DIGITAL MANUFACTURING PLATFORMS FOR CONNECTED SMART FACTORIES

D2.11 Reference Architecture and Blueprints (Version 1)

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Abstract: A report on the first 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.

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Contents

HISTORY

Version	Date	Modification reason	Modified by
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0.2	02/10/2019	Added Sections 2 and 3, and a first draft of Section 5	Angelo Marguglio
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1 Executive Summary

One of the challenges in implementing Autonomous Quality (AQ) processes and solutions is the development of the QU4LITY **Reference Architecture (RA)** for digital ZDM solutions for smart manufacturing, based on innovative technologies and on relevant sector standards such as RAMI 4.0. Then, building from there, **blueprints** may be 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 will also develop a **Reference Implementation (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 first release of the QU4LITY RA and the overall, abstract design of a QU4LITY-based system. It also reports on the initial technological choices and standardization framework identified for the QU4LITY RI. The full specification of both the RA and RI will be the result of the incremental development process as part of the activities within T2.6.

The QU4LITY RA will not be 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 Platform Industrie 4.0 initiative (RAMI 4.0), the Industrial Internet Consortium (IIRA and OpenFog RA).

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 providing solid backgrounds. Following this experience, the Digital Shopfloor Alliance Reference Framework has been adopted as the main input to further enhance it for ZDM scenario, exploiting it adherence to standards and the openness toward the integration of multiple digital enablers.

Firstly, a wide range of state-of-the-art standards and open source frameworks, platforms and tools have been briefly assessed in order to determine their suitability as baseline assets (see Section 3 and 4).

Consistently with this approach, Section 5 presents the QU4LITY 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 *Digital Infrastructures* providing common services such as connectivity and distributed processing capabilities. Moreover, the QU4LITY RA groups system functionality into three distinct **Functional Domains** (*Adaptive Digital Shopfloor Automation*, *Multiscale ZDM Processes* and *User-Centric ZDM*), which are orthogonal to the Tiers, and four **Crosscutting Functions** (*Security*, *Digital Infrastructures* and *Digital Models*) 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 provided in this document (see Section 5) 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 an initial validation of the QU4LITY RA's design against the project's requirements and reference use cases (UC), which are the outcome of previous deliverables (D2.1 and D2.3), an overview of the project vision is presented in Section 5.1. Then, QU4LITY 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 5.3, 5.4, 5.5 and 5.6).

As the QU4LITY RA is, at this stage, an abstract design, this document also reports about the methodology suggested (and further explored in the next iteration) to provide blueprints for actual implementations, in order to set up a sound development playground for the RI (see Section 6). Generally speaking, the QU4LITY RI will be a working, fully integrated platform prototype 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. D2.11, "Reference Architecture and Blueprints (Version 1)") aims to report on the initial results of tasks T2.6 ("Reference Architecture, Open APIs and Blueprints for Autonomous Quality Solutions"). However, relevant information to the starting or 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 initial version of the deliverable, foreseeing further details in the outcomes of the other WPs.

Task T2.6 follows an incremental-iterative approach, which is still an ongoing activity, thus only initial results are included in D2.11 and the final results will be reported in M27 in the scope of D2.12 ("Reference Architecture and Blueprints (Final version)").

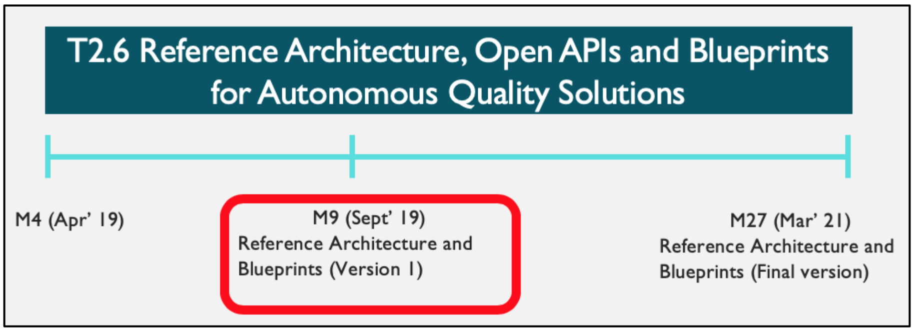

Figure 1 – Task T2.6 timeframe and related deliverables

The purpose of task T2.6 is to identify key challenges to be overcome by 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 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 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. Generally speaking, 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 (RA)** will be designed using an architecture-centered, scenario-driven, iterative development process.

The QU4LITY 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 and reported in Section 3.3 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 and D7.1).

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.

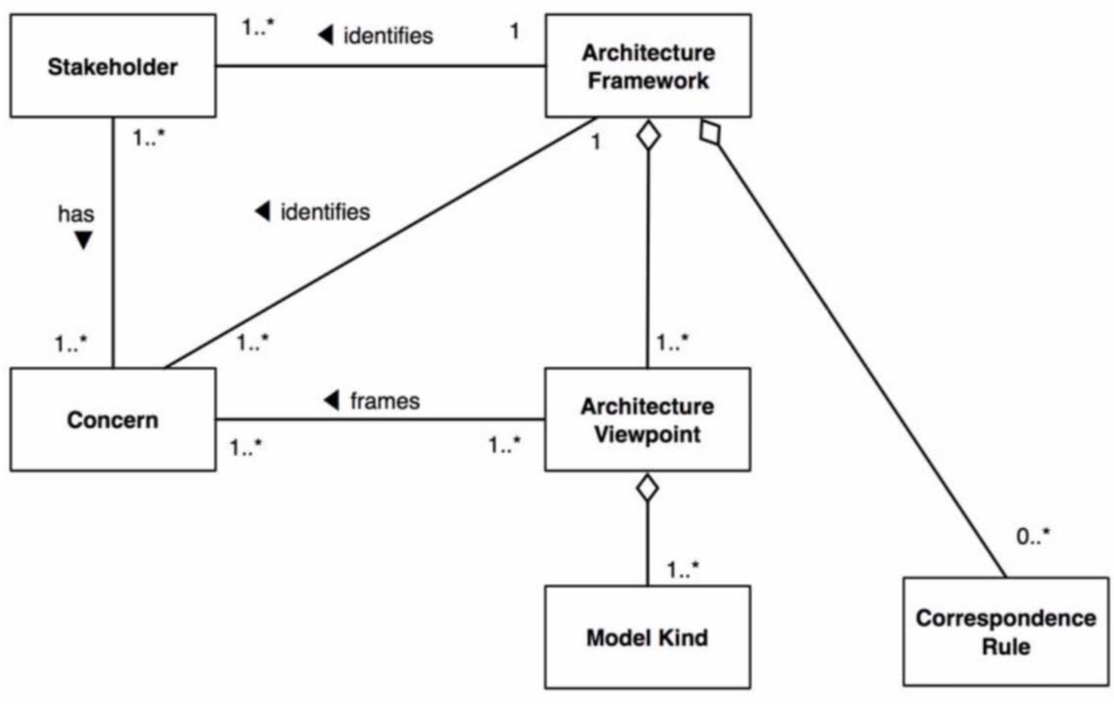

Figure 2 – The Architecture Framework entity model in ISO/IEC/IEEE 42010

In the context of the QU4LITY Architecture Framework (further described in Section 5), 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 following Section 4.

Note however that the QU4LITY RA architecture has considered high-level requirements of D2.1, rather than the low-level technical ones that will be further analyzed in the scope of WP3, WP4 and WP5. This is because the presented QU4LITY 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.

2.3 Document Structure

D2.11 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.

- **Background and Vision**: An analysis of other EU context and initiatives 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 digital enablers 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 the technical developments in WP3, WP4 and WP5.

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

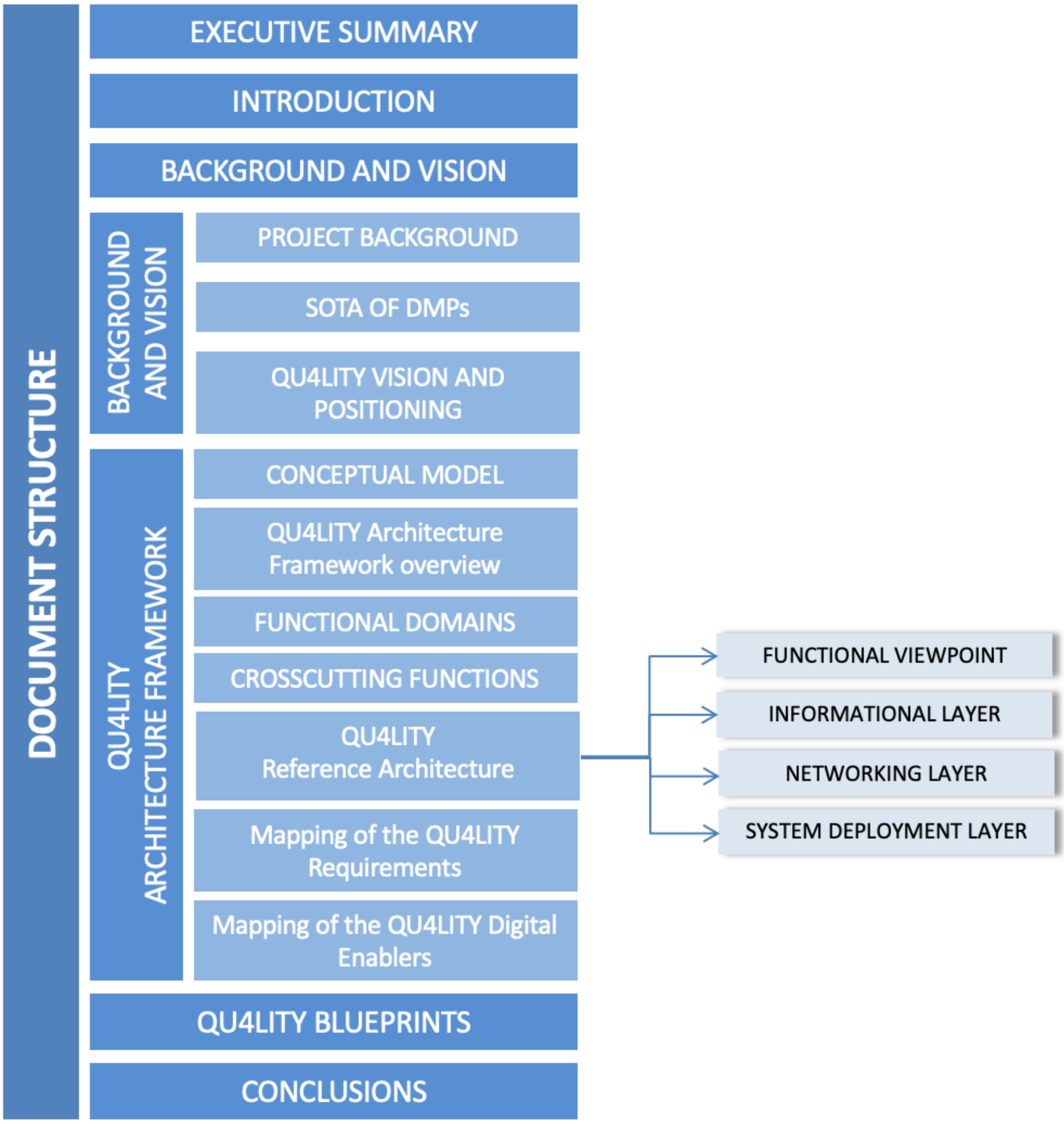

Figure 3 – D2.11 document structure

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, due to the fact that 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 have to 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.

In particular 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). As a consequence, 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.

The following sections will present the state of play of Digital Manufacturing Platforms and their role within the QU4LITY vision, while the next Section 4 will present a short state of the art of the main reference architectures already available in the manufacturing arena.

3.2 State of the art in Digital Manufacturing Platforms for ZDM

Manufacturing industries are continuously facing the challenge of operating their manufacturing processes in order 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 shop-floor/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 behavior.
- 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 (Nondestructive 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 in order 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, taking into account 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 in order 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 have to 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 considered to be 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.

3.2.1 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]**¡Error! No se encuentra el origen de la referencia.**.

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.

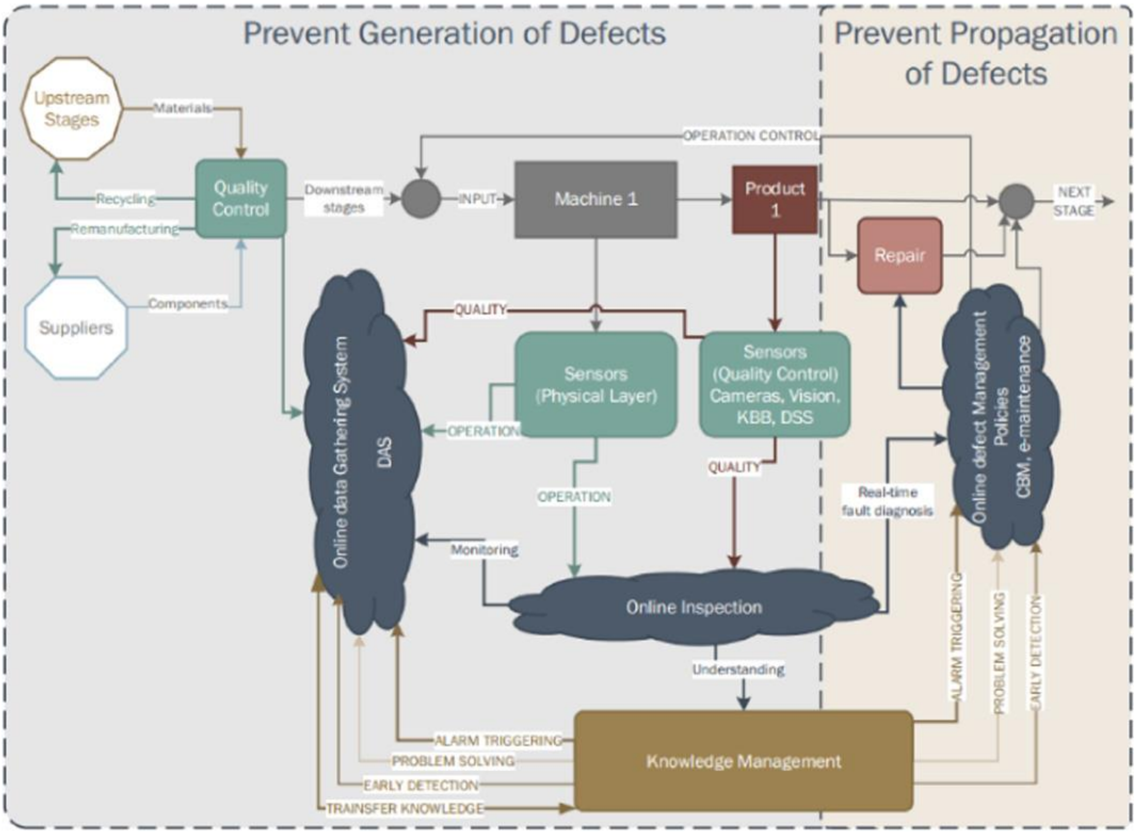

Figure 4 – Zero defect manufacturing system

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. This 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 of 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 (Work-station and Quality) are logged into servers with time indexes. Wireless or cable transmission of data are achieved through a local area network. In order 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 is able to solve the problems arising in the production to maximize performance signalling strategies for handling the possible defects.

Manufacturing processes have to 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 55):

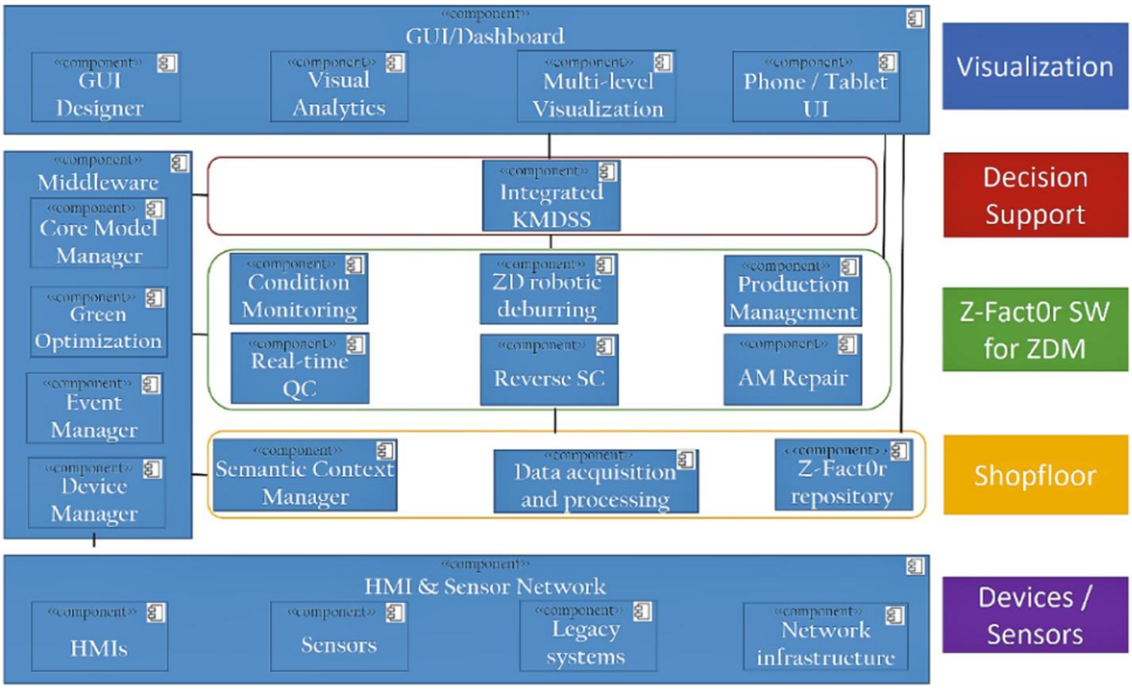

Figure 5 – Z-Fact0r System Architecture

- 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.
- Shop-floor 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.

In general, the idea of Z-Fact0r complete solution comes from the knowledge on the blackboard's architectural pattern that provides a computational framework for the design and implementation of systems, that need to integrate large and diverse specialized components. This Z-Fact0r blackboard architectural pattern provides the essential communication elements (middleware) for sharing information among components. In this context, novel correlation of machine behaviour with the process performance and the produced quality provide a vital feedback to the control loop in manufacturing systems.

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 is able to 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.

3.2.2 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 6), 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:

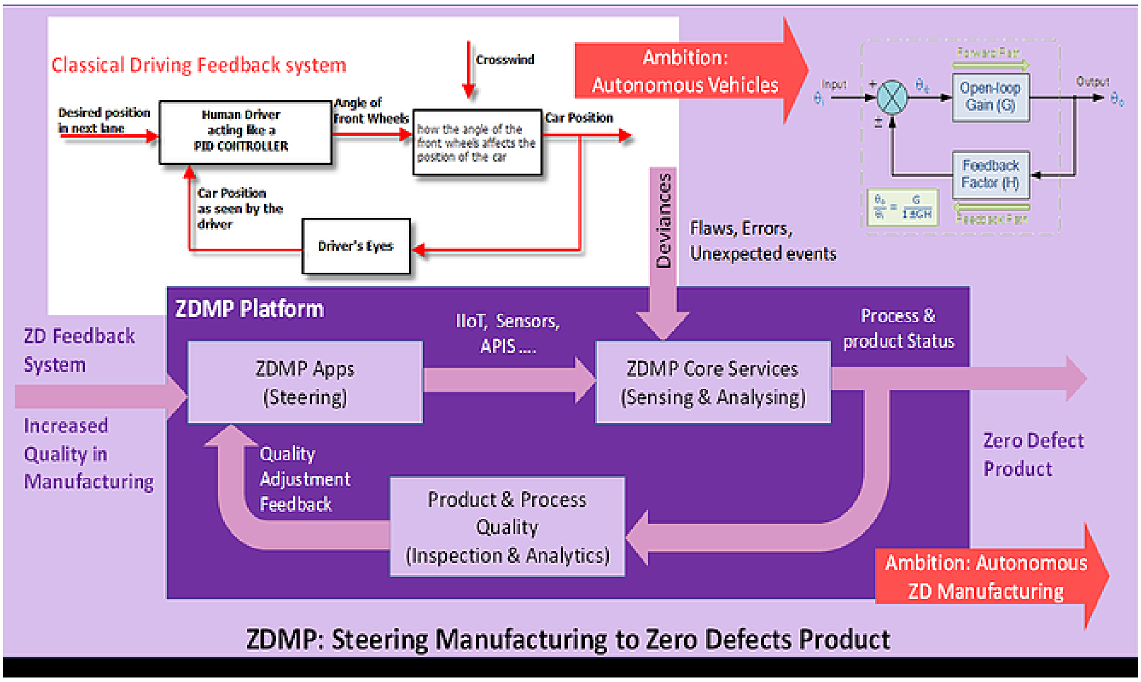

Figure 6 – ZDMP System Architecture

- To build applications that monitor, manage and control connected devices.
- To collect and analyze 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.

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.

3.2.3 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 ZeroDefect 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 in the near future, 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 future 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.

3.3 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.

4 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 have to be taken in consideration, in order to match all the stakeholders' expectations as much as possible.

4.1 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 also 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].

4.1.1 IIRA

4.1.1.1 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 in order to collect information from the shopfloor on the one hand and on the other to interact with shopfloor devices and processes in order 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's 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.

4.1.1.2 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 takes into account 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 QU4LITY 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 a number of 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 77.

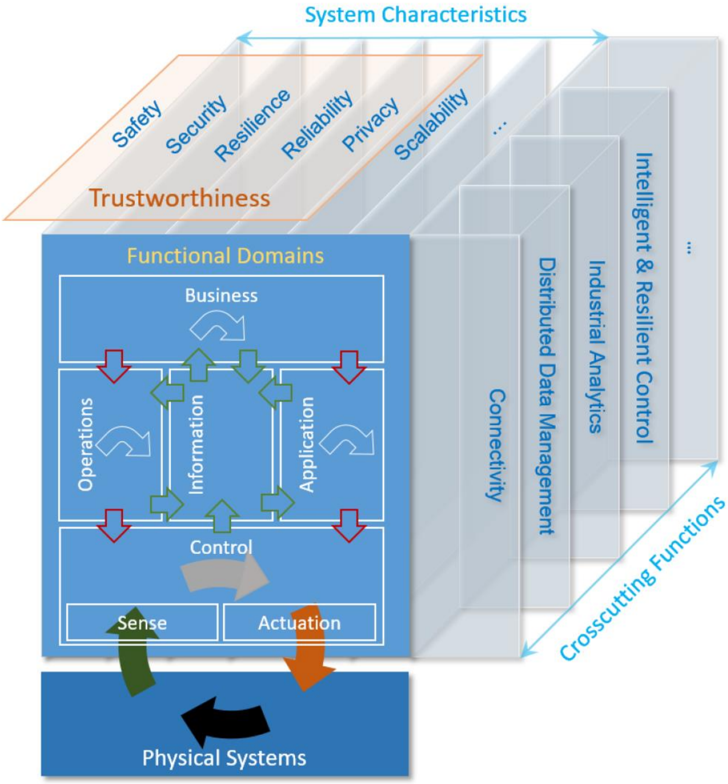

Figure 7 – Functional Domains and Cross-Cutting Functions specified in the IIRA[1]

Note that Figure 77 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 88 presents the functional decomposition of the control domain i.e. it presents the main components of a control application. The latter include sensing and actuation functionalities, which are driven by an Executor that takes into account an abstract modelling of various entities. The IIRA includes similar break downs for the rest functional domains of the IIRA.

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[1] The Industrial Internet of Things Volume G1: Reference Architecture Version 1.9, June 19, 2019

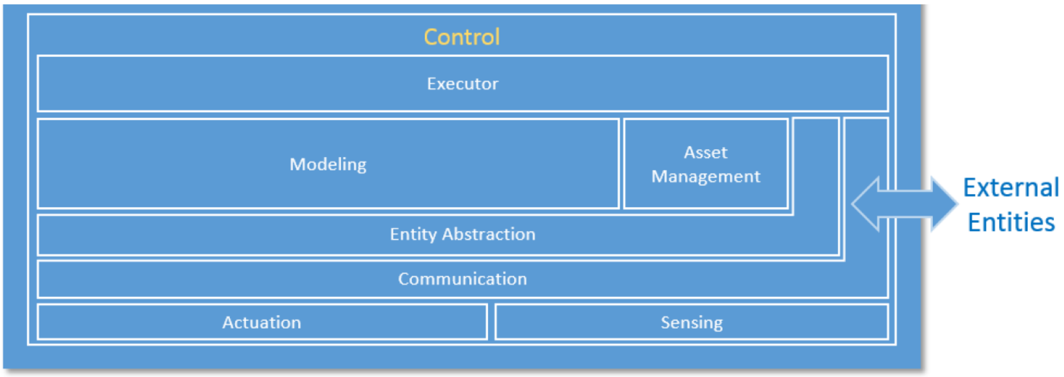

Figure 8 – Functional Decomposition of the Control Domain

4.1.1.3 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 99. 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 have to 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 of these tiers.

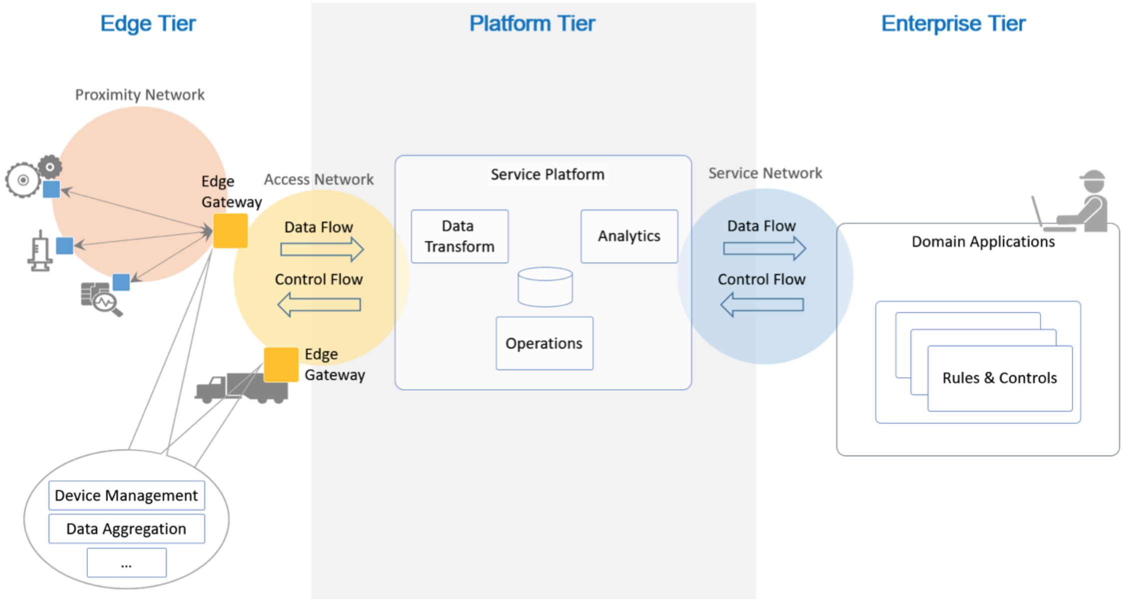

Figure 9 – Three Tier Implementation Architecture specified in the IIRA

4.1.1.4 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 1010, 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.

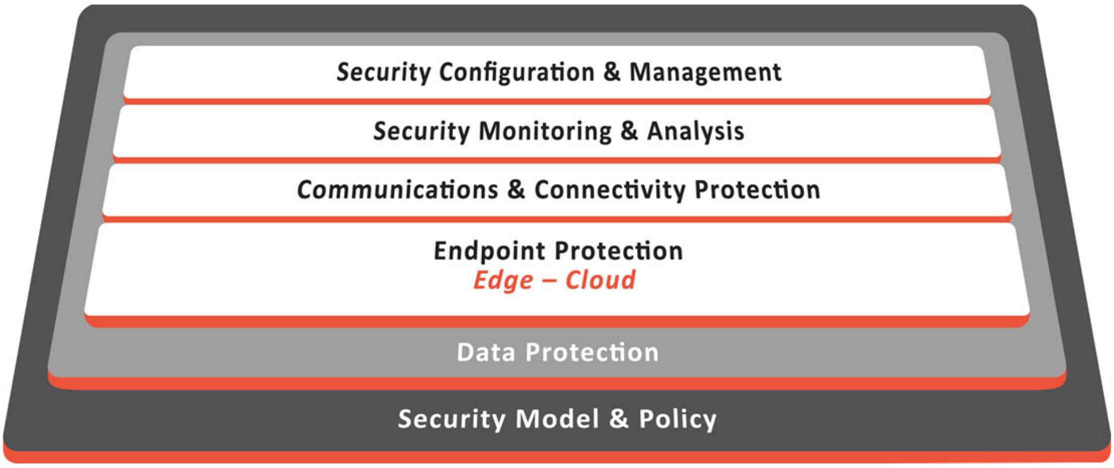

Figure 10 – Functional Overview of the IISF

4.1.1.5 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 QU4LITY 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 QU4LITY 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 RA of the FAR-EDGE project [1].
- **Cross-Cutting Functions**: The QU4LITY 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 QU4LITY 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 QU4LITY 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.

4.1.2 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 test-beds 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.

4.1.2.1 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 111). 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 11 - Pillars of OpenFog

- **Security Pillar:** Security is one of the important topics in any IoT solution. This pillar describes all of the mechanisms that can be applied to make a fog node secure, starting from the silicon level up to the software application. There isn't 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 does what it is supposed to do.
- **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.

4.1.2.2 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 122. The grey vertical bars represent the perspectives, whereas the horizontal coloured bars include the views.

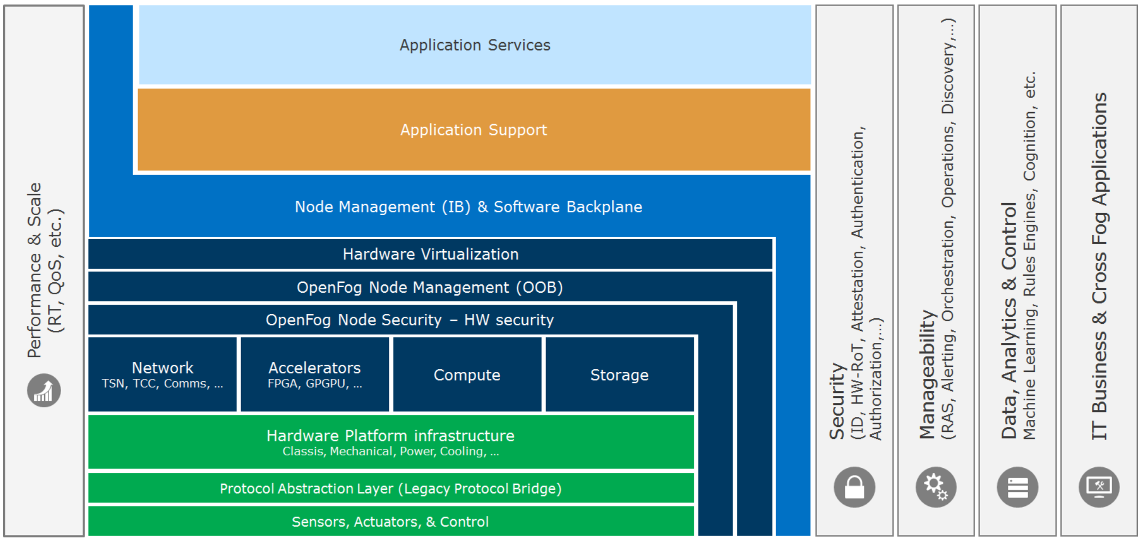

Figure 12 – OpenFog Reference Architecture Description (views) and Perspectives

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 122, 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 shouldn’t 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 in order 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 133). 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 have to 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.

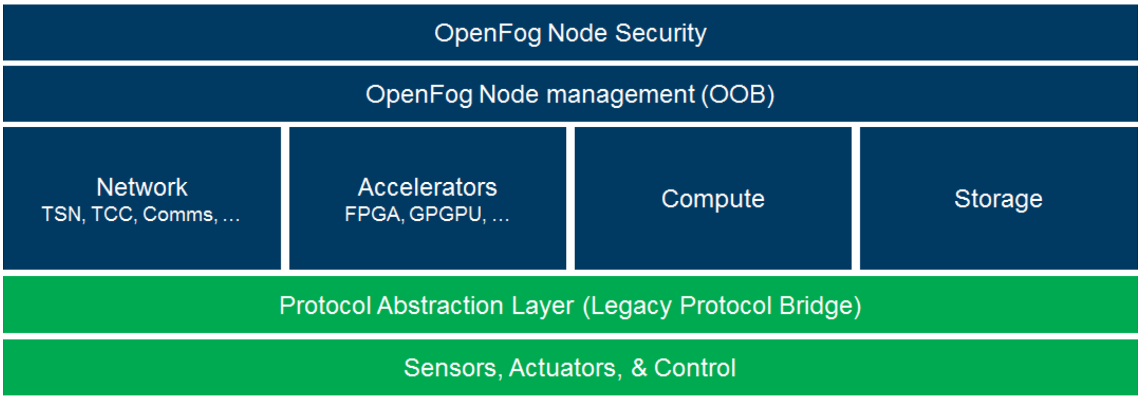

Figure 13 – OpenFog RA Node View

- **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 144). 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 mechanism 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.

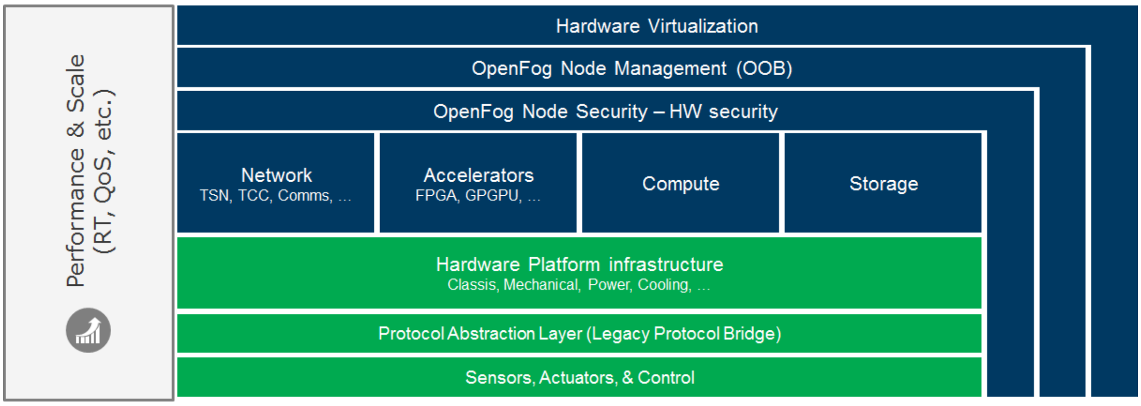

Figure 14 – OpenFog RA System Architecture View

- **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 155). 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, fulfill 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 actually interacts with the overall management system.

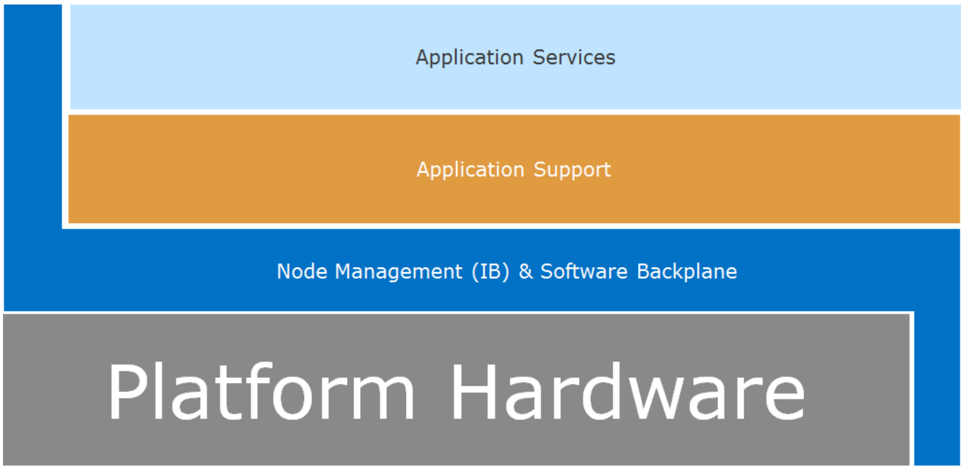

Figure 15 – Software Architecture View

4.1.2.3 QU4LITY Relationship and Alignment to OpenFog RA

The OpenFog RA inspires the development of the QU4LITY 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 QU4LITY RA. The following concepts can be looked into 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 kind of applications. The security concepts already identified for the OpenFog RA can be applied in the overall QU4LITY RA, as it has to 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 QU4LITY RA.

4.2 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 Platform 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 cooperations 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 main 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.

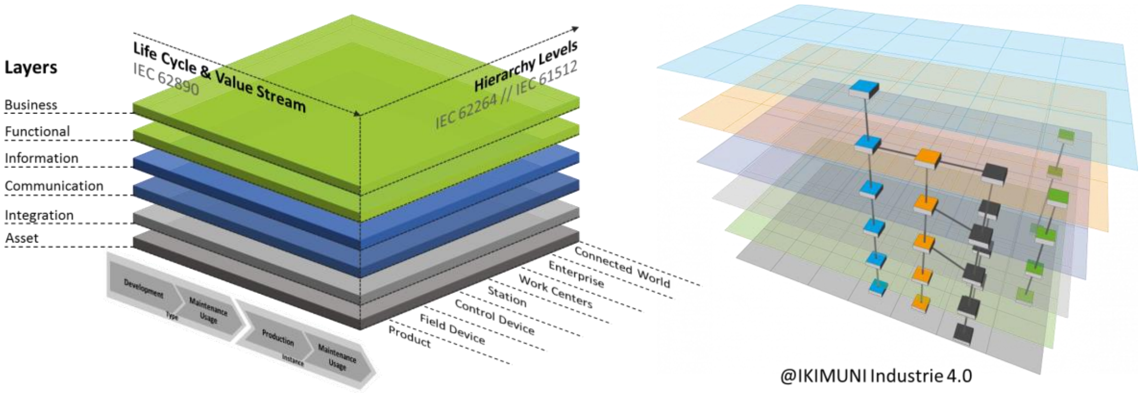

Figure 16 – Structuring capabilities (Source: Fraunhofer IPA, based on ZVEI and IKIMUNI Industrie 4.0)

Analysis of RAMI 4.0 according to various criteria (based on D2.11 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, as e.g. 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)[2]
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 177). The interoperability of I4.0

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[2] https://www.iiconsortium.org/pdf/JTG2_Whitepaper_final_20171205.pdf

Components is greatly dependant on the properties that support the adequate description of products and services in the B2B area.

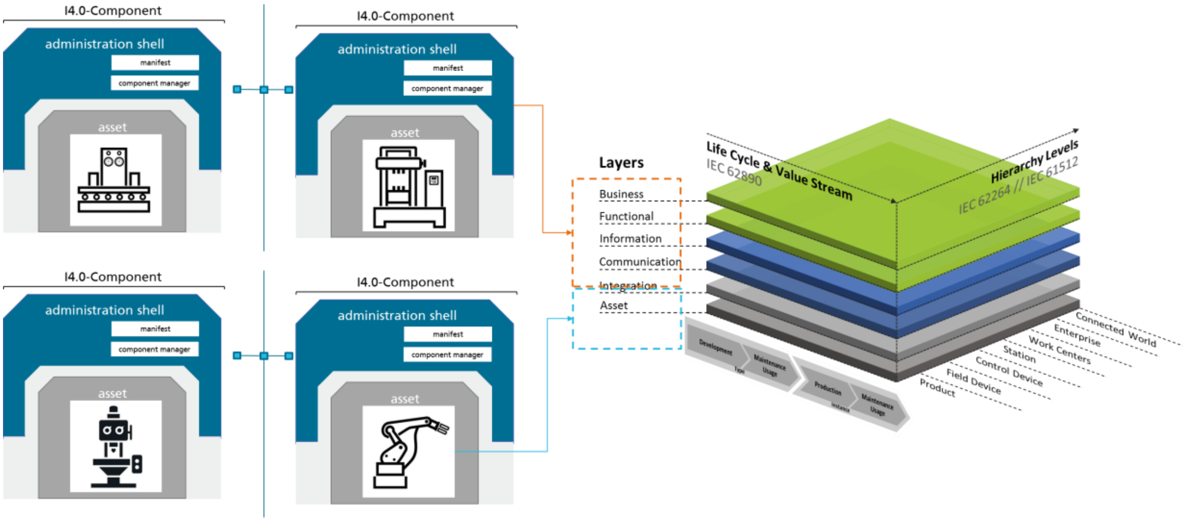

Figure 17 – RAMI 4.0 correlations with the Industrie 4.0 Component and Asset Administration Shell[3]

4.3 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, Deadalus, FAR-EDGE) provide a complete CPPS solution allowing SMEs to access all the different components in order to develop digital automation cognitive solutions for their manufacturing processes.

4.3.1 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

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[3] 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

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.

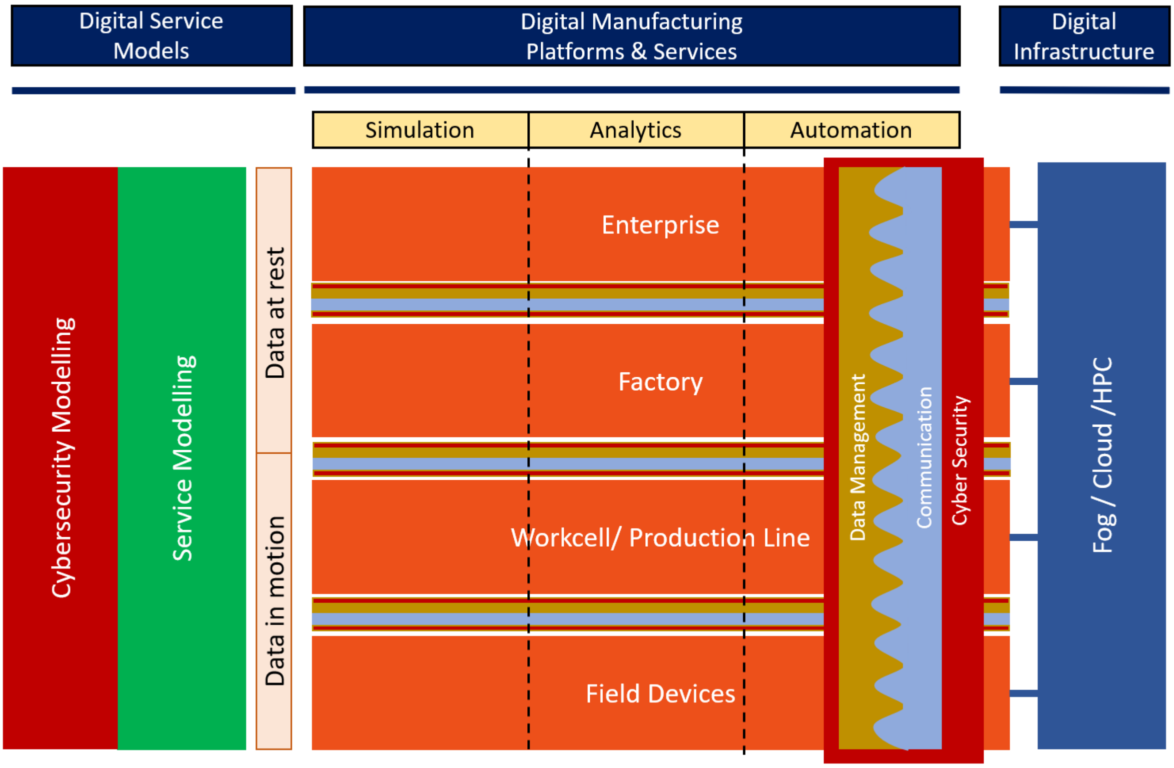


Figure 18 – DSA Reference Framework

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 the figure above). 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 199 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.

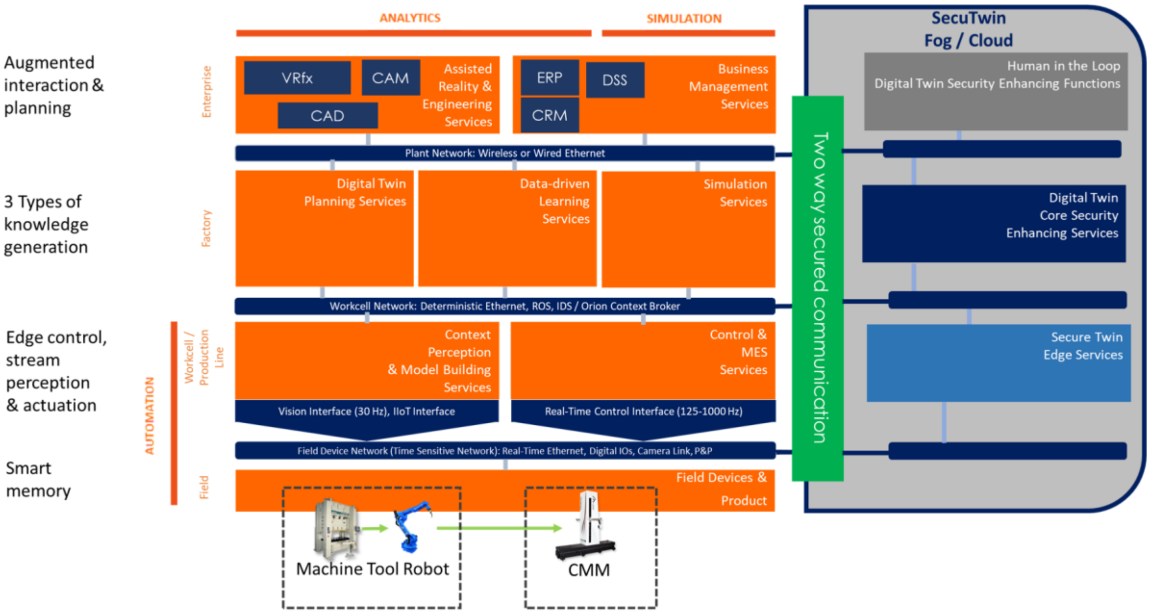


Figure 19 – DSA Reference Framework focused on the Digital Infrastructure Pillar

- **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.

5 QU4LITY Architecture Framework

5.1 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 will indicate relations between the core conceptual elements, including defined goals, miscellaneous information sources, and task-specific actions.

Using the methodology presented in Section 2.2, the following diagram (see Figure 2020) 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*.

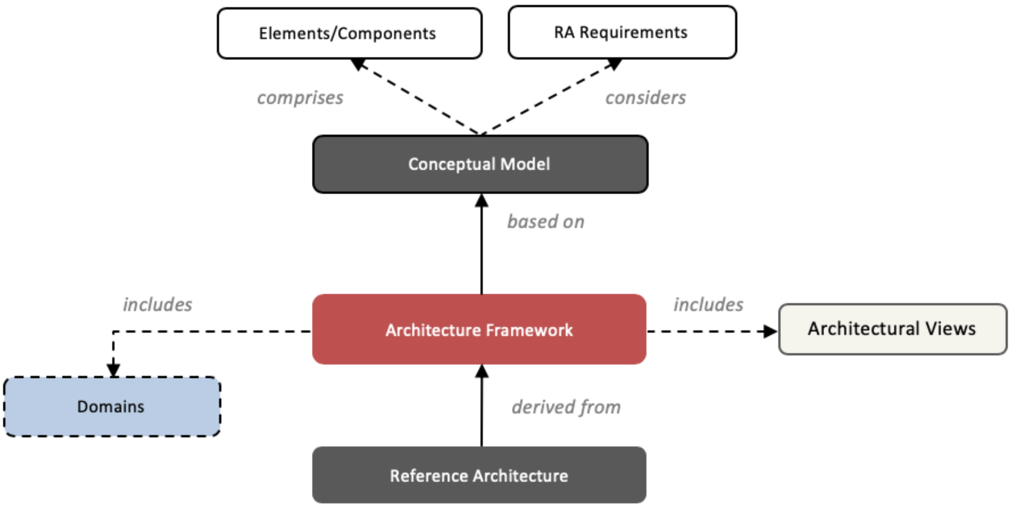


Figure 20 – QU4LITY RA Conceptual Model

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 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 play 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 current standards and so that these are able to handle human errors and other hardware failures.

- **Compliance Requirements of the QU4LITY 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 QU4LITY 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 QU4LITY RA during the next step.

5.2 QU4LITY Architecture Framework overview

Starting from the needs described in the previous section, the QU4LITY 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.

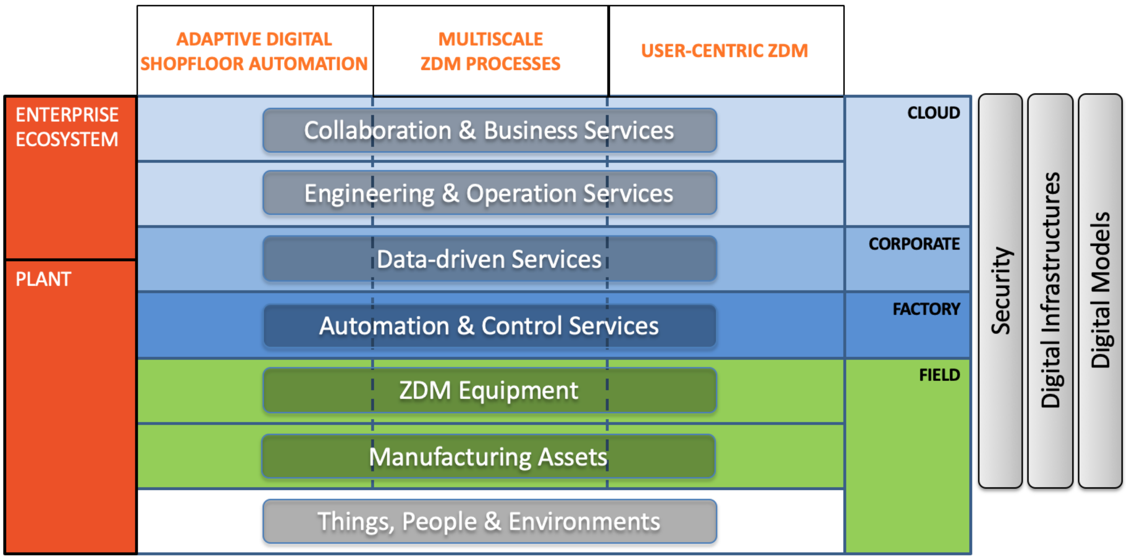


Figure 21 – QU4LITY Architecture Framework overview

According to the QU4LITY RA, the functionality of a ZDM Digital Manufacturing Platform can be decomposed into three high-level **Functional Domains** – *Adaptive Digital Shopfloor Automation*, *Multiscale ZDM Processes* and *User-Centric ZDM* – and three **Crosscutting (XC) Functions** – *Security*, *Digital Infrastructures* and *Digital Models*.

5.2.1 QU4LITY RA 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 211) 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 *Digital Infrastructures* and *Digital Models* XC Functions.
- **Multiscale ZDM 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 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.
- **User-Centric ZDM**: 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 222 provides a graphical representation of the identified Functional Domains.

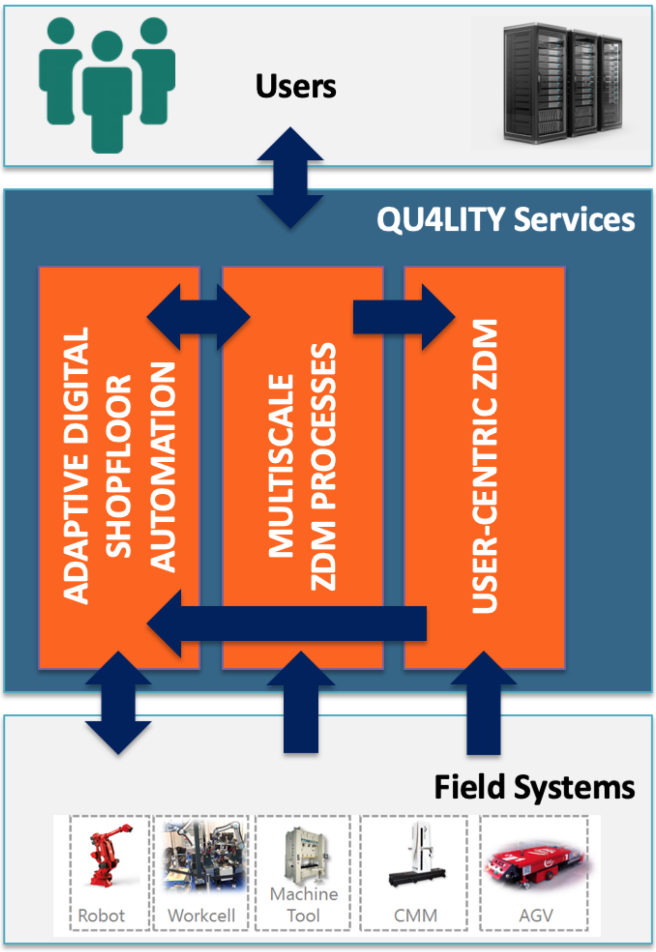


Figure 22 – QU4LITY RA Functional Domains

5.2.2 QU4LITY RA Service Domains

The above-mentioned Functional Domains can be refined using another perspective, given by the Service Domains as shown in Figure 233, 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.

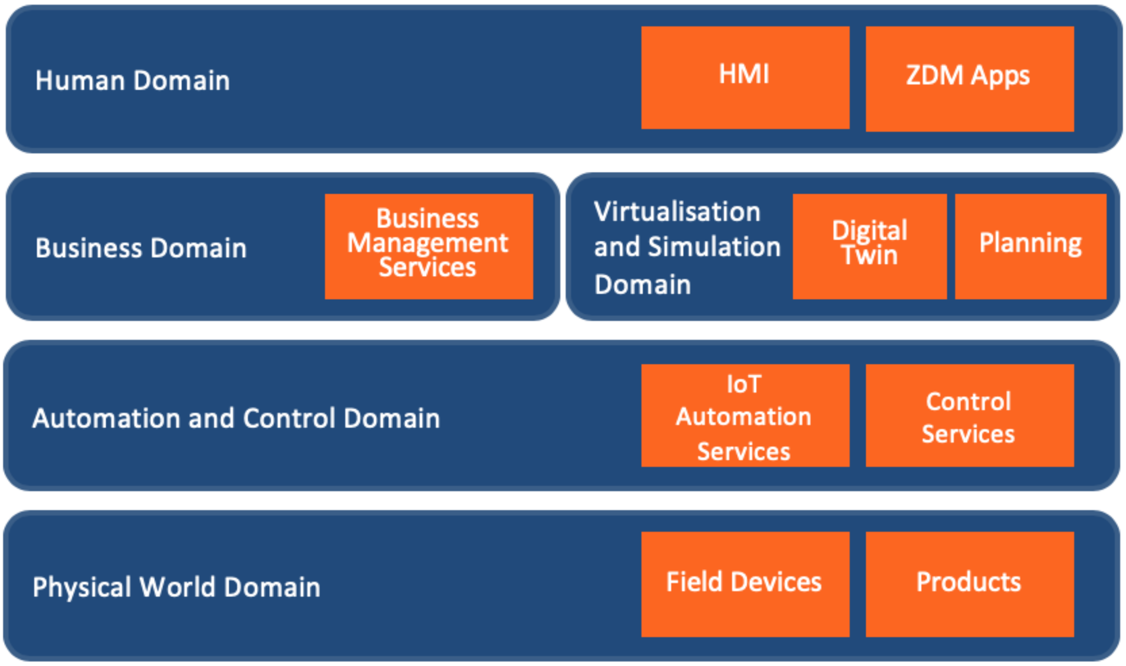


Figure 23 – QU4LITY RA Service Domains

5.2.3 QU4LITY RA 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:

- **Security:** Functions securing the system against the unruly behaviour of its user and of connected systems. These generally include digital identity management and authentication, access control policy management and enforcement, communication and data encryption.
- **Digital Infrastructures:** Functions that ensure the connectivity and process capabilities to support the business logic (QU4LITY 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:** Functions for the management of digital models and their synchronization with the real-world entities they represent. Digital modes 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.

5.2.4 QU4LITY Reference Architecture

The QU4LITY Reference Architecture (or QU4LITY 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 4, 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 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 in order 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 in order to guarantee the delivery of the expected outcomes of T2.6 in this time-critical activity of the project.

Following this standard approach, Figure 244 and Figure 266 show that the identified QU4LITY RA Service Domains (presented in Section 5.2.2) 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.

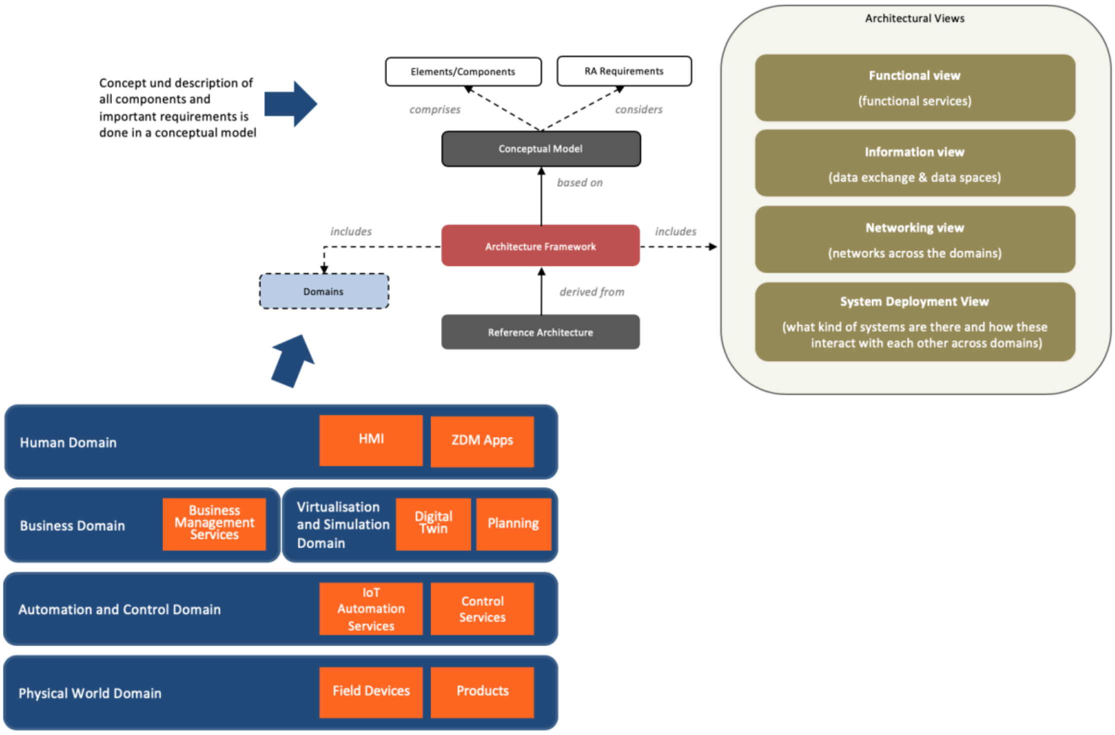


Figure 24 – QU4LITY RA Service Domains vs. QU4LITY Architectural Views

The prime role of the QU4LITY 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 QU4LITY RA is described more in details in the following. The diagram in Figure 255 presents the overall QU4LITY 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.

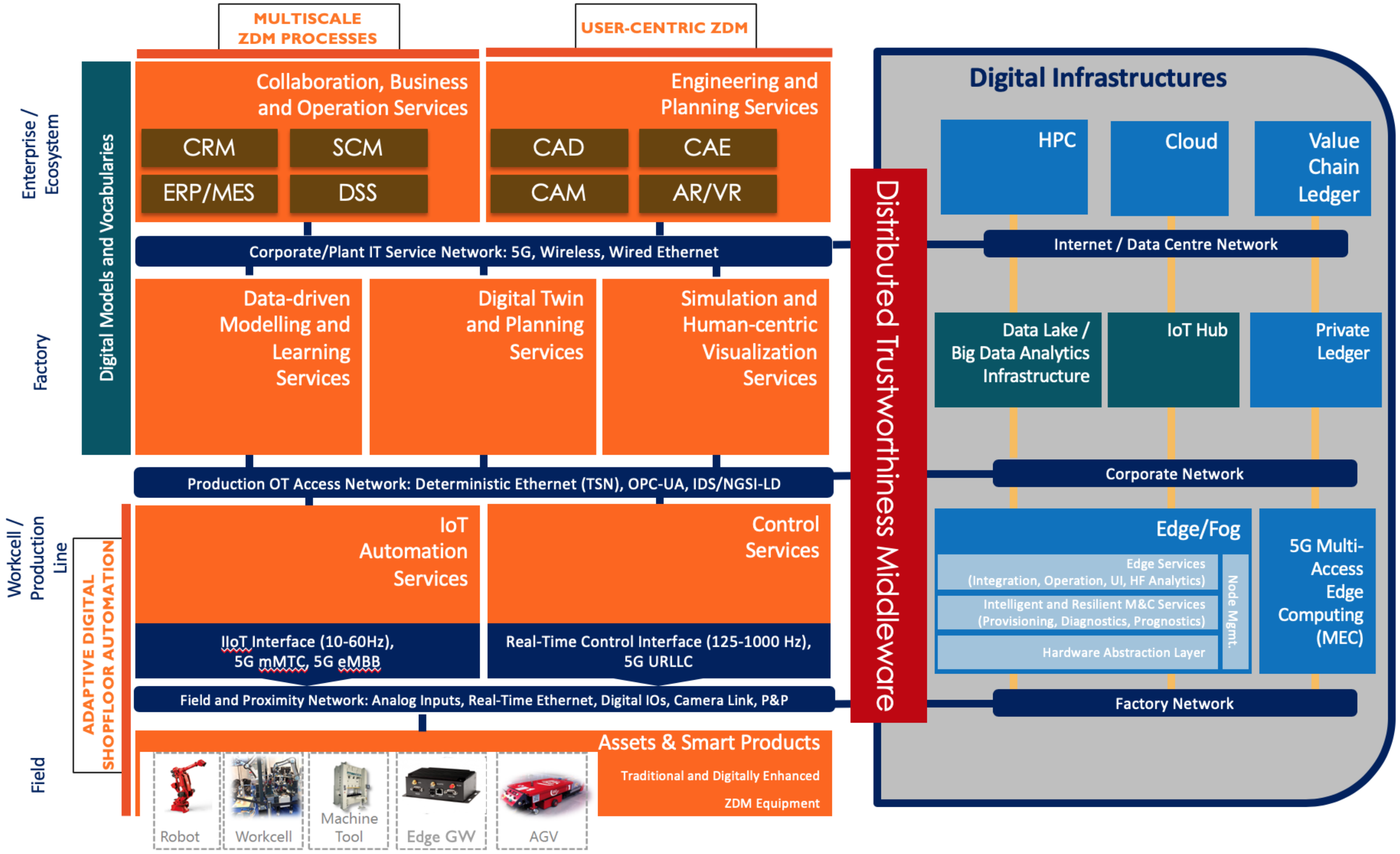


Figure 25 – QU4LITY Reference Architecture

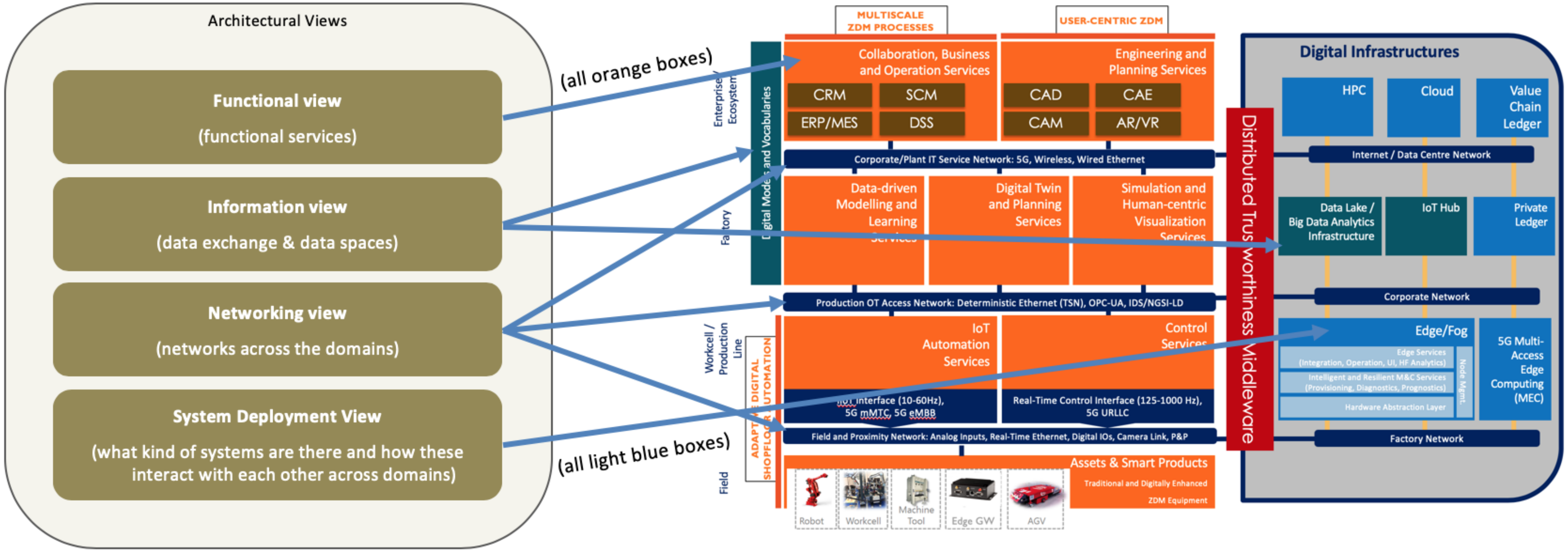


Figure 26 – QU4LITY Architectural Views vs. QU4LITY RA

Figure 266, finally, show how the different view (i.e. Functional, Information, System Deployment and Networking) can be mapped in the presented QU4LITY RA.

The QU4LITY RA has been designed to be generic, but it becomes an application- or service-specific system architecture or a target system architecture when the RA is tailored to a specific set of business requirements.

5.2.4.1 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 255.

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**
    - **Data-driven Modelling and Learning 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 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 Human-centric 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**
    - **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.
    - **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.

5.2.4.2 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 255, 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.
- **IoT Hub**: 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.
- **Data Lake / Big Data Analytics Infrastructure**: A data lake is a centralized repository, providing resilience and scalable storage solutions for both structured and unstructured data. These solutions are often paired with Big Data Analytics Infrastructure 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.

5.2.4.3 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 255, can be implemented by means of a range of different network technologies, which are used depending on the particular 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 / Fiber) and wireless connections including Wireless LANs (Wi-Fi), Mobile (cellular) networks and 5G links.
- **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.

5.2.4.4 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.

5.3 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 QU4LITY 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 QU4LITY RA follows:

- **Scalable, Reliable and High-Speed Connectivity for ZDM (WP3/T3.1)**: Connectivity should be a cross-cutting function in the QU4LITY RA. All elements of a ZDM platform should be able to benefit from high bandwidth access to devices, CPS systems and other data sources. A part 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 QU4LITY 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 QU4LITY 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 BigData Analytics for ZDM (WP3/T3.3)**: This task comprises two distinct sets of digital enablers for BigData 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 BigData 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 QU4LITY 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 end-points of QU4LITY 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 QU4LITY RA.

5.4 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 QU4LITY 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 QU4LITY 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", "T4.2 Enhanced Distributed Communication and Control" and "T4.3 ZDM Platforms Digital Upgrades Implementation". Furthermore, these services will also enable interoperable interactions of machines as part of task "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.

5.5 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 QU4LITY 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 QU4LITY 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 QU4LITY RA. They have a clear functional mapping on the QU4LITY RA and the collaborative multi-scale processes building block of the latter. Note that the collaboration functionalities of the QU4LITY 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 QU4LITY 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 QU4LITY 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.

5.6 Mapping to the QU4LITY work-packages

The following Figure 277 shows how the different work-packages are expected to contribute, in terms of specification and reference implementation, to the concrete realization of the QU4LITY 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.

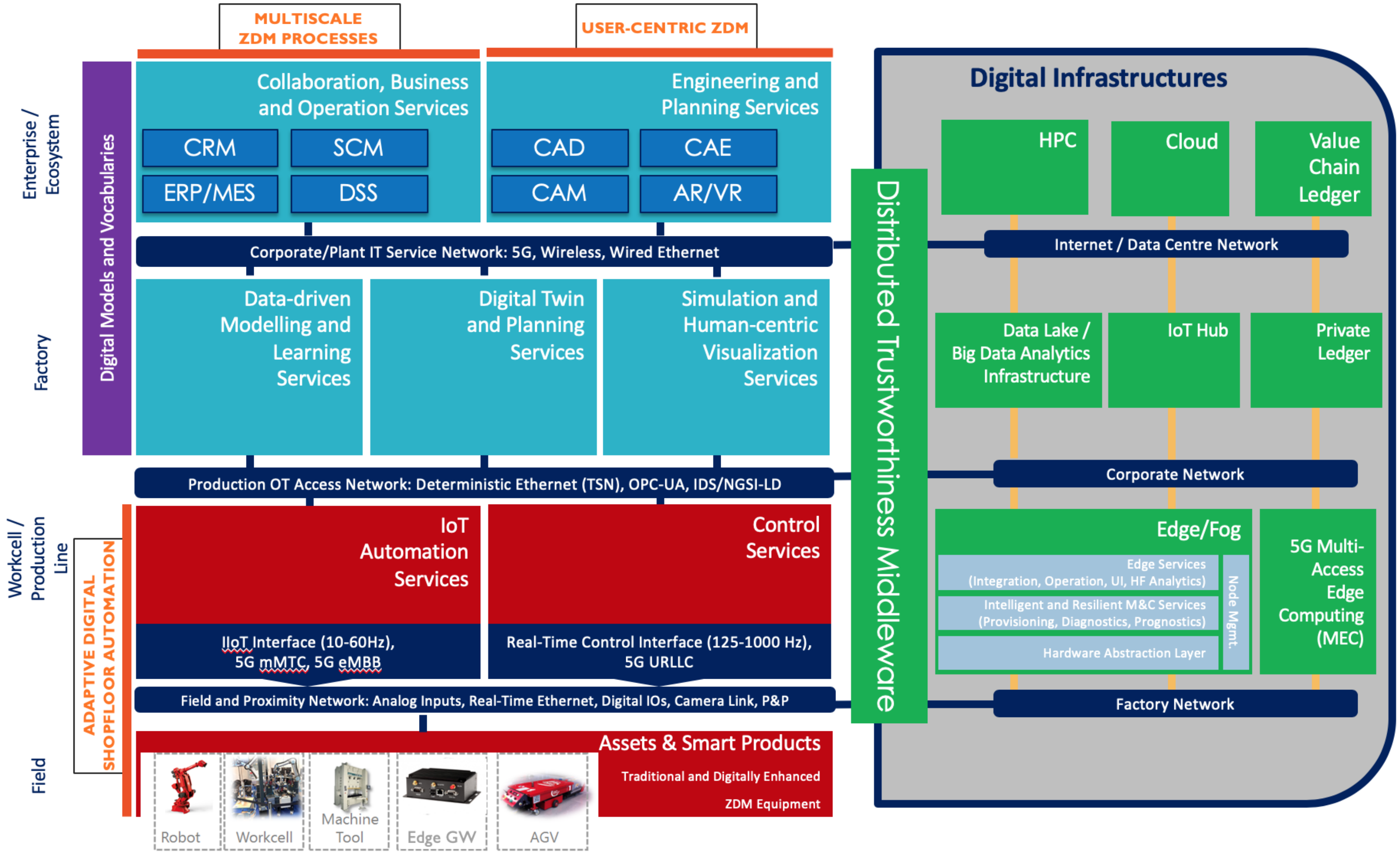


Figure 27 – QU4LITY RA mapping toward the project work-packages

6 QU4LITY Blueprints

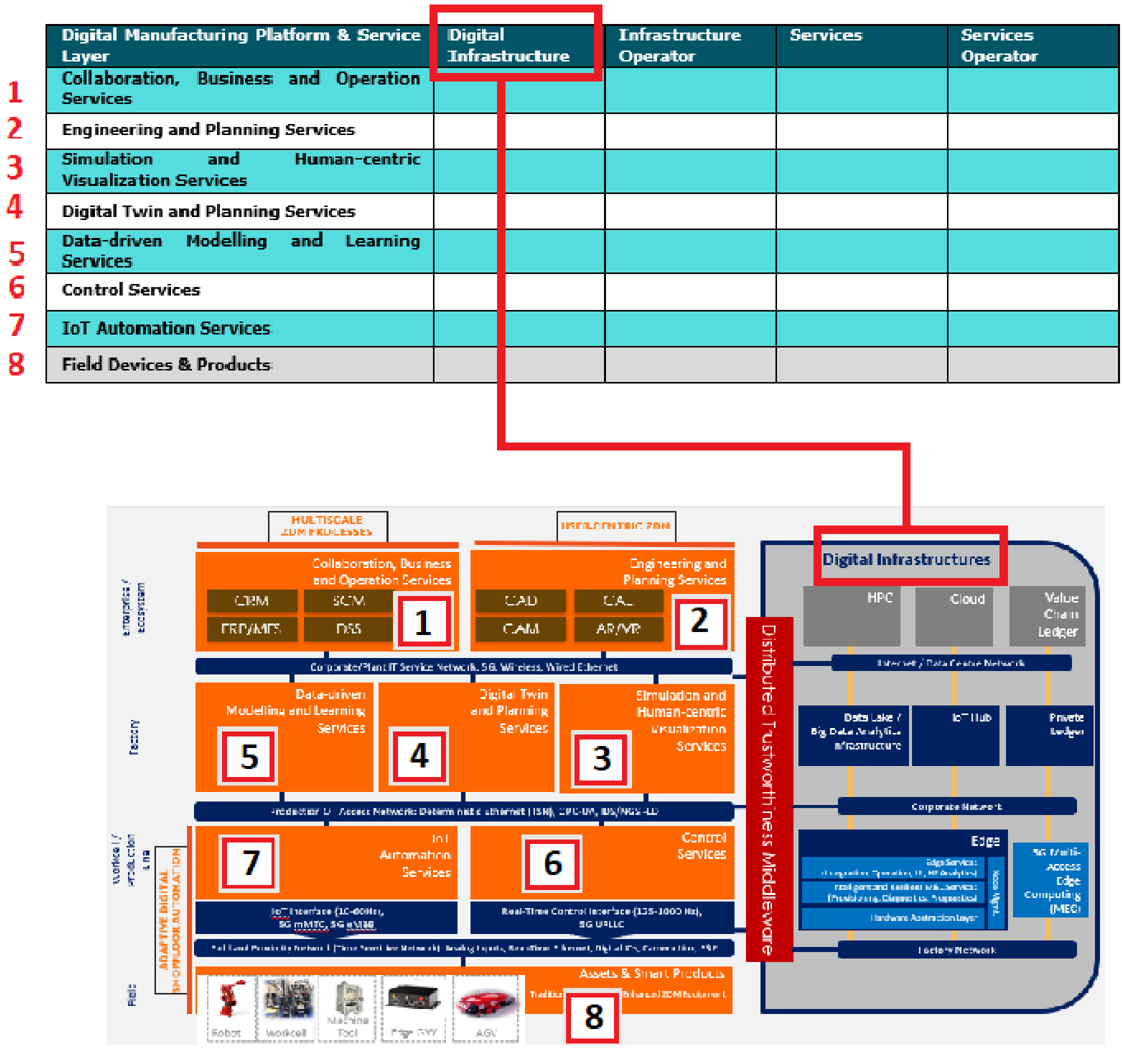
6.1 Methodological approach

This chapter will explain the methodology carried out to map the pilots of the projects within the QU4LITY 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. Once that everything is well defined, each pilot will complete the table below, providing information about the new services to be implemented on the pilot and specifying the digital infrastructure that this service will require.

Table 1 – QU4LITY RA services mapping table

Digital Manufacturing Platform & Service Layer	Digital Infrastructure	Infrastructure Operator	Services	Services Operator
Collaboration, Business and Operation Services				
Engineering and Planning Services				
Simulation and Human-centric Visualization Services				
Digital Twin and Planning Services				
Data-driven Modelling and Learning Services				
Control Services				
IoT Automation Services				
Field Devices & Products				

In completing this table, each pilot must describe the digital infrastructure (cloud, PC, Data Center…) required by the implemented service, the operator of that infrastructure, service type description and who is the operator of the service.



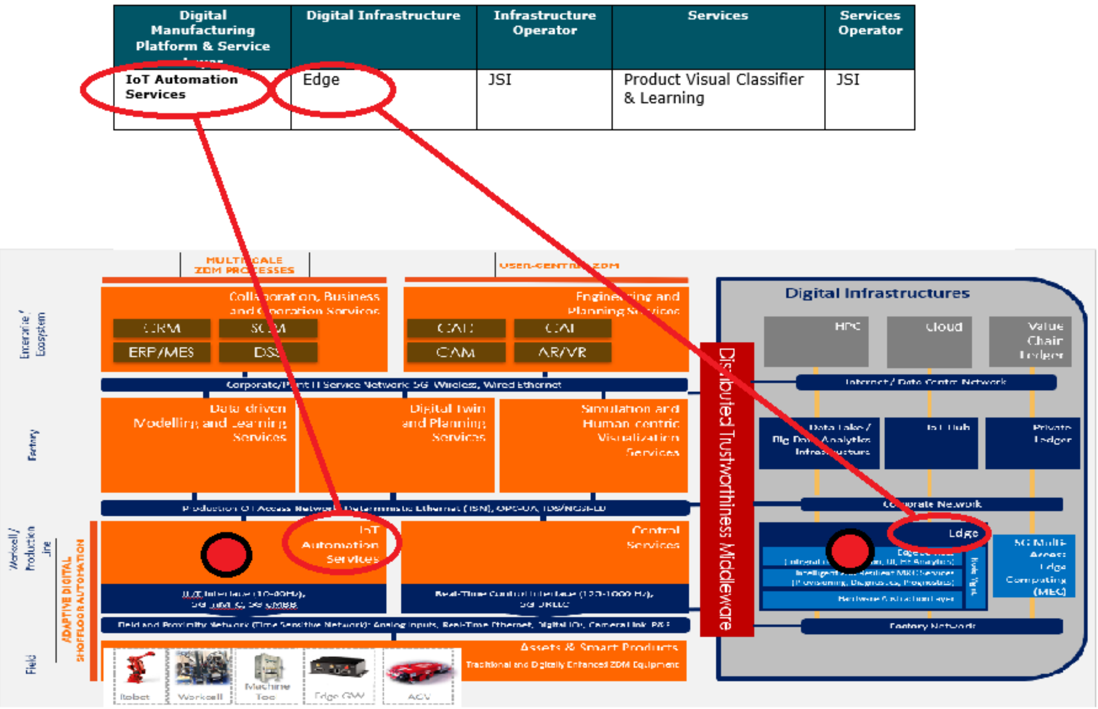
	Digital Manufacturing Platform & Service Layer	Digital Infrastructure	Infrastructure Operator	Services	Services Operator
1	Collaboration, Business and Operation Services				
2	Engineering and Planning Services				
3	Simulation and Human-centric Visualization Services				
4	Digital Twin and Planning Services				
5	Data-driven Modelling and Learning Services				
6	Control Services				
7	IoT Automation Services				
8	Field Devices & Products				

Figure 28 – Relation between the table and the RA

This is a demonstration of how the RA is completed once the table is filled.

Digital Manufacturing Platform & Service Layer	Digital Infrastructure	Infrastructure Operator	Services	Services Operator
IoT Automation Services	Edge	JSI	Product Visual Classifier & Learning	JSI

Figure 29 – Mapping example



Digital Manufacturing Platform & Service Layer	Digital Infrastructure	Infrastructure Operator	Services	Services Operator
IoT Automation Services	Edge	JSI	Product Visual Classifier & Learning	JSI

Figure 30 – Mapping example

In the current stage of development, the pilots' team in QU4LITY have identified the business process, however the complete information about the components is not yet available (It is being collected in the third chapter of the Trial Handbook[4]).

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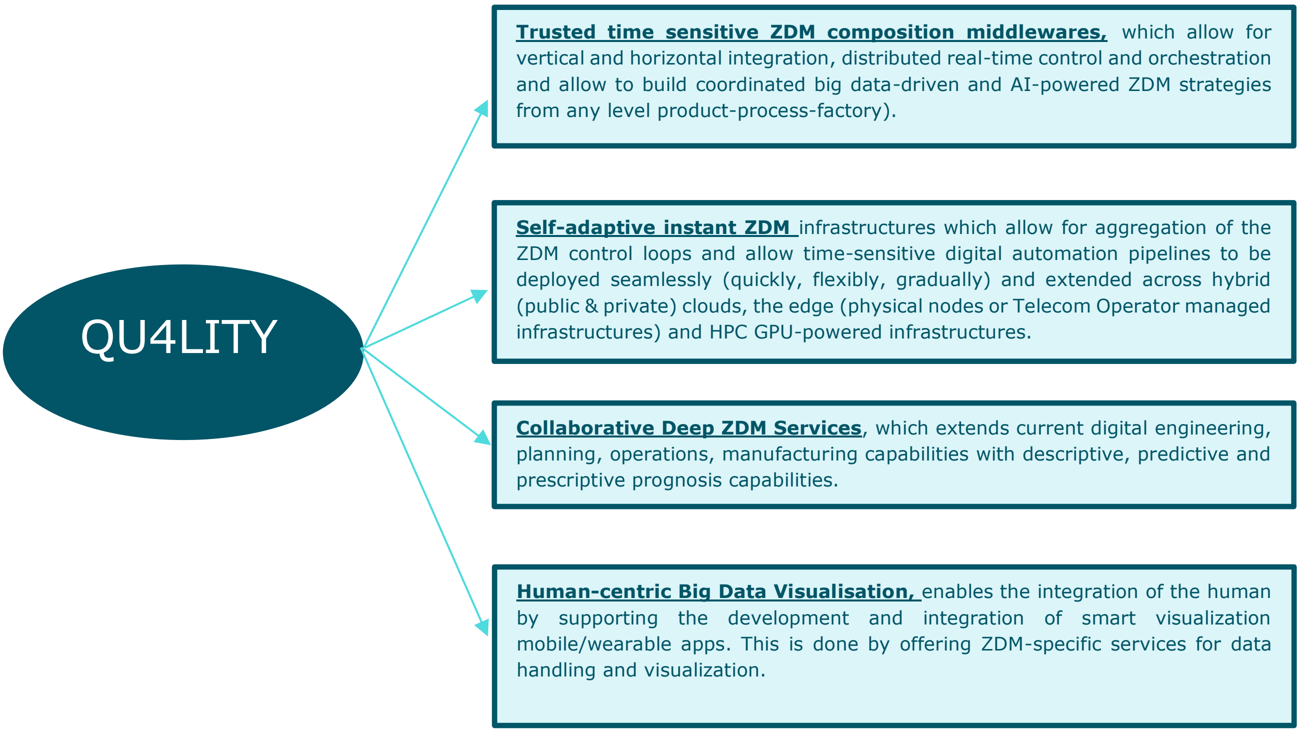
[4] The Trial Handbook is the methodology used in QU4LITY to manage the development of the pilots. The details of this methodology are presented in D7.1

6.2 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:



Trusted time sensitive ZDM composition middlewares, which allow for vertical and horizontal integration, distributed real-time control and orchestration and allow to build coordinated big data-driven and AI-powered ZDM strategies from any level product-process-factory).

Self-adaptive instant ZDM infrastructures which allow for aggregation of the ZDM control loops and allow time-sensitive digital automation pipelines to be deployed seamlessly (quickly, flexibly, gradually) and extended across hybrid (public & private) clouds, the edge (physical nodes or Telecom Operator managed infrastructures) and HPC GPU-powered infrastructures.

Collaborative Deep ZDM Services, which extends current digital engineering, planning, operations, manufacturing capabilities with descriptive, predictive and prescriptive prognosis capabilities.

Human-centric Big Data Visualisation, enables the integration of the human by supporting the development and integration of smart visualization mobile/wearable apps. This is done by offering ZDM-specific services for data handling and visualization.

Figure 31 – 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

7 Conclusions

This deliverable introduces the QU4LITY RA, providing the high-level design of a QU4LITY-based system and outlining the methodology to derive the Reference Implementation 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 preliminary results 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 for Digital Manufacturing Platform.
- The QU4LITY RA addresses functionalities in three distinct, yet interrelated and complementary domains: Adaptive Digital Shopfloor Automation, Multiscale ZDM Processes and User-Centric ZDM.
- The QU4LITY RA enables a wide range of ZDM use cases and scenarios.
- 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 a sound basis for development and integration activities that will be performed as part of technical work packages, notably WP3, WP4 and WP5. In particular, it defines 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.

The QU4LITY RA and Platform design will also drive the implementation of the experimental facilities in WP6 and pilot use cases in the scope of WP7. As a general rule, use cases might require some customization of the RI; such customization, however, should rely on the approach and standards identified in the RA but extending them to solve specific needs for the pilot.

Note however, new amendments and contributions will be consolidated in the next release of the QU4LITY RA, since development and integration activities are likely to introduce revisions to this RA design, resulting from:

- New findings and technological choices made during the detailed design and implementation of individual Platform Components;
- Changes in requirements and use cases (as already outlined in deliverable D2.1, the project is ready to embrace changes in technical and business requirements);
- External evolution of the project’s KETs and endorsed standards.

Future revisions to the overall QU4LITY RA will be reported as part of D2.12.

8 References

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List of abbreviations

Abbreviation	Explanation
AEP	Application Enablement Platform
AF	Architecture Framework
AQ	Autonomous Quality
AR	Augmented Reality
B2B	Business to Business
CAD	Computer Aided Design
CPPS	Cyber-Physical Production Systems
CPS	Cyber-Physical Systems
DoA	Description of Action
DIN	German Institute for Standardization
DSA	Digital Shopfloor Alliance
DSS	Decision Support System
DT	Digital Twin
FP7	Framework Programme 7
FoF	Factories of the Future
HPC	High Performance Computing
IaaS	Infrastructure as a Service
IEC	International Electrotechnical Commission
IIC	Industrial Internet Consortium
IIoT	Industrial Internet of Things
IIRA	Industrial Internet Reference Architecture
IIS	Industrial Internet Systems
IMS	Intelligent manufacturing systems
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
OEM	Original Equipment Manufacturer
OPI	Overall Performance Indicators
OT	Operational Technology
PPP	Public Private Partnership
RA	Reference Architecture
RAMI 4.0	Reference Architecture Model for Industry 4.0
RI	Reference Implementation
RF	Reference Framework
SME	Small Medium Enterprise
SOA	Service-Oriented Architecture
ToC	Table of Content
VR	Virtual Reality
XC	Crosscutting
ZDM	Zero Defect Manufacturing

Partners

INTELLIMECH CONSORZIO PER LA MECCATRONICA	SIEMENS	AtoS
AIRBUS	MONDRAGON	NXT CONTROL
ATB Institut für angewandte Systemtechnik Bremen GmbH	Continental	RIA STONE
UNIMETRIK METROLOGY AND CALIBRATION	Technology Transfer System	EPFL ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE
SQS	FAGOR FAGOR ARRASATE	TTTech Ensuring Reliable Networks
tu technische universität dortmund	thyssenkrupp	Jožef Stefan Institute Ljubljana, Slovenia
PRIMA INDUSTRIE	eit Digital	ENGINEERING
PACE a TXT company	innovalia ASSOCIATION	Telefonica
Synesis sustainable automation	ghi	UNPARALLEL
DANOBAT	POLITECNICO MILANO 1863	Whirlpool CORPORATION
VTT	VISUAL COMPONENTS	ASTI
Fraunhofer	cea	INTERNATIONAL DATA SPACES ASSOCIATION
PHILIPS	ATLANTIS	aic AUTOMOTIVE INTELLIGENCE CENTER
KOLEKTOR	AIT	SINTEF
+GF+	Technische Universität Braunschweig	TNO innovation for life