HORIZON 2020

# ZDMP: Zero Defects Manufacturing Platform

ZERO DEFECTS Manufacturing Platform ZDMP

## WP2: Business Challenge: Vision, Market, Use Cases, and Interlinking

## D2.4: Manufacturing Reference Model Analysis Document-
## Vs: 1.1

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**Abstract**

This deliverable analyses prominent reference models for digital manufacturing platforms, presents an alignment against the Research and Development activities in the ZDMP project, and delivers recommendations concerning the ZDMP architecture definition and standardisation activities based on the analysis.

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# Project Partners:

For full details of partners go to www.zdmp.eu/partners

# Executive Summary

The purpose of this deliverable is to provide an adequate framework for the ZDMP architecture definition and standardisation activities. This document provides recommendations for the development of architectural models of the platform, aligned with cutting edge reference models and standards for digital manufacturing platforms. It also provides guidance to identify relevant standards for project activities, and standardisation activities where the ZDMP project could make relevant contributions. It is therefore the starting point for the main architectural definition and standardisation activities, which will be documented in:

- Global Architecture Specification and Update (ZDMP D4.3a): Global architecture of the platform identifying main components and interactions
- Functional Specification and Update (ZDMP D4.4a): In-depth definition of the functionalities and behaviours of the various ZDMP components
- Technical Specification and Update (ZDMP D4.5a): Technical specifications of the different ZDMP components
- Standardisation Plan and Status Report (ZDMP D4.6a): Ensures compliance with existing standards and connects the project to standardisation forums

The reference models that have been considered in this document are:

- Reference Model for Industrie 4.0 (RAMI 4.0), from the Platform Industrie 4.0 consortium
- Smart Manufacturing Ecosystem, from the National Institute of Standards and Technologies (NIST)
- Intelligent Manufacturing System Architecture (IMSA), from the Republic of China State Council
- Industrial Internet Reference Architecture (IIRA), from the Industrial Internet Consortium

This list has been obtained from the Description of Action (DOA) and includes the most prominent reference models and reference architectures to address the ZDMP concept. Note that the purpose of this document is to provide non-binding recommendations, based on the analysis of the aforementioned reference models, not mandatory requirements.

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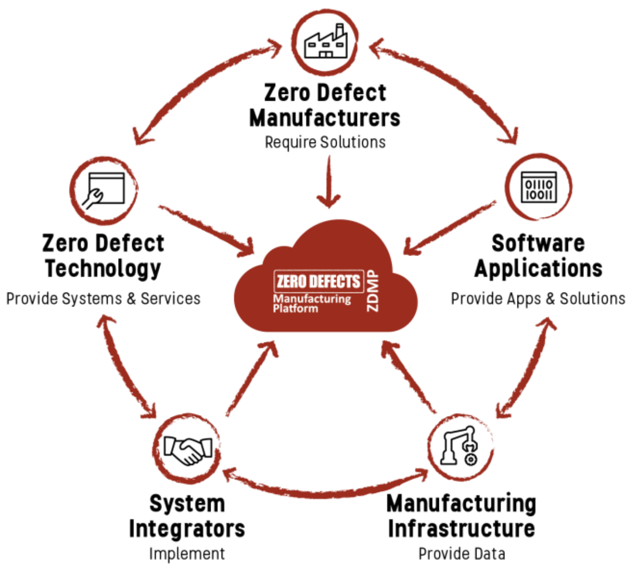
# 0 Introduction

## 0.1 ZDMP Project Overview

ZDMP – Zero Defects Manufacturing Platform – is a project funded by the H2020 Framework Programme of the European Commission under Grant Agreement 825631 and conducted from January 2019 until December 2022. It engages 30 partners (Users, Technology Providers, Consultants and Research Institutes) from 11 countries with a total budget of circa 16.2M€. Further information can be found at www.zdmp.eu.




In the last five years, many industrial production entities in Europe have started strategic work towards a digital transformation into the forth-industrial revolution termed Industry 4.0. Based on this new paradigm, companies must embrace a new technological infrastructure, which should be easy to implement for their business and easy to implement with other businesses across all their machines and systems. The concept of zero-defects in the management of quality is one of the main benefits deriving from the implementation of Industry 4.0, both in the digitalisation of production processes and digitalisation of the product quality.

To remain competitive and keep its leading manufacturing position, European industry is required to produce high quality products at a low cost, in the most efficient way. Today, the manufacturing industry is undergoing a substantial transformation due to the proliferation of new digital and ICT solutions, which are applied along the production process chain and are helping to make production more efficient, as in the case of smart factories. The goal of the ZDMP Project is to develop and establish a digital platform for connected smart factories, allowing to achieve excellence in manufacturing through zero-defect processes and zero-defect products.

ZDMP aims at providing such an extendable platform for supporting factories with a high interoperability level, to cope with the concept of connected factories to reach the goal of zero-defect production. In this context, ZDMP will allow end-users to connect their systems (i.e. shop-floor and ERP Systems) to benefit from the features of the platform. These benefits include product and production quality assurance, among others. For this, the platform provides the tools to allow following each step of production, using data acquisition to automatically determine the functioning of each step regarding the quality of the process and product. With this, it is possible to follow the production orders and its status, and optimize the overall processes regarding time constraints and product quality, achieving the zero defects.

## 0.2 Deliverable Purpose and Scope

The purpose of this ZDMP deliverable, D2.4: Manufacturing Reference Model Analysis Document, is to act as liaison between the ZDMP project and cutting-edge reference models and standards for digital manufacturing platforms, mainly the RAMI 4.0 reference model and Industrie 4.0 standardisation activities. This document provides recommendations to align the architectural models of ZDMP with standard reference models and best practices. It is therefore important that Task leaders and Work Package leaders of related project activities read it to take into consideration the provided recommendations, so as to facilitate coordination and promote the use of standards throughout the project, and also to encourage contributions to standardisation activities. It is expected that the different reference models mature or evolve during the project, but the emphasis is made in providing a good starting point for these activities, and therefore it is not intended nor needed to update or resubmit this deliverable.

## 0.3 Target Audience

The Manufacturing Reference Model Analysis Document is a Public document. Although primarily aiming at project participants, it is of interest for a wider audience, including researchers, or academics in the fields of digital manufacturing platforms and interoperability, and professionals involved in standardisation activities.

## 0.4 Deliverable Context

This document provides a framework and starting point for the definition of the ZDMP architecture and standardisation activities. Its relationship to other documents is as follows:

- **Global Architecture Specification and Update (ZDMP D4.3):** Global architecture identifying ZDMP components and their interactions. This document provides non-binding recommendations to align the global architecture with international reference models and standardisation activities.
- **Functional Specification and Update (ZDMP D4.4):** In-depth definition of the functionalities/behaviours of all ZDMP components. This document provides non-binding guidelines to align the definition of functional specifications with best practices recommended by standardisation organisations.
- **Technical Specification and Update (ZDMP D4.5):** Outcome of the project-wide software engineering process. This document provides guidelines to align the definition of the technical specifications with technical standards promoted in the different reference models.
- **Standardisation (ZDMP D4.6):** Describes the connection between the project and standardisation forums and monitors the compliance of the project with international standards. This document provides a baseline for standard compliance and provides guidelines to facilitate the participation in standardisation activities.

## 0.5 Document Structure

This deliverable is broken down into the following sections:

- **Section 1: Approach:** An introduction to this deliverable including a general overview of the purpose of the document and the approach
- **Section 2: Smart Manufacturing Reference Architecture Analysis:** Analysis of cutting-edge reference models for smart manufacturing and alignment with ZDMP project development activities
- **Section 3: Recommendations:** Recommendations for the definition of the architectural models of ZDMP and standardisation activities based on the analysis
- **Section 4: Conclusions:** Summary of the main conclusions of the document

- **Annexes**:
  - **Annex A**: Document History
  - **Annex B**: References

## 0.6 Document Status

This document is listed in the Description of Action as "public".

## 0.7 Document Dependencies

This document has no preceding documents or further iterations.

## 0.8 Glossary and Abbreviations

A definition of common terms related to ZDMP, as well as a list of abbreviations, is available at http://www.zdmp.eu/glossary.

## 0.9 External Annexes and Supporting Documents

Annexes and Supporting Documents:

- None

## 0.10 Reading Notes

This document contains a brief summary of the main characteristics of the different reference models under analysis. The descriptions are supported by external bibliographic references. The intention of this document is not to describe in detail the aforementioned reference models, but to highlight and summarise the definitions and considerations which the different recommendations are based on. Also, it is important to emphasize that the nature of the recommendations in this document is non-binding. Task leaders and Work Package leaders will choose whether to follow the recommendations in this document or not during the development of the corresponding activities.

# 1 Approach

Reference Models for digital manufacturing platforms, such as the Reference Architecture Model for Industry 4.0 (RAMI 4.0) [DIN+91345], provide a solution-neutral reference architectural model for digital manufacturing solutions. This represents a common structure and language to describe and specify system architectures. There are four relevant reference models that have been taken into consideration in this deliverable:

- Reference Architecture Model for Industry 4.0 (RAMI 4.0) [DIN+91345]
- National Institute of Smart Manufacturing Ecosystem [NIS+3001] from NIST
- Intelligent Manufacturing System Architecture (IMSA) [FMI+2018]
- Industrial Internet Reference Architecture (IIRA) for Industrial Internet of Things (IIoT) Systems [IIC+ 20170131]

In the context of the ZDMP project, the alignment of project activities to these definitions is beneficial because reference models provide a framework for the standardisation of relevant technical systems, from development, through integration, to operation. The liaison and coordination with reference models early in the project will provide the right orientation to standardisation and system architecture definitions, and it will foster component orchestration, collaboration with relevant organisations, and internationalisation.

The main objective of the ZDMP project is to develop a Reference Platform, Applications, SDK, and Marketplace for Zero Defect Product and Process Quality in any factory. The different reference models have not been designed to address such a wide concept. Instead, the fundamental purpose behind them is to facilitate collaborative manufacturing, through the interconnection of production assets, by providing a digital description of such assets, and a definition of the interfaces between them.

Bearing this in mind, the approach taken in this document first decomposes the ZDMP project into smaller parts to later map them into the RAMI 4.0 reference models. The RAMI 4.0 reference model serves as a starting point. This mapping is then extrapolated to other prominent reference models, using available alignment reports to map from RAMI 4.0 into the corresponding reference models, or providing such alignment in this document in cases where they are not available in the bibliography. The mapping is then used to derive recommendations for the project. The mapping also allows the identification of potential gaps into the reference models and suggests extensions to reinforce them. The result is a set of recommendations and an adequate reference architectural model to guide the definition of the system architecture, as well as further standardisation activities within the project.

The division is based on the Work Package structure of the project and the high-level functional blocks that are mentioned in the DOA. It is represented in Figure 1.

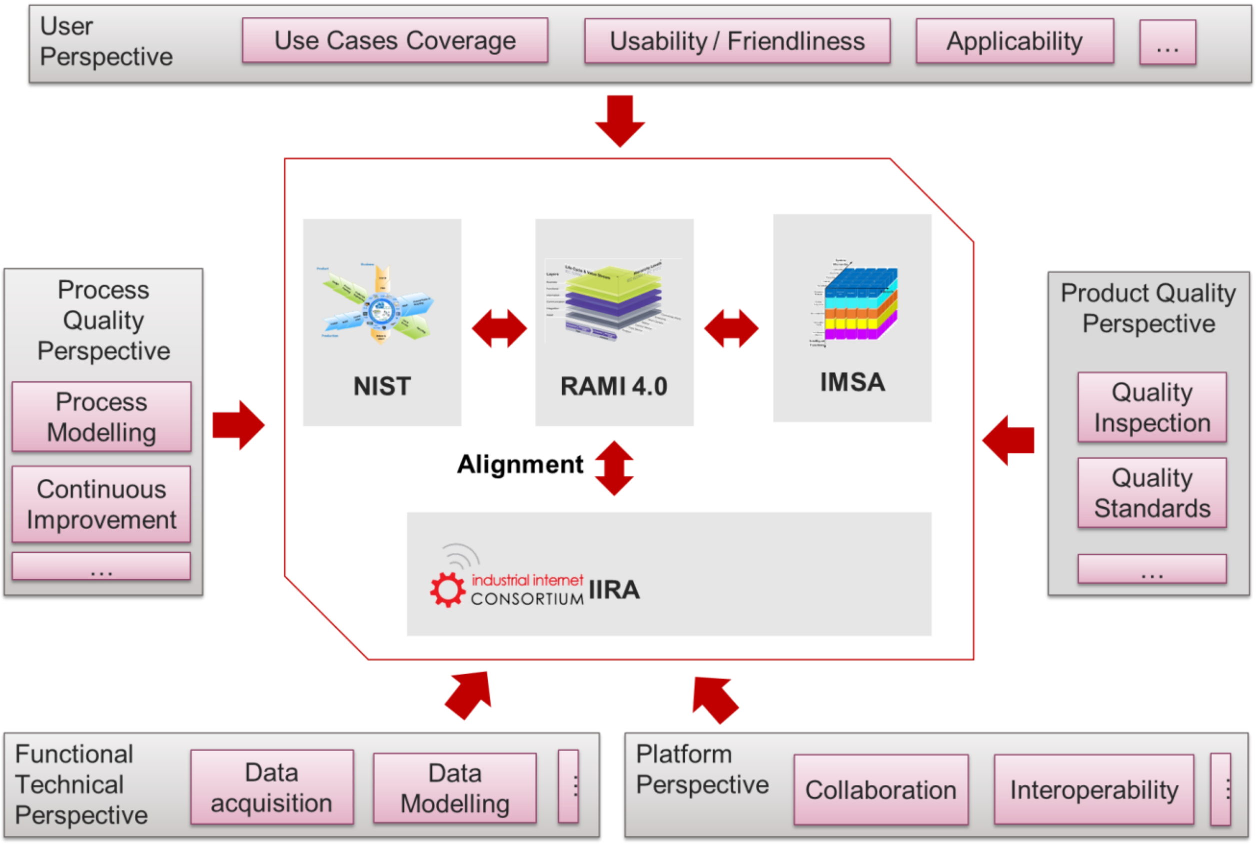



Figure 1: Reference Model Analysis Approach

The key aspect is to regard the results of development activities as technical objects, and map them to the RAMI 4.0 reference model. Later the result is analysed from the five different perspectives, listed below:

- **Functional/Technical Perspective**: Regards the ZDMP Core Services and middleware components as digital assets, and maps them to the reference models to:
  - Draw recommendations for the architecture of digital manufacturing platform core services, regarding functional and technical aspects like data acquisition or data modelling
  - Support the analysis of the suitability of the different reference models to address the digital manufacturing platform core services
  - Propose recommendations to define an adequate framework for the development of these core services within Work Package 5

- **Platform Perspective**: Regards the ZDMP Platform Building software deliverables as digital assets, and maps them to the reference models to:
  - Provide means to analyse the suitability of the different reference models to address the digital manufacturing platform concept, regarding platform aspects such as collaboration or software development
  - Proposes recommendations to define an adequate framework for the development of the software deliverables in Work Package 6

- **Process Quality Perspective**: Regards the Process Quality orientated services (eg manufacturing process models and process optimisation algorithms) as digital assets, and maps them to the reference models to:
  - Provide a means to analyse the suitability of the different reference models to address the zero defects paradigm for process quality, regarding aspects such as process modelling or continuous improvement methodologies
  - Define an adequate, standard-based, framework for the development of these software deliverables within Work Package 7

- **Product Quality Perspective:** Regards the Product Quality orientated services (eg product models and product optimisation algorithms) as digital assets, and maps them to the reference models to:
  - Provide means to analyse the suitability of the different reference models to address the zero defects paradigm for product quality, regarding aspects like product quality or products standards
  - Define an adequate framework for the development of these software deliverables within Work Package 8

- **User Perspective:** Regards the different ZDMP use cases in the project pilots as digital assets, and maps them to the reference models to:
  - Provides an analysis of the suitability of the different reference models to address the end user expectations
  - Propose recommendations to define an adequate framework for the development of these use cases within Work Packages 9 and 10

Based on this approach, the remainder of the document is structured as follows:

- **Section 2.1** contains a brief description of the different architectural reference models regarded in the analysis
- **Section 2.2** contains the mapping of ZDMP components to the RAMI 4.0 reference model
- **Section 3** takes into consideration the results of the mapping and the alignment between RAMI 4.0 and other reference models to provide recommendations considering the different perspectives
- **Section 4** contains some final conclusions

# 2 Smart Manufacturing Reference Architecture Analysis

## 2.1 Cutting Edge Smart Manufacturing Reference Models and Architectures

### 2.1.1 Reference Architecture Model for Industry 4.0

The RAMI 4.0 [DIN+91345] is a unified architectural reference model that provides a collective understanding for Industry 4.0 standards and use cases. It can be regarded as a kind of map of Industry 4.0 concepts. In RAMI 4.0, Industry 4.0 (I4.0) components are defined in their structure and functions. The model provides an orientation for plotting the requirements of sectors together with national and international standards in order to define and further develop Industry 4.0 concepts and products. Overlapping standards and gaps can thus be identified and resolved, enabling integration across value added networks.

RAMI 4.0 is based on three-dimensional coordinate system (Layers, Life Cycle & Value Stream and Hierarchy Levels), which is represented below in Figure 2. This structure can be used to systematically organize and further develop Industry 4.0 concepts and technologies.

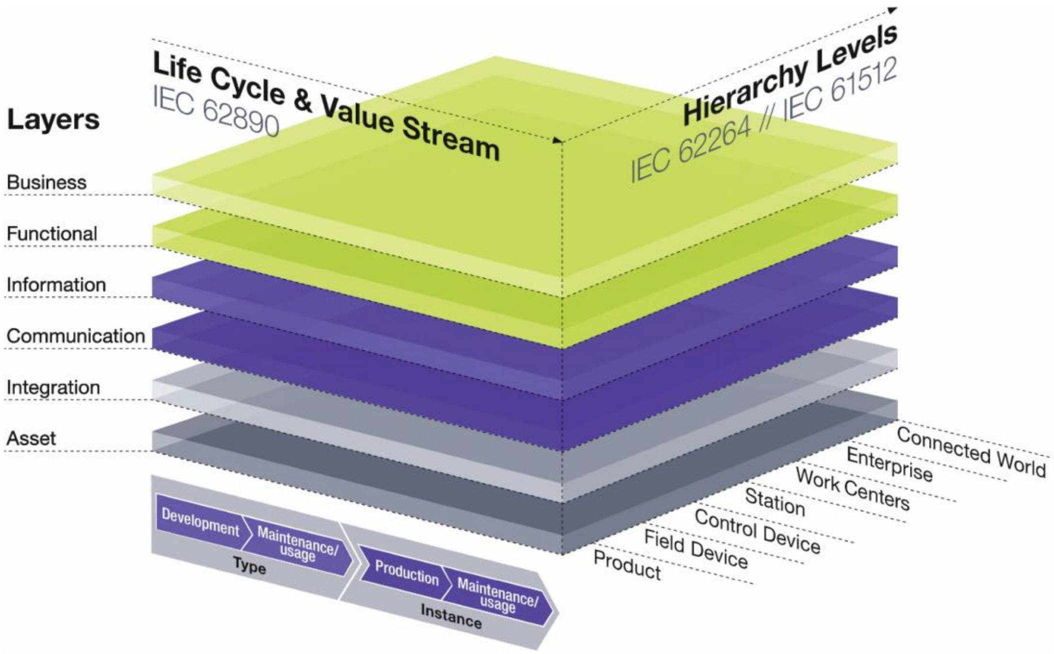



Figure 2: RAMI 4.0 reference model layers (source: [DIN+91345])

RAMI 4.0 regards any technical asset of the factory as an entity that can be represented in the digital world. RAMI 4.0 also provides specifications for the administration shell, which is the part of the I4.0 component that includes all the relevant information for representing the asset and its technical functionality. I4.0 components interact with each other through Service Oriented Architecture (SOA) based interfaces provided by the administration shell, which can be thus regarded as a standardised digital representation of the asset.

Due to the importance of the RAMI 4.0 definitions in the approach, the three dimensions are briefly introduced in the next sections.

#### 2.1.1.1 Layers

Layers represent different Information Technology (IT) management layers of an Industry 4.0 project implementation, organised in a vertical axis. Each layer gathers different manageable parts of the system (eg data maps, communications, hardware), provides services to the upper layer, and orchestrate services from bottom layers. The different layers defined are:

- **Business Layer:** Maps the business model, the overall process, and the rules that the system has to follow. The business model layer ensures the integrity of the functions in the value stream. It also provides the regulatory and legal framework conditions. The business layer orchestrates the services of the functional layer and receives events that inform of the progress of the business process.
- **Functional Layer:** Provides the runtime and modelling environment for the services which support business processes. Remote access and horizontal integration take place in the functional layer, except for processes that are only relevant for lower layers (eg reading diagnosis data) or that is not relevant to permanent functional or horizontal integration (eg maintenance).
- **Information Layer:** Describes the data that is used, generated, or modified by the technical functionalities of the asset. This includes data persistence, provisioning, integration, and integrity. It receives events from the physical asset via lower level layers and applies the adequate processing and transformation to support the functional layer services.
- **Communication Layer:** Provides uniform communication and data formats to access information and interfaces to access the functions of an asset from other assets.
- **Integration Layer:** Represents the transition from the physical world to the information world. The integration layer contains a representation of the properties and process-related functions of an asset and reports events from the physical world. The integration layer includes asset documentation, software and firmware, or human-machine interfaces (HMI).
- **Asset Layer:** Represents reality, ie the physical instance of the asset which is represented by all other layers.

#### 2.1.1.2 Life Cycle & Value Stream

The second axis in the RAMI 4.0 reference model represents the life cycle of products and systems, taken from IEC 62890 [IEC+62890]. The product life-cycle model first introduces a differentiation between product type and product instance. A product type is characterized by a unique product identifier, the documentation (development documents, manufacturing and test descriptions, technical documentation, etc.) and required certificates. This definition of product type is valid for either hardware and software products, or software or hardware parts of products that bundle both hardware and software components. A product instance on the other hand is an individual instantiation of a product type. A product instance is characterized by an unambiguous instance identifier such as a serial number or ordering number.

From this fundamental differentiation, the product life-cycle is divided into phases that refer to the product type and other phases that refer to the product instance. All activities that are performed concerning the development, maintenance, and service of a product type, regardless of how often it is manufactured, refer to the product type. Similarly, all activities that are performed regarding the production, maintenance, and servicing of a product refer to the product instance.

In the context of RAMI 4.0, the generic life-cycle model of a product type starts with the development phase, in which the product type is developed and tested in the targeted system environment. The development phase includes activities such as product type design, sales ramp-up, testing, or piloting, and ends with the delivery release of the product type, when the product is released for sale. The operational businesses of the product type finishes with the end of product sales, typically when the product is to be obsoleted. During the product sales (and typically for an extended period thereafter), the product type is under the maintenance phase, where configuration management and after-sales support activities take place. Configuration management comprises all activities related to the management of the different versions and revisions of the product type. Depending on service level agreements, one or several versions of the product type will have independent after-sales support phases. The sum of these phases is called the product life-cycle, where the term cycle refers to the fact that there is a recurring sequence of the different phases in the context of a particular product type.

The product instance generic life time model starts with the production phase, when the instancing of the product type begins. After the product instance is sold, the product instance enters the use phase, which starts with the product commissioning, installation, or activation, and ends with the decommissioning, de-installation or with an irreparable defect. Each product instance has a life time that comprises the production and use phases, ie starts with production and ends with the start of disassembling or disposal of the instance. The product life time is independent and can be significantly longer than the life-cycle of the product type.

#### 2.1.1.3 Hierarchy levels

The third axis of the RAMI 4.0 reference model is the hierarchical representation of the different functional levels of the factory, based on the IEC 62264 and IEC 61512 standards. For a uniform consideration covering different manufacturing system architectures, the different functional levels that are included in the RAMI 4.0 hierarchy levels do not match on a one-to-one basis the hierarchical levels in the aforementioned standards. The relationship between both hierarchies is described below:

- **Connected world:** Describes the relationship between an asset or combination of assets and another asset or combination of assets at a different installation or company.
- **Enterprise:** Any business organisation, initiative, venture, or undertaking with a defined mission. An enterprise is a collection of one or more sites. It is responsible for determining what products will be manufactured, at which sites and in general how they will be manufactured.
- **Site:** A site is a physical, geographical, or logical grouping determined by the enterprise. A main production capability usually identifies a site and generally they have well-defined manufacturing capabilities. Planning and scheduling normally involve sites. This level is not included in the RAMI 4.0 hierarchy level, but it is described here to better describe lower levels.
- **Area:** A physical, geographical or logical grouping determined by the site. Areas generally have well-defined capabilities and capacities. Areas may contain one or more of the lower-level hierarchical level elements. As with sites, this level is omitted

in the RAMI 4.0 hierarchical levels, but it is introduced to clarify the description of the levels below.

- **Work centres:** Depending on the manufacturing system organisational model (discrete, batch, continuous), areas are organised in high level manufacturing elements (eg production line, storage zone, process cell). In RAMI 4.0 all of these higher-level elements are unified into the work centre concept to ensure a consistent application across different organisational models. Thus, work centres represent the highest level element that performs manufacturing functions and is regarded in the production planning and scheduling. Work centres have well defined manufacturing capabilities and throughput capacities. A work centre groups one or several work units. Some examples are “Bottling Line”, or “Assembly Line”.
- **Work units:** Represent lower level elements that perform manufacturing functions and are regarded in the production planning and scheduling. Some examples are work cells for discrete manufacturing process, or process units for batch manufacturing processes. Work units have well-defined manufacturing capabilities and capacities and are composed of lower level equipment units that are not regarded in the production planning and scheduling.
- **Control Device:** Represents the logical control of field devices.
- **Field Device:** Represents a device installed at the field level, which interacts physically with the manufacturing process and the products (eg a sensor).
- **Product:** Describes the product to be manufactured.

#### 2.1.1.4 Administration Shell Specifications

[FMI+2018] provides specifications for the exchange of information with the administration shell. OPC UA is the core communication standard for I4.0 compliant communications. Both client/server and publish/subscribe communication patterns are supported, as highlighted in [FMI+2018]. Figure 3 shows the I4.0 communication protocol stack.

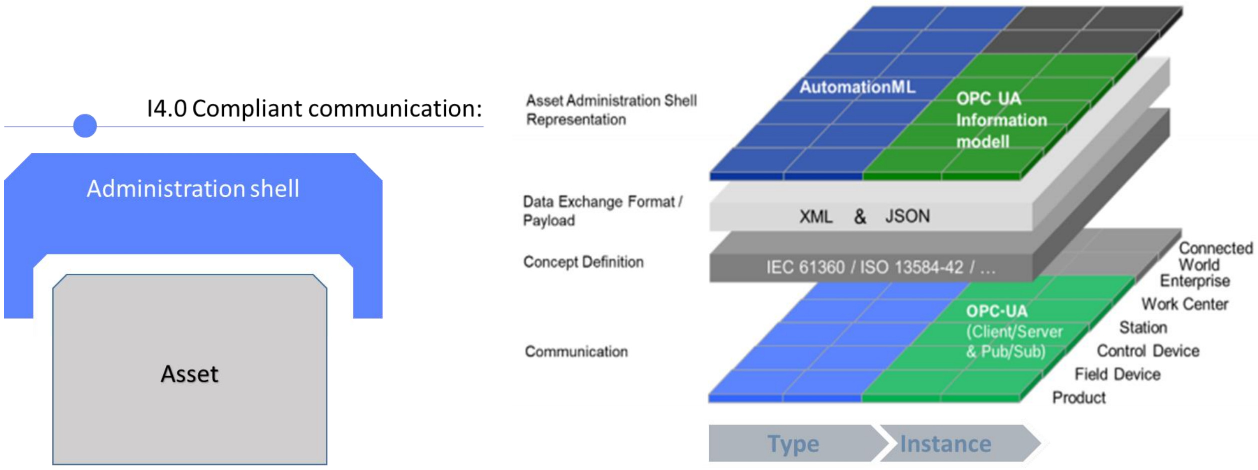



Figure 3: I4.0 Communication protocol stack

The administration shell also defines the data models for the exchange of information between partners in the value chain. The specification defines the structure of the administration data models. The main components and standards used are:

- **Concept:** ISO 13584 [ISO+13584] Industrial automation systems and integration standard is the basis for the conceptual definition of the asset and its parts

- **Design:** AutomationML [LUS+16] (a standard-based mark-up language to exchange design data) and the corresponding mapping to OPC UA [OPC+16] is used to share product engineering data, particularly during the product type development phase
- **Production:** OPC UA Information models are used to exchange production operations data, during the product instance Production and Usage phases
- **Serialisation:** Both XML and JSON schemas are derived from the models described above
- **Mapping:** Resource Description Framework (RDF) is used to map this information and enable the exchange of information using semantic technologies

Regarding information access control, the specifications define an Attribute Based & Role Based Access (ABAC) model for access control to information. ABAC allows to establish different access policies for different user roles for the different elements of the information model of an administration shell.

Additionally, the specification defines a package file format, the Asset Administration Shell (AASX), to exchange the full or partial structure of the administration shell.

### 2.1.2 NIST Smart Manufacturing Ecosystem

The National Institute of Standards and Technology (NIST) promotes the Smart Manufacturing vision [NIST+3001] as a fully integrated, collaborative manufacturing system able to cope with the challenges for quality, efficiency, and personalization that manufacturing companies are facing today. Through the adoption of NIST Smart Manufacturing standards, small-to-medium sized companies can implement this vision, benefitting from public documentation, reference software implementations, and conformance testing. The Advanced Manufacturing Series (AMS) provide different specifications for Smart Manufacturing Systems (SMS) and are described below. Besides the specifications in the AMS series, [NIST+8107] describes the standard landscape for SMSs. The document contains a detailed description of the characteristics and enabling technologies of SMS, and a comprehensive list of standards and standardisation activities relevant for SMS, from three different perspectives:

- **Product Lifecycle Management (Product):** Includes 6 phases for the product development lifecycle (design, process planning, production engineering, manufacturing, use & service, and end-of-life, and recycling). This perspective is equivalent to the RAMI 4.0 Life Cycle & Value stream dimension.
- **Production System Lifecycle (Production):** Defines 5 phases in the lifecycle of production equipment: design, build, commission, operation & maintenance, and decommission and recycling. This perspective is also equivalent to the RAMI 4.0 Life Cycle & Value Chain, from the point of view of the manufacturing equipment provider.
- **Business Cycle for Supply Chain Management (Business):** This perspective regards the plan-source-make-deliver-return phases of the Supply-chain operations reference model (SCOR). This perspective can also be mapped to the Life Cycle & Value stream of the RAMI 4.0 model in collaborative use cases.

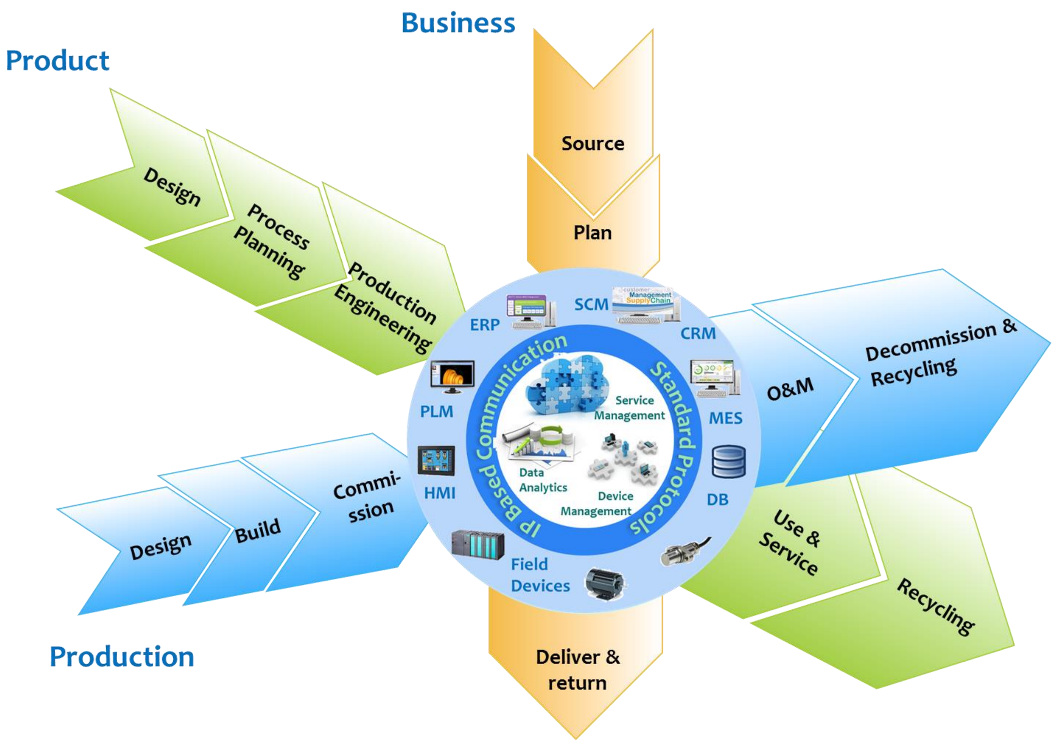



Figure 4 Smart Manufacturing Ecosystem Perspectives.

Regarding the AMS Series, Part 1 – "Reference Architecture for Smart Manufacturing" [NIS+3001] provides a modelling framework for specifying the architecture of both collaborative production systems and the software systems that supports them. The Reference Architecture for Smart Manufacturing Part 1 contains functional models to identify production activities – from product design to production – and descriptions of information flows between them. The different activities depict the life-cycle of products and can be aligned to the IEC 62890 product life-cycle model Instance Production phase described above. Distribution, maintenance and dispatching are out of the scope of the reference architecture, and product design is not expanded in the document, so the entire reference model can be regarded as a detailed description of the activities and data workflows within the instance production phase.

NIST "Software Requirements Specification to Distribute Manufacturing Data" [NIS+3002] defines general functional and non-functional requirements for the distribution of manufacturing data across an enterprise. The document covers Volatile Data Streams (VDS) and Query-able Data Repository (QDR) applications for internal and external data access to manufacturing data. VDS applications are based on the MTConnect HTTP protocol [MTC-18], whereas QDR applications should use an HTTPS client-server REST-compliant communication and therefore, there are significant differences between AMS-2 and the I4.0 connectivity whitepaper.

NIST "Guide to Industrial Wireless Systems Deployments" [NIS+3005] aims to provide a framework for integrated manufacturing design and analysis. The objective is to facilitate the integration and exchange of information between the product design and the product manufacturing phases, focusing on big data analytics and (deep) machine learning algorithms rooted in cloud services. The framework defines a four-layer model which can be mapped to the RAMI 4.0 layers. The framework is consisted of the following layers:

- **Manufacturing System layer:** Represents the physical system and can be mapped to the RAMI 4.0 asset layer

- **Model Ecosystem layer:** This layer contains the modelling environment and runtime for the digital models of the manufacturing layer. It can be mapped to the RAMI 4.0 Integration layer, Communication layer and to some extent to the Information layer
- **Transformation layer:** This layer collects the digital model data and applies model-transformations processes to adapt the data for the cloud services. These functionalities are located in the information layer of the RAMI 4.0 model
- **Cloud layer:** This layer includes third-party Big Data analytics services, implementing the functional and business functions of the RAMI 4.0 model

Finally, AMS 300-4 Guide to Industrial Wireless System Deployments and AMS [NIST 300-4] and AMS 300-6 Securing the Digital Threat for Smart Manufacturing [NIST 300-6] provide additional guidelines for the configuration of wireless networks and block chain-based product data traceability. Figure 5 shows the alignment between the RAMI 4.0 reference model and the Smart Manufacturing Ecosystem and AMS 300 specifications.

#### 2.1.2.1 Alignment to RAMI 4.0

Figure 5 shows to the right the three dimensions of the RAMI 4.0 model and to the left the three perspectives of the Smart Manufacturing Ecosystem and AMS specifications. Between them, a "\" symbol indicates that the corresponding definitions are complementary, a "~" symbol indicates that they are similar and a "≠" symbol that they are not similar.

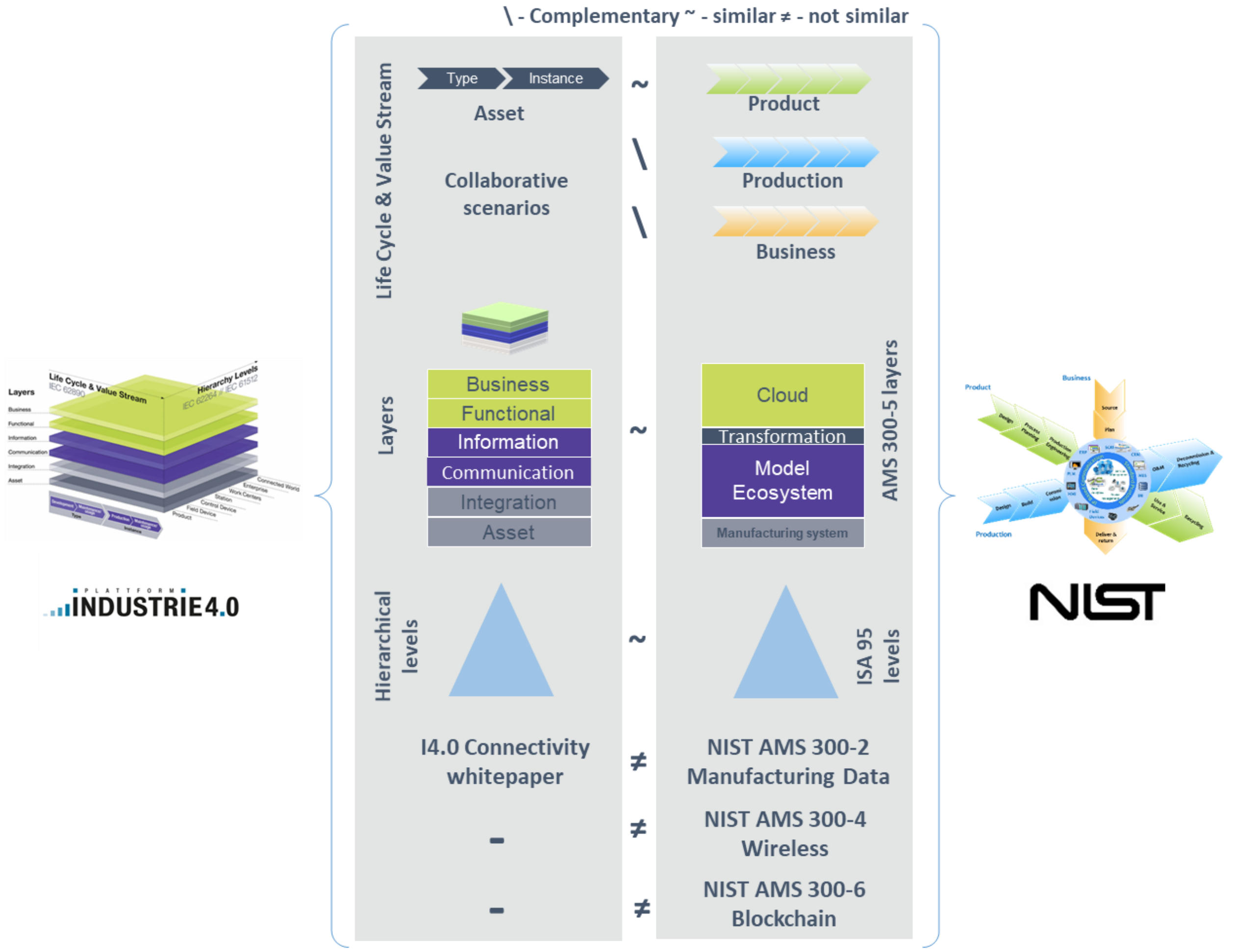



Figure 5 Alignment of RAMI 4.0 and Smart Manufacturing Ecosystem

### 2.1.3 Smart Manufacturing Standardisation Reference Model

China's national Intelligent Manufacturing System Architecture (IMSA) [SHA+17] is the response of the State Council of the People's Republic of China to foster the standardisation works that will guide the upgrade of Chinese manufacturing towards intelligent manufacturing. Introduced in the "Made in China 2025" document, the intelligent manufacturing concept involves the integration of new information technology, new materials, numerical control tools, novel equipment, and machinery as key areas to support the development of the Chinese economy.

IMSA is basically a guideline for the construction of standards to facilitate the interconnection of manufacturing processes, since this interconnection and interoperability is regarded as the key to materialise the intelligent manufacturing concept. The IMSA provides a three dimensional system architecture reference model which is very similar to the RAMI 4.0 model. It is consisted of three dimensions: lifecycle, system hierarchy, and Intelligent Functions. The lifecycle dimensions describe value creation stages, System hierarchy represents the organisational levels of manufacturing activities, and Intelligent Functions represent high-level functionalities provided by ICT technologies.

#### 2.1.3.1 Alignment to RAMI 4.0

[FMI+2018] provides a description of the IMSA Reference model dimensions and element-to-element alignment to RAMI 4.0. The main conclusion from this document is the high level of alignment between both specifications: the three dimensions in both reference models are almost equivalent in scope and the different elements in each dimension can be mapped almost one by from one reference model to the other. Figure 6 summarises the results of the mapping, using the same structure, symbols, and legends as Figure 5.

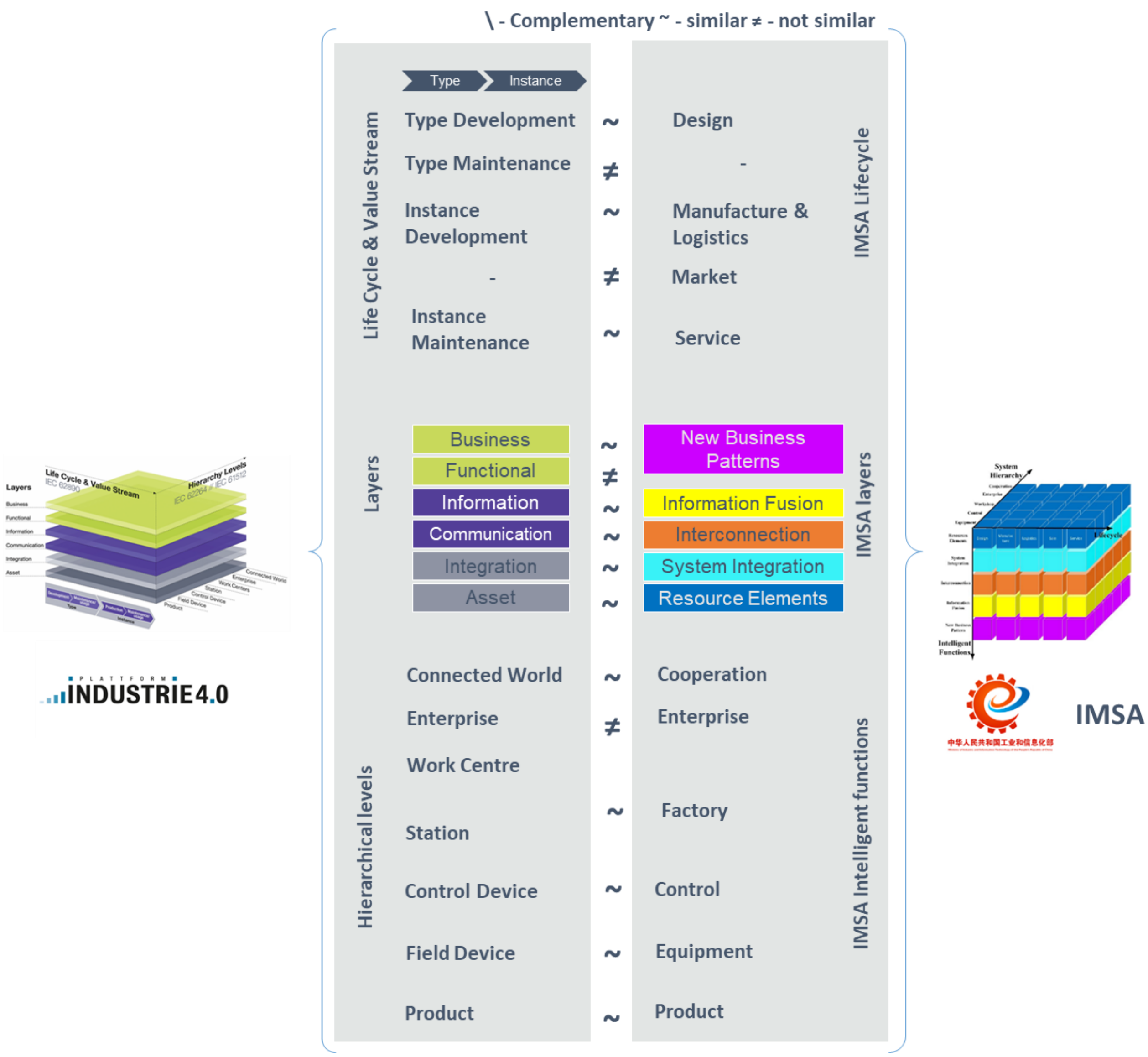



Figure 6 Alignment of RAMI 4.0 and IMSA reference models

### 2.1.4 Industrial Internet Consortium Reference Architecture

The Industrial Internet Reference Architecture (IIRA) for Industrial Internet of Things (IIoT) Systems [IIC+ 20170131] was first published in 2015 by the Industrial Internet Consortium (IIC) Task group. Consortium members include systems and software architects, business experts and security experts in different IIoT application domains, mainly Energy, Healthcare, Manufacturing, Public Domain, and Transportation. The reference architecture enables Industrial Internet of Things (IIoT) system architects to design their own systems using a common vocabulary, a standard-based architecture framework, and reference architecture. These follow the ISO 42010 System and software engineering architecture standard [ISO+42010], where the architecture of software systems is described, analysed, and defined to solve specific concerns from the viewpoint of different stakeholders. In the case of IIRA, as shown in Figure 7, the following Viewpoints are defined:

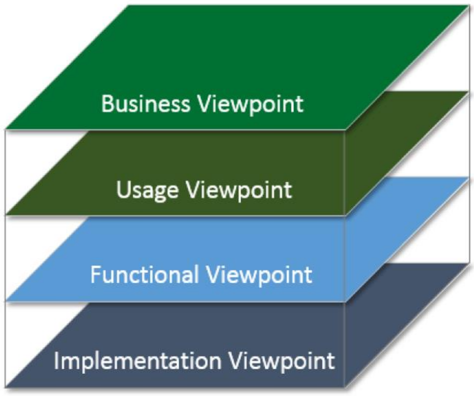



Figure 7 IIRA Reference Architecture Viewpoints (source [IIC+ 20170131])

The following sections describe the main elements and descriptions of the different IIRAs viewpoints.

### 2.1.4.1 Business Viewpoint

The business viewpoint allows the identification of the business concerns of the different users of IIoT solutions, such as business value, expected return of investments, or maintenance costs. It identifies the main stakeholders and their business vision, values and objectives in establishing an IIoT system in a specific business and regulatory context.

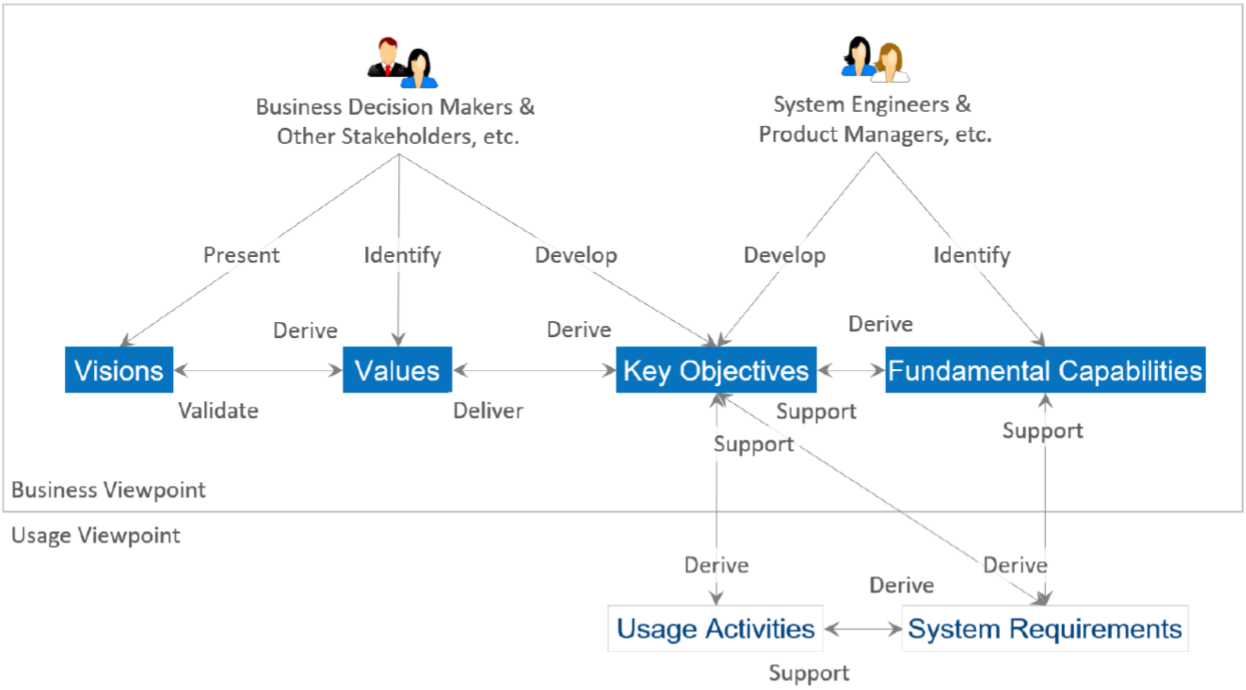



Figure 8 illustrates the IIRA´s vision and value driven model and main concepts: stakeholders, vision, key objectives, and fundamental capabilities, described in the list below.

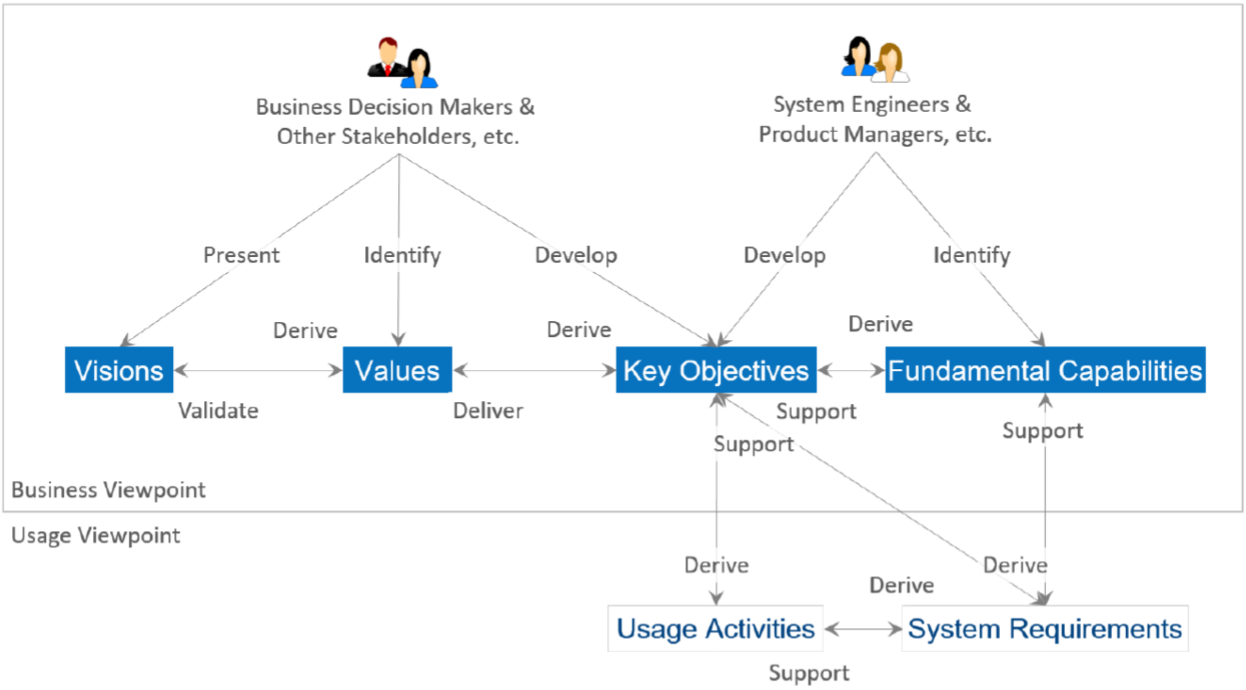



Figure 8 IIRA´s Vision and Value Driven Model (source [IIC+ 20170131])

- **Stakeholders:** Actors in each organisation with a major stake in the business and a strong influence in its direction. Stakeholders are the main drivers of the conception and development of the system
- **Vision:** Future (to-be) state of the organisation
- **Values:** Rationale, narrative description of why the vision has merit for the stakeholders as well as for the users of the resulting system
- **Key Objectives:** Quantifiable high-level business and technical outcomes of the system results in the context of delivering the values
- **Fundamental capabilities:** High-level specification of the ability of the system to complete specific business tasks, characterised by quantifiable attributes to measure the success of the system

### 2.1.4.2 Usage Viewpoint

The usage viewpoint describes how the system realizes the fundamental capabilities identified in the business viewpoint, through their decomposition into tasks (units of work) and activities (how the system is used) between different system components. This viewpoint addresses the concerns of expected system usage, typically represented as sequences of activities involving human or logical users. The main elements of the usage viewpoint model are shown in Figure 9.

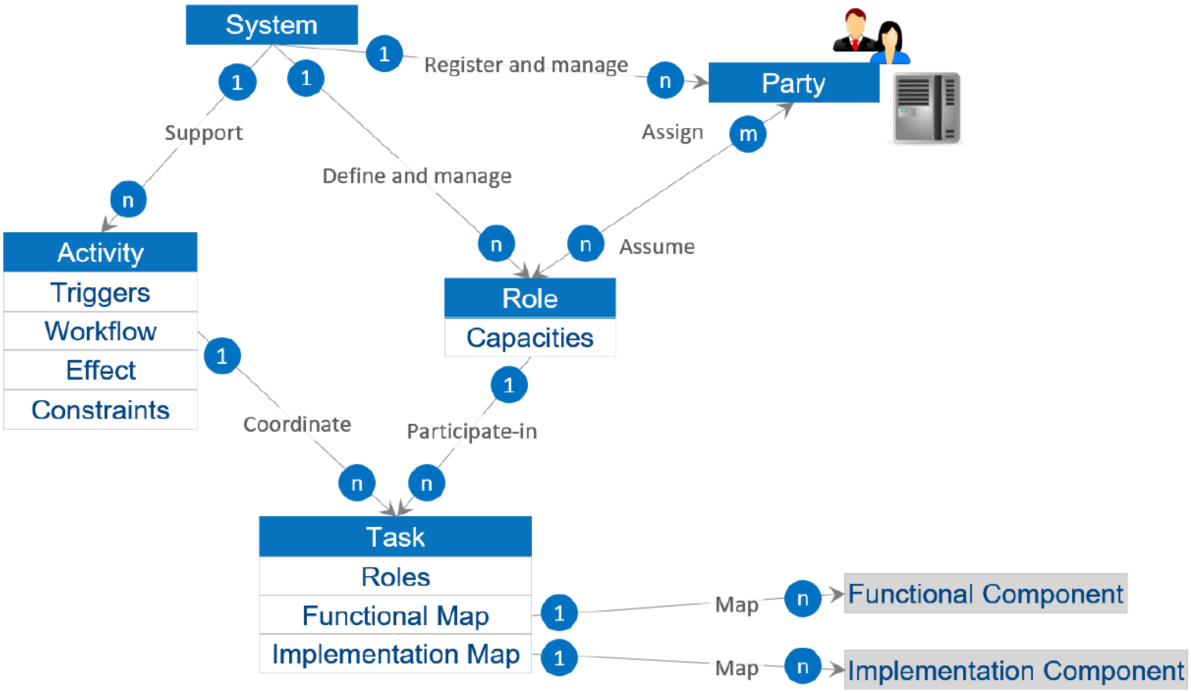



Figure 9 Tasks, Activities, Roles, and Parties in IIRA`s usage viewpoint (source [IIC+ 20170131])

- **Task:** Basic unit of work, such as the invocation of an operation, a transfer of data or an action of a party, carried out by a party assuming a role:
  - **Functional map:** Map of the functions or functional components of the task
  - **Implementation map:** Map of the implementation component the task relies on for its execution
- **Role:** Set of capacities assumed by an entity to initiate, participate in the execution of, or consume the outcome of a task
- **Party:** Agent (human or automated) that has interest and responsibility in the execution of a task. An agent executes a task assuming a role with the right capacities for the execution of the task
- **Activity:** Specified coordination of tasks (and possibly other activities) required to user or operate the system, consisted of the following elements:
  - **Trigger:** Conditions that initiate an activity, optionally associated with a role responsible for initiating or enabling the execution
  - **Workflow:** Organisation of tasks (sequential, parallel, conditional, iterative)
  - **Effect:** Difference in the state of the system after the successful completion of an activity
  - **Constraints:** Characteristics that must be preserved during the execution of the activity

### 2.1.4.3 Functional Viewpoint

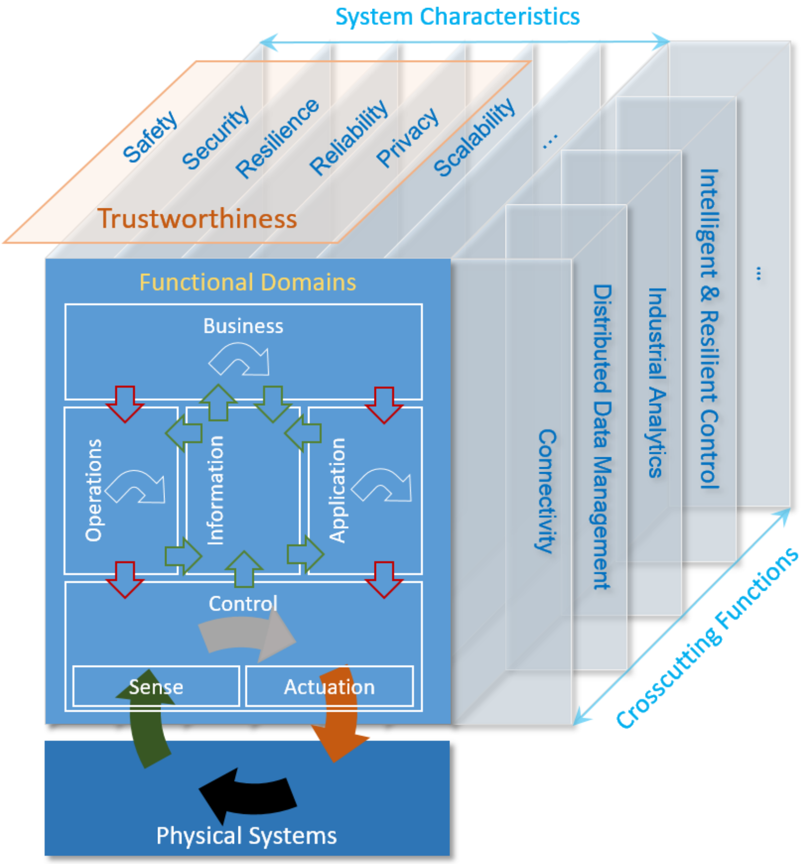



Figure 10 IIRA's Functional Domains, Crosscutting Functions and System Characteristics (source [IIC+ 20170131])

The functional viewpoint decomposes a typical IIoT System into functional parts, to describe the system structure and interrelations, interfaces, and interactions between its functional components, as well as with external systems. Thus, the functional viewpoint establishes five functional domains (industrial control, operations, information, application, and business), five system characteristics (safety, security, resilience, reliability, privacy, and scalability), and four crosscutting functions (connectivity, Distributed data management, industrial analytics, and intelligent & resilient control) depicted in Figure 10 and described as:

- **Functional domains:** Decomposition of the distinct functionalities of a distributed industrial control system into physical domains:
    - **Control domain:** Functions performed by industrial control systems, mainly reading sensor data (sense) and control through actuators (actuation)
    - **Operations domain:** Functions for management, monitoring and optimisation of control domain functionalities (prognostics, optimisation, monitoring and diagnostics, deployment, management)
    - **Information domain:** System modelling, data collection, persistence, transformation, and analysis
    - **Application domain:** Application logic and rules to realize specific business functionalities, User Interfaces and Application Programming Interfaces to expose functionalities for humans and external applications

    - **Business domain:** Functions to enable end-to-end operations of the IIoT system including those supporting business processes, also integrating with traditional specific functions. Examples include Enterprise Resource Planning (ERP), Customer Relationship Management (CRM), or Manufacturing Execution System (MES).
- **Crosscutting functions:** Functionalities that enable the Industrial Internet that need to be provided to enable the functional domains:
    - **Connectivity:** Functionalities enabling information sharing and collaborative manufacturing
    - **Distributed Data Management:** Coordination of data management tasks across system components
    - **Industrial Analytics:** Application of analytics on the data collected from industrial assets
- **System Characteristics:** System properties emerging from the interactions between system parts:
    - **Trustworthiness:** Coordination and integration of different functions implemented in the different system components to guarantee overall system safety, security, resiliency, reliability, and privacy
    - **Scalability:** Functions to enable or facilitate the efficient deployment of large-scale instances of the system

The functional viewpoint is also concerned with the distribution of functional domains across distributed computational resources in different deployment patterns. Considerations on the use of technologies such as cloud computing, containerisation, Infrastructure-as-a-Service (IaaS), Platform-as-a-Service (PaaS), or Software-as-a-Services (SaaS) to distribute the different functional domains are also part of the functional viewpoint.

#### 2.1.4.4 Implementation Viewpoint

The implementation viewpoint deals with the technologies needed to implement functional components, communication schemes, and procedures involved during their lifecycle. The implementation viewpoint defines three patterns for a coherent IIoT System implementation: three-tier architecture pattern, gateway-mediated edge connectivity and management architecture pattern, and the layered databus pattern.

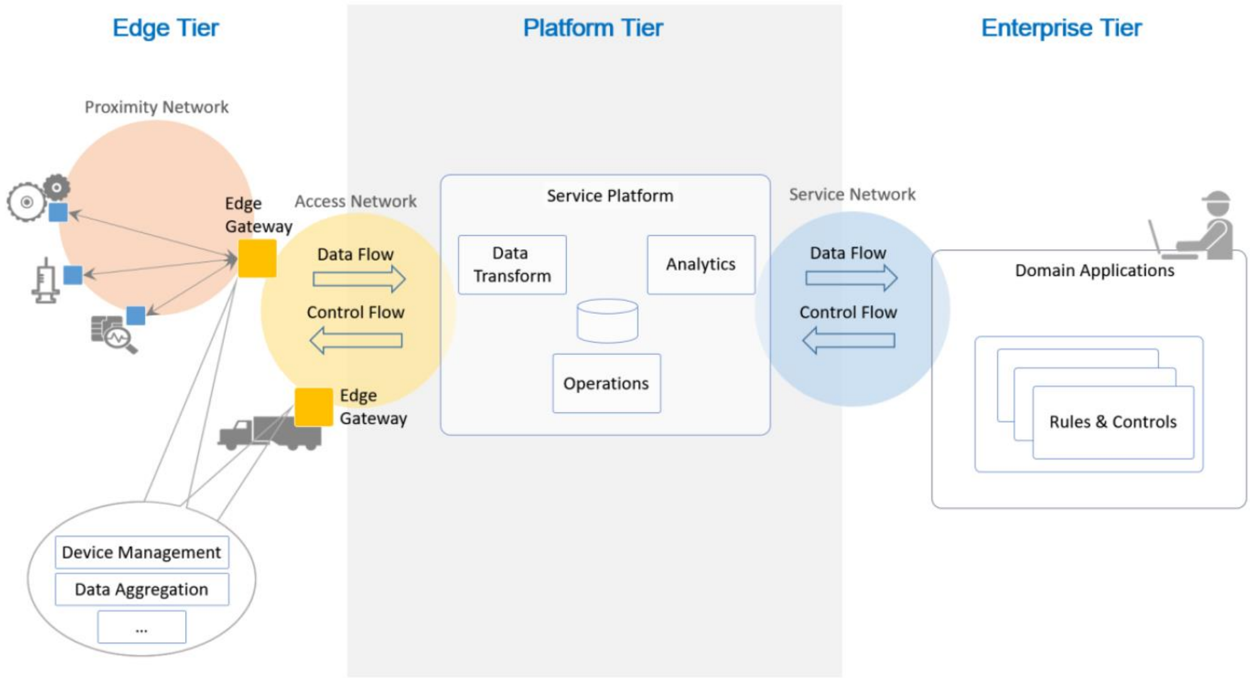



Figure 11 IIRA's Three-tier architecture pattern (source [IIC+ 20170131])

The three-tier architecture pattern divides the system into three tiers (edge, platform, and enterprise) and three networks (proximity, access, and service). The pattern is represented in Figure 11. The edge tier collects data from sensors, actuators, devices, control systems, or any asset in the proximity of the physical system, which are collectively called the edge nodes. For this purpose, the edge tier uses the proximity network. The access network enables connectivity between the edge tier and the platform tier. The platform tier consolidates operation processes, performs data analytics, and transformation functions with respect to data flows.

It also offers management functions on edge nodes and dispatches control messages from the enterprise tier to the edge tier. The service network enables connectivity between the services in the platform tier, as well as between platform and enterprise tiers. The enterprise tier implements domain-specific applications, decision support systems, and provides user interfaces to end-users. It implements the rules and control logic of the system and issues control commands to the platform and edge tiers.

The gateway-mediated edge connectivity and management pattern, and the layered databus pattern are more specific instances or variations of the three-tier architectural patterns that deal with connectivity solutions to interconnect the different tiers in specific network topologies.

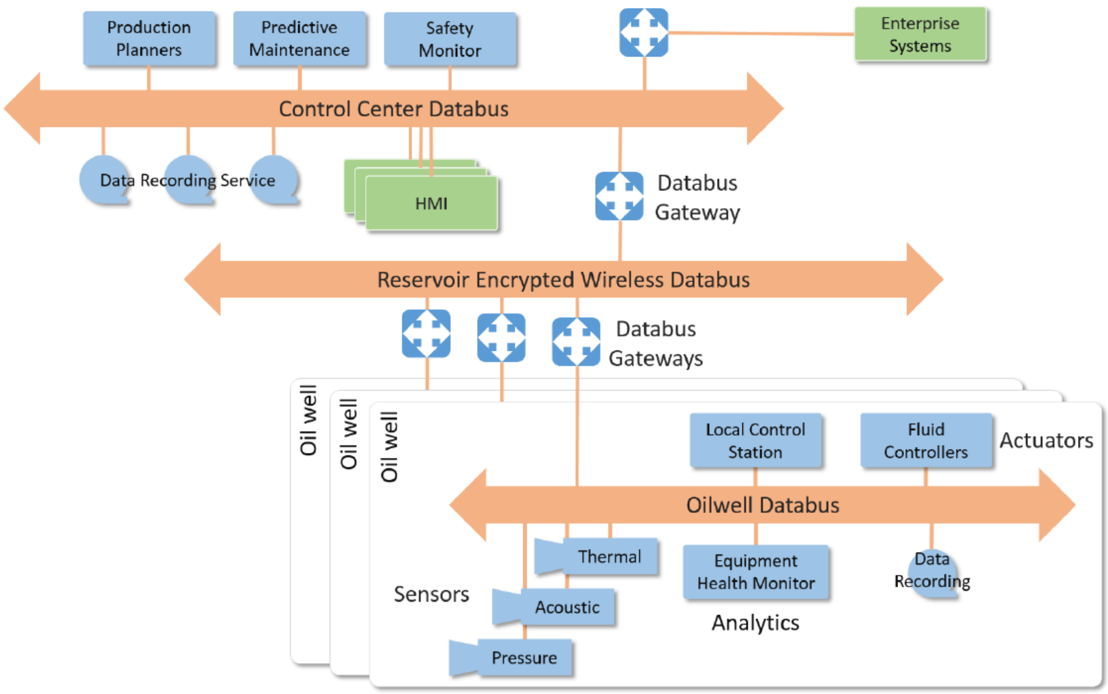



Figure 12 IIRA's Databus architectural pattern (source [IIC+ 20170131])

In the gateway-mediated edge connectivity pattern, a single edge gateway bridges the local connectivity of the IIoT system in a specific location to the wide area network. In the more general three-tier architectural pattern, edge nodes can move and the access network needs to implement load-balancing functions to balance the load of the different edge gateways. Therefore, the gateway-mediated edge connectivity architectural pattern is suitable in deployments where there is little mobility of edge nodes and there is no need to deal with mobility across edge node clusters.

Similarly, the layered databus architectural pattern is a common pattern for applications that have connectivity requirements across different logical layers of the system. A databus is a logical representation of the functions that enable communication between endpoints at a particular system layer, and a databus gateway is a logical entity that enables communication between different system layers. As an example, Figure 12 shows a three layer architecture (sensors and actuators, control, and enterprise systems) with three data buses interconnecting the different assets in the different layers, and databus gateways to interconnect the different databuses between them.

### 2.1.4.5 Alignment to RAMI 4.0

[IIC+20171205] provides an alignment between IIRA and RAMI 4.0. The main conclusion of the alignment is that both reference models have different emphasis in scope and depth and consequently, much of the differences are complementary and helpful to analyse a manufacturing IIoT system application. This whitepaper maps and aligns the two reference architectures to identify convergent and complementary parts. The result of the alignment is summarised in Figure 13.

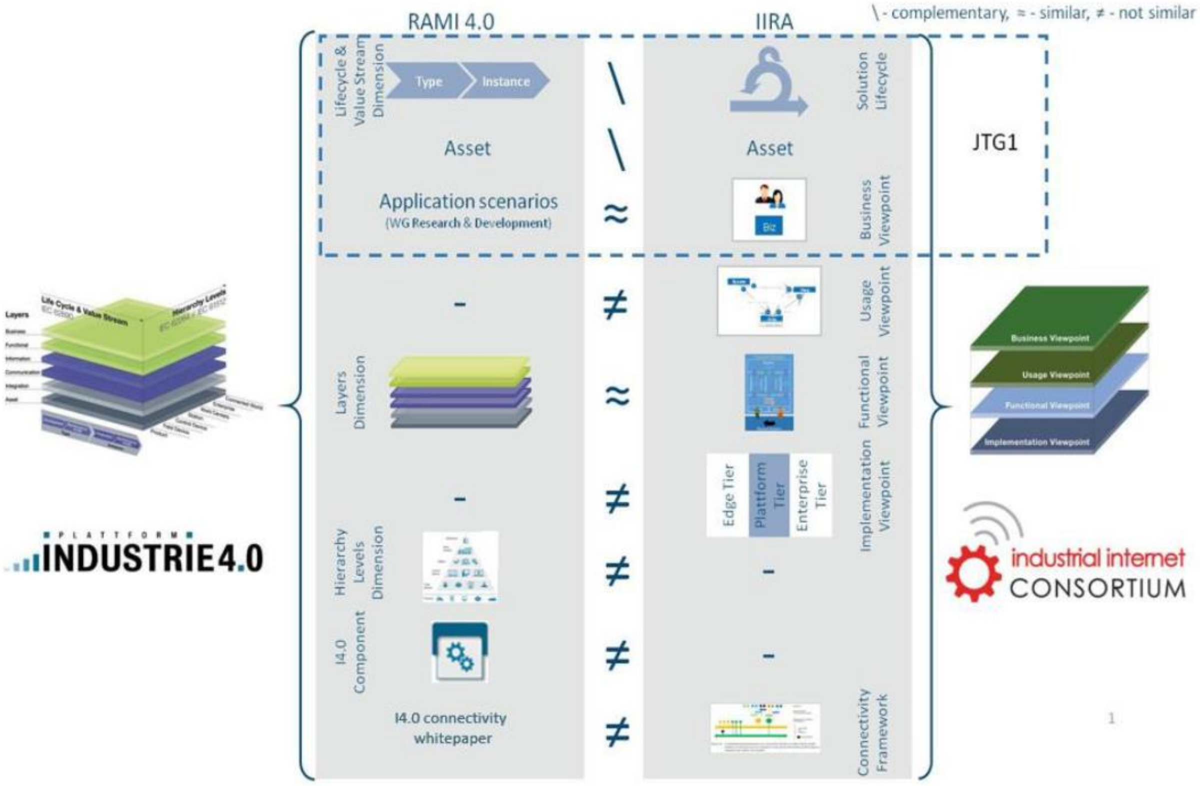



Figure 13 IIRA and RAMI 4.0 alignment

As shown in the figure, the IIRA Usage and implementation Viewpoints are complementary to RAMI 4.0, since there is no counterpart element in the RAMI 4.0 reference model. The IIRA business viewpoint is complementary to the RAMI 4.0 Lifecycle dimension, since it contains additional definitions useful to better describe the concerns of the different actors and organisations involved in the product life cycle from a business point of view.

The layer dimension is similar to the functional domains of the Functional Viewpoint, but RAMI 4.0 is more specific to manufacturing and therefore better suited to applications for the manufacturing sector. The cross-cutting functions and system characteristics of IIRA are in that sense complementary to the layer dimension. Connectivity is the only divergence found between both reference models, although there are some similarities between the protocol stacks defined in the IIC connectivity framework for the manufacturing domain and the I4.0 connectivity whitepaper of Platform Industry 4.0.

## 2.2 Coverage Analysis

### 2.2.1 Functional/Technical Perspective

In ZDMP, Work Package 5 deals with activities aimed at providing basic building blocks to support the ZDMP platform, implementing a set of core services that are transversal to high-level functionalities. In particular, Task T5.1 is an IIoT framework to manage manufacturing assets (eg physical sensors and devices) and handle all the data they produce. Task T5.2 develops concepts for privacy and security handling in the context of an industrial network. T5.3 deals with data harmonisation, semantic enrichment, and interoperability. Task T5.4 integrates platform functions and provides both runtime and modelling environments for collaborative manufacturing processes. T5.5 delivers the runtime environment to execute the different services in the available (edge-cloud) infrastructure and finally, Task 5.6 implements machine-learning and analytics services.

Figure 14 depicts the mapping of the activities of ZDMP WP5 to the RAMI 4.0 reference model.

| WORK PACKAGES | | WP5: ZDPM Core Services and Middleware | | | | | |
|---|---|---|---|---|---|---|---|
| Tasks | | T5.1: Data Acquisition and IIoT | T5.2: Robust Industrial Network Support | T5.3: Data Harmonisation and Interoperability | T5.4: Orchestration | T5.5: Distributed & Autonomous Computing | T5.6: AI and Analytics |
| RAMI 4.0 | | | | | | | |
| Layers | | | | | | | |
| RAMI 4.0 | Business | N/A | ✓ | N/A | N/A | N/A | N/A |
| | Functional | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| | Information | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| | Communication | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| | Integration | ✓ | N/A | N/A | N/A | ✓ | N/A |
| | Asset | ✓ | N/A | N/A | N/A | ✓ | N/A |
| | Life Cycle & Value stream (IEC 62389) | | | | | | |
| | Type (Development) | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| | Type (Maintenance /Usage) | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| | Instance (Production) | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| | Instance (Maintenance /Usage) | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| | Hierarchy Levels (IEC 62264) | | | | | | |
| | Product | N/A | N/A | N/A | N/A | N/A | N/A |
| | Field Device | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| | Control Device | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| | Station | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| | Work Centers | N/A | ✓ | ✓ | ✓ | N/A | ✓ |
| | Enterprise | N/A | ✓ | ✓ | N/A | N/A | ✓ |
| | Connected World | N/A | ✓ | ✓ | N/A | N/A | ✓ |

Figure 14 Mapping of RAMI structure in the Technical Perspective (Core Services)

T5.1 and T5.2 cover the communication layer (standard secured communications). T5.2 may also be mapped partially to the business layer, since it also includes some legal and regulatory conditions that are transversal to all platform services. T5.3 represents many aspects of the information layer, including formal description of models and rules, consistent integration of different data sources, or structured data provision, among others. T5.4 is related to the functional layer, since it orchestrates asset functionalities. Task T5.5 can be associated to the asset layer, since edge devices and cyber-physical systems are part of the physical world. Task 5.6 is linked to the functional and business layers, since machine learning and analytics services will leverage decision support services and expert systems at these levels.

Considering the lifecycle and value stream dimension of the RAMI 4.0 model, all Work Package 5 Tasks are linked to both the product type (development and maintenance), and product instance (both production and maintenance), since the provided functionality is transversal to all platform use cases.

Regarding the hierarchy dimension; T5.1 covers all layers from product to enterprise since the aim is to collect data from any manufacturing asset, both manufacturing devices and legacy software. Similarly, T5.2 activities are linked to all dimensions from devices upward, since security and privacy are aspects that must be considered at all levels. T5.3 activities deal with harmonisation and interoperability of data coming from the control device and field device levels, up to the enterprise, and even from different companies (connected world). T5.4 deals with the modelling and execution of application processes that potentially coordinate distributed assets, and therefore collaborating assets and services can be linked to any hierarchy layer. T5.5 distributed computing is also transversal to all hierarchy levels, as services will be deployed in the edge-cloud continuum. Potential applications of machine learning and advance analytics are also transversal to all hierarchy layers and therefore the same considerations apply for T5.6.

### 2.2.2 Platform Perspective

Task T6.1 SDK: Applications and Service Builder represents a fully documented Application Programming Interface (API) framework which supports functions for the development of manufacturing-related applications (apps). The “ZDMP App Store” is an App marketplace created in Task T6.2 Secure Business Cloud, where existing apps are provided, and manufacturing users can request new applications (which developers can then build). Task T6.3 Human Collaboration Environment supports collaboration between users across and between factories. The core platform which represents the interface between RTD components, manufacturing systems, marketplace, service framework, and end user applications is created in Task T6.4 Platform Integration and Federation. It includes a web portal with a monitoring dashboard and supports the development and administration of Apps. In the scope of Task T6.5 Inter-platform Interoperability the ZDMP platform supports messaging, data stream analytics, complex event processing, integration technology, and external platform integration absorbed typically from WP5 tasks. The platform further considers fault tolerance and Quality of Service (QoS) requirements. Task T6.6 General Cross-Task Integration and Improvement is a buffer time activity to support WPs 5-8, their integration and testing, and therefore it is not relevant in the context of this deliverable. For this reason,

Figure 15 depicts the mapping of WP6 development activities to the RAMI 4.0 reference model.

| WORK PACKAGES | | WP6: Platform Building | | | | |
|---|---|---|---|---|---|---|
| Tasks | | T6.1: SDK: Applications and Service Builder | T6.2: Secure Business Cloud | T6.3: Human Collaboration Environment | T6.4: Platform Integration and Federation | T6.5: Inter-platform Interoperability |
| RAMI 4.0 | | | | | | |
| Layers | | | | | | |
| RAMI 4.0 | Business | N/A | ✓ | ✓ | ✓ | ✓ |
| | Functional | N/A | ✓ | ✓ | ✓ | ✓ |
| | Information | N/A | ✓ | ✓ | ✓ | ✓ |
| | Communication | N/A | ✓ | ✓ | ✓ | ✓ |
| | Integration | N/A | ✓ | N/A | ✓ | ✓ |
| | Asset | N/A | N/A | N/A | N/A | N/A |
| | Life Cycle & Value stream (IEC 62389) | | | | | |
| | Type (Development) | ✓ | ✓ | ✓ | ✓ | ✓ |
| | Type (Maintenance /Usage) | ✓ | ✓ | ✓ | ✓ | ✓ |
| | Instance (Production) | ✓ | ✓ | ✓ | ✓ | ✓ |
| | Instance (Maintenance /Usage) | ✓ | ✓ | ✓ | ✓ | ✓ |
| | Hierarchy Levels (IEC 62264) | | | | | |
| | Product | N/A | ✓ | N/A | ✓ | ✓ |
| | Field Device | N/A | N/A | N/A | N/A | N/A |
| | Control Device | N/A | N/A | N/A | N/A | N/A |
| | Station | N/A | ✓ | N/A | ✓ | ✓ |
| | Work Centers | N/A | N/A | N/A | N/A | N/A |
| | Enterprise | N/A | ✓ | ✓ | ✓ | ✓ |
| | Connected World | N/A | ✓ | N/A | ✓ | ✓ |

Figure 15: Application of RAMI 4.0 in Platform Building

The developed platform represents a central component of the ZDMP project and, thus, the Tasks in WP6 cover many RAMI4.0 layers. More specifically, Tasks T6.2-T6.5 cover all virtual layers from the Business layer down to the integration layer, where the Business layer specifies the business functions, models the rules that the system has to follow, and provides a link between different business processes. The Functional layer provides the environment which supports business processes, horizontally integrates the various functions, and formally describes the functions. The Information layer concerns all data-related aspects and event-related rules. The communication between the services and components happens in the Communication layer. The integration layer connects the physical assets with the digital world.

The concepts behind the platform-building-related aspects in WP6 apply to all four phases of the Life Cycle & Value Stream axis in RAMI4.0.

Tasks T6.2-T6.5 belong to the Enterprise hierarchy level, because they all concern functions and interactions on the business organisation level. Tasks T6.2, T6.4, and T6.5 also belong to the Connected World, Station and Product levels. In this context, the Station level performs administrative activities to examine the operation of events and processes, eg deploying apps (T6.2) or monitoring communication (T6.4) and device interaction on real-time information (T6.5). The App Store itself (T6.2), administrative apps and a web portal with a monitoring dashboard (T6.4) and the platform support for messaging, data stream analytics, complex event processing, and external platform integration (T6.5) represent products that are created in ZDMP and are thus located at the Product level.

The Service Builder of Task T6.1 is a development tool for developing I4.0 components rather than a product or asset itself. However, since the Layers and the Hierarchy of the RAMI4.0 model rather describe working assets and not such development tools, Task T6.1 is not well really in the scope of RAMI4.0.

### 2.2.3 Process Quality Perspective

Work Package 7 deals with services to ensure process quality. In T7.1 Preparation Stage, Start-up optimisation, machine learning models linked to simulation models are used to detect and correct organisational errors. The models are interconnected with the real production system to be able to detect and correct errors in the preparation of the production equipment. T7.2 Production Stage: Equipment Performance Optimisation develops black-box regression models that are able to detect and correct process errors, which can cause the appearance of defects. The objective of T7.3 Production Stage: Material and Energy is to develop models to detect anomalies in the consumption of resources (materials, energy) and infer the relationship between these anomalies and future defects. Finally, T7.4 provides supervision systems to balance the different optimisation goals, and user interfaces to support decision making.

Figure 16 depicts the mapping of WP7 development activities in the RAMI 4.0 reference model.

| WORK PACKAGES | | WP7: Process Quality Assurance | | | |
|---|---|---|---|---|---|
| Tasks | | T7.1: Preparation Stage: Start-up optimisation | T7.2: Production Stage: Equipment Performance Optimisation | T7.3: Production Stage: Material and Energy Efficiency | T7.4: Process Quality Assurance |
| RAMI 4.0 | | | | | |
| Layers | | | | | |
| RAMI 4.0 | Business | ✓ | ✓ | ✓ | ✓ |
| | Functional | ✓ | ✓ | ✓ | ✓ |
| | Information | N/A | N/A | N/A | N/A |
| | Communication | N/A | N/A | N/A | N/A |
| | Integration | ✓ | ✓ | ✓ | ✓ |
| | Asset | N/A | N/A | N/A | N/A |
| | Life Cycle & Value stream (IEC 62389) | | | | |
| | Type (Development) | N/A | N/A | N/A | N/A |
| | Type (Maintenance /Usage) | N/A | N/A | N/A | N/A |
| | Instance (Production) | ✓ | ✓ | ✓ | ✓ |
| | Instance (Maintenance /Usage) | ✓ | ✓ | ✓ | ✓ |
| | Hierarchy Levels (IEC 62264) | | | | |
| | Product | N/A | N/A | N/A | N/A |
| | Field Device | N/A | N/A | N/A | N/A |
| | Control Device | ✓ | ✓ | ✓ | ✓ |
| | Station | ✓ | ✓ | ✓ | ✓ |
| | Work Centers | ✓ | ✓ | ✓ | ✓ |
| | Enterprise | ✓ | ✓ | ✓ | ✓ |
| | Connected World | N/A | N/A | N/A | N/A |

Figure 16: Application of RAMI 4.0 in Process Quality Assurance

In the RAMI 4.0 model layers, WP7 results are primarily located in the business, functional, and integration layers. Regarding the business layer, it is expected that in many use cases the production equipment is connected to functional layer services of supply chain collaborators, for instance, external optimisation services provided by the manufacturing equipment provider. Hence, the required orchestration of functional layer services is positioned at the business layer. As for the functional layer, the description of functions, the runtime and modelling environment, and the rules and decision-making logic that support the digital models are located at the functional layer. The connected world level could also be taken into consideration in collaboration scenarios and optimisation of processes in the supply network.

These services will be supported by ZDMP core services at the Information, Communication, and Integration layers. The information layer contains the event processing runtime environment required to synchronise the digital model with the physical system, the persistence of the data which represent the models, and the provision and transformation of data required by the functional Layer. The communication layer services will enable the data flows between the information layer and the control of the integration layer. The integration layer services provision the required configuration information to physical assets and generates the events that represent changes in the process status towards the communication layer. To achieve strict synchronisation requirements, the event generation and process control functions must be able to process raw sensor data. This implies that machine learning and signal processing algorithms need to be partitioned between the functional and the integration layer, with the latter running on top of edge computing ZDMP services.

In the life cycle & value stream dimension, WP8 results are primarily located at the instance production (from the perspective of the production system owner) and type maintenance usage (from the perspective of the manufacturing equipment provider).

Finally, regarding hierarchy levels, the enterprise, work centres, station, and control device levels are involved in start-up and equipment performance optimisation, as well as material and energy efficiency, in extension to process quality assurance. All these levels need to be analysed in detail to achieve optimisation.

### 2.2.4 Product Quality Perspective

Task T8.1 Characterisation and Modelling provides material characterisation, physical product descriptions, virtual product modelling and methods for the traceability of the product. Task T8.2 Pre-Production defect detection uses the output of T8.1 to predict and anticipate defects during manufacturing process by applying AI tools and data analytics services, providing feedback to further improve T8.1 models. With respect to the T8.3 Product In-Line Inspection, this Task involves the detection of defects during manufacturing production activity, by the application of non-destructive techniques and solutions. These include the use of advanced sensors, cameras, measuring systems based on AI and artificial vision. This Task also impacts T7.2 Equipment Performance Optimisation with its feedback. Finally, T8.4 Product In-line Defect Prediction aims to supervise each individual part along the entire supply chain, collecting all relevant information in the process, in order to identify critical trends that might result in downstream defects. This Task combines outputs of T8.1, T8.3 and T7.2 to trigger alarms and actions when deviations are detected. Figure 17 depicts the mapping of WP8 development activities in the RAMI 4.0 reference model.

| WORK PACKAGES | | WP8: Product Quality Assurance | | | |
|---|---|---|---|---|---|
| Tasks | | T8.1: Characterization and Modelling | T8.2: Pre-Production Defect Detection | T8.3: Product In-Line Inspection and Defect Detection | T8.4: Product In-line Defect Prediction |
| RAMI 4.0 | | | | | |
| Layers | | | | | |
| RAMI 4.0 | Business | ✓ | ✓ | ✓ | ✓ |
| | Functional | ✓ | ✓ | ✓ | ✓ |
| | Information | ✓ | ✓ | ✓ | ✓ |
| | Communication | N/A | N/A | N/A | N/A |
| | Integration | N/A | N/A | ✓ | ✓ |
| | Asset | N/A | N/A | N/A | N/A |
| | Life Cycle & Value stream (IEC 62389) | | | | |
| | Type (Development) | ✓ | ✓ | N/A | N/A |
| | Type (Maintenance /Usage) | ✓ | ✓ | N/A | N/A |
| | Instance (Production) | N/A | N/A | ✓ | ✓ |
| | Instance (Maintenance /Usage) | N/A | N/A | ✓ | ✓ |
| | Hierarchy Levels (IEC 62264) | | | | |
| | Product | ✓ | ✓ | ✓ | ✓ |
| | Field Device | N/A | N/A | ✓ | ✓ |
| | Control Device | N/A | N/A | ✓ | ✓ |
| | Station | ✓ | ✓ | ✓ | ✓ |
| | Work Centers | ✓ | ✓ | ✓ | ✓ |
| | Enterprise | ✓ | ✓ | ✓ | ✓ |
| | Connected World | N/A | N/A | N/A | N/A |

Figure 17: Application of RAMI 4.0 in Product Quality Assurance

In the RAMI 4.0 model layers, all WP8 Task activities are connected to the Business, Functional, and Information layers. The Business layer ensures the integrity of functions in the value stream and orchestrates services in the Functional Layer.

The Functional layer hosts the description of functions, the modelling environment, and the rules that support the digital models. The Information layer provides the persistence of data representing the models and receives and integrates new knowledge and data into the models. The Integration layer provisions the required configuration information to physical assets and generates the events that represent changes in the process.

Integration and Asset layer are not included in T8.1 and T8.2 as they represent physical components and how they integrate with the virtual world, whilst the models are already digital components. Nevertheless, T8.3 and T8.4 are connected to the Integration layer because it provisions information on the assets, generates associated events and allows interaction with them.

In the Life Cycle & Value Stream dimension, T8.1 and T8.2 are primarily located at the Type Development and Type Maintenance Usage, as they involve the creation and maintenance of models and prototypes. On the other hand, T8.3 and T8.4 are located in the Instance Production and Maintenance level value streams, because their scope of action is in-line production.

Regarding Hierarchy Levels, mainly the Enterprise, Work Centres, Station, and Product levels are involved in developing and maintaining up to date the models and actions performed in all WP8 Tasks. It is worth considering that T8.3 and T8.4 cover also Field and Control Device levels, because the relationship of their work with sensors and actuators deployed in the floor plant.

### 2.2.5 User Perspective

Figure 18 depicts the mapping of ZDMP pilots in the RAMI 4.0 reference model. All four ZDMP pilots present a wide coverage of all layers and can be mapped to most of the elements of all three axis of the RAMI 4.0 model. For a complete description of the four pilot sectors and all their use-cases, please refer to deliverable D024 – ZDMP D2.3 Industry Scenarios and Use Cases.

The automotive sector includes three use-cases aimed to detect and predict defects in different production processes (UC1.1, UC1.2) and to prevent them by optimizing the manufacturing process (UC1.3). In brief they are:

- UC1.1: Defects detection and prediction in aluminium injection operations. This use case deals with models of die casting of aluminium parts that are able to learn the relationship between process parameters and out of tolerance parts in a distributed manufacturing scenario
- UC1.2: Defects detection and prediction in machining operations. This use case deals with detection and prevention of out of tolerance parts in machining operations based on the same principles as UC1.1
- UC1.3: Defects reduction by optimization of the machining process. This use case deals with the optimization of the performance of the machining process based on the relationship between process parameters and overall performance

In the RAMI 4.0 model layer, this application scenario involves the integration, communication, and information layers, consisting in processing and analysis of physical variables. Functional and business layers, while being involved by the exchange of information with the suppliers resulting from the analysis of physical variable data (or patterns in the data), are not the main focus of the use case.

Considering the life cycle & value stream, UC1.1 and UC1.2 are located in the instance production and maintenance level value streams, because their scope of action is quality prediction in in-line production. UC1.3 aims to optimize the manufacturing operation, therefore affecting the quality of the product at type level.

On the Hierarchical level, UC1.1 and 1.2 focus on the product level, since in both cases the baseline is the quality inspection of the final product, in order to detect defects. These use-cases involve all the steps of the hierarchy, up to the connected world level, where the information resulting from the analysis can be exchanged with the other stakeholders of the value chain. Differently, UC1.3 finds its main focus in the station level and the work centre. In this case data is collected at machine level, registering a set of the parameters in normal conditions and detecting the deviation from such condition. In this case product and field devices are not considered.

The machine tools sector focuses on applications to assess the machine condition involving all relevant actors of the supply chain (UC2.1), to automate parameters tuning (UC2.2) and to prevent human error by modelling the manufacturing operation before its execution (UC2.3):

- UC2.1: Process alert system for machine tool failures prevention. This use case implements continuous condition and process monitoring and early warning systems to prevent error in moulds for plastic injection
- UC2.2: Ongoing and automatic machining process parameter tuning. This use case deals with the optimization of the moulding machining process based on collected real time data
- UC2.3: geometric mould specifications and working area check. This use case deals with the automatic modelling of the mould specifications and working area to improve the performance of the anti-collision software in the plastic moulding machine

In the RAMI 4.0 model layer, this application scenario involves all layers, with focus on the integration, communication, and information layers, since it mostly implies processing and analysis of physical variables. UC2.1 also affects the functional and business layers by providing data to the supply chain actors, who can gain an overview on their products functioning at customer premises. UC2.3 also work on the asset layer, modelling the physical manufacturing process and anticipating its evolution.

In the life cycle & value stream dimension, all Machine Tool Sector Use-Cases are located in the instance production and maintenance level value streams, because their scope of action is in-line production and in the maintenance of the specific machine.

Regarding hierarchy levels, mainly the station, control device, field device, and product levels are involved. UC2.3 targets all four works on all four levels, exploiting a laser scanner (field device) to scan the product as installed on the machine (product level) to create a 3D model to feed the anti-collision system running on the numerical control (control level) that prevent collisions at machine level (Work Unit). UC2.1 and UC2.2 are involve a slightly higher layer, not involving directly the work piece or additional sensors, but gathering data through the native sensors of the equipment. The connected world layer is considered partially involved in UC2.1, since, from the point of view of the stakeholders that located higher in the value chain, e.g. machine producer, sub-systems producer, this use-case provides a global view upon the products they have sold and their current functioning.

The electronic sector includes two use-cases:

- UC3.1: Incoming component inspection. This use case deals with the automatic generation and reporting of quality inspection procedures of incoming electronic components
- UC3.2: Using Artificial Intelligence to detect the optical defect. This use case applies machine learning and AI to enhance an artificial vision system for quality inspection.
- UC3.3: Smart assembly line monitoring and control system: this use case implements support systems for operators and managers to improve assembly line performance based on data collected in real time.

This application scenario can be mapped in the RAMI 4.0 model layer dimension on functional, information, and communication for what concerns UC3.1 and on communication, integration, and asset for UC3.2. The business layer is not affected by either application scenarios.

Considering the life cycle & value stream, all use-cases are focusing on the instance layers, both in the production and in the usage.

From the hierarchical point of view UC3.1 primarily involves the product and field device levels for the quality assessment, the control device and the station, for the automatic generation of the reports, and the enterprise level, for the storage of these documents. UC3.2 focuses on the product and field device levels.

The construction sector includes three use-cases aimed respectively to trace construction materials across the supply chain (UC4.1), to prevent stone cutting defects (UC4.2), and to detect defects in the steel tubes production process (UC4.3):

- UC4.1: Zero defects manufacturing of stone tiles. This use case deals with continuous monitoring of stone cutting, stone slab polishing, and stone slab final cutting processes to detect and correct errors
- UC4.2: Zero defects of supply material – reception. This use case automates material reception quality control reporting to optimize operations at the construction site.
- UC4.3: Construction materials traceability: This use case collects information about construction materials to enhance traceability

In the RAMI model layer, this application scenario involves all layers. UC4.1 focuses on the business and functional layers while the other use-cases involve the lower levels.

Concerning the life cycle & value stream, all use-cases are focusing on the instance layers, UC4.1 and UC4.3 both in the production and in the usage, and UC4.2 is related to product type development.

At the Hierarchical level, UC4.2 and 4.3, being both targeting defect detection technologies, have a focus span ranging from the product level up to the station used to manufacture it. UC4.1 targets the communication and tracking across the supplier chain, strongly involving the connected world and the enterprise levels.

| WORK PACKAGES | | WP9-WP10: Pilots | | | |
|---|---|---|---|---|---|
| Tasks | | T9.4: Large and Traditional Sectors: Automotive | T9.4: Large and Traditional Sectors: Machine Tools | T10.4: SME and Enhanced Sector cases: Electronics | T10.4: SME and Enhanced Sector cases: Construction |
| RAMI 4.0 | | | | | |
| Layers | | | | | |
| RAMI 4.0 | Business | (✓) | ✓ | N/A | ✓ |
| | Functional | (✓) | ✓ | ✓ | ✓ |
| | Information | ✓ | ✓ | ✓ | ✓ |
| | Communication | ✓ | ✓ | ✓ | ✓ |
| | Integration | ✓ | ✓ | ✓ | ✓ |
| | Asset | ✓ | ✓ | ✓ | ✓ |
| | Life Cycle & Value stream (IEC 62389) | | | | |
| | Type (Development) | N/A | N/A | N/A | N/A |
| | Type (Maintenance /Usage) | ✓ | N/A | N/A | N/A |
| | Instance (Production) | ✓ | ✓ | ✓ | ✓ |
| | Instance (Maintenance /Usage) | ✓ | ✓ | ✓ | ✓ |
| | Hierarchy Levels (IEC 62264) | | | | |
| | Product | ✓ | ✓ | ✓ | ✓ |
| | Field Device | ✓ | ✓ | ✓ | ✓ |
| | Control Device | ✓ | ✓ | ✓ | ✓ |
| | Station | ✓ | ✓ | ✓ | ✓ |
| | Work Centers | ✓ | N/A | ✓ | ✓ |
| | Enterprise | ✓ | N/A | ✓ | ✓ |
| | Connected World | ✓ | (✓) | N/A | ✓ |

Figure 18: Application of RAMI 4.0 in the Pilots

# 3 Recommendations

## 3.1 General Recommendations

### 3.1.1 Global Architecture Description

Regarding the system architecture description, the recommendation is to use a combination of RAMI 4.0 and IIRA architectural models, since they are both complementary and can both contribute to facilitate the definition of the architecture in the ZDMP project.

The ISO 42010 architecture description [ISO 42010] used in IIRA provides an adequate framework for the definition and description of the global architecture of ZDMP. IIRAs viewpoints can be used in T4.3 Architectural Principles and Design, as illustrated in Figure 19, to describe the ZDMP system architecture. Inputs from T2.1 Project Inception and Vision Consensus, and T2.3 Industry Sector Scenarios, Use Cases, and KPIs can be used to define the different elements of the IIRA Vision and Value-Driven model (stakeholders, vision, values, and fundamental capabilities). Moreover, T2.3 Industry Sector Scenarios, Use Cases, and KPIs can be the input to describe the use cases through the models and concepts of the Usage viewpoint (Party, Role, Task, Activity, and System).

As for the Functional viewpoint, the RAMI 4.0 Layer dimension can be used to identify the functional components of the system, their relationships, and interactions. These definitions should be used as a reference for the functional specifications of ZDMP (Task 4.4 Functional Specification). Section 3.2.1 contains some additional recommendations to describe the system architecture with IIRA's Business, Usage, and Functional viewpoints, taking the use case definitions as an input.

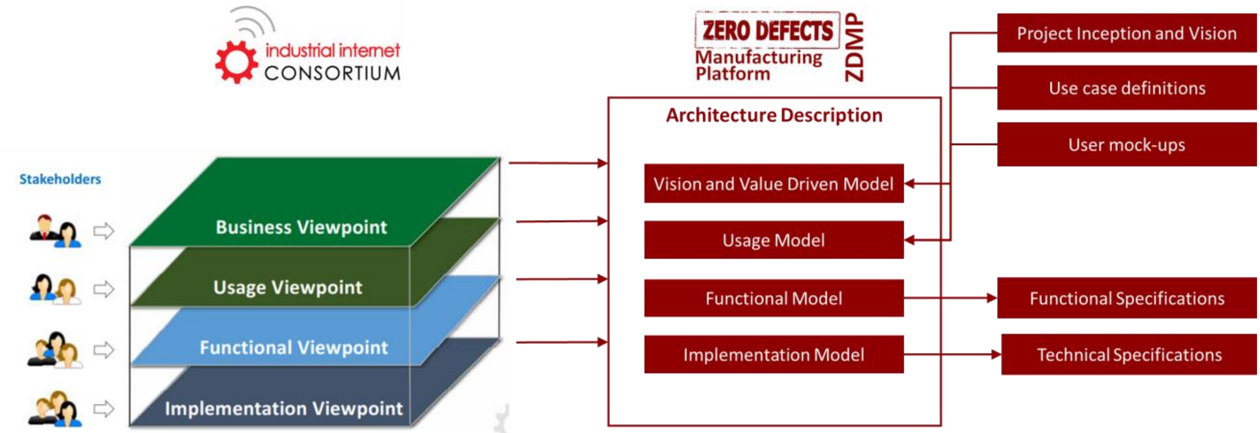



Figure 19: Relationships between IIRA's viewpoints and ZDMP architectural description

The implementation viewpoint can be used to describe the general architecture of ZDMP system, the distribution of components, their interfaces and the topology of the different interconnections. The IIRA reference model defines different architectural patterns for coherent IIoT systems. The global architectural pattern, IIRA's three tier IIoT System Architecture (Edge, Platform, and Enterprise), is well aligned to the description of work in ZDMP, the reference digital manufacturing platforms such as vf-OS that are the technological base of ZDMP, and other prominent reference architectures such as NIST Smart Manufacturing Ecosystem. In this architectural pattern, the edge tier collects data from the edge nodes in the proximity network. The platform tier provides the runtime for core data services (eg Data Transformation, Analytics), consolidates processes and operations, and manages the exchange of information (data flows and control flows) between the edge tier and the enterprise tier. The enterprise tier implements domain-specific applications, decision support systems, and provides user interfaces to end-users.

It is recommended that T4.3 Architectural Principles and Design uses this architectural pattern as a reference for the description of the system architecture from an implementation viewpoint. Figure 20 shows a tentative (non-binding) alignment of the main high-level functional blocks of the ZDMP system architecture identified in the DOA and the three tier IIoT system architecture pattern.

As pointed out in Section 2.2.3, some aspects of the ZDMP Platform (mainly development engagement, application development, and discovery) are external to the enterprise that instantiates the IIoT system and thus out of the scope of IIRA's global architectural pattern. For this reason, these components are shown outside of the three-tier architectural model in the figure, in a fourth tier (eg Collaboration tier) differentiated from the Enterprise layer. Robust Industrial Network Support should follow security-by-design principles and ensure security and privacy of applications during the entire life-cycle, from development to maintenance, and therefore, it is transversal to the entire architectural reference model. Distributed and Autonomous Computing is transversal to the IIoT system instance and therefore to the three tier global architectural pattern. The rest of the high level functional blocks can be mapped to specific tiers of the IIRA reference architecture.

Data acquisition and IIoT is mainly located at the edge layer, since industrial sensors, actuators, and control data are the most relevant sources of information in ZDMP. However, there are other relevant sources of information across different company levels that also need to be modelled and integrated, in this sense Section 3.2.3 contains additional recommendations regarding connectivity, alignment to RAMI 4.0, and interoperability with the administration shell, IIRA and NIST Smart Manufacturing Ecosystem. Also, an important consideration to bear in mind is that communication is bi-directional, since some of the use cases presented in the previous section presented the requirement to set up values on machines based on the results of analysis.

Data Harmonisation and Interoperability, AI and Analytics, and orchestration, monitoring, and alerting can be located in the platform tier, although these functionalities can be de-centralised and be to some extent available also at the edge tier (ie Distributed and Autonomous Computing). ZDMP applications use the different service APIs and implement the user interfaces and therefore are at the enterprise tier. Platform Integration and Federation and Inter-Platform Interoperability exchange data with external services and are therefore also located at the enterprise tier.

Following these general recommendations, ZDMP can effectively implement a methodology to define the system architecture in a way that will facilitate the identification of related IIoT standards.

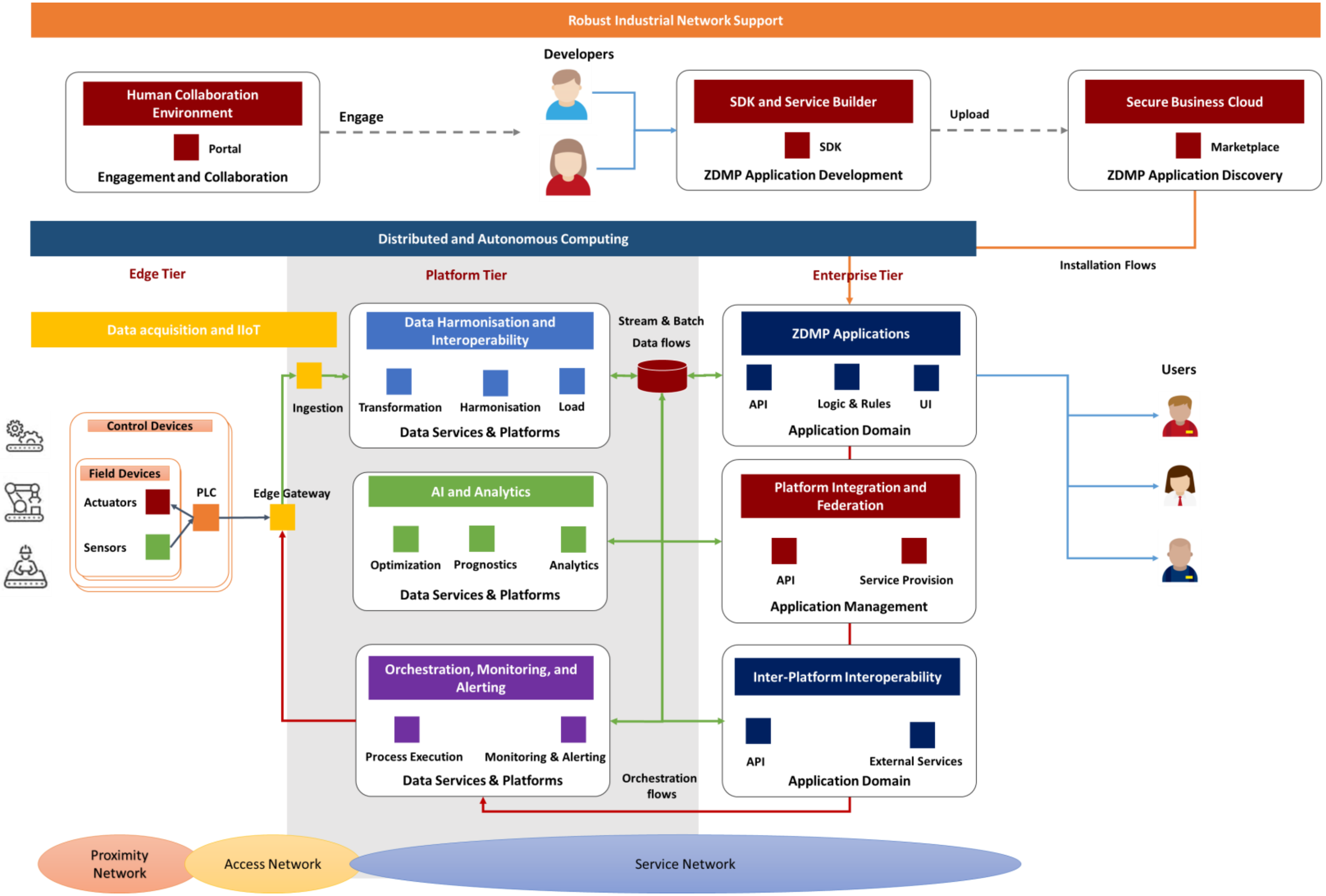



Figure 20: Alignment of ZDMP high-level functional blocks and IIRA's three tier System Architecture

### 3.1.2 Standardisation

Most manufacturing standards have already achieved a high degree of maturity, but they need to be extended or adapted, and combined with new standards in the context of digital manufacturing. [DIN+2018] describes the roadmap for standardisation and highlights the main standardisation topics and needs in the context of digital manufacturing. ZDMP T4.6 Standardisation will actively contribute to standardization for project results that are suitable for this purpose. To guide these activities, this section aligns the main results of the project with the needs for standardisation identified in the roadmap:

- **Development:** The roadmap highlights that developers should be provided with suitable standards that lay down the specific requirements for the development of software and hardware for I4.0 applications. Development tools and methodologies for digital manufacturing is one of the main research areas of ZDMP. Application developers need standards to guide the development of secure applications. [OWASP+2019] provides a development guide for secure Internet applications (ie security-by-design principles). [ISO+62443] describes the requirements for the development of secure industrial control products. ZDMP will establish contact to the respective standardisation committees.
- **Open source:** Open source projects complement standardization in different ways. [DIN+2018] highlights the importance of open source in I4.0 and recommends that collaboration of standardisation and open source is evaluated in suitable pilot projects. ZDMP is an open source project, extensively using other open source resources and could be positioned as a project of relevance for standardisation activities.
- **Digital models:** An Adequate representation of the physical world in digital models is one of the main topics of the roadmap. The integration of process data information into the right models is also a major concern among ZDMP project partners. Therefore, standardisation on specific extensions to improve available standard modelling frameworks for manufacturing process can also be a key contribution from the ZDMP project.
- **Process Quality:** One of the main objectives of ZDMP Process Quality is to detect and correct possible errors before they occur. Predictive maintenance strategies require the cooperation of different actors and standards are essential tools to regulate the cooperation between them (eg manufacturing equipment providers, Service Providers, maintenance managers and operators). ZDMP use cases will use condition monitoring and predictive maintenance systems and therefore the project could contribute to standardisation activities related to maintenance, maintainability, and the life cycle of production systems.
- **Product Quality:** The zero defects paradigm in ZDMP relies on the adequate treatment of all the information that can be collected through the production of a product, to detect and avoid production defects. This strongly relates to the life cycle record of products, that is, to all the information that is accumulated through the life cycle of an asset.
- **Use cases:** Use cases in ZDMP can contribute to the definition of the terminology, the requirements, and properties of Industry 4.0 applications in very specific domains (eg automation, electronics or construction). Thus, the project can contribute to the standardisation of the terminology, requirements, semantics, properties, and ontologies for Industry 4.0 applications in the domains of the project pilots.

It is also recommended that the requirements, both the generic requirements and specific requirements of the use cases, are analysed to identify related standards that are relevant for the implementation of each requirement, assigning standards to requirements by means of a standards navigator. This is the approach taken in [PI+2018]. Figure 21 shows a table template that can be used to present the candidate standards related to the implementation of each requirement.

| Requirement ID | Requirement Description | Related standards |
|---|---|---|
| | | |

Figure 21: Requirement candidate standards specification table template

## 3.2 Specific Recommendations

### 3.2.1 Business and Usage Viewpoint Recommendations

Use cases need to be described with sufficient degree of abstraction to identify the different components of the system, the information flows, and the standards available for implementing them during the definition of the global architecture. IIRAs Business and Usage viewpoints provide an adequate structure for the definition of use cases and objectives, and the linking to the functional and implementation viewpoints, and it is therefore recommended to use this framework.

As shown in Figure 22, The Business Viewpoint and the Usage Viewpoint together have a similar structure to standard templates for the definition of use cases, and therefore, it is rather straightforward to map the available ZDMP use case descriptions to the Business and Usage architectural viewpoints.

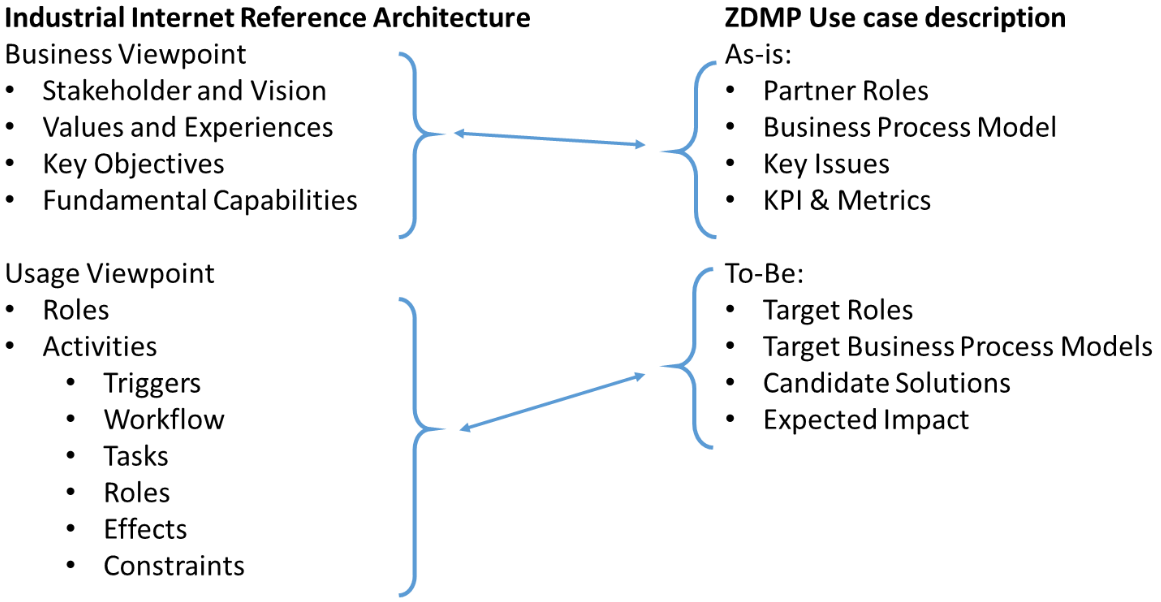



Figure 22: IIRA and ZDMP use case description structure

As shown in the figure, the Business viewpoint mainly contains the scope, objectives and narrative description of the use case. The Usage viewpoint captures the description of the technical details and the step by step analysis of the use case. In the definition of the workflow of the activities, the different components of the system and the exchange of information between them is identified.

In the context of the business viewpoint, ZDMP use case descriptions contain a narrative description of the use case, a description of the key participants, and high-level Key Performance Indicators (KPIs). This information can be analysed together with the T 2.1 Project Inception and Vision Consensus to identify the different stakeholders, their vision, and values, in a unified manner across use cases, and also considering other key stakeholders from the general project vision. Regarding key objectives, it is recommended to derive low level KPIs from the high-level KPIs in the use case descriptions, using the standard ISO 22400 [ISO+22400]. This standard specifies key KPIs used in manufacturing operations management, by means of their formula, corresponding elements, and time behaviour, among other characteristics. The definition of low level KPIs with this standard will facilitate the evaluation and validation of the different use cases.

Concerning the Usage viewpoint, ZDMP use case descriptions comprise a high-level, step-by-step analysis of the expected result (requirements) that can be the basis to generate the usage viewpoint description with greater level of detail during the architecture definition. To visualize the use case workflows, it is recommended to use the Business Process Model and Notation (BPMN) format, which is adequate to describe usage viewpoint triggers, tasks, and workflows. Another alternative is to use Unified Modelling Language (UML) workflow diagrams as in [PI+2018]. Regardless of the format, it is important to identify all parties, both human (eg operators, managers), and automated (assets in RAMI 4.0 terminology, like machines, or legacy software).

### 3.2.2 Functional Viewpoint Recommendations

This section is concerned with the definition of the functional components of the platform. Once the different parties and workflows are identified in the usage viewpoint, it is recommended to use the RAMI 4.0 hierarchical level dimension to locate the user roles in the different use cases across the different organisational levels, so that the functional viewpoint collects all the information concerning data flows across connected factories. Instead of IIRA´s functional domains, it is recommended to use RAMI 4.0 hierarchical levels. This is because there is a direct relationship between the RAMI 4.0 hierarchical levels and the different functional levels in a secure industrial network, as defined in cyber-security standards like [IEC+62443], and therefore connections will occur through secure conduits between levels. Figure 24 provides an example of how to represent information flows between assets in the RAMI 4.0 RAMI 4.0 hierarchical level dimension. In the example, each asset (or group of assets) is associated to an Asset Administration Shell (AAS) which comprises the digital representation of the asset. At each level, the figure also shows different the different user roles involved in the application (named App_1 role 1, 2, and 3 in the figure).

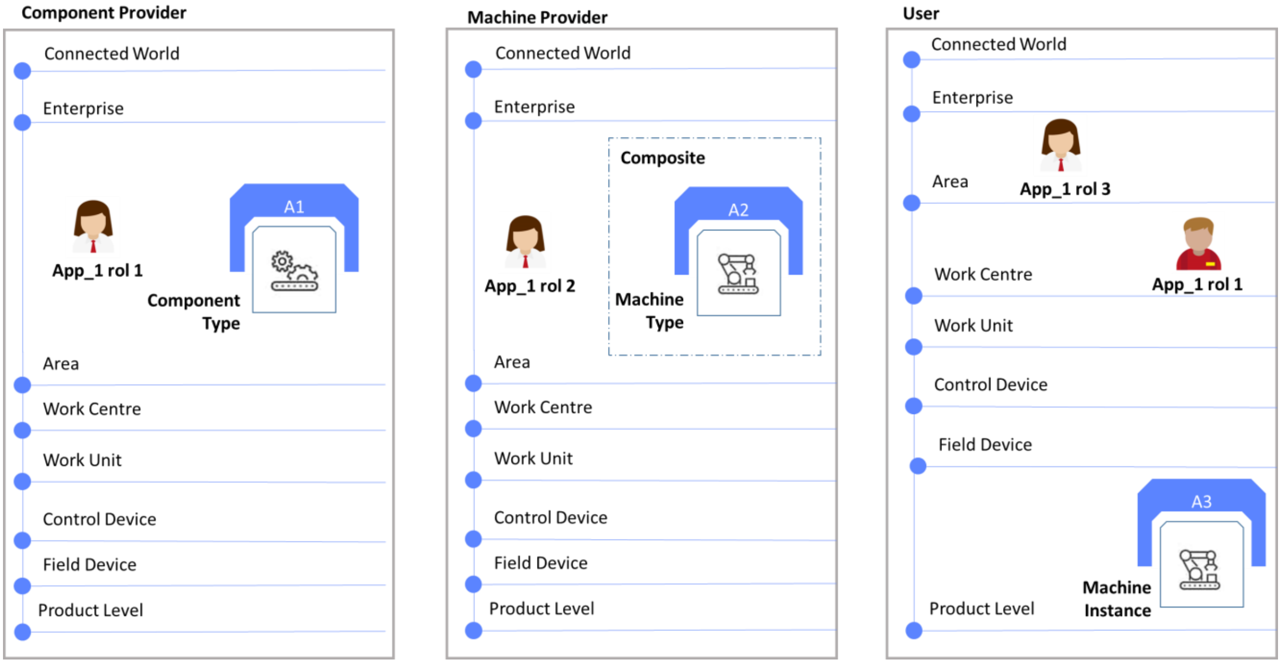



Figure 23: IIRA and ZDMP use case description structure

Regarding the technical specifications, it is also recommended to use RAMI 4.0 administration shell meta-models to capture the information that needs to be exchanged between manufacturing assets. It is recommended to use UML class diagrams to represent the data elements that need to be exchanged between the different assets, and the description of the service interfaces that should be used. Figure 24 contains an UML class diagram of the AAS meta-model, obtained from [PI+2018], which contains additional examples that can be used as a reference.

It is also recommended to use UML class models and UML sequence or Activity diagrams to define the formats and structure of the information messages between the different assets.

With these recommendations, the Functional View, and functional specifications, will comply with the guidelines and specifications of both IIRA and RAMI 4.0 reference models.

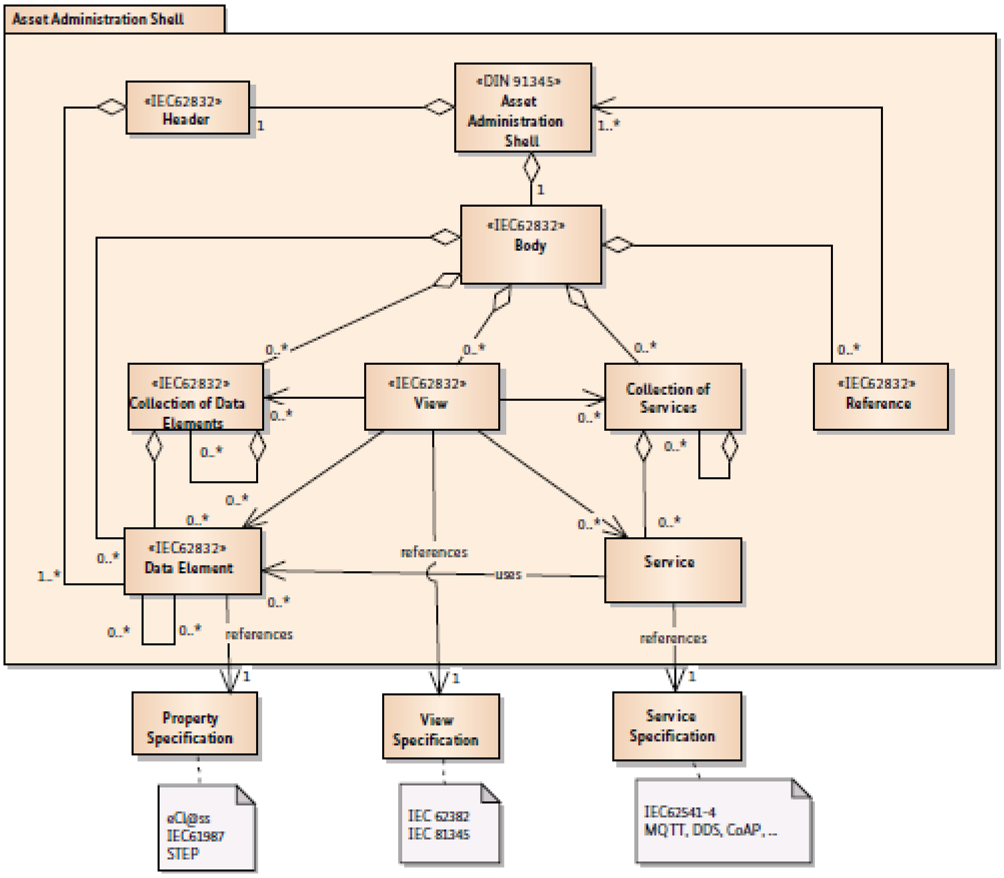



Figure 24: AAS UML class meta-model

### 3.2.3 Implementation Viewpoint Recommendations

The implementation viewpoint should provide details on how the AAS will be deployed to the ZDMP computing infrastructure, [PI+2018] describes different deployment patterns that can be used in a consistent IIoT System from different views: physical proximity, distribution, virtualisation, and lifecycle:

- **Proximity:** Physical proximity of the asset to the AAS:
  - **Asset-based:** AAS hosted in asset's runtime environment
  - **Edge/Fog based:** AAS hosted in a computing environment in the local IT infrastructure of the enterprise
  - **Cloud based:** AAS hosted in cloud infrastructure
- **Distribution:** Distribution of AAS data elements and services across different runtime environments:
  - **Centralized AAS:** 1-to-1 relationship between asset and AAS and unique entry point (eg URL) for the AAS
  - **Distributed AAS with loose coupling:** Information for an asset under the same AAS and multiple entry points for the AAS, distributed based on the different organizations that need access to the different data elements
  - **Distributed AAS with Aggregating Node:** An aggregating AAS provides a single access point to access all the information of the asset, collecting information from other lower level AAS distributed among collaborators
- **Virtualisation:** Virtualisation of the runtime environment of the asset

- **Operating System:** No virtualisation
- **Hypervisor Deployment:** Runtime environment in virtual machines managed by a hypervisor
- **Container:** Container based runtime environment (eg Docker)

It is recommended that ZDMPs architecture considers the different trade-offs among these patterns in the implementation viewpoint, and that the different considerations are linked to the IIRAs architectural patterns taking into account as well the specific requirements of the different use case scenarios. It is also recommended that the different candidate open source technologies are checked against these considerations to guide make or buy decisions for the ZDMP core technologies.

It is also important that the implementation is described in a format that effectively captures the selected deployment patterns. In this sense, one recommendation is to use a multi-layered approach to describe the implementation and selected patterns for the different system components, such as the C4 model[1]. The C4 model comprises four different levels of abstractions to visually communicate the system architecture: context, containers, components, and code.

The first level of abstraction, context, shows a high-level description of the system being described, focusing on user, user roles, and interactions with the systems. As indicated above, it is recommended to use the three-tier architectural pattern as a reference, but also to take into account the functional viewpoints to better describe the proximity network and the interactions between different hierarchical levels.

The container abstraction level further decomposes the system into separately runnable/deployable units. This level of abstraction will capture the different deployment patterns that have been selected for both the AAS as well as for the decomposition of the ZDMP platform building blocks into components. At this level of abstraction, it is possible to identify the different data and control flows between containers and therefore the requirements and interdependencies between physical and virtual connections at the container boundaries.

The component abstraction level identifies the major structural building blocks of each container, that is, the inner structure and main components within each container. This level is a refinement of the functional, describing to greater detail how the different functionalities are implemented. Finally, the optional code abstraction level provides additional UML class diagrams and meta-models to describe the inner code and data structures of each component.

[1] https://c4model.com/

# 4 Conclusions

This deliverable presents an analysis of different cutting edge reference models and architectural reference models for digital manufacturing platforms. They provide in many cases complementary views on digital manufacturing platforms and, in general, it is rather straightforward to align the definitions they contain.

The RAMI 4.0 reference model contains the specifications of the administration shell, which can be regarded as a standardised digital representation providing interfaces to interact with any manufacturing asset. The analysis showed that the level of maturity of RAMI 4.0 is the most advanced among the different reference models under analysis. Besides this, there are several alignment reports available between the RAMI 4.0 and other reference models, which make it easier to extrapolate any mapping to RAMI 4.0 to the other reference models. Therefore, the RAMI 4.0 has been selected as the reference model for analysis, and the different alignment reports have been used to complete the analysis.

Although Section 3 is primarily based on IIRA, it is important to note that the alignment between the RAMI 4.0 and the Smart Manufacturing Ecosystem from NIST has been specifically developed in this deliverable, and in this sense, it is an additional result of this work. The main divergence between the different reference models is found in the standardised protocol stacks and data formats to exchange data. This is an important aspect which has to be taken into consideration in the design of the platform, concerning inter-platform communication and IIoT data acquisition. In this sense, it is recommended that ZDMP components, mainly IIoT data acquisition and data transformation, incorporate technologies to deal with high levels of diversity in edge communications networks.

The different functional blocks of the ZDMP platform have been mapped to the RAMI 4.0 reference model to find out to what extent they are covered in this reference model. The main conclusion is that aspects regarding software development, application marketplaces, collaboration between developers, and collaboration between developers and users, are the most innovative aspects of the platform with respect to the reference models under analysis. The mapping of these functionalities into the different reference models was difficult, and in fact all these aspects are highlighted in the I4.0 roadmap [DIN+2018] in the list of relevant topics and standardisation needs. The three-tier global architectural pattern of IIRA has been extended with a new tier, named collaboration, to address this. Also these topics have been highlighted in this deliverable for future collaboration with and contribution to standardisation activities.

Finally, this document provides a set of non-binding recommendations to align the global architecture definition, functional specifications, and technical specifications to the guidelines and examples promoted by the different reference models under analysis. The recommendations provide a standard framework to structure the technical information generated in the project, to help both project participants and project reviewers process this information. Following these recommendations should ensure interoperability with state-of-the-art manufacturing systems and also favour contributions to standardisation activities from the ZDMP project and therefore enhance the dissemination of the ZDMP platform.

As a summary, the main recommendations in this deliverable are listed in the table below, together with the target Task, reference model or standard, and priority level (either HIGH, MEDIUM, or LOW).

| Recommendation | Target | Reference | Priority |
|---|---|---|---|
| Align project vision and uses cases and clearly identify main stakeholders and key objectives | T4.1 | IIRA | HIGH |
| Use standard frameworks like ISO 22400 to define use case Key Performance Indicators | T4.1 | ISO 22400 | HIGH |
| Use the IIRA framework to describe the ZDMP platform architecture | T4.3 | IIRA | MEDIUM |
| Use IIRA's Business, Usage, and Functional Viewpoints to refine the use case descriptions | T4.3 | IIRA | MEDIUM |
| Use IIRA implementation viewpoint to describe system implementation | T4.3 | IIRA | MEDIUM |
| Align the ZDMP high-level system architecture description to the three-tier IIoT architectural pattern | T4.3 | IIRA | HIGH |
| Consider trade-offs and caveats of the different deployment patterns, including timescales impact upon development, regarding physical proximity, distribution, virtualisation, and lifecycle in the context of ZDMP | T4.3 | IIRA | HIGH |
| Check compliance of the different candidate solutions and off-the-shelf options with the preferred deployment patterns to see if/where there are overlaps between them and if they are reasonable in the context of ZDMP | T4.3 | IIRA | MEDIUM |
| Use a multi-layered approach (such as the C4 model) to describe the system implementation at different levels of abstraction (eg context, containers, components, and code) | T4.3 | C4 model | MEDIUM |
| Use the three-tier IIoT architectural pattern as a reference, then the RAMI 4.0 hierarchical level dimension to better describe the proximity network and align with Defence In-Depth strategies as those promoted in ISA 62443 | T4.3 | RAMI 4.0 | MEDIUM |
| Identify data and control flows between containers, requirements, and interdependencies between physical and virtual connections at the container boundaries, also taken into account cyber-security standards (ISA 62443) | T4.3 | C4 model | MEDIUM |
| Cleary identify all parties ( both human and automated ) and corresponding user roles involved in the different use cases | T4.4 | IIRA | HIGH |

| | | | |
|---|---|---|---|
| Use the RAMI 4.0 hierarchical level dimension to locate user roles across the different organisational levels | T4.4 | RAMI 4.0 | HIGH |
| Use RAMI 4.0 administration shell meta-models to capture the information that needs to be exchanged between manufacturing assets | T4.4 | RAMI 4.0 | LOW |
| Use UML activity (use case) diagrams or equivalent faster, lighter weight alternatives (eg EventStorming) to define the formats and structure of the information messages between the different assets | T4.4 | RAMI 4.0 | MEDIUM |
| Use UML class diagrams and meta-models to describe the inner code and data structures of (sub)components | T4.5 | C4 model | LOW |
| Identify and link requirements and related standards by means of a standard navigator | T4.6 | None | MEDIUM |
| Identify collaboration points with standardisation activities, mainly in the areas of software development, collaboration, and the zero defects paradigm. | T4.6 | RAMI 4.0 | HIGH |

Figure 25: Recommendation summary

Regarding Task T4.3 (Global Architecture), the main recommendation is to use an ISO 42010 [ISO+42010] framework such as IIRA [IIC+ 20170131] to describe the platform architecture. Section 3.1.1 shows that the DOW is reasonably aligned with IIRA`s viewpoints (business, usage, functional, implementation) and that it is reasonably straightforward to use this standard to describe the ZDMP system architecture. In this sense, T4.3 can provide an alignment of the project vision and the different use cases to identify the main stakeholders and key objectives, completing the business and usage viewpoints as described in Section 3.2.1.

Regarding deployment and implementation, aligning the ZDMP system architecture description to the (IIRA's) standard-based three-tier IIoT architectural pattern will facilitate the documentation, development, deployment, and dissemination of ZDMP platform. Section 3.1.1 provides a preliminary alignment of the high-level ZDMP functional blocks taken from the DOW and this architectural pattern. From this high-level system description, it is possible to consider different deployment patterns in the context of ZDMP and select the most suitable deployment pattern for ZDMP regarding different aspects like physical proximity, distribution, virtualisation, and lifecycle (see Section 3.2.3). The make-or-buy decisions to integrate already identified software solutions can take into account compliance with the selected deployment patterns.

Concerning T4.4 (Functional Specifications), it is recommended to use standard-based definitions for the KPIs used for evaluation purposes, such as those provided in ISO 22400 [ISO+22400] regarding manufacturing operations management. An important objective of the functional specification is to clearly identify all interconnections across different organisational levels and in this sense, it is recommended to use the RAMI 4.0 hierarchical levels dimension to locate the different user roles as indicated in section 3.2.2. Some of the user roles will correspond to automated actors (ie assets such as machines or legacy software) and therefore, it is recommended to use administration shell meta-models and UML class and sequence diagrams to identify the data elements that will be exchanged between them. This will provide all the necessary context information to describe the system implementation with sufficient level of detail.

Regarding T4.5 (Technical Specifications), a multi-layered approach such as the C4 model can be used to better describe the implementation of the different ZDMP platform components and subcomponents, also taking into account deployment decisions to clearly identify the system implementation at different levels of abstraction. This detailed description will provide means to better describe the proximity network, identifying the required physical and virtual boundaries between containers to comply with cyber-security standards like ISA 62443 [ISA+62443].

Thus, T4.3 will provide a global description of the ZDMP platform that can be further developed in T4.4 and T4.5. These tasks will describe with greater detail the functional and implementation viewpoints, respectively. The main drawback in this approach is that it is hard to draw a line between the (high-level) functional and implementation viewpoint descriptions provided in T4.3 and those provided in T4.4 and T4.5. However, since the three tasks are developed in parallel and with strong cooperation between the different partners involved, this deliverable only makes a recommendation for the boundaries between such descriptions, but at the end it is up to the Work Package and Task leaders to make the final decision to balance the corresponding deliverables and align them with the DOW.

# Annex A: History

| Document History | |
|---|---|
| **Versions** | V0.4<br>• First draft proposal to be discussed at kick-off meeting<br>• RAMI 4.0 Mapping example<br>• RAMI 4.0 Description<br>• Coverage Analysis<br>• First draft version of 2.1.2. NIST Smart manufacturing Ecosystem<br>• First draft version of Smart Manufacturing Standardisation Reference Model<br>• First draft version of Industrial Internet Consortium Reference Architecture<br>• First draft version of General Recommendations<br>V0.6:<br>• Revision and redrafting of Smart Manufacturing Reference Architecture Analysis<br>V0.7:<br>• Section 0<br>• Conclusions<br>V0.8-9:<br>• Revision 1 comments and redrafting<br>• Several changes across all sections to comply with project guidelines<br>• Improved description of<br>V1.0:<br>• Revision 2 comments and redrafting<br>• Added final summary table to conclusions<br>V1.1:<br>• Revision 3 comments and redrafting<br>• Redrafting of section 2.1<br>• Improving use case descriptions |
| **Contributions** | UPV:<br>• Raúl Poler<br>• Ángel Ortiz<br>• Francisco Fraile<br>SOFT:<br>• Christian Melchiorre<br>FIDIA:<br>• Alessia Focareta<br>ITI:<br>• Santiago Cáceres<br>• David Todoli<br>SAG:<br>• Verena Henrich<br>TAU:<br>• Ronal Bejarano<br>DIN:<br>• Christian Grunewald<br>ICE:<br>• Stuart Campbell |

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