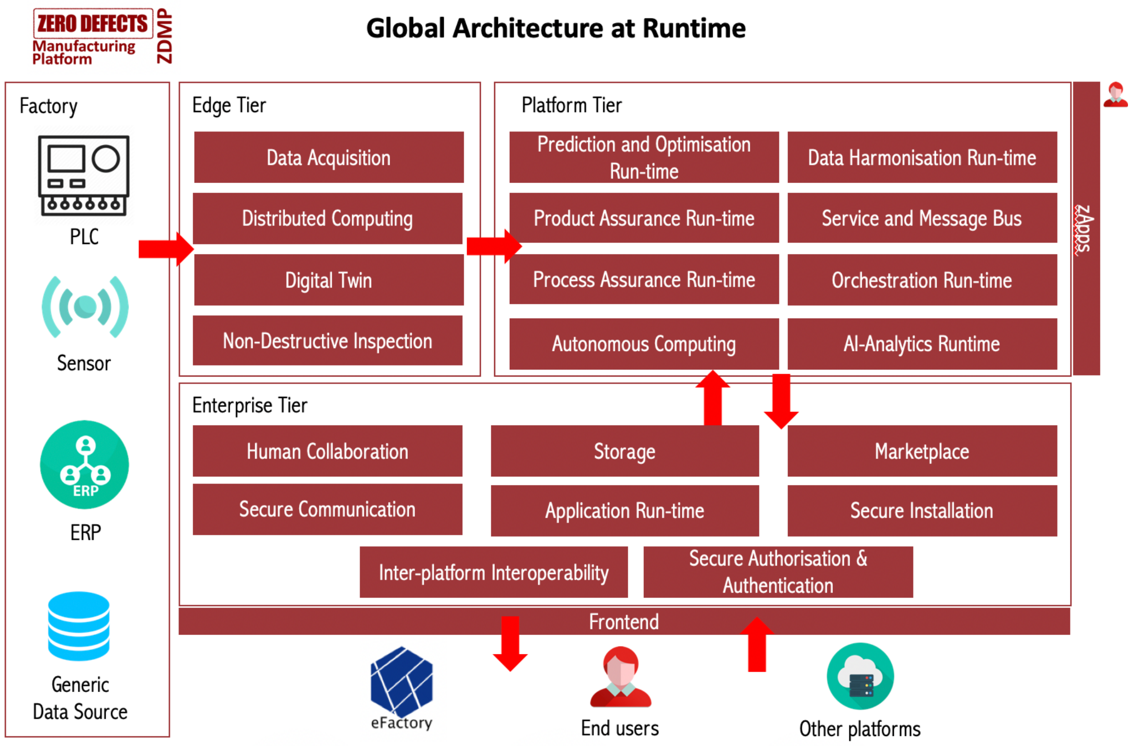

Figure 34 – ZDPM Global Architecture at Runtime

The Global Architecture at Runtime of ZDPM is shown in Figure 34. It shows that ZDPM is a wide platform which integrates many technologies. The platform is based on the following foundations:

- **Container first.** Each component is developed to be executed inside Docker containers. The containers allow scalability, composability and cross platform technologies.
- **Extensibility.** Each container is wrapped in an API, using OpenAPI specification, to allow interoperability with other components and services.
- **Distributed Architecture.** All components are executed in a distributed way. ZDPM uses orchestration technologies such as Docker Swarm and Kubernetes.
- **Composability**. ZDMP components are building blocks in the architecture and can be used with different ways. This approach allows heterogeneous solutions and adapts them to a single system, through a service and message bus.

- **Secure**. ZDPM architecture includes security controls such as: centralised authentication and authorisation, secure communications through SSL, continuously monitoring using SIEM and auditability of every action performed in the platform per user.
- **Big data and AI driven.** ZDPM provides the infrastructure and tools for AI models using Big Data techniques.
- **Connectivity**. Ready to connect with the most used protocols.
- **Developer experience.** ZDPM architecture provides several tools for development of new components.
- **Extensible.** The core functionality can be extended by purchasing new components in the marketplace.
- **Interoperable.** ZDPM can connect and exchange data with other platforms or services through APIs.

In terms of the usability of other research projects, ZDMP will reuse outcomes/ concepts of other research projects such as Cloud Collaborative Manufacturing Networks (C2NET), Cloud-based Rapid Elastic Manufacturing (CREMA) and especially Virtual Factory Operating System (vf-OS), which already includes more generic SDK/App building concepts. Focusing on the Zero Defects concept, ZDMP aims at supporting both process and product quality assurance in dedicated work packages (WP7 and WP8). In addition, ZDMP will focus on the integration activities and develop suitable kick-start applications for the 4 domains pilots, as well as shape the holistic environment.

Virtual Factory – Operative System (vf-OS) [21] offers a manufacturing orientated cloud platform, supporting a multi-sided market ecosystem, that provides a range of services for the connected factory of the future, allowing manufacturing companies to develop and integrate better manufacturing and logistics processes.

Cloud-based Rapid Elastic Manufacturing (CREMA) [21] models, configure, execute and monitor manufacturing processes, providing end-to-end support for Cloud manufacturing by implementing real systems and testing and demonstrating them in real manufacturing environments.

C2NET [21] creates cloud-enabled tools for supporting the SMEs supply network optimization of manufacturing and logistic assets based on collaborative demand, production and delivery plans.

The ZDMP Apps will be built through the ZDMP SDK (Software Development Kit) and take advantage of proven technology in other areas such as CREMA, C2NET and especially vf-OS. The platform enables the collaboration of actors throughout the zero defects supply chain.

4ZDM: Cluster on Zero-Defects Manufacturing

The 4ZDM Cluster is the European Initiative around the FoF Zero Defect Manufacturing priority which aims to promote the adoption of Zero-Defect production and quality control systems by Industry. One significant step forward of 4ZDM Cluster has been the mind change from thinking on individual projects (Midemma, Muprod, Ifacom, Mefafit) to think on common targeted markets or industrial sectors. Apart from that, 4ZDM Cluster has addressed common research fields and manufacturing processes.

Creating clusters of FoF project activities, according to their objectives and addressed themes, is an effective way to enhance the impact of FoF projects. FOCUS is an umbrella project which will help to promote the work of five distinct clusters covering 21 projects. The five participating clusters in FOCUS will share experiences and best practices to stimulate the take-up of project results and investigate how to best exploit synergies. Not only within these participating clusters now, but foremost to define an approach that can also work for future clusters.

The clusters within FOCUS are: Zero Defect Manufacturing (4ZDM), Clean Factories, Robotics, High Precision Manufacturing (High Micro) and Maintenance and Support; The five participating clusters in FOCUS will share experiences and best practices to stimulate the take-up of project results and investigate how to best exploit synergies. Not only within these participating clusters now, but foremost to define an approach that can also work for future clusters. Therefore, FOCUS is a diverse 'community', but representative of the European manufacturing industry, enabling us to meet our objectives.

Currently, the European Commission is recommending clustering activities within running projects. But why this and why now? Basically, clustering identifies and takes advantage of commonalities and tries to avoid any overlap. Some benefits and advantages associated with clustering are listed below:

- Speeding up industrial exploitation and take-up of results of FoF PPP projects.
- Stimulation of networks and alliances for further RTD and industrial innovation in the addressed technology and application areas.
- Added value beyond the original scope of the FoF PPP projects by exploiting synergies and sharing best practices.
- Increased industrial presence and awareness of FoF PPP activities.
- More effective execution of activities of common interest, such as IPR management and standardization.
- Anticipation of business trends and market prospects.
- Joint exploitation, thus paving the way towards a higher industrial impact.
- Networking activities that may identify common business and commercial opportunities soon, as well as the potential creation of spin-offs and start-ups based on the research results.

Within this context, 4ZDM has been the first in starting the cluster engine, with four EC-funded FP7 projects from the Zero-Defect Manufacturing concept. Below, there is further detail about its activities and plans. Indeed, 4ZDM believes that this is much more than four individual projects together; the cluster aims to share technological approaches and results for common applications and processes and is planning to contribute to a common ZDM system architecture, to a European ZDM paradigm and even to international standards on ZDM:

- Common targeted section and market applications.
- Common addressed manufacturing processes.
- Share technological approaches within ZDM.
- Share demonstrator cases and research results.
- Contribution to a common ZDM reference architecture.
- Common vision of a European ZDM paradigm.
- Contribution to international standards.

The 4ZDM cluster gathers several related projects, identifies common interests and synergies and creates collaborative spaces under the zero-defect manufacturing concept. Through the dissemination of research results developed within industrial cases, it identifies commercial and business opportunities around ZDM. The cluster is paving the way towards an efficient transfer that will allow increased industrial impact. Finally, in the longer term, 4ZDM will aim at the definition of a ZDM vision, paradigm and system architecture.

The cluster is promoted by IK4-Ideko, Tecnalia, Politecnico di Milano, Philips and NTNU (leaders of involved projects) and is fully supported by the European Commission. 4ZDM involves 58 partners (16 end-users, 18 technology providers, 24 RTDs/Universities) and 8 countries, as well as critical sectors such as automotive, aeronautics, medical, machinery, energy systems and consumer goods. The industrial impact of 4ZDM may be around 40% of the EU manufacturing sector.

ZDM is and emerging paradigm aiming at going beyond traditional six-sigma approaches in highly technology intensive and strategic manufacturing sectors through knowledge-based approaches. The ZDM approach brings added-value in particular in those industrial environments with high requirements such as mass production of high-added value parts, small batches, customized production or mass customization.

The ZDM paradigm in an industrial factory approach is composed of five relevant field and layers. On one hand, workpiece, components and machine and manufacturing process (in where error sources are located and ZDM tools should be implemented). On the other hand, shopfloor/plant and value-chain (in a more strategy layer).

The main objectives of the ZDM approach are to get zero-defects in a production environment (i.e., to get it right at the first time), to achieve waste/scrap reduction, lower production costs, shorter production times, higher productivity and competitiveness, and last but not least, a higher resource and energy efficiency. All these goals should bring a significant competitiveness increase and job creation for the EU manufacturing industry.

Among the challenges that the ZDM approach brings to industries, it is worth to highlight the identification of error sources and types, the identification of most problematic phases within a Life Cycle Assessment (LCA) approach, the clustering of errors (and subsequent solutions) according to the most common levels in an industrial shopfloor activity, and finally, the development and implementation of suitable ZDM tools as solutions for the upstream generation and downstream propagation of production defects.

Apart from the individual project results, the cluster actuation may bring several advantages when identifying synergies and address other initially not considered targeted markets/sectors. This way, the 4ZDM Cluster can generate new potentials for exploitation of individual project results.

ForeSee Cluster

The minimization of costs, optimal reliability and production efficiency with a low environmental impact, as well as safety of operations are increasingly important issues for every industry [26]. The Boston Consulting Group reports that improvements in maintenance productivity can enable 10-20% savings on labour, repair, and maintenance (R&M) parts and tools, and utilities, which together account for 15% of total costs for the typical organization. This means that improving maintenance can reduce conversion costs by 2- 4% [27]. Maintenance should thus be considered a key operation function of manufacturing enterprises [28]. Its strategic position can greatly vary from one company to another – it can either be internalized using dedicated, in-house teams or either fully or partially outsourced to maintenance service providers. Maintenance touches on all processes of a manufacturing company. Besides avoiding equipment breakdown, a sound maintenance strategy should be aimed towards improving business performance and maximising profits in terms of productivity, quality, and logistics management [30].

Industrial maintenance service providers have long benefited from structural drivers such as outsourcing maintenance to subcontractors, or the increasing complexity of industrial equipment, etc. But in a market that is gradually maturing, strategic changes must be made, particularly to stop the race to the lowest bidder. This is a trend that is gradually leading the profession into a dangerous deflationary spiral and pushing some customers to reinternalize repair and maintenance work, as managers are not fully satisfied with the quality of services in relation to costs.

While industrial maintenance service providers have been used to an average annual growth rate in Europe of more than 6% since the early 2000s, the dynamic has tended to slow down since 2009. The economic crisis and the difficulties encountered by client companies have resulted in a record number of company failures and closures of production units, accentuating the structural phenomenon of deindustrialisation.

Moreover, the growth potential in the petrochemical and steel site maintenance segment, the sector's two main opportunities according to Xerfi [33], is currently particularly low. Almost all companies have already outsourced these functions, only carrying out the exploitation of their operations: as an example, groups operating petrochemical sites (Total, ExxonMobil, Ineos, Solvay, etc.) already outsource all maintenance tasks.

It is also difficult for maintenance stakeholders to conquer new markets. The sectors that could be potentially the most promising, such as the agricultural and food industries or the pharmaceutical industry, are still only opening to outsourcing to a limited extent.

More than the high cost, the main obstacle is confidentiality. Companies do not want their manufacturing secrets to be disclosed by outside parties. The risks of loss, over the years, of technical expertise and know-how are also put forward as reasons for not using subcontractors.

As a result, the average outsourcing rate (share of activity outsourced to external companies) in the field of industrial maintenance in Europe has been capped at around 35% since 2010. In the absence of this main driver of growth, the activity of maintenance generalists tends to run out of breath. According to Eurostat, industrial maintenance, repair, and installation in Europe represented approximately 170 billion euros in 2015.

The deterioration of the economic environment has also aggravated the decrease in the activity of maintenance contractors in recent years. Faced with shrinking order volumes and uncertain prospects, decision-makers have been forced to make trade-offs. The budgetary restrictions imposed by industrial firms have been particularly focused on maintenance, one of the main items of expenditure, which effects are not immediately quantifiable. Moreover, the capacity utilisation rate in industry has remained below the long-term average since 2009, potentially resulting in fewer breakdowns and malfunctions. However, this trend is expected to reverse as economic conditions improved since 2015.

One factor that weighs on the profession's turnover is prices. While they increased by 2.8% in 2012, the rates for repairs and maintenance of industrial sites increased by only 0.8% in 2015. Maintenance service providers face strong market power from their customers, which has been increasing in recent years. Companies no longer hesitate to renegotiate their contracts and seek to use competition to obtain the most advantageous prices. It is thus becoming increasingly difficult for maintenance and repair operators to pass on price increases to customers.

Of course, the drivers of growth are less strong today compared to the prosperous periods of the 2000s. However, industrial maintenance professionals will always benefit from a comfortable growth rate. According to Xerfi estimations, the turnover of "unit outage" specialists averages 4.3% per year between 2016 and 2018. It must be said that maintenance contracts run over several years, so operators in the profession benefit from recurring revenues and are therefore less sensitive to economic conditions. Moreover, with the improvement of their business prospects, contractors will have the means to be more aggressive, to implement new maintenance strategies, in connection with industrial modernization projects.

7.1.1.1 Incentives and Barriers to Predictive Maintenance Adoption in Industry

Traditional maintenance value drivers are the most prominent reasons companies plan to adopt predictive maintenance solutions according to a 2018 PricewaterhouseCoopers report (see Figure 35, source: [34]). Improving overall equipment efficiency (OEE) is by far the most motivating reason, followed by costs savings, extending the lifetime of ageing assets, reducing health, safety, environment and quality risks, increasing end-customer satisfaction and in last place, capturing new revenue streams.

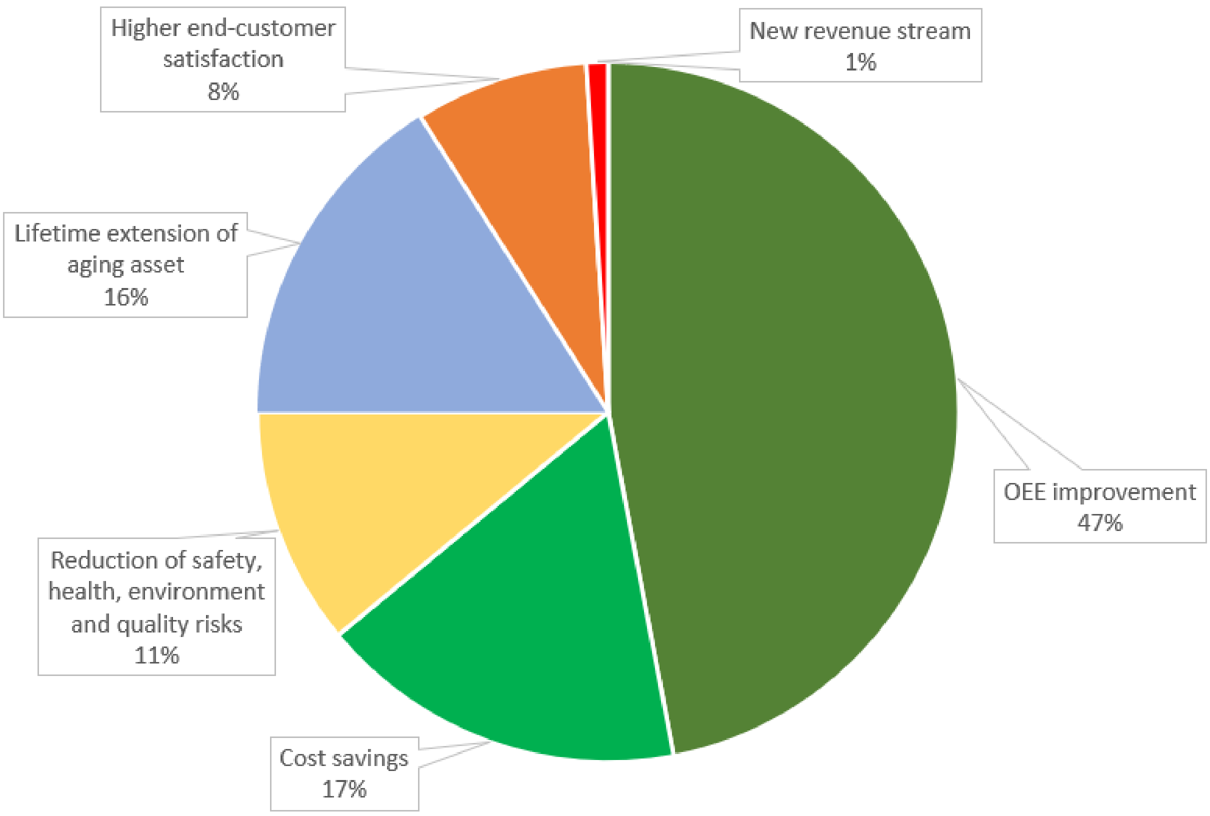

Figure 35 – Perceived Benefits of Predictive Maintenance Solutions

The reasons for companies not planning to adopt predictive maintenance are manifold and help understand the barriers that need to be overcome for predictive maintenance solutions to be more widely adopted by industry.

A main factor is the perceived lack of resources and skills required to support deployment. Companies feel that they are already struggling with the level of skill required to support Industry 3.0 practices. Many companies consequently do not feel they are prepared with regards to resources and skills to tackle the problems inherent in a data-driven, Industry 4.0 application such as predictive maintenance. They prefer to invest in addressing more pressing issues such as ageing infrastructure, regulatory demands, and commodity pricing pressures – even though predictive maintenance could contribute to alleviating some of these issues.

A further intrinsic challenge which hinders industrial adoption of predictive maintenance is the limited availability of data. Whilst current predictive maintenance solutions clearly deliver economic benefits when fully up and running, companies often experience that implementing the solutions in the first place can be more difficult and costly than expected. Large companies need a significant amount of time and resources to collect, scrub, and share necessary data than a start-up needs to train the solution itself.

The problem is even more pronounced in industries where data ownership is a concern. This is especially problematic in scenarios in which the operation and maintenance of assets and thus data ownership may be split across different parties. It is also a challenging issue where legacy assets are prevalent, which is often the case. Although sensor and data management technology costs are sinking, and increased connectivity and the adoption of standard platforms are helping to alleviate these challenges, it is still unclear who will eventually own the data and if analytics application providers require access to data to build mature solutions. A related issue is that of data security. The potential lack of guarantees from current cyber security technologies on their effectiveness in data protection in Industry 4.0 applications is a further barrier towards the widespread adoption of Predictive Maintenance solutions [35].

Another factor hindering adoption is a disconnect between development and evolution cycles in the IT and the industrial sectors. The IT industry is used to rapid cycles of product evolution, where today's state-of-the-art can be expected to be out of date within three years. In the manufacturing and wider industrial world, these cycles of development can take up to 40 years, especially where critical equipment is involved. As a result, many industrial companies postpone adopting new technologies, because upfront costs are expensive, technologies may not be proven, and leaders may be reluctant to change processes that may have been intact for over 30 years. Ironically, the lure of new features and the dynamic pace of change in predictive maintenance causes many industrial companies to delay decisions until the dust has settled.

Predictive maintenance solutions typically require a high degree of vertical customization. Specific models often must be developed for each use case. This model-driven approach offers a high degree of accuracy, but at a high cost - the lack of horizontal replicability across industries reduces economies of scope and hinders widespread adoption. Furthermore, developing new models for each specific use case is laborious and cost intensive. This partly explains why condition monitoring – which is largely a horizontal and repeatable solution – is more widely adopted. The industry is changing, however, as a newer generation of solutions driven by artificial intelligence and data-driven machine learning approaches that accelerate deployment and training cycles.

Furthermore, predictive maintenance solutions need to address a richer array of business problems and offer actionable decisions and solutions to users, not simply flag failures. We are starting to see this happen as predictive and prescriptive maintenance applications integrate ever-larger sets of input - delivering more useful output not just at the asset level, but for the factory and eventually the enterprise.

Appendix B. Relevant Reference Architectures

In the context of the Industrial Internet, also known as Industry 4.0, Reference Architectures (RA) are fundamental assets, as they serve as the link between system architects and the different participants in the manufacturing chain as plant personnel, engineers, business consultants, etc. The final objective of this collaborative work is to find the convergence between the OT and the IT to match the expected business outcomes.

In this area of research, there exist several working groups putting their efforts on providing different reference models, approaching the topic from different points of view and perspectives. In this regard, two consortia: i) IIC (Industrial Internet Consortium and ii) Working Group for Industry 4.0, are providing promising results in terms of recommendations and guidelines, the first one in form of the Industrial Internet Reference Architecture (IIRA) and the second one the Reference Architecture Model for Industry 4.0 (RAMI 4.0). Both reference architectures, that will be presented in more detail in the following chapters, are nowadays main sources of information when Industrial Internet Systems (IISs) are to be designed and developed. Common objective of both approaches is to provide a collaborative and data-driven environment, capable to transform the processes efficiency in the industrial domain.

To support industries digitisation, the references models presented use the IoT, services, personnel, and machines as central components to decompose functions, services, and processes into more intuitive, simpler, and functional subprocesses. In this manner, in the next chapters it will be described which architectural patterns are followed by the reference models, how the information is managed among the different layers of the architecture, how is the communication between the different layers, etc. In addition to the reference architectures presented above, in further chapters the Digital Shopfloor Alliance, a manufacturing-oriented Service Reference Framework align with the RAMI 4.0 that arises from EU projects like AUTOWARE [22], Deadalus [23] and FAR-EDGE [24] will be introduced.

Following the terminology defined in the ISO/IEC/IEEE 42010 [2], the importance of selecting the correct architectural framework to define an information technology system in an industrial environment resides on the fact that those systems are usually composed by a set of interconnected machines or industrial equipment, that can produce vast amounts of data. The correct definition of the information system will allow companies to gather, exchange, transmit and analyse all data generated during a manufacturing process, with the aim of improving its efficiency and performance, reducing the number of defects and failures during production phase. Consequently, to follow the recommendations coming from the experts' community is a good practise when architectural decisions must be taken in consideration, in order to match all the stakeholders' expectations as much as possible.

Industrial Internet Consortium (IIC)

The IIC, that stands for Industrial Internet Consortium, is a global not-for-profit partnership of industry, government, and academia, founded in March 2014. It is composed by a set of members offering different profiles and perspectives, from small and large technology innovators, vertical market leaders, to researchers, universities, and government organizations.

The IIC aims at bringing together the organizations and technologies necessary to accelerate the growth of the industrial internet by identifying, assembling, testing, and promoting best practices. In this context, members work collaboratively to speed the commercial use of advanced technologies and on giving the organisations the necessary guidance to strategically apply digital technologies and achieve digital transformation.

The IIC helps technology users, vendors, system integrators and researchers achieve tangible results as they seek to digitally transform across the enterprise though the realisation of multiple activities and programs [25].

Industrial Internet Reference Architecture (IIRA)

Overview

QU4LITY promotes the concept of autonomous quality in the scope of cognitive digital manufacturing deployments. A main characteristic of this concept is the collection and use of digital information about the physical processes of the shopfloor towards automating and optimizing quality management processes, with a view to reducing defects to zero. As such, QU4LITY systems will be essentially Internet of Things (IoT) systems that take advantage of Cyber Physical Systems (CPS) and IoT devices to collect information from the shopfloor on the one hand and on the other to interact with shopfloor devices and processes to automate quality management. In this context, the Industrial Internet Reference Architecture (IIRA) is reviewed and used to influence the specification and the design of the QU4LITY Reference Architecture.

The IIRA specifies a common architecture framework for developing interoperable IoT systems for different vertical industries. Hence, it can be seen as an open architecture, which specifies the structuring principles of non-trivial IoT systems, while leveraging standards and being applicable to a variety of industrial sectors. The IIRA emphasizes interoperability and practical deployment of IoT technologies. It is high-level, yet quite detailed in terms of the specification of the stakeholders and the components that comprise IIRA compliant IoT systems. However, it is not a proper vehicle for specifying the low-level implementation details of an IoT systems. Rather, it is mainly used for specifying structuring principles of IoT systems, as well as for communicating concepts and boosting stakeholders’ collaboration.

IIRA Viewpoints and Functional Domains

The IIRA has been specified following the detailed analysis of several IoT use cases in different sectors. Based on this analysis, it presents the structuring principles of IoT systems in four different viewpoints:

- **The business viewpoint**, which identifies the stakeholders that engage in the development, deployment and operation of an IoT system, including their business vision and objectives. The business viewpoint considers the overall business and regulatory context, in which the IoT system operates.
- **The usage viewpoint,** which specifies the actual usage of the IoT system. This usage is illustrated based on sequences of activities that may be performed by human actors and/or logical components (e.g., system or system components).
- **The functional viewpoint,** which specifies the functionalities of the IoT system. To this end, it illustrates the functional components that comprise an IoT system along with their interfaces and interactions. It also presents any interactions with external logical modules (e.g., external subsystems).
- **The implementation viewpoint,** which comprises the implementation technologies that are used to implement the functional components, along with information about their lifecycle and the realization of the communication between them.

While all four viewpoints are important for the realization of an IoT system, it's the functional viewpoint that is the most important when it comes to engineering and implementing an IoT system. Therefore, in the scope of the Q-RA specification, the functional viewpoint is prioritized. QU4LITY can greatly benefit from the way such functionalities are specified in the scope of the IIRA. In particular, the IIRA functional viewpoint specifies several individual/distinct functionalities, which are called functional domains. Hence, any IoT system (like a QU4LITY ZDM system) can be decomposed in "functional domains", which are important building blocks that are applicable across different vertical domains and applications. In particular, the IIRA decomposes a typical IoT/IIoT system into five functional domains, namely a control domain, an operations domain, an information domain, an application domain, and a business domain as outlined in Figure 36. At the level of the information domain, IIoT systems compliant to the IIRA handle data volumes that exceed the capacity of conventional database management system i.e., at the information domain Big Data management is needed. This is also the case with modern quality management and ZDM systems (e.g., the pilots' system of QU4LITY) that typically manage large volumes of industrial data including process, maintenance and logistics data.

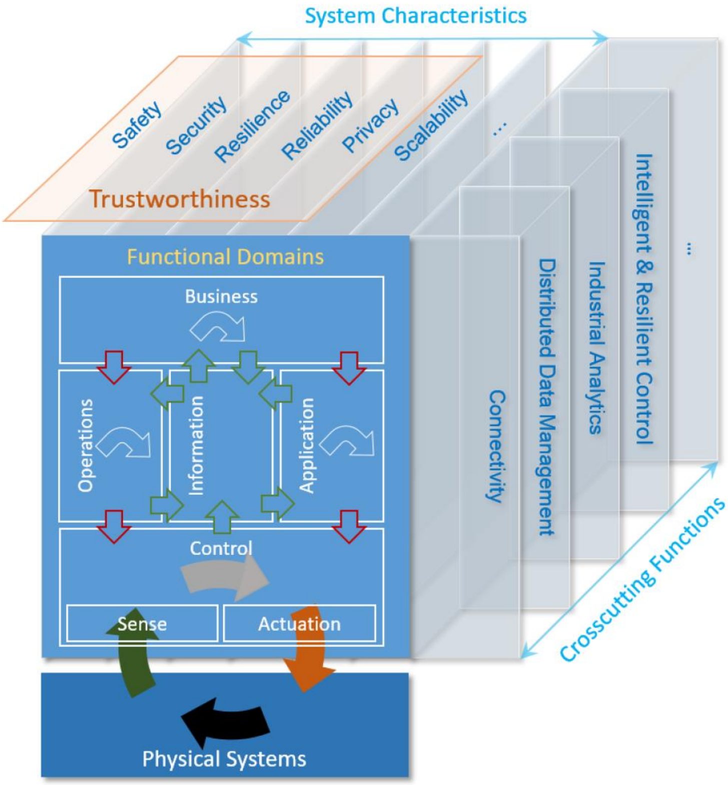

Figure 36 – Functional Domains and Cross-Cutting Functions in the IIRA

Note that Figure 36 [41] illustrates also some cross-cutting functions, i.e., functions that are domain agnostic. These include connectivity, distributed data management, industrial analytics and intelligent control. These cross-cutting functions are all applicable to QU4LITY. For example, connectivity ensures that all systems and devices (regardless of their functionality) can connect to each other on the shopfloor. Likewise, data acquired from the various systems and devices needs to be appropriately routed to different applications across all available functional domains, which illustrates the importance of the distributed data management functionalities. As another example, all functionalities of QU4LITY compliant systems, including control functionalities, simulation functionalities and predictive analytics functionalities for quality management, need to take advantage of some form of industrial analytics.

In addition to specifying the cross-cutting functionalities, the IIRA provides a more detailed break-down of the components and functionalities of each functional domain. For example, Figure 37 presents the functional decomposition of the control domain, i.e., it presents the main components of a control application. The latter includes sensing and actuation functionalities, which are driven by an Executor that considers an abstract modelling of various entities. The IIRA includes similar break downs for the rest functional domains of the IIRA.

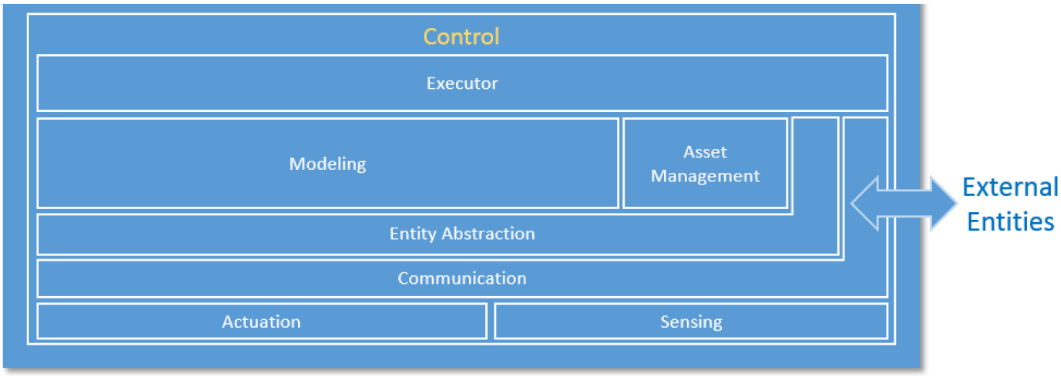

Figure 37 – Functional Decomposition of the Control Domain

IIRA Implementation Viewpoints - Architectural and Implementation Patterns

Significant implementation insights for the QU4LITY architecture can be derived by the implementation viewpoint of the IIRA. One of the main architectural patterns that are suggested within the IIRA is the three-tier architecture, which follows the edge/cloud computing paradigm, as shown in Figure 38. It includes an edge, a platform and an enterprise tier, which are connected together through different networks and function as follows:

- The edge tier collects data from the edge nodes, using the proximity network (e.g., a local area network). The tier is characterized by breadth of distribution, location, governance scope and the nature of the proximity network. These characteristics vary based on the requirements of specific use cases. The latter may include real-time use cases and operations that must take place close to the field.
- The platform tier receives, processes and forwards control commands from the enterprise tier to the edge tier. It consolidates processes and analyses data flows from the edge tier and other tiers. Furthermore, it offers management functionalities at both the device and asset level, while offering non-domain specific services such as data query and analytics.
- The enterprise tier implements domain-specific applications, decision support systems and provides interfaces to end-users including operation specialists. The enterprise tier leverages data flows from the edge and platform tier and issues control commands to both tiers.

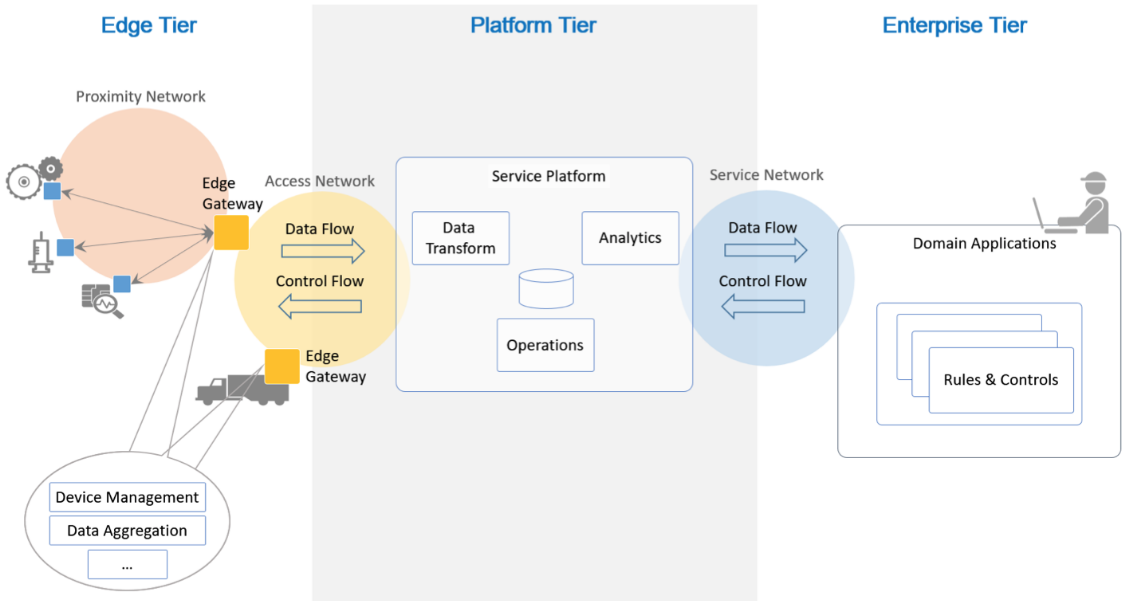

Figure 38 – Three Tier Implementation Architecture specified in the IIRA

Figure 38 illustrates the layered databus pattern, which can support the implementation of IIRA compliant systems. Databus enables real-time analytics across low level systems (e.g., smart machines) close to the field, towards implementing local control, automation and real-time analytics. Furthermore, another database instance can be used to support the communication of higher-level systems for supervisory control and monitoring. Databus is a very common construct in data intensive systems: It is a logical connected space that facilitates communications across different end points leveraging the use of data that comply with a common schema.

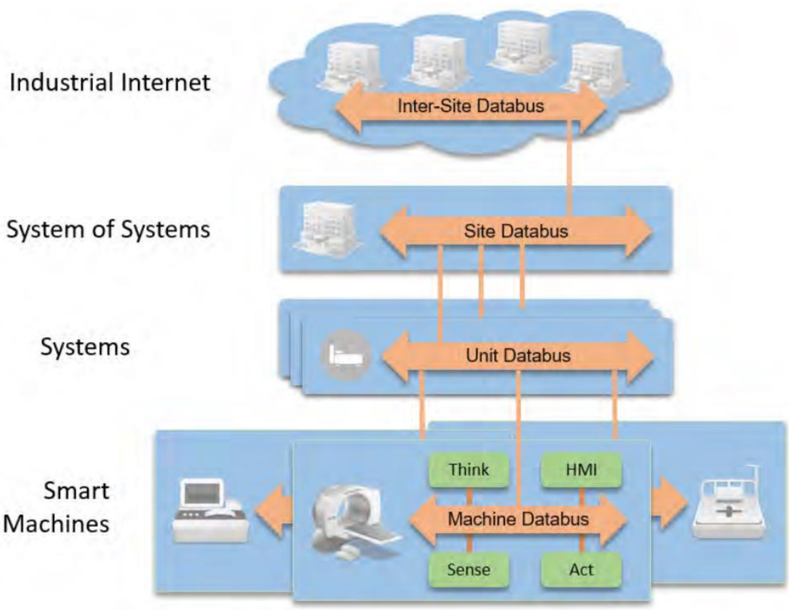

Figure 39 – Layered Databus Architecture

The implementation of the QU4LITY pilot systems adhere to the Q-RA and make use of the above listed patterns:

- Three tier architecture including edge computing implementation for control operations close to the field.
- Databus patterns for communication and seamless information exchange across heterogeneous systems at different levels of the three-tier architecture.

The Industrial Internet Security Framework (IISF)

The IISF provides a guide for understanding and implementing security for systems that comply with the IIRA. In particular, the IISF provides guidelines for securing each component of the IIRA, while at the same time binding these components together in a trustworthy system. It pays special emphasis on what needs to be done to secure traditional Operation Technology (OT), as conventional IT security solutions do not apply directly to OT systems and services.

The IISF specifies a range of functionalities that are applied across all components of the IIRA in a horizontal approach i.e., as a cross cutting function. As illustrated in Figure 40, these include protection of data, protection of (edge/cloud) endpoints, protection of communications and connectivity, security monitoring & security analytics, as well as security configuration and management.

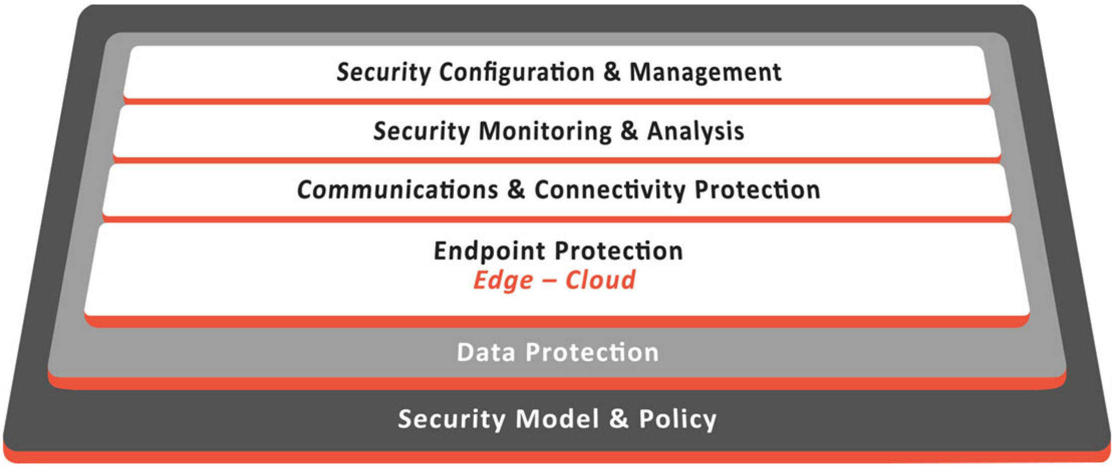

Figure 40 – Functional Overview of the IISF

QU4LITY Relationship and Alignment to IIRA

The IIRA inspires the development of the QUALITY RA in the following directions:

- **Specification of Functional Domains**: Similar to the IIRA's concept of functional domains, the Q-RA should specify functionalities that are specific to ZDM and Quality Management in manufacturing. These individual (ZDM specific) functionalities can then be mapped to functional domains of the Q-RA. The specific functionalities of these domains will be driven by the QU4LITY requirements and specifications as documented in earlier deliverables of WP2. They could include simulation, analytics, control and information sharing functionalities. Note that a similar approach has been adopted in the specification of the architecture of the FAR-EDGE project [1].
- **Cross-Cutting Functions**: The Q-RA should provide some cross-cutting functionalities like connectivity, distributed data routing and data analytics. These functionalities will be used by various functional domains of the Q-RA. Some of the QU4LITY Digital Enablers will provide the means for implementing such cross-cutting functionalities in efficient ways (e.g., 5G connectivity could be a cross cutting functionalities, while data routing based on Industrial IoT Data management platforms could be another one).
- **Three-tier implementation**: From an implementation perspective a three-tier architecture could be fit for purpose for the implementation of Q-RA compliant systems. The QU4LITY architecture should provide implementation views in-line with the three-tier architecture.
- **Security as Cross-Cutting Functionality**: QU4LITY should offer cybersecurity features, which will be implemented as a cross-cutting functionality that will be offered across all levels of an QU4LITY system i.e. across devices, edge tiers, platform tier and enterprise tier, especially in terms of security configuration and analytics.

OpenFog

The OpenFog Consortium is a public-private initiative, which was founded in 2015 and have many similarities with the IIC. The founding members of the OpenFog Consortium included Microsoft, Dell, Cisco, ARM, Intel and Princeton EDGE Lab and were aiming at solving problems that occurred around development and deployment of edge computing and cloud computing, as well as technical difficulties around latency and controlling assets at the edge.

The OpenFog RA is intended to help engineers, architects, and business leaders to understand their specific requirements and how fog nodes can be applied to a given scenario. The overall goal is to increase the market segments (use cases) for fog computing, and its business value. The OpenFog consortium aim to create testbeds to adapt the high-level architecture to the identified market segments.

In January 2019, the IIC and the OpenFog Consortium announced that they have combined the two largest and most influential international consortia in Industrial IoT, fog and edge computing into a more extensive IIC. The goal of the new IIC is to drive the momentum of the industrial internet, incorporating the development and promotion of industry guidance and best practices for fog and edge computing.

Pillars of OpenFog RA

The OpenFog RA is driven by a set of core principles, that are defined as the Pillars of the OpenFog RA (see Figure 41). These pillars represent the key attributes that a system needs to follow the definition of the OpenFog definition of a horizontal, system-level architecture that provides the distribution of computing, storage, control and networking functions closer to the data source (users, things, etc.) along the cloud-to-thing continuum. The pillars describe requirements to every part of the fog supply chain: component manufacturers, system vendors, software providers and application developers.

Figure 41 – Pillars of OpenFog

- **Security Pillar:** Security is one of the important topics in any IoT solution. This pillar describes all the mechanisms that can be applied to make a fog node secure, starting from the silicon level up to the software application. There is not a single solution for each fog node. It rather describes the mechanisms that can be applied to make a fog node secure on each level.
- **Scalability Pillar:** This pillar addresses the dynamic technical and business needs behind fog deployments. The scalability targets fog node internals (through the addition of hard- or software) as well as the externals, where fog networks should be scalable through addition of new fog nodes to assist in heavy load operation or storage and network connectivity, to enlarge the overall fog network.
- **Openness Pillar:** Openness is essential for the success of ubiquitous fog computing solutions. Proprietary or vendor lock-in can have as a result that only limited suppliers can be available, and thus negatively influence system costs, quality and innovation. Openness is also an essential feature for interoperability between different systems, enabling additional the scalability of the overall network by providing the possibility to integrate systems from different vendors.
- **Autonomy Pillar:** Autonomy enables fog nodes to continue to provide the designated functionality even during external service failures. Decision making will be based on all levels of the system, including near to the device. Autonomy at the edge level means autonomy and intelligence present at the local devices.
- **Programmability Pillar:** Programmability enables to deploy different applications to the fog nodes and the possibility to modify the system on software as well as on the hardware layers. The addition of virtualization

(inclusion of virtual machines) provides also the possibility that multiple operators can access the system at the same time, and have their own environment where they can program their application on the fog node.

- **Reliability, Availability, and Serviceability (RAS) Pillar:** Reliability, availability and serviceability (RAS) are of vital importance These topics refer to hardware, software as the applications running on the node. Reliability defines that the fog node will continue to deliver its designated functionality under normal as well as unexpected behaviour. Availability defines continuous operation (management, control, orchestration, etc.) of the system, which is quite often measured in uptime. Finally, serviceability relates to providing the correct operation to the system, meaning the application performs correctly.
- **Agility Pillar:** Agility focuses on transforming data into information that is needed for the actions within the system. It also deals with the highly dynamic nature of fog deployments and the need to respond quickly to changes inside the network and the deployment, like new data or new requests.
- **Hierarchy Pillar:** Computational and system hierarchy is not always of importance to fog architectures. Many deployments have a different hierarchy, varying from cloud level to shopfloor level. The hierarchy is completely dependent on the application where the fog nodes will be deployed but is of importance to building up the system.

OpenFog Reference Architecture

Besides viewpoints, two other concepts are used to describe the OpenFog RA, namely: *views* and *perspectives*. A view is defined as a representation of one or more structural aspects of the architecture. In the current version of the OpenFog RA, the structural aspects are the Node view, System Architecture view and Software Architecture view. Consecutively, a perspective is identified as a cross-cutting concern of the architecture, which currently include performance, security, manageability, data analytics and control, and finally IT business and cross fog applications. These views and perspectives will be highlighted in the following part. An overview of the OpenFog RA, distinguished in views and perspectives is depicted in Figure 42. The grey vertical bars represent the perspectives, whereas the horizontal-coloured bars include the views.

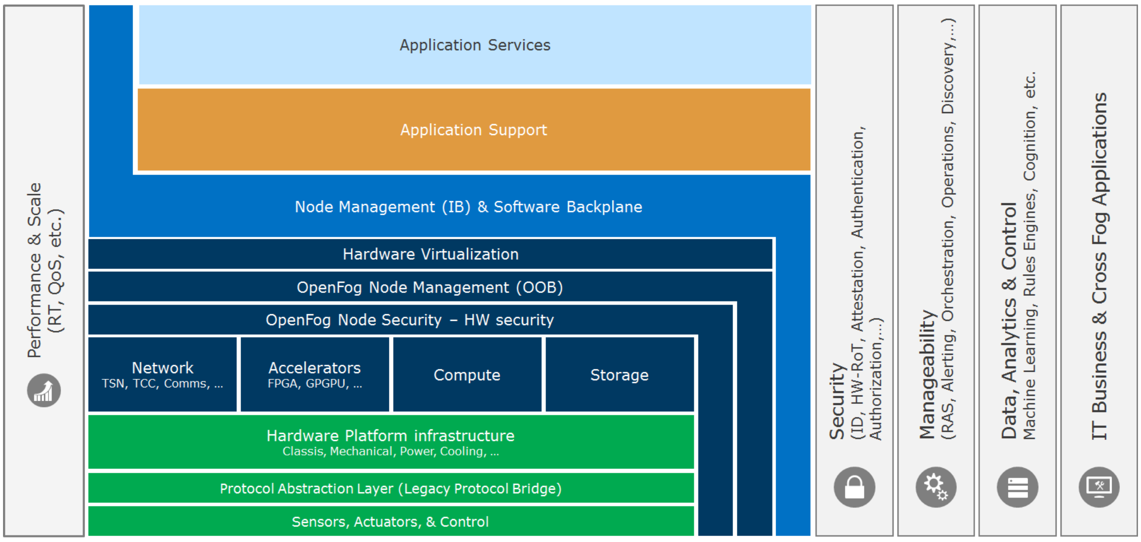

Figure 42 – OpenFog Reference Architecture Description (views) and Perspectives

Cross-cutting perspectives are assigned throughout different fog implementations. "Cross-cutting" refers to functionalities/capabilities that are applied across different architectural layers. As can be seen in Figure 42, there are five cross-cutting perspectives identified for the OpenFog RA.

- **Performance and Scale Perspective:** When fog computing brings some of the intelligence from the cloud to the edge of the network, the performance of the overall system will improve. Additionally, fog computing enables the system to better adapt to changing traffic patterns, meaning that performance improvements happen faster and are also more relevant to business case requirements. Another aspect with respect to performance is that improvements in one area should not negatively influence other processes taking place inside the node. Finally, virtualization and containerization technologies add to the scalability (and additionally the isolation) of the overall system.
- **Security Perspective:** Within a fog computing infrastructure, end-to-end security must cover the whole system between the cloud and the devices on the edge of the network. Security already begins on the lowest level of the system, which is the individual hard- and software of the fog node. On top of secure nodes, the different secure layers must be built, guaranteeing secure node-to-node communication, node-to-next-level communication and node-to-cloud communication.
- **Manageability Perspective:** This perspective focuses on the new manageability model for the fog nodes, as fog nodes will become more autonomous, capable of making decisions in the controlled process or to participate in services provided by other fog nodes. The management of these new deployment approach for god nodes varies from traditional system, as fog nodes will either be dispersed, fixed or non-fixed and could also be

positioned in environmentally harsh conditions, making the management more difficult.

- **Data, Analytics and Control Perspective:** Fog computing provides users the possibility capture, store, analyse and transport data over all the levels of the organization. Another advantage is that by using fog computing, only the relevant data can be analysed and sent over the network. Fog nodes will capture the data directly from the source, analyse and process at the same time the important data that is directly needed at the source and provide an action back to the controller. At the same time, the node can transfer other datasets into the cloud or to other locations for other processing, thereby optimizing the whole system.
- **IT Business and Cross-fog Applications Perspective:** Cross-fog applications require that there is an understanding and adoption of smart objects and associated data models used within the applications. This knowledge is critical for applications to establish interoperability between different fog nodes and application and through that create additional value.

As mentioned before, next to the perspectives, the OpenFog RA description is a composite of different views. Multiple layers of the OpenFog RA are encapsulated in the different identified views.

- **Node View:** The node view is the lowest level view that is utilized inside the architectural description (see Figure 43). Stakeholders involved in this viewpoint are mainly the system on chip designers, silicon manufacturers, firmware architects and system architectures, thus focusing on the lowest design level of the actual fog node. This view describes the most important aspects for a fog node design before it could be included into a (fog) computing network within a factory. The following concepts must be considered:
    - *Security:* as already mentioned before, node security is of vital importance to the overall security of the system. This includes protection for interfaces, compute, etc.
    - *Management:* Interfaces to manage the nodes from high levels inside the overall network, so the node can be managed from different position inside the system
    - *Network:* Each fog node must be able to communicate through the network. If time sensitive and time aware information is required, Time Sensitive Networking (TSN) may be needed.
    - *Accelerators:* Many nodes use accelerators to satisfy required latency and power constraints given by the applied scenario.
    - *Compute:* A node should be providing general purpose compute capabilities, enabling also to integrate legacy software on the node.
    - *Storage:* Storage capabilities are required for a node the take control of an action or to learn new features for the controlled system
    - *Protection Abstraction Layer:* As many sensors and actuators today are proprietary, they are not capable of directly interacting with the fog

node. The abstraction layer enables to bring these devices in interaction with the node.

- *Sensors, Actuators and Control:* These hard- and software-based devices are mostly located on the shopfloor and are the lowest level elements in IoT. Many can be connected to a single fog node, and need to be able to interact with the node.

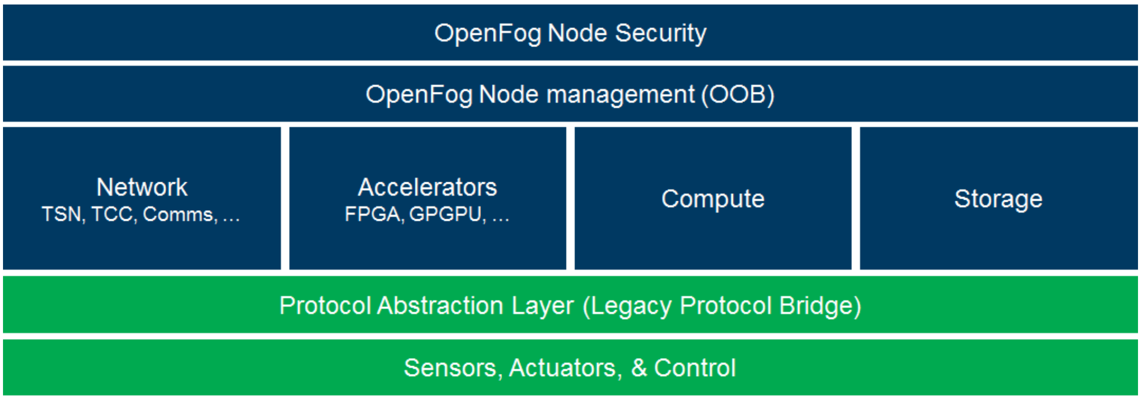

Figure 43 – OpenFog RA Node View

- **System Architecture View:** The system view of the OpenFog RA is composed of one or more node views combined with other components to create a platform (see Figure 44). The stakeholders involved with this view are mainly system architects, hardware OEMs, and platform manufacturers. This view includes the node view, but although only a single node view is included, but the system architecture must be able to support multiple nodes. Therefore, the performance and scale perspective are included to highlight that multiple nodes can be supported. The following concepts are of importance in this view:
  - *Hardware Platform Infrastructure:* Fog nodes must prove robust mechanical support and protection for their internal components. Additionally, these devices must often survive in harsh environmental conditions.
  - *Hardware Virtualization:* (Hardware-based) virtualization mechanisms are nowadays available in almost all processor hardware used to create fog platform. Virtualization is of major importance to fog nodes supporting multiple entities to share the same physical device and improves additionally the security of the system enabling system not to interact with each other.

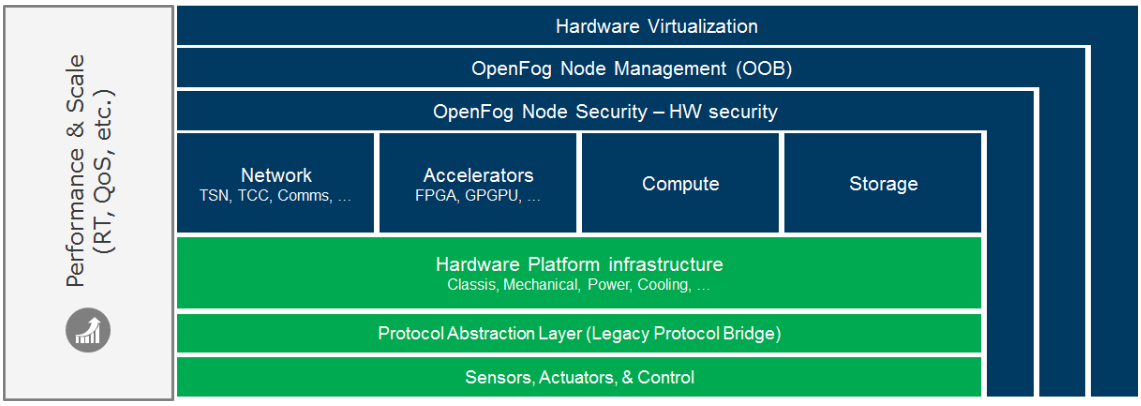

Figure 44 – OpenFog RA System Architecture View

- **Software Architecture View:** The software architecture view is composed of software running on a platform that consists of one or more node views in combination with other components to create a system addressing a given scenario (see Figure 45). The stakeholders involved in this view are mainly system integrators, software architects, solution designers, and application developers of a fog computing environment. Within this view, high level layers are identified:
  - *Application Services:* Services that are dependent on infrastructure, provided by the other layers, fulfil specific end use case requirements and solve domain specific requirements.
  - *Application Support:* Software that is already running in the infrastructure that has no influence on any specific application or use case but is required to support and facilitate the services that are needed for the specific application.
  - *Node Management and Software Backplane:* This refers to the general operation and management of the available nodes and the communication between the different nodes and the overall system. In Band (IB) management refers to how software interacts with the overall management system.

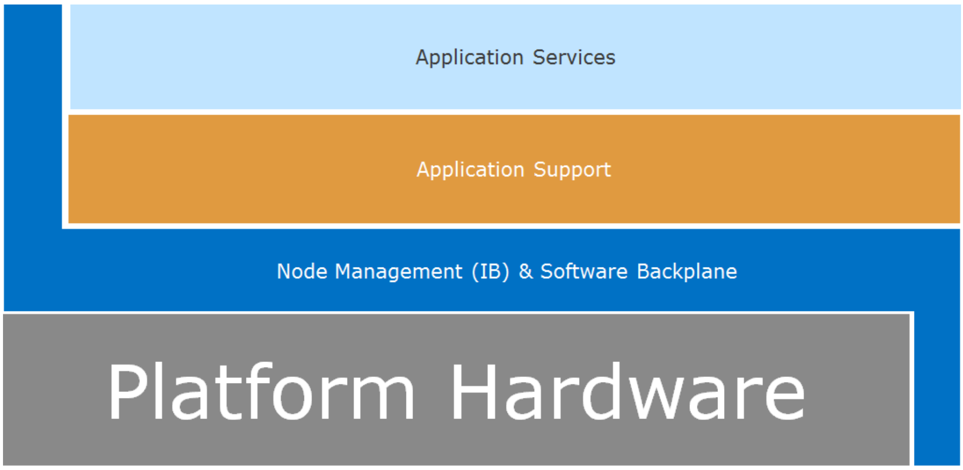

Figure 45 – Software Architecture View

QU4LITY Relationship and Alignment to OpenFog RA

The OpenFog RA inspires the development of the Q-RA in a similar way as the IIRA. As there is overlapping between these RAs, similar concepts from both RAs can be applied to the Q-RA. The following concepts can be investigated for the QU4LTIY RA:

- **Cross-cutting/Cross-fog applications:** Many applications within QU4LITY will have different functionalities, varying from communication, control, etc. These technologies can run on different fog nodes within the applications or the complete pilot line and can be possible distributed over multiple nodes. This will result that applications can run on different nodes depending on where resources are potentially available.
- **Security:** Security is one of the main topics in all kinds of applications. The security concepts already identified for the OpenFog RA can be applied in the overall Q-RA, as it must be applied on all levels from the architecture, starting from the lowest (shopfloor) level up to the highest (cloud) level.
- **Hierarchy Concept:** Fog nodes, and clearly depicted in the description of the OpenFog RA, enable a new hierarchy concept for the networking architecture in IoT applications. Fog nodes will bring knowledge and autonomy closer to the edge of the network, thus closer to the machines (sensors and actuators) on the shop floor. This will require a new hierarchy concept inside the whole architecture, taking technology from the cloud into the edge and having data faster and more directly available to the machines, thus resulting in optimized behaviour. This approach needs to be considered in the Q-RA.

Reference Architecture Model 4.0 (RAMI 4.0)

The **Reference Architecture Model 4.0 (RAMI 4.0)** is one of the prominent reference architectures for Industry 4.0 use. The first version of the reference architecture appeared in April 2015 and was led by the ZVEI together with the VDI/VDE-GMA, DKE and partners in the industry association Plattform Industrie 4.0, including Bitkom and VDMA. This was almost the same time when the Industrial Internet Consortium (IIC) promoted the Industrial Internet Reference Architecture (IIRA). The goal of both architectures is to define a uniform framework for advanced industrial information and communication technologies as well as automation and production technologies. At the same time both standards belong to the category of open standards and has the aim to support business models and innovative solutions, providing a well-defined vocabulary and structure.

Recently, RAMI 4.0 has been successfully recognized in national and international standardization committees and cooperation as DIN standard (**DIN SPEC 91345**) and international pre-standard (**IEC PAS 63088**).

Some of the RAMI 4.0 peculiarities have already been shortly discussed in the previous Deliverables. Deliverable D2.3 *Autonomous Quality Vision for ZDM and Quality Management Excellence* mentioned RAMI 4.0 as one of the important standards that fit in the vision of ZDM and deliverable D2.7 *Standards Compliance and Interoperability Specifications* focuses on RAMI 4.0 as a suitable method to verify the interoperability potentials of QU4LITY Pilots and to build a common interoperable framework. The focus in this document, however, lies in the **architectural aspects of RAMI 4.0.** These aspects need to be taken into consideration when considering the QU4LITY reference architecture.

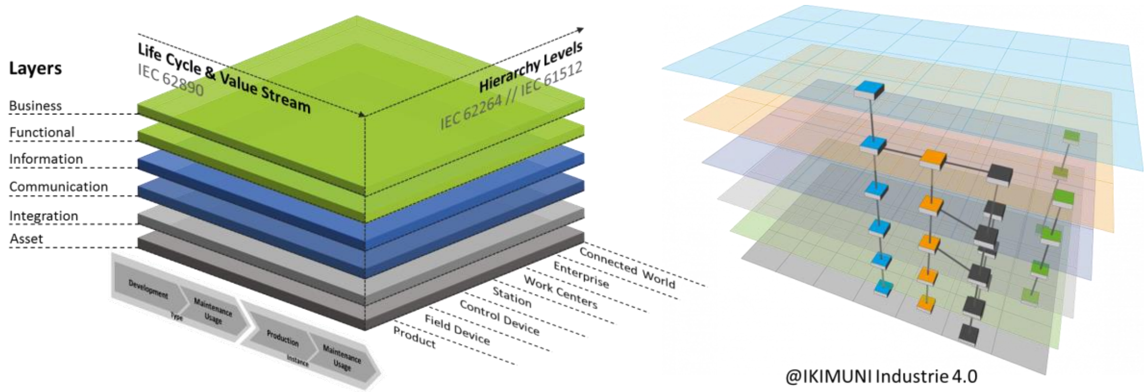

Figure 46 – Structuring capabilities (Source: Fraunhofer IPA, based on ZVEI and IKIMUNI Industrie 4.0)

Analysis of RAMI 4.0 according to various criteria (based on T2.6 task objectives):

1. **Industrial context:** RAMI 4.0 has a strong industrial focus, managing the entire value chains along with product lifecycles. Thus, RAMI 4.0 is fully applicable for manufacturing.
2. **Structuring capabilities:** The architecture is very suitable for structuring technologies as it offers a common structure and language for the uniform description and specification of concrete system architectures. There are helpful tools, for example the XML-based visualization tool for browser, that makes it possible to use the RAMI 4.0 for Industrie4.0-based modelling.

3. **Compliance:** Though each architecture was developed independently with different objectives and scopes, they share very common aspects and approaches. RAMI 4.0 compliance has been analysed with respect to IIRA in the Joint Whitepaper "Architecture Alignment and Interoperability" of the IIC and Platform Industrie 4.0 (IIC: WHT:IN3:V1.0:PB:20171205)[3]
4. **IIOT:** Though RAMI 4.0 does not specifically address the topic of IoT as e.g., *ISO/IEC 30141*:2018 Internet of Things (IoT) - Reference Architecture, a short analysis of both architectures shows compatibility (based on current work of ISO TC 184/ IEC TC 65 JWG 21 *Smart manufacturing reference model(s)).*
5. **Interoperability:** Interoperability is one of the major topics in RAMI 4.0. This can be understood both, firstly, as interoperability across and/or among the layers and, secondly, it can cover the aspects of interoperability inside each layer.
6. **B2B:** The Industrie 4.0 Component and the Asset Administration Shell are key features of RAMI 4.0 that help to reflect a physical object across RAMI 4.0 layers into the informative world (Figure 47). The interoperability of I4.0 Components is greatly dependant on the properties that support the adequate description of products and services in the B2B area.

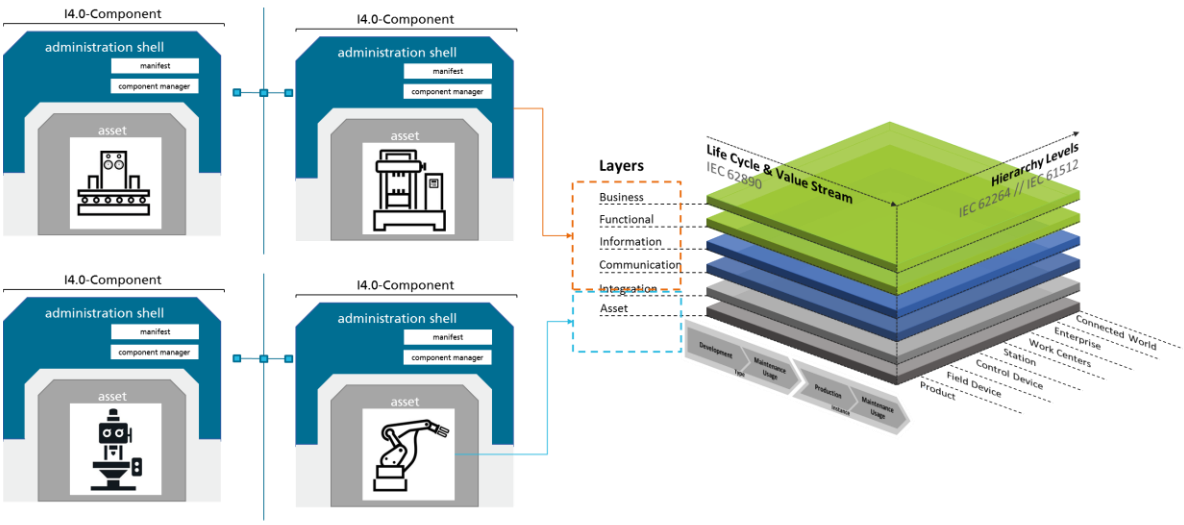

Figure 47 – RAMI 4.0 correlations with the Industrie 4.0 Component and Asset Administration Shell[4]

Industrial Internet Architecture (IIA)

In 2019, the Chinese Alliance of industrial internet (AII) released the Industrial Internet Architecture (IIA) version 2.0 [36]. The architecture includes three aspects: the business view, function architecture and implementation framework.

[3] https://www.iiconsortium.org/pdf/JTG2_Whitepaper_final_20171205.pdf
[4] Source: Fraunhofer IPA, after ZVEI Leitfaden "Welche Kriterien müssen Industrie-4.0-Produkte erfüllen, https://www.zvei.org/fileadmin/user_upload/Presse_und_Medien/Publikationen/2016/November/Welche_Kriterien_muessen_Industrie-4.0-Produkte_erfuellen_/ZVEI-LF_Welche_Kriterien_muessen_I_4.0_Produkte_erfuellen_17.03.17.pdf

Through the construction of the three major functional systems of network, platform, and security, the Industrial Inter- net realizes the integration of IT and OT and the connection of the three systems based on data integration and analysis [37].

The core of industrial internet is the data-driven intelligence that is based on overall interconnection. For both industry and Internet perspective, network, data and security are their common foundation and common support.

"Network" is the supporting basis for industrial system interconnection and industrial data transmission and exchange, including the network interconnection system, identifier resolution system and application supporting system. It performs the seamless delivery of information data between the production system units, and between the entities of the production systems and business systems with the ubiquitous and interconnected network infrastructure, robust and deployable identifier resolution system, as well as the central and generic application supporting system, thereby to build new type of machine communication ways, equipment connection ways by wired and wireless technology, and supporting production models with features of real-time sensing and collaborative interaction to generate.

"Data" is the core driver of industrial intelligence, including functional modules such as data collection and exchange, integrated processing, modelling and analysis, decision optimization, and feedback and control. It can enable precision computing and complicated analysis of the production site, information of the collaborative enterprises, and customer needs through collection and exchange of massive data, by collection and exchanging of massive data, integrated processing of heterogeneous data, edge computing of machine data, fixed iteration of experience models, and cloud-based big data computing and analysis, thereby producing management decisions for enterprises operation and control commands for machine running to drive the intelligence and optimization of equipment, operation management and commercial activities.

"Security" refers to the protection of networks and data in industrial internet, including equipment security, network security, controlling security, data security, application security and comprehensive security management. It tries to protect network infrastructure and system software from internal and external attacks, reduce the risk of unauthorized access of enterprise data, guarantee the data transmission and storage security, and realize the all-around protection of both the industrial production system sand the business systems. The industrial internet architecture is shown in Figure 48 as below.

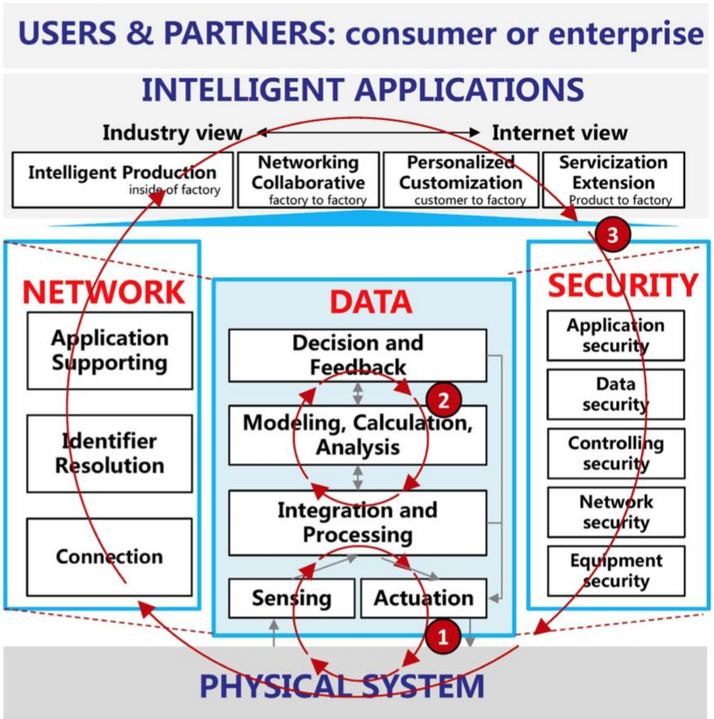

Figure 48 – Industrial Internet Architecture (Internet, 2019)

Based on network, data and security, the industrial internet will build three optimization close loops oriented to intelligent industrial development. The first close loop is oriented to equipment operation optimization, the core of which is real- time sensing and edge computing based on machine operation data and production environment data, to bring about dynamic optimization and adjustment of the machines and equipment, and develop smart machines and flexible production lines; the second is oriented to production operation optimization, the core of which is integrated processing and big data modelling analysis based on information system data, manufacturing execution system data, and control system data, to realize dynamic optimization and adjustment of production operation management and generate intelligent production models for various scenarios; and the third is oriented to enterprise collaboration, user interaction and optimization of products and services, the core of which is comprehensive integration and analysis based on supply chain data, user requirement data and product and service data, to produce new models like network-based networking collaboration, personalized customization and servitization extension. (Internet, 2019)

As shown in Figure 49, the platform architecture includes three layers: edge layer, PaaS layer and SaaS layer [38].

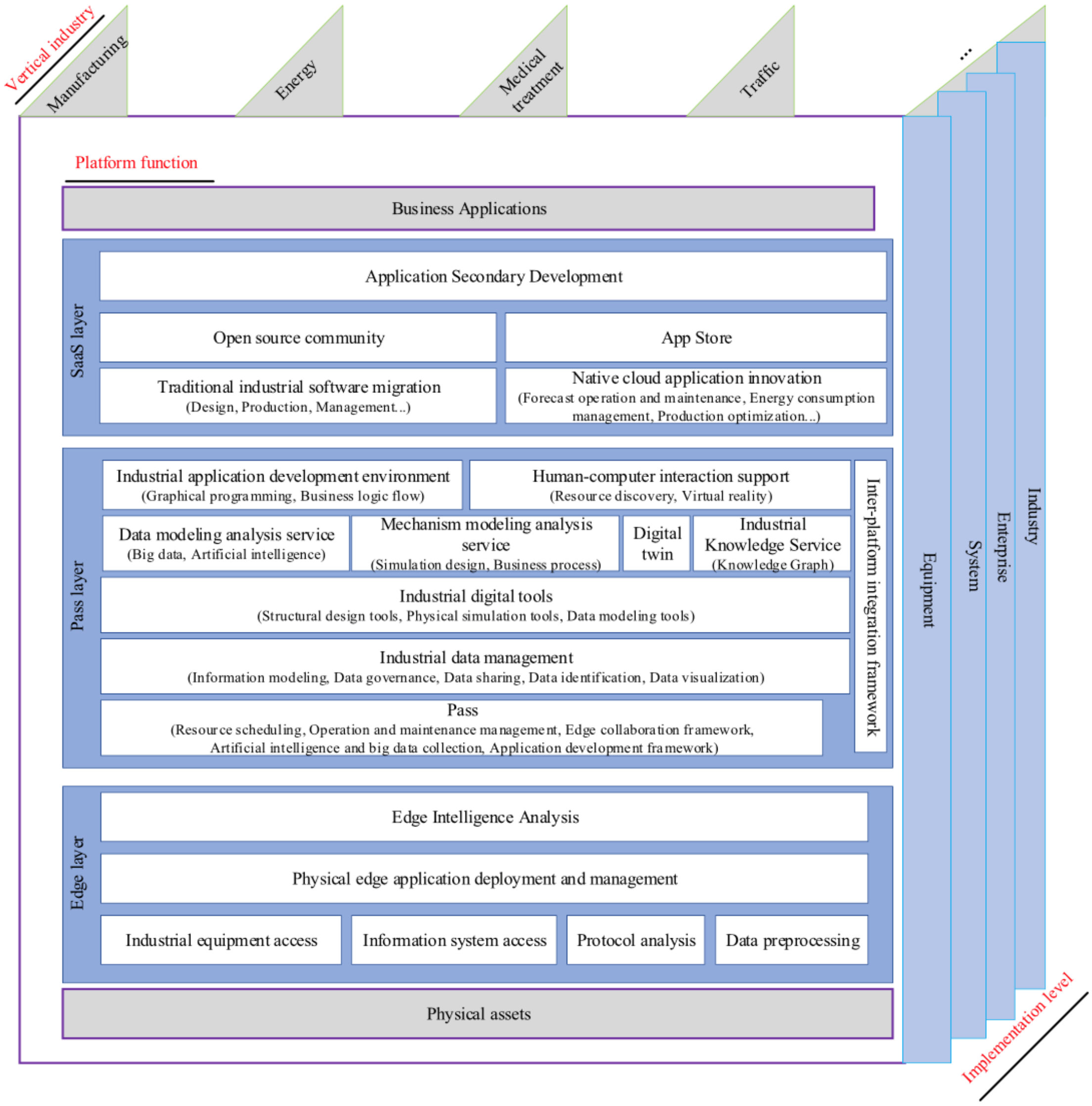

Figure 49 – Industrial Internet platform architecture (Internet, 2019)

Digital Shopfloor Alliance (DSA)

The Digital Shopfloor Alliance (DSA) is a Service Reference Framework (RF) that aligns the cognitive manufacturing technical enablers, i.e., robotic systems, smart modular machines, cloudified control, secure cloud-based planning systems and applications to facilitate the development and deployment of cognitive automation systems while exploiting cloud technologies and smart services. Moreover, the DSA has a broad industrial capability, maps applicable technologies to different areas (IT/OT) of the enterprise and serves as a guide for deployment of Industry 4.0 technologies and smart digital manufacturing platforms and services supported by open international standards.

The main objective of the DSA is to provide a reliable, cost-effective integrated platform to provide solutions and services to support small European enterprises, both in terms of customized and flexible applications.

The three projects involved in the DSA (AUTOWARE, Daedalus, FAR-EDGE) provide a complete CPPS solution allowing SMEs to access all the different components to develop digital automation cognitive solutions for their manufacturing processes.

DSA Service Reference Framework Layers

This reference framework service consists of four main pillars (Modelling, Digital services, Digital infrastructure, Cybersecurity) and four layers/levels (as can be seen in the figure below), which target all relevant layers where digital service platforms can be deployed to cover the whole manufacturing process, from the shopfloor to the cloud. Moreover, those four layers of the architecture organize all the components/applications of a SME in their corresponding architecture layer depending on the intended functionality and smart service workflow. The layers are fully aligned with those proposed by **RAMI 4.0** IEC 62264 specifications.

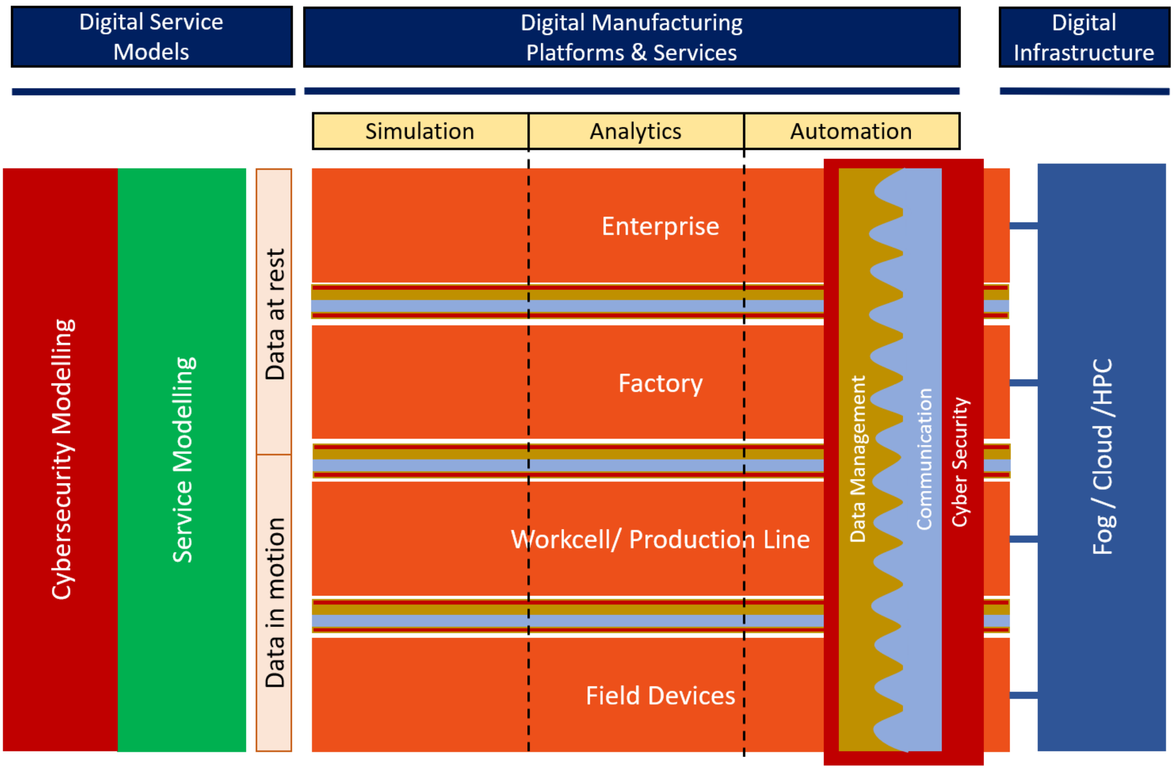

Figure 50 – DSA Reference Framework

The digital service pillar is decomposed in various layers as follows:

- **Enterprise.** The enterprise layer is the top layer of the reference service framework and encompasses all IT enterprise services.

- **Factory.** At the factory layer, a single factory is depicted. This includes all the various workcells or production lines available for the complete production. This layer is connected to services needed to manage the production holistically.
- **Workcell/Production Line.** The workcell layer represents the individual production line or cell within a company. Nowadays, a factory typically contains multiple production lines (or production cells), where individual machines, robots, etc. are located in. Therefore, this layer refers to services mainly addressed to the management and operation of such working environments.
- **Field Devices.** The field devices layer is the lowest level of the reference architecture, where the actual machines, robots, conveyer belt, etc., but also controllers, sensors and actuators are positioned. This layer is also the one where the actual product is placed. Therefore, embedded services related to the control and operation of the individual machines and manufactured products are placed in this layer.

The four layers are connected by three main pillars:

- **Modelling Pillar.** This pillar focuses on the modelling of the different technical components inside the different layers (green column in Figure 50). On each layer, different tools or technologies are applied and for all of them different modelling approaches are available. The interested reader can refer to the Figure 51 for a sample of open modelling and engineering tools available.
- **Digital Infrastructure Pillar.** This pillar is intended for the Fog/Cloud/HPC infrastructure required for the operation of the digital services pillar as well as communication and data distribution enablers to create direct interaction between the different layers. This layer is therefore focused on the enablers for (Big) Data ingestion, processing and management both data in motion and data at rest.
- **Cybersecurity**. This pillar is focusing on offering a reliable and secure use of the communication and information technologies. This safe and reliable environment should be offered through all layers of the company, from the plant to the cloud.

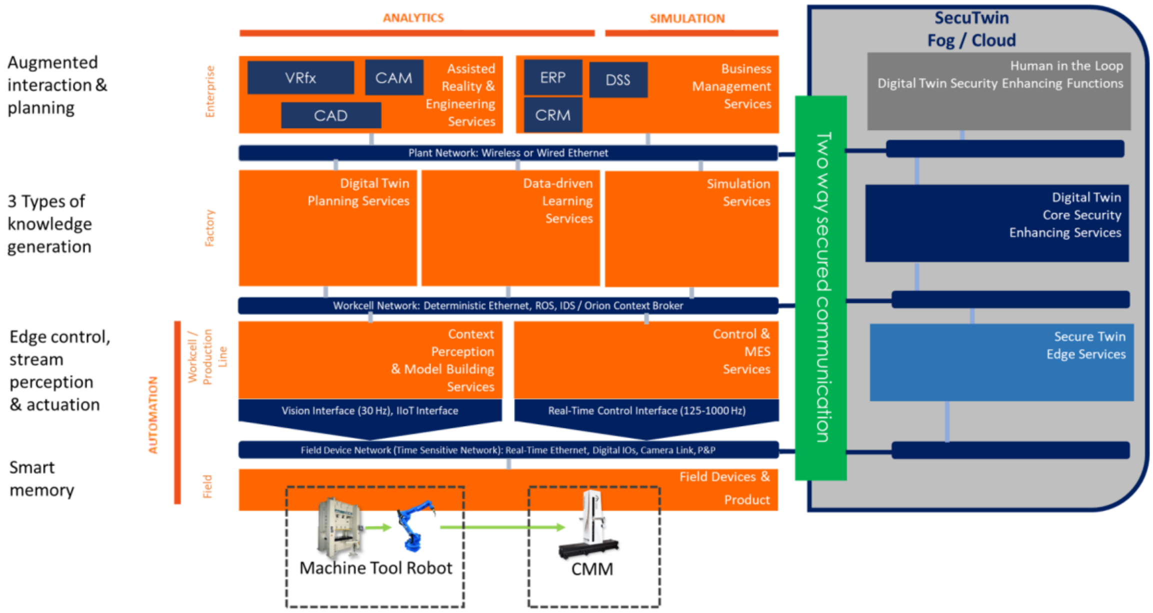

Figure 51 – Digital Infrastructure Pillar of the DSA Reference Framework

DSA and IEC61499

The IEC 61499 architecture represents a component solution for distributed industrial automation systems aiming at portability, reusability, interoperability and reconfiguration of distributed applications. IEC 61499-based control technology can be used to programme a complete plant and equipment, even with several controllers in a distributed control system. Distributed intelligence is thereby enabled what is an essential prerequisite for Industry 4.0.

The IEC 61499 standard allows:

i. the design and modelling of distributed control systems and application execution on distributed resources (not necessarily PLC),
ii. the creation of portable and interchangeable data and models and the re-utilization of the code,
iii. the seamless management of the communication between the different function blocks of an application (independently from the hardware resource they run on), and
iv. the decoupling of the elements of the CPS (its behavioural models) from the physical devices and reside (designed, used and updated) in-Cloud, within the "cyber-world", where all the other software tools of the virtualized automation pyramid can access them and exploit their functionalities.

Among others, code modularity, reusability and reconfigurability of systems are the main features that are advertised as practical benefits of applying this Standard. The result is the ability of designing more flexible and competitive automation systems by providing the functionality to combine hardware components and software tools of different vendors within one system as well as the reuse of code.

As mentioned in Chapter 0, the European initiative DAEDALUS, financed under the Horizon 2020 research programme, is one of the three projects involved in the DSA, along with AUTOWARE and FAR-EDGE. The core enabling component of DAEDALUS vision is the automation platform resulting from the evolution of the IEC 61499 standard. The project was conceived to enable the full exploitation of the CPS' virtualized intelligence concept, through the adoption of a completely distributed automation platform based on IEC 61499 standard.

When considering all the features of the IEC 61499 standard, it can be a great asset in achieving the main goal of the DSA. The HW independence, reusability and portability of developed applications saves costs and provides the ability to develop flexible applications customized for users from different domains by exploiting pre-defined libraries of FBs.

Digital Factory Alliance (DFA)

The Digital Factory Alliance is a European Community of Digital Factories that has been created to answer the industry's needs in terms of:

- Accelerating the innovation and commercial exploitation of digital products that could develop and unfold the values in its Manifesto (digital-for-all).
- Building a cross-border, cross-sectorial, network of trusted products and companies that perform competitive processes, with the goal of advancing towards the values of the manifesto.
- Pursuing a fast RoI in today's digital investments, without compromising any future decisions, needs and processes regarding digital transformation.

All the above mentioned is achieved by promoting the use of Open Standards and common and open data models, by having common certification processes of digital components and systems, and, finally, and most relevantly at this point, by sharing a common vision and Reference Architectures.

To facilitate the replicability of the Zero-X manufacturing lighthouse trials and Nig Data-powered AI-driven solutions piloted, the DFA relies on the alignment and harmonization of three reference models. The DFA model thus counts on three different Reference Architectures:

- A Big Data Pipeline RA (Data-Driven 4.0 Factory RA): the DFA model is fully aligned with ISO 20547 to drive Industry 4.0 Big Data pipeline and process engineering and operation. The goal is to ensure universality and transferability of trial results and big data technologies as well as economies of scales for big data platform and technology providers across sectors.
- A Manufacturing Data Space RA (IDSA RA): the DFA model adopts the DIN27070 International Data Spaces Association (IDSA) Reference

Architecture, which has been recently adopted by Gaia-X Federated European Industrial Data Cloud RA. DIN27070 is compatible with Hyperledger distributed ledger RA and SOLID. The goal is to ensure sovereignty and trust in manufacturing data sharing spaces and connected digital value chain processes.

- A Manufacturing 4.0 Digital Service Integration RA (**which is precisely Q-RA**): the DFA model applies a Digital Service Integration Reference Architecture (DSI-RA) fully compliant RAMI 4.0 and IIRA. The goal is to ensure a perfect alignment between big data processes, platforms and technologies with overall digital transformation and intelligent automation efforts in Zero Factories and connected supply manufacturing networks.

In this last case, the objective for this evolution of the DSA Framework in the Digital Services Implementation Architecture, from the architectural point of view, has been to graphically highlight the convergence of IT and OT technologies within a factory, from the automation degree of the physical lay-out (Intelligent Automation) to the intelligence of the control platforms (Artificial Intelligence).

The objective of each of them is:

- The Intelligent Automation intends to enhance and deepen in the automatization of operations and regarding the transport of materials between Workcells within a Factory. Towards higher levels, different degrees of Manufacturing Flexibility are obtained, the overall objective being the ability to maximise the customisation of products and the different specifications that can be produced, by making minimal changes to the lay-out or equipment set-ups.
- The Artificial Intelligence refers, in the first place, to the Vertical Integration of the information within a company (the CIM pyramid of Industry 3.0), but also intends to enlarge the knowledge the human factor has regarding the manufacturing processes. Firstly, by making context-self-aware equipment regarding the environment the machines and lines work at, and, next, by transforming these newly acquired data to planning and action capabilities through an ever-learning platform, being the decision-making increasingly lying on the machine.

For this, the concept of Autonomous Equipment has been elaborated and a two-dimensional scale has been proposed, documented on the recently submitted D4.4. All QU4LITY Pilots will be evaluated against this categorization (as all Pilots' components are mapped within the Q-RA in Section 5 of this document), as common KPI. The convergence of OT and IT layers is, thus, more than ever, present in the reference model which constitutes the Q-RA.

The final version of the DFA Digital Service Implementation RA is highlighted below, and its layers and different modules and infrastructures will be thoroughly documented in the upcoming Section 4 – QU4LITY Architecture Framework.

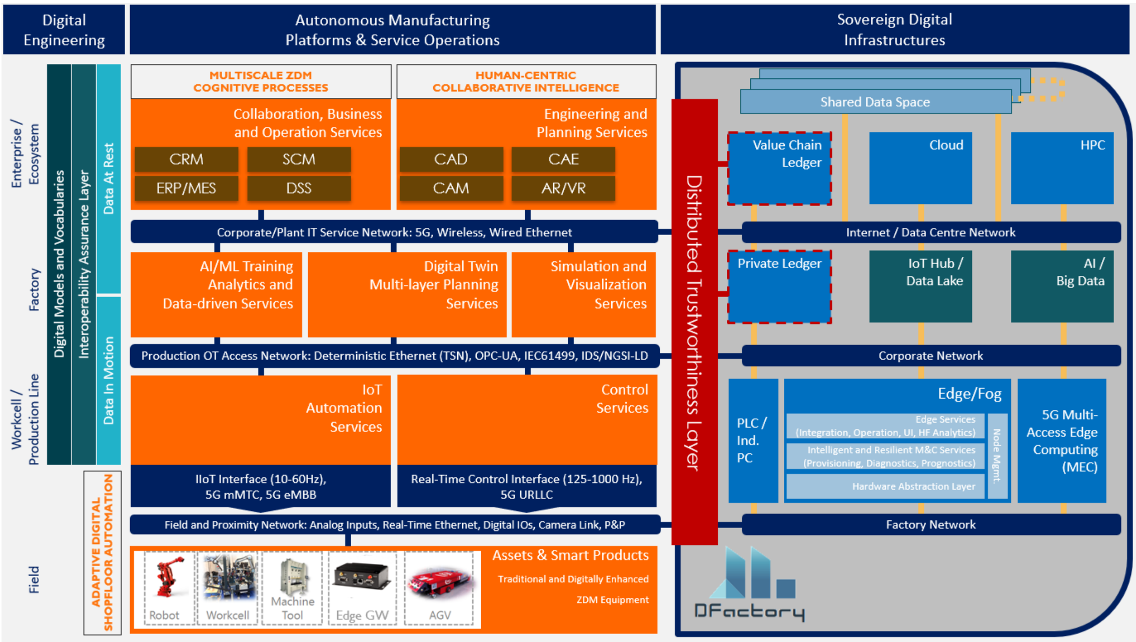

Figure 52 – DFA's Digital Services Implementation Reference Model