AUTOWARE

Wireless Autonomous, Reliable and Resilient Production Operation Architecture for Cognitive Manufacturing

D1.3b AUTOWARE Cognitive Digital Automation Framework

Document Owner	TTT		
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Dissemination level	Public	**Dissemination nature**	Report
Date	17/10/2018	**Version**	V1.0

European Commission

Version History

Nr.	Date	Author (Organization)	Description
0.1	14/08/2018	TTT	Deliverable structure and ToC
0.2	31/08/2018	TTT	First inputs available (WP2, WP3)
0.3	20/08/2018	TTT	Updated requirements included
0.4	26/09/2018	TTT/INNO/CNR/UMH/JSI	Final version of AUTOWARE Framework and Reference Architecture
0.5	01/10/2018	TTT	Finalization of description of Reference Architecture
0.6	02/10/2018	TTT	Version ready for review
0.7	15/10/2018	JSI	Version with visible changes, proposed by the reviewer
1.0	17/10/2018	TTT	Final version

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Acronyms

AR	Augmented Reality
AV	Augmented Virtuality
CPPS	Cyber-Physical Production Systems
CPS	Cyber-Physical System
DSA	Digital Strategic Alliance
HPC	High Performance Computing
IIC	Industrial Internet Consortium
IIoT	Industrial Internet of Things
IIRA	Industrial Internet Consortium Reference Architecture
IoT	Internet of Things
PbD	Programming by Demonstration
RA	Reference Architecture
RAMI4.0	Reference Architecture for Manufacturing Industry 4.0
SDA-SP	Software Defined Autonomous Service Platform
SMME	Small, Medium and Micro-sized Enterprises
VR	Virtual Reality
WP	Work Package

Executive Summary

This public deliverable (D1.3b) presents the updates made to the AUTOWARE Reference Architecture and AUTOWARE Framework based on the results and experiences gained during the first half of the AUTOWARE project. It is the final deliverable of the work performed in Task 1.4 "Cognitive Digital Automation Framework & Architecture Specification". The results in this document are based on the result in the predecessor deliverable D1.3a, where a first version of the AUTOWARE Reference Architecture was presented. For this task, input has been requested from all partners, varying from requirements to the industrial demonstrators down to the requirements of the individual technical components. The goal has been to represent all the technologies developed within the AUTOWARE project inside the Reference Architecture and the AUTOWARE Framework.

The defined Framework and Reference Architecture will function as a guideline and basis for the development of Cyber-Physical Production System (CPPS), targeting mainly Small, Medium and Micro-sized Enterprises (SMMEs). Based on the requirements identified in previous tasks, the reference architecture has been further refined and finalized

Additionally, all AUTOWARE technical partners have used the reference architecture to position its technologies in it, to guarantee that all project results are covered in the architecture, and are thereby targeting the overall Industry 4.0 goals of providing cognitive automation application development and application of autonomous manufacturing processes to stay competitive on the European market.

Finally, the defined AUTOWARE Reference Architecture and Framework will function as a basis for the future work, where partners from AUTOWARE, in cooperation with other European research projects, aim to define an open consolidated ecosystem for targeting the challenges of Industry 4.0.

Keywords

Reference Architecture, Framework, Requirements, RAMI 4.0, FAR-EDGE, Daedaelus, Manufacturing.

1. Introduction

1.1 Purpose and Scope

The objective of the AUTOWARE project is to build an open consolidated ecosystem that lowers the barriers of SMMEs (Small, Medium & Micro-sized Enterprises) for cognitive automation application development and application of autonomous manufacturing processes. Within AUTOWARE, we will advocate for a multi-layer, largely decentralized, dynamically controlled factory IT system, where intelligence is spread among the manufacturing execution system, controllers, and decentralized cloud/fog platforms.

From a technical perspective, the AUTOWARE Framework offers many features and concepts that are of great importance for cognitive manufacturing and in particular to the automatic awareness abilities that AUTOWARE is primarily aiming at:

- **Open Platform:** Platforms contain different technology building blocks with communication and computation instances with strong virtualization properties with respect to both safety and security for the cloudification of CPPS services.
- **Reference Architecture:** Platforms focused on harmonization of reference models for cloudification of CPPS services have to make a template style approach for flexible application of an architectural design for suitable implementation of cognitive manufacturing solutions, e.g., predictive maintenance, zero detect manufacturing, energy efficiency, etc.
- **Connectivity using IoT:** Multi-level operation (edge, cloud) and function virtualization through open interfaces allow native support for service connection and disconnection from the platform, orchestrating and provisioning services efficiently and effectively.
- **Dynamic Configuration:** Software-defined operation of systems allow automatic integration of other systems to connect or disconnect from the system; dynamic configuration including scheduling is implemented. The deployment of new functionalities, new services and new system structures pose new safety and security system requirements. Components must be more dynamically configured and validated, and finally integrated into these systems.
- **Autonomous Controls:** High automation levels and autonomy require a high degree of design and development work in the area of sensors and actuators on the one hand and a high degree of efficient and robust sensor fusion on the other.
- **Virtualization of near real-time functions:** Control functions can be virtualized and executed away from machine environments and machine data can be

accessed remotely in real-time. This enables a large variety of novel functionalities as it allows the geographical distribution of computationally intensive processes, executed remotely from the location of action.

1.2 Contributions to other WPs and deliverables and document structure

In Work Package 1 ("Scenario, KPIs & Reference Model"), the AUTOWARE consortium will define requirements, indicators and provide a suitable framework and reference architecture to be used for all technical development that is taking place in WP2-WP4. Additionally, the work in WP1, together with the results of the technical work packages set the basis for the pilot development taking place in WP5. The defined reference architecture forms the main basis for all technological and usability enablers developed and the technical developments occurring in the pilot development.

Vice versa, the technical work packages and the experiences from the technical developments have also majorly influenced the structuring and modelling of the reference architecture and the framework. Business and technical requirements, identified in deliverables D1.1 and D1.2 have been used as a baseline for the architecture. Furthermore, all technical work packages have been using the reference architecture to position the technological enablers inside the architecture and providing feedback if components have been missing or modifications are necessary. Based on these feedbacks, the final Framework and Reference Architecture has been defined.

The deliverable is built up as follows:

- Chapter 2 gives an overview of the applicability of the previous reference architecture with respect to the technical enablers and showing how we can map them to the reference architecture.
- Chapter 3 identifies the requirements identified by the industrial use cases and how they can be mapped into the reference architecture
- Chapter 4 presents the updated AUTOWARE Framework and Reference Architecture based on all the knowledge gathered from the technical work packages and the industrial use cases.
- In Chapter 5, future work is presented, where the AUTOWARE Reference Architecture is mapped to the RAMI 4.0 Architecture (to conform to Industry 4.0) and the first approach for cooperation with other European Research projects (i.e. FAR-EDGE and Daedalus) is presented to provide an open consolidated ecosystem for Industry 4.0.
- Finally, Chapter 6 concludes this deliverable.

1.3 Target Audience

This deliverable is intended to be a guideline for the AUTOWARE consortium partners for modelling the industrial use cases. Additionally, the AUTOWARE Framework and Reference Architecture is also dedicated to the larger audience. It is especially targeting different potential users that aims to use the developments from the project. These users can vary from system integrators, end users, software developers up to policy makers that decide in which direction the developments of Industry 4.0 is going.

2. Instances of AUTOWARE Reference Architecture

The first version of the AUTOWARE Reference Architecture (RA) has been used by the technical work packages to develop instances of the AUTOWARE RA. These are targeting the technologies from these work packages, that is either communication and data management, as well as software services. The following two subchapters will shortly introduce the developed instances. Details that are more technical can be found in the related deliverables, which are referenced in the subchapters.

2.1 WP2 – Deterministic Wireless Mobile CPPS Connectivity & Data Management

Work Package (WP) 2 mainly deals with two interconnected technological enablers to achieve the objectives set out in the AUTOWARE project. The two topics are (a) the heterogeneous communication infrastructure that will support the ubiquitous connectivity of Cyber-Physical Production Systems (CPPS) and (b) the data management schemes which are built upon the (vertical and horizontal) communication infrastructure that enable efficient data distribution within the factory.

One of the goals of WP2 is to define and specify a reference communication and networking architecture of the general AUTOWARE RA to support CPPS connectivity and data management that are able to meet the communication requirements in terms of reliability, robustness and latency of industrial applications in Industry 4.0.

The introduction of Cyber-Physical Systems (CPS) and the Internet of Things (IoT) technologies in industrial environments fuels the evolution towards intelligent digitalized and networked (i.e. connected) factories, where components and machines can communicate with each other. The AUTOWARE RA supports the (heterogeneous) communication network and data management system, enabling data exchange within the layers, but also between the different layers, thereby exploiting the Fog and/or Cloud concepts (see Figure 1).

Industrial applications demand a wide range of different communication requirements that are difficult to be efficiently satisfied with a single communication technology. With this in mind, the communication architecture defined (based on the AUTOWARE RA) exploits the different capabilities of the available communication technologies (wired and wireless) to meet the wide range of requirements of industrial applications.

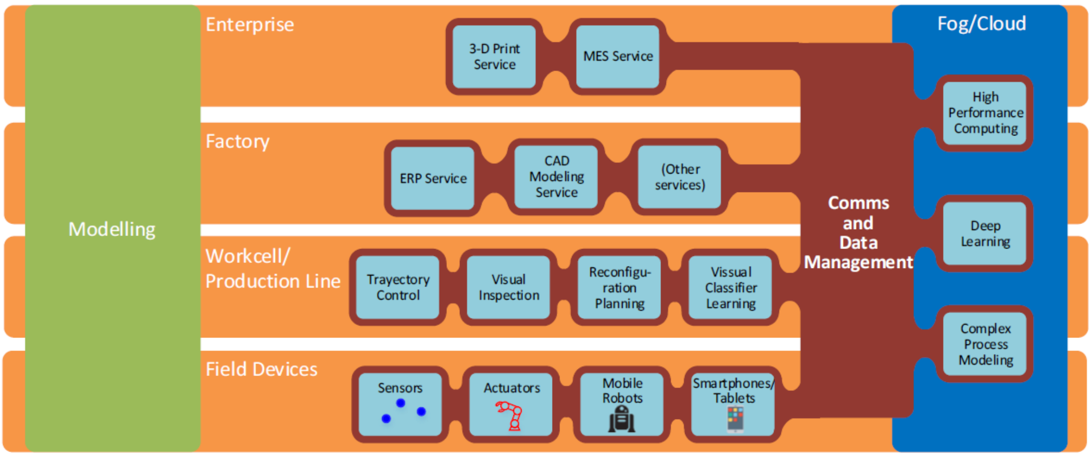

Figure 1: Communication network and data management system into the AUTOWARE Reference Architecture (user plane)

For the data management concept introduced in WP2, a hierarchical management architecture is proposed that supports the heterogeneous communication technologies. These heterogeneous communication technologies are integrated in a hierarchical communications and data management architecture where decentralized and local management decisions are coordinated by a central coordinator that ensures the efficient global operation of the system. A central entity guarantees the coordination of local and distributed managers resulting in a mix of centralized management (orchestration), and decentralized operation of the communication and data management functions. Distributed management entities are in charge of the local managers and ensures an efficient global management and operation of the whole heterogeneous network. Different management strategies can be applied at each tier to meet the requirements of the application they support. Figure 2 provides an overview of how orchestrators and local managers (LM) can be positioned inside the AUTOWARE RA (i.e. inside a factory) and perform the interaction between the different layers. Additionally, it can be seen which resources are required and how possible distribution of the data management capabilities are established within a factory.

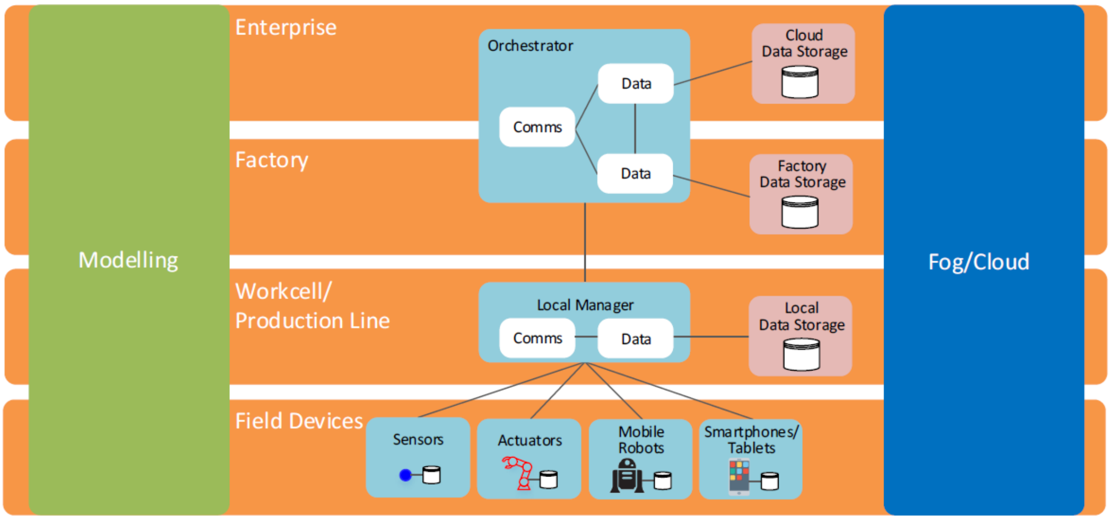

Figure 2: Integration of the hierarchical and multi-tier heterogeneous communication and data management architecture into the AUTOWARE reference architecture (control plane)

More detailed information about the explicit instances of the reference architectures with respect to heterogeneous communication (i.e. wireless and/or wired) and data management defined in WP2, can be found in the according deliverable [AUTOWARE_D2.1, 2018].

2.2 WP3 – Software Defined Autonomous Service Platform

The goal of WP3 is to introduce the concept of a Software Defined Autonomous Service Platform (SDA-SP), including its configuration capabilities for flexible processes. This platform will provide for inclusion of software units needed for execution of various automation functionalities that can be included using a "software as a service" model. Due to recent development of new technical enablers (e.g. IoT, Cloud, Edge/Fog, High Performance Computing (HPC), etc.) it is possible to introduce a service-based approach for many components inside a manufacturing system. Within WP3, a service based platform is presented, where, using technological enablers, production tasks at all levels can access various services and functionalities, using Fog/Cloud solutions and other previously mentioned enablers. The advantage of using a service-based approach, is that companies can directly use the tasks/services from providers instead of having to develop them by themselves.

In WP3, various services have been identified and positioned in the different levels of the overall system, creating a reference architecture of the SDA-SP based on the proposed general AUTOWARE RA (see Figure 3). Additionally, communication links and interfaces between the different horizontal levels are introduced required for vertical communication in service-based production systems. As mentioned before, although these services are functionally related to the assigned level, they can run explicitly on this level, but can be also located/transferred to either the Cloud of the Fog.

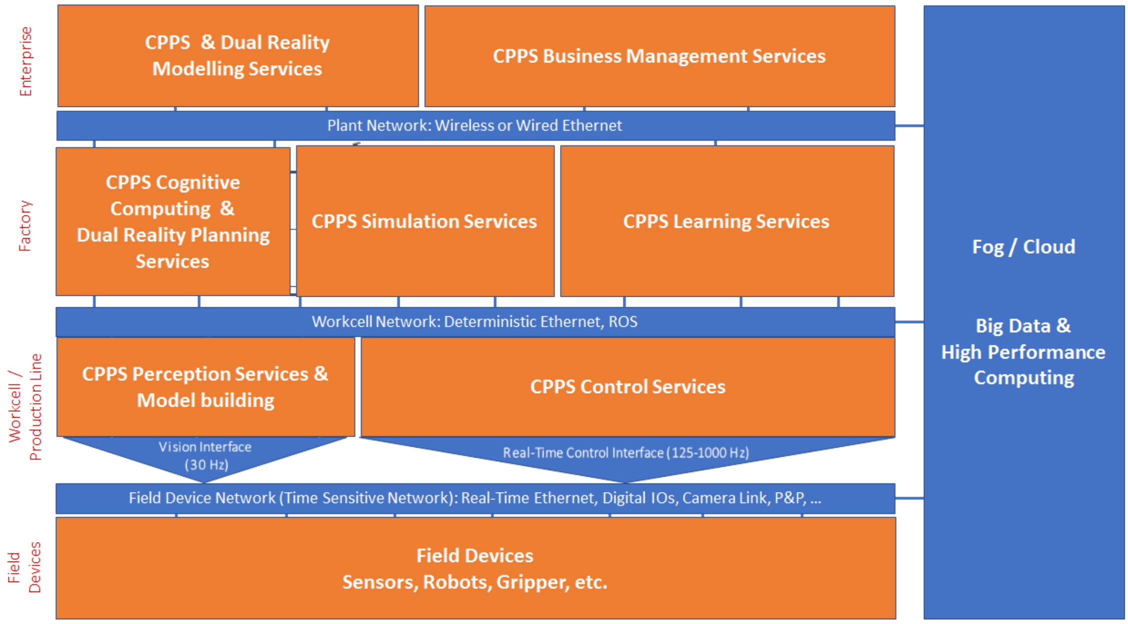

Figure 3: Reference Architecture of the SDA-SP, including the identification of potential services at the different layers in the AUTOWARE RA.

To show the applicability of the general AUTOWARE RA, within WP3, the SDA-SP Reference Architecture is applied to three different real-world production scenarios (from which two are also neutral production facilities inside the AUTOWARE project). In the following, we are briefly high lightening these scenarios.

The first production scenario for SDA-SP RA application and demonstration is an flexible and reconfigurable production robotic workcell, which is a perfect example of a Cyber-Physical Production System (CPPS). The goal of the highly automated workcell is to show the operation for a number of real-world tasks that require and involve fast reconfiguration to define and then execute the required production tasks with high content of assembly operations. Figure 4 depicts the different services necessary for the reconfigurable robot work cell, varying from simulation, machine learning, task execution, control and vision services. Additionally, it shows the required communication interfaces between the different levels.

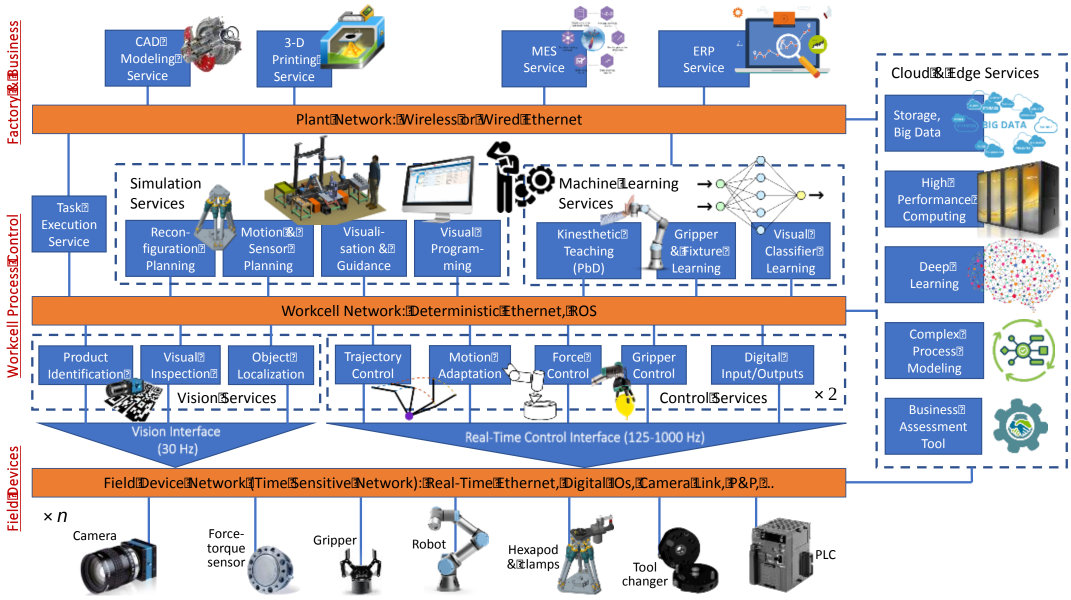

Figure 4: Decomposition of the planning, deployment, re-configuration and control into functional groups and/or modules

The second production scenario is targeting dual reality services, focusing on technologies from the field of Virtual Reality (VR), Augmented Reality (AR) and Augmented Virtuality (AV). These services will allow a seamless synchronization between real and virtual environments, so objects form the real world can influence the behavior of virtual objects and vice versa.

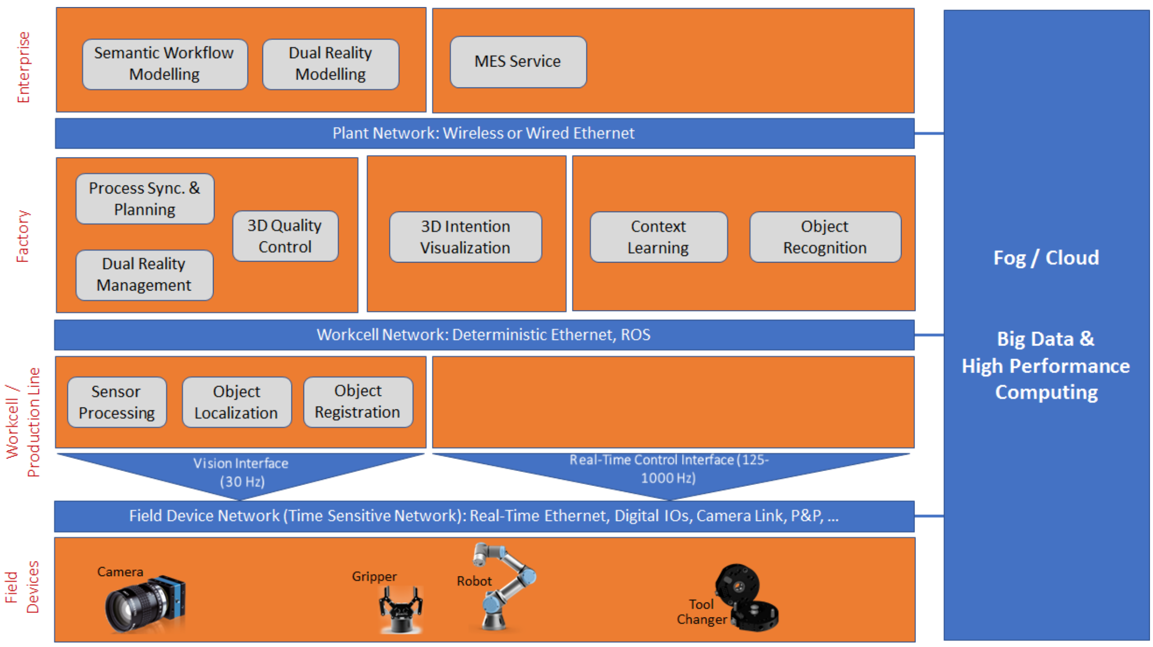

Figure 5: Dual Reality Reference Implementation of the SDA-SP

Approaches that are applied here include semantic workflow modelling, where existing product engineering and production planning data is made available for a secondary use, namely for cooperative assembly tasks between human and robots. A second approach that is introduced here is the dual-reality management, which allows dynamic virtual environments to be enriched with virtualized physical production environments (Augmented Virtuality). Hereby, 2D/3D sensor data is being used and performs a continuous mapping of the real world into a virtual world, providing the human worker with additional manufacturing data.

The final scenario is the usage of the SDA-SP in a smart production line, which is seen as the technological answer to current and emerging global-economical changes, such as shortened product life spans, customer-oriented approach to provide added products value, and low batch-sized production. This approach is presented at the SmartFactory^{KL} production line. Various components from the SmartFactory, which are considered inside the AUTOWARE project, are mapped to the reference architecture and depicted in Figure 6.

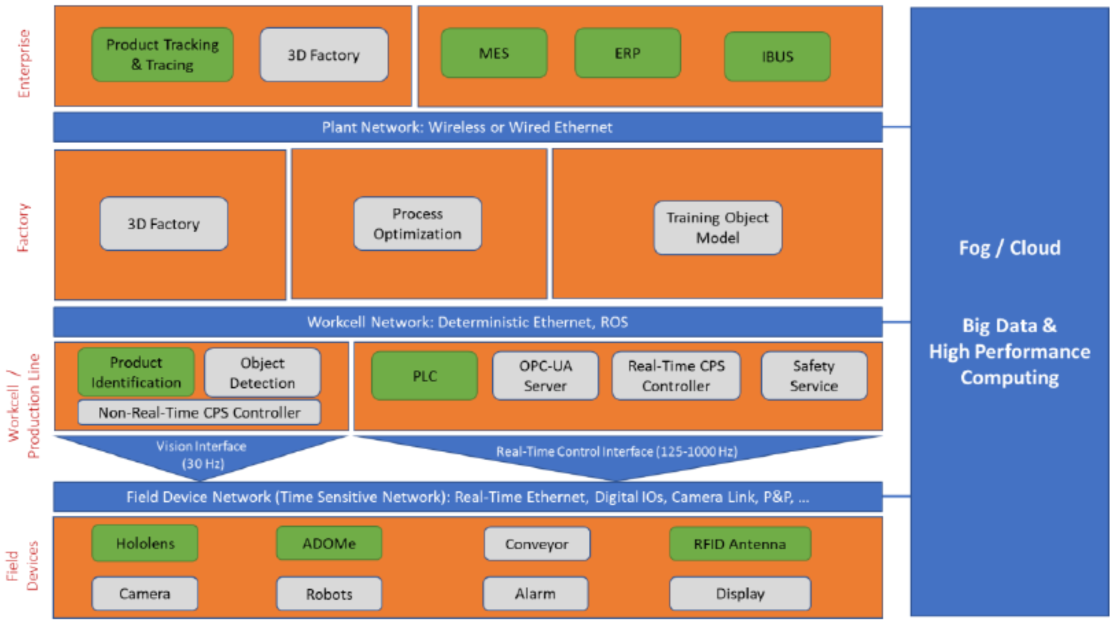

Figure 6: SmartFactory^{KL} system architecture for I4.0 production plants. The green blocks show the already existing components in the plant

More detailed information about the explicit instances of the reference architectures defined in WP3 can be found in the related deliverable [AUTOWARE_D3.1, 2017].

3. Requirements from Industrial Use Cases

Inside the AUTOWARE project, different manufacturing environments are considered; these provide industrial and manufacturing requirements which have to be fulfilled by the AUTOWARE Reference Architecture. The following environments are available:

- **Neutral experimental facilities** where the developed components are integrated, tested and validated in a realistic manufacturing environment. The following infrastructures are considered:
  - Modular production processes (SmartFactory^{KL}),
  - Reconfigurable workcells (JSI),
  - Collaborative robotics environments (Tekniker).
- **Industrial production lines,** where the technical solutions are developed, integrated and finally validated against real-life manufacturing challenges and constraints. The following production facilities are considered:
  - Industrial cognitive automation for the recycling industry (STORA),
  - Manufacturing of pneumatic automation products (SMC)

These production facilities cover a large bandwidth of functionalities and capabilities, varying from complete manual operations, through complete autonomous operation, up to human-robot interactive manufacturing. Elaborate use case descriptions can be found in the according deliverable D1.1 [AUTOWARE_D1.1, 2017].

For the first version of the AUTOWARE RA and the AUTOWARE Framework, the neutral facilities and industrial production lines have provided the project consortium with (industrial) requirements. The aim has been to cover as many requirements as possible within the defined RA and Framework. In the second phase of the project, the before mentioned partners have been contacted again to review and potentially update their requirements based on the experience in the first half of the AUTOWARE project. The following subsections will describe the facilities with their updated requirements, which will function as a basis for the updated version of the AUTOWARE Framework and Reference Architecture. For the reference architecture, mainly the technical requirements from the different facilities are considered. An extensive description of the updated requirements from the facilities and production lines can be found in deliverable D1.2b [AUTOWARE_D1.2b, 2018].

3.1 Neutral reconfigurable working cell experimentation infrastructure

The neutral reconfigurable working cell infrastructure represents a new kind of an autonomous, ROS-based reconfigurable robot workcell, which focuses on small lot-sizes production, which often takes place within SMMEs. This workcell is based on novel ICT technologies for programming, monitoring and executing assembly operations in an autonomous way. It can be nearly automatically reconfigured to execute new assembly tasks efficiently, precisely, and economically with a minimum amount of human intervention.

	Business Goal	Business Requirement	Technical Requirement
Enterprise	• Cost of manufacturing per product		• Ability to transfer large quantities of training data to IT systems outside of the workcell
Factory			• Fast setup times for a new assembly process
WorkCell/Production Line	• Number of available assembly operations • Cycle time of assembly processes • Time needed to prepare a new assembly process		• Sufficient number of assembly operations implemented • Automated assembly cycle time comparable to the manual production
Field Devices		• Enable the application of robotics for customized production	• Visual quality control •

Table 1: JSI: mapping business goals and requirements to AUTOWARE RA levels

3.2 Neutral experimentation infrastructure for intelligent automation applications for robotic industrial scenarios

The infrastructure for intelligent automation applications focuses mainly on the reduction of manual processes, by integrating more and more autonomous systems in the manufacturing process. In the setup applied in the AUTOWARE project, an autonomous mobile platform will be used to reduce the accidents by having the mobile platform interact with a two-armed robot manipulator. The aim is to improve the coordination between the two platforms, resulting in an improvement in efficiency in the manufacturing process.

Additionally, adaptation to changes in operating conditions will also be considered by providing flexibility to the system, needed to react to different environment and production conditions. Finally, to increase the robustness of the system, cognitive competences will be considered for better task planning between the two platforms (based on improved communication).

	Business Goal	Business Requirement	Technical Requirement
Enterprise	• Reduction Costs of manufacturing per product	• Technological support	• Real-time information communication and processing
Factory	• Coordination among productive systems • Flexible trask planning		• Wireless robust and reliable communication
WorkCell/Production Line	• Efficient transport • Safety ratio	• Higher efficiency in assembly cell	• Multipurpose assembly cell combining material transport and assembly operations.
Field Devices	• Efficient navigation • Accuracy of system localization	• Flexible and collaborative robotics in manufacturing	• Standard communication mechanisms in the workcell components • Mobile platform as a CPS • Autonomous navigation • System localization

Table 2: TEK: mapping business goals and requirements to AUTOWARE RA levels

3.3 Neutral cognitive digital automation process experimentation infrastructure

The technical requirements of SmartFactory are the security of product data, track-trace of product, wearable guided system, and distributed data storage., The accessibility of each product data among factories departments should be controlled in distributed databases because the process knowledge and design information are shared as determined by specific contracts with each company. In terms of data handling, the real-time information about products and machines is provided, needed to accomplish the appropriate decisions in given time. Track and trace architecture for products enables achieving real-time data update of the factory database. Another problem that is tackled is the burden on the machine maintenance operators and manual assembly operators, that must deal with many manuals and instructions for customized machines and products. Wearable devices are introduced to reduce the effort of human operators to learn how to handle new machine and products. The related operation data should be distributed in order to enable physical reconfiguration of production machines.

	Business Goal	Business Requirement	Technical Requirement
Enterprise			• Security of product data
Factory	• Setup time needed to integrate with mfg. service, Time to find root cause of quality problem	• Fast quality control	• Wearable guided system • Track and trace of product
WorkCell/Production Line		• Reduction of reconfiguration time	• Standardized information protocol. • Physical interface of production modules
Field Devices			• Distributed data storage

Table 3: SmartFactory[KL]: mapping business goals and requirements to AUTOWARE RA levels

3.4 Industrial Cooperative Assembly of Pneumatic Cylinders

The goal for the cooperative assembly of pneumatic cylinders use case is to support and improve the manual assembly process of cylinders by using collaborative robotics.

Currently, the process is still performed fully manually; the goal is to relieve the human worker from assembly tasks that are tedious and can be better performed by cognitive robots. The overall goal for the company SMC is to increase effectiveness and productivity of the manufacturing.

Development of a safe and secure human-robot interaction system is a research topic on its own and many concepts have to be taken into account. In the scope of the AUTOWARE project, only a certain part will be targeted. The goal is to reduce human intervention by implementing a Human-Robot-Interaction concept, thereby increasing flexibility by rapidly switching from one product variant to another, and maintaining constant scalability with respect to the assembly of the individualized product.

	Business Goal	Business Requirement	Technical Requirement
Enterprise	• Manufacturing cost/Assembly personnel working cost • Training of employees	• Reduction of the assembly personnel working costs and the manufacturing costs • Economic efficiency regarding the acquisition of costs • Increase of the competitiveness of the German production facility • Gain of know-how • Marketing tool	•
Factory	• Productivity	• Increase of productivity • Ensuring consistent high quality level and documentation of the measuring results • Traceability of the assembled products and verifiability of quality complaints	• Storage of quality assessment results • Ensure consistent quality and comparable results

WorkCell/Production Line	• Productivity quality • Safety of the human-robot collaboration	• Automation of manual assembling steps • Safety concept • Production flexibility	• Extraction of production information from the PLM system • Detection of current assembly state • Robust material capturing of assembly parts • System's sensors provide sufficient data and accuracy • Automatic adapt to different sized objects and workflows • Reduction of assembly time • Safe human-robot collaboration • Support of repetitive and monotonous assembly steps
Field Devices			• Tool and component visualization • Tools and components detection • Automatic part scan and quality features check • Gripping and handling of components

Table 4: SMC: mapping business goals and requirements to AUTOWARE RA levels

3.5 Industrial Cognitive Automation Validation

In the final use case, the goal is to increase the quality of a waste material separating application based on improved cognitive visual inspection and validation. The challenge is to separate waste material from the target material based on fast vision systems. The system needs to be able to continuously adapt to the varying conditions of the waste, e.g. the amount and quality of the material. Different materials are constantly produced and more and more and more waste is generated, which needs to be faster separated.

The inspection system needs to be able to consistently distinguish different kind of material waste (i.e. carton from paper) and perform the separation correctly.

	Business Goal	Business Requirement	Technical Requirement
Enterprise			
Factory			
WorkCell/Production Line	• Paper/Cardboard separation efficiency • Time needed to adapt to a batch of different quality to be sorted	• Enable the application of computer-based vision analysis and fog-cloud deep learning solutions for "conveyor belt" automation scenarios	• Manage and reduce change over time (downtime) • Increase Task Completion Time (speed of the process)
Field Devices			

Table 5: STORA: mapping business goals and requirements to AUTOWARE RA levels

4. Updated AUTOWARE Framework

As shown in the previous chapters, the first version of the AUTOWARE Framework and its included Reference Architecture were elaborate enough to cover the requirements from the different pilot lines and include the developed technologies from the technical work packages. Nevertheless, research and discussions between the partners within the work packages have also shown that certain aspects or technologies are not clearly depicted or represented inside the defined RA (e.g. communication, simulation, etc.).

After collecting all the technical requirements and the comments from the technical work packages (i.e. WP2 – WP4), discussions have taken place in order to update the AUTOWARE RA. Additionally, first inter-project cooperation have started between AUTOWARE and other research projects to align the different available reference architectures. More information about this can be found in section 5.

Finally, the goal of AUTOWARE is to conform to Industry 4.0, and therefore the Reference Architecture for Manufacturing Industry 4.0 (RAMI 4.0) has constantly been reflected upon during the design process to maintain compatibility with the requirements of Industry 4.0. The following subsections will present the final AUTOWARE Reference Architecture and the overall AUTOWARE Framework.

4.1 AUTOWARE Reference Architecture

The AUTOWARE Reference Architecture (RA) aligns the cognitive manufacturing technical enablers (i.e. robotic systems, smart machines, advanced control, secure planning systems, cloud-based service and application platforms) to provide cognitive automation systems as solutions while exploiting cloud technologies and smart machines as a common system. AUTOWARE leverages a reference architecture that allows harmonization of collaborative robotics, reconfigurable cells and modular manufacturing systems control architectures with data-driven industrial service reference architectures supported by secure and edge-powered reliable industrial (heterogeneous) communication systems (e.g. 5G, WiFi and OPC-UA TSN) and high performance cloud computing platforms (e.g. CloudFlow [CloudFlow, 2018]) across cognitive manufacturing competence domains (simulation, analytics and automation).

The final aim of the AUTOWARE RA is to have a broad industrial applicability, map included technologies to different areas, and to guide technology and standards development. From a structural perspective, the AUTOWARE RA covers two different areas denoted as domains:

- **Design domain:** it describes the design and development methods, tools and services for designing AUTOWARE CPPS. The components of the design domain enable users to intuitively design the applications.
- **Runtime domain:** this domain includes all the systems that support the execution and operation of the AUTOWARE autonomous CPPS.

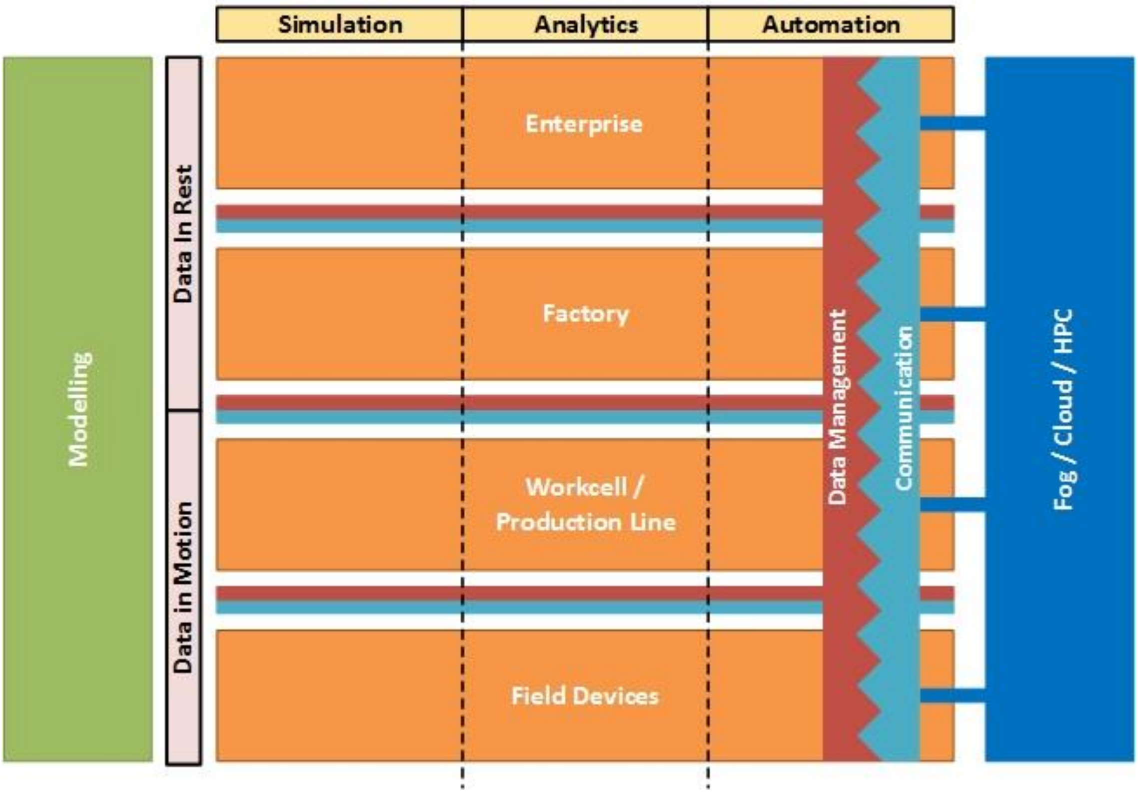

Figure 7: Updated AUTOWARE Reference Architecture

The AUTOWARE RA has four levels (see Figure 7), which target all relevant levels for the modelling of autonomous CPPS in the view of AUTOWARE:

- **Enterprise:** The enterprise level is the top level of the AUTOWARE RA and encompasses all enterprise's systems and factories, as well as interaction with such entities from third parties.
- **Factory:** At the factory level, a single factory is depicted. This includes all the various workcells or production lines available for the complete production.
- **Workcell/Production Line:** The Workcell level represents the individual production line or cell within a company. Nowadays, a factory typically contains multiple production lines (or production cells), each containing individual machines, robots and other components.
- **Field Devices:** The field device level is the lowest level of the reference architecture; at this level the actual machines, robots, conveyer belts, etc., but also controllers, sensors and actuators are positioned.

4.1.1 Communication and Data Management

One of the main comments that was received from the technical work packages was that the (heterogeneous) communication concepts, together with the data management (which is closely tied to the communication), were not properly projected inside the RA. In the first version, communication and data management were included in the Fog/Cloud pillar.

Although Fog and Cloud solutions are by nature accessed by CPPSs through communication channels, they do not directly provide the communication; they can be better seen as more technical enablers (or services) that can be exploited by the end users to have various applications being executed on these solutions.

AUTOWARE RA aims – in line with Industry 4.0 views - is that all levels of and AUTOWARE RA conformant systems can directly interact with each other. For example, in new applications like e.g. secure remote access for remote maintenance, the communication is required from the top to the bottom level of the reference architecture. The architecture can more be seen as a communication or automation pillar than the classical automation pyramid. Within the updated AUTOWARE RA, the (heterogeneous) communication technologies are depicted so that communication takes place between in the levels, between two adjacent levels, but can also directly take place between levels that are separated further from each other (i.e. Factory and Field level). As the Data Management technology is closely related to the communication technologies, the Data Management has been aligned with the updated communication technology.

4.1.2 Modelling

The modelling vertical in the AUTWOARE Reference Architecture (green column in Figure 7) focuses on the modelling, programming and configuration aspects of the different technical components inside the different horizontal layers. It is an essential component of the digital twin approach. On each layer, different tools or services are applied and for all of them different modelling approaches are required and available. The goal of the modelling approaches is to ease the end user/system developer/system integrator developing the tools or technologies for the different levels. Depending on the tasks, it could be also possible to have modelling approaches that take the different layers into account and make it easier for the users to model the interaction between the different layers.

The AUTOWARE Digital Abilities (more in detail described in section 4.3) additionally use legacy systems/technologies that are already available from other resources, like EU projects, technology providers, etc. Important concepts here are taken from the FiWare

Foundation, ROS, Docker, etc. (see Figure 8). These existing technologies can significantly increase the acceptance of the newly developed technologies, as they are developing on the basis of technologies that are widely spread and accepted in the Industry 4.0 communities.

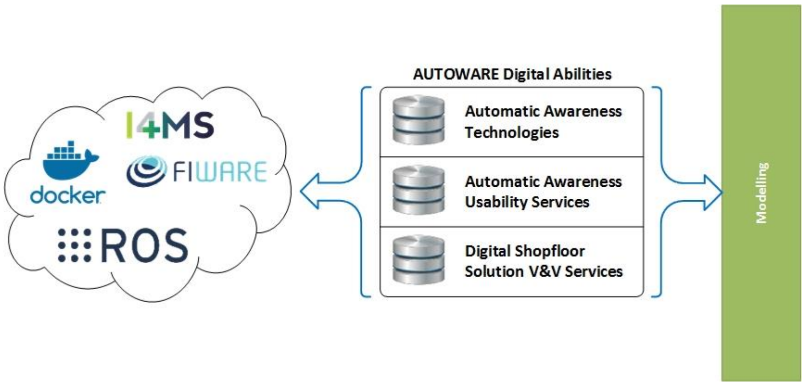

Figure 8: Modelling of application using AUTOWARE Digital Abilities, that are using pre-existing technologies.

4.1.3 Simulation, Analytics and Automation

A new perspective viewpoint has been added to the reference architecture, which is the functional viewpoint. The functional viewpoint distinguish between the "Simulation", "Analysis" and "Automation"concepts of the results of the AUTOWARE project. The functional viewpoints are positioned in a vertical way, as they can cover all levels of the RA, varying from the top level all the way done to the field level, simulating for example robot controllers or representing virtual sensors.

Simulation is one of the most important concepts with CPPS. The idea of "digital twin" is entering the manufacturing process at rapid pace, where next to real manufacturing, simulated manufacturing lines are being used to test and validate new approaches. Digital twin refers to a digital copy of the physical assets, processes, people, devices, etc. within a factory. Within the AUTOWARE project, technologies like Augmented Reality (AR), Virtual Reality (VR) and Augmented Virtuality (AV) are introduced for bringing in simulated aspects in the manufacturing processes.

Analytics is mainly focusing on collected data from all the processes and levels for acquiring a better understanding of the production processes taking place within the factories or enterprises. This data can vary from integral statistical data to real-time data coming directly from the machines (see section 4.1.4). Analytics can be used to directly influence the manufacturing process (for example, to identify an anomaly or error occurring in the actual process, which could damage the product or the equipment). It can be also used over a longer period to optimize the overall production process in order to increase revenue or reduce costs. Although analytics is not directly in the focus of the

AUTOWARE project, it is of major importance to Industry 4.0, and therefore already considered in the AUTOWARE Reference Architecture.

Configuration is a very important topic, which is often overseen in the definition of the manufacturing process. Machines, robots, etc. are not functioning directly out of the box, and therefore the configuration process is as important as the functioning process. If machines are not intuitive to configure and setup times are too high, related solutions are not applicable, especially for SMMEs. Therefore, configuration is definitely worth consideration.

Automation deals with the on-line configuration and control of the real processes in the actual factories. It thus targets, among others, the programming of machines and controlling of real machines (e.g. robots, CNC machines, conveyor belts), communication between machines, human-machine interaction, integrating sensors for process control, etc.

4.1.4 Data Perspective

As Industry 4.0 is very data-intensive, the concept of data needs to be included into the AUTOWARE Reference Architecture. Within AUTOWARE, two data domains are being considered, namely the "data in motion" and "data in rest".

Data in rest refers to data that has been collected from various sources distributed over the factory and is first analyzed after the actual event (e.g. throughput, statistics, error reporting) has occurred. This data is mostly evaluated at the higher levels of the factory, thus not directly at the work floor. This data can be used to optimize the processes in the company or also to use for marketing concepts or to give an overview of monthly results inside the company.

Data in motion is collected similarly to data in rest, but the analysis of this data is different, as it is analyzed in real-time as the event happens. An example could be the tracking of mobile robots and detecting if they enter areas that could endanger either the robot itself or the human workers. This data can directly influence the production process and needs to be react to in a real-time manner. This data is mostly used on the direct shopfloor.

The handling and storage of this data can be performed on different platforms. Direct real-time interaction with the data is more likely to be done with local storage or fog/edge based solutions, whereas the non-real-time analytics is more likely to take place in the cloud.

4.2 AUTOWARE Business Values

Every day new technologies appear on the market and for many SMMEs it is very difficult to have a clear overview and understanding what is really available and useful for their company. Many European initiatives (e.g. I4MS) and other interesting platforms provide solutions, but many of them are isolated solutions.

AUTOWARE aims to develop an Autonomous Factory Ecosystem around its Business value allowing SMMEs to have a clear understanding of the competitive advantage gain when implementing their manufacturing processes using the provided access to a set of new generations of tools and solutions capable of integrating and supporting CPPS and digital services (i.e. cloudifications, reconfigurable robot cells, fog-based solutions, etc.).

A further aim is to provide an open CPPS solution hub ecosystem that gathers all resources together, thus enabling SMMEs to access all the different components in order to develop digital automation cognitive solutions for their manufacturing processes in a controlled manner and with quantifiable business impact.

4.3 AUTOWARE Digital Abilities

As an initial and crucial step towards autonomous shopfloor operation, AUTOWARE provides a set of digital technologies and services for setting the foundation of automatic awareness in a digital shopfloor. Automatic awareness is the precondition for any form of more advanced autonomous decision and/or self-adaptation process. Autonomous digital shopfloor operations require integration across multiple disciplines. Openness and interoperability needs to be facilitated across all levels of the RA in a harmonized manner to ensure future digital shopfloor extendibility as industry gradually adopts digital abilities and services to build their competitive advantage.

The AUTOWARE digital abilities contain three components, namely "technologies", "usability services" and "V&V services", which facilitate the different users of the AUTOWARE Framework to interact with the system on different levels.

The first component are the technology enablers. They can be identified as technical tools, methods and components developed or provided within the AUTOWARE framework. Examples of technology enablers within AUTOWARE are robotic systems, smart machines, cloudified control systems, fog nodes, secure cloud- and fog-based planning systems as well as solutions to exploit cloud and fog technologies and smart machines as a common system. These technologies are conformant to a set of automatic awareness integrated technologies, like ROS for reconfigurable robotic cell and collaborative robotic bi-manipulation technologies, smart product memory technology, OpenFog edge computing and virtualization technology, 5G-ready distributed data processing and reliable wireless mobile networking technology, etc.

Second to that are the usability services, intended for a more cost-effective, fast and usable modelling, programming and configuration of integrated solutions based on AUTOWARE enabling automatic digital shopfloor awareness technologies. This includes for example augmented virtuality services, CPPS trusted auto-configuration services or robot programming by demonstration (PbD) services.

Finally, AUTOWARE provides validation and verification (V&V) services for digital shopfloor solutions (CPPS). Although systems can be designed to work correctly under several environmental conditions, in practice it is enough if they work only under specific well defined conditions. Certification processes (following international standards) help to guarantee correct operation under certain condition and increase the credibility, visibility and acceptability of CPPS to potentially new customers.

4.4 AUTOWARE Roles

The potential roles that are influenced by or influence the AUTOWARE Framework remain similar to the ones defined in the first version of the Framework. No necessary changes have been identified in the past period. The following roles have been identified as important to the AUTOWARE Framework:

- Software developer
- Automation equipment provider
- Hardware developer
- System integrator
- Technology developer
- End User (SMEs)
- Policy maker

4.5 Standards

AUTOWARE focuses on many different technologies (e.g. communication, cloud/fog-based solutions, reconfigurable robots, etc.) that can be adopted to introduce CPPS in manufacturing processes at SMMEs. For many of these technologies, standards are defined or in the process of definition. These standards are closely linked to the Validation and Verification (V&V) services. The better the technologies uphold their respective standards, the better the V&V process is and the higher the acceptance rates will be at the SMMEs.

Deliverable D7.2 [AUTOWARE_D7.2, 2018] provides an overview of the currently identified standards that are of interest for the developments within the AUTOWARE project. The following standards are identified:

- IEEE 802.1 Time-Sensitive Networking (TSN)
- Web Ontology Language (OWL)
- Work place safety and certification according to the DGUV
- VDI/VDE 2634 – Optical 3D-measuring systems
- Wireless Communication Standards
    - 3GPP
    - Industrial IEEE 802.11
    - IEC WirelessHART
    - IEEE 802.15.4e
    - IETF RPL
    - IETF 6TiSCH
- Robot Operating System (ROS)
- ISO 10218-1:2011 and 10218-2:2011
- ISO/TS 15066:2016
- IEC 62541 – OPC UA, OPC UA TSN
- ISO CD 21919
- XML3D

For a more detailed description of the standards, the reader is referred to the beforementioned deliverable.

4.6 AUTOWARE Framework

The sections before described the different components that are encapsulated in the AUTOWARE Framework. Compared to the first version, the set of components remain the same, but specifications have been updated/extended by new knowledge gained during the first phase of the project.

Figure 9 presents the final version of the AUTOWARE Framework, containing all the relevant parts for the overall AUTOWARE project. This framework will be applied for the rest of the project and used as basis for the final developments/integration and exploitation concepts inside the project.

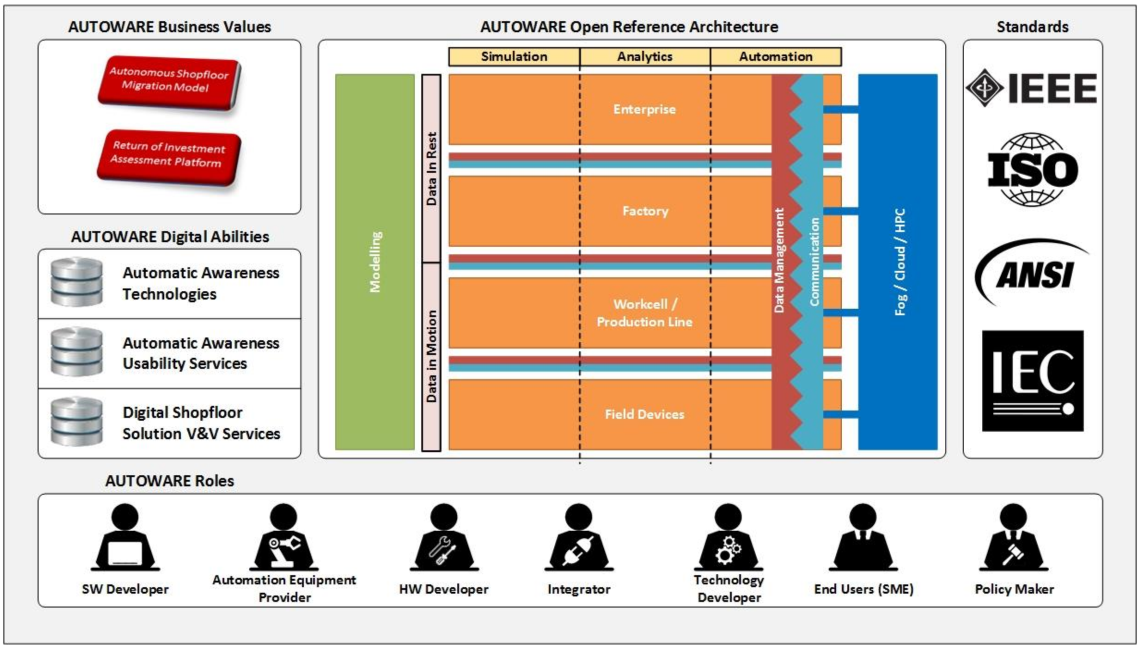

Figure 9: Updated AUTOWARE Framework

5. Cooperation Towards Generic Reference Architecture

5.1 AUTOWARE Framework and RAMI 4.0 compliance

One of the main goals of the overall AUTOWARE Framework and Reference Architecture is to be related to the RAMI 4.0, as this is the identified reference architecture for Industry 4.0. Our aim is to keep the developments within the AUTOWARE project related to the topics of Industry 4.0 and keep the Reference Architecture and the Framework related to the RAMI4.0, but also to extend their scope to address the smart service, the data-centric service operations and future autonomous service demands.

To establish the link between AUTOWARE and RAMI 4.0, the consortium mapped the different concepts and components of the AUTOWARE Framework to the RAMI 4.0 model. Figure 10 up to Figure 12 show the result of this mapping. As it can be observed, the layers of the RAMI 4.0 architecture are well covered by the digital abilities enablers (technologies and service). Moreover, the business value matches with the vision of the business layer of the RAMI4.0 architecture. On the hierarchical axis, the mapping is provided with the layers of the AUTOWARE reference architecture; whereas the lifecycle coverage for type and instance are addressed through the modelling pillar and the Fog/Cloud/HPC layers. This strict mapping ensures that the AUTOWARE Framework not only supports Industry 4.0 scenarios, but also that they can further develop advanced concept like data-driven autonomous operations.

In the previous version of this deliverable (D1.3a), a first mapping between AUTOWARE and RAMI 4.0 was done. This process is repeated and refined to show the conformity of the updated AUTOWARE Framework and Reference Architecture to RAMI4.0 and to the scope of Industry 4.0.

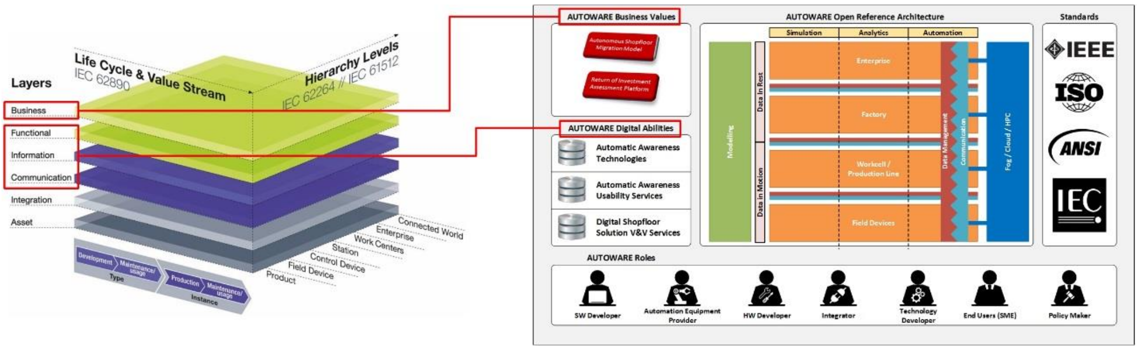

Figure 10: Mapping AUTOWARE – RAMI4.0: Business values and Digital Abilities

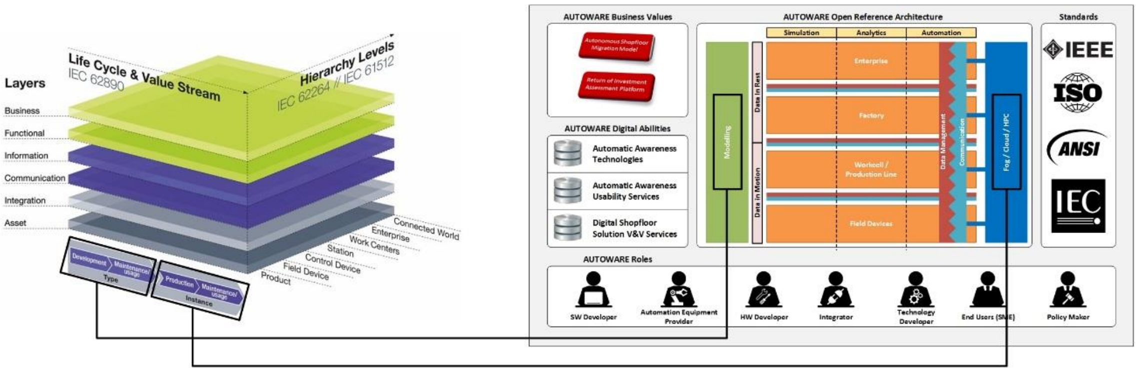

Figure 11: Mapping AUTOWARE – RAMI4.0: Modelling and Cloud/Fog

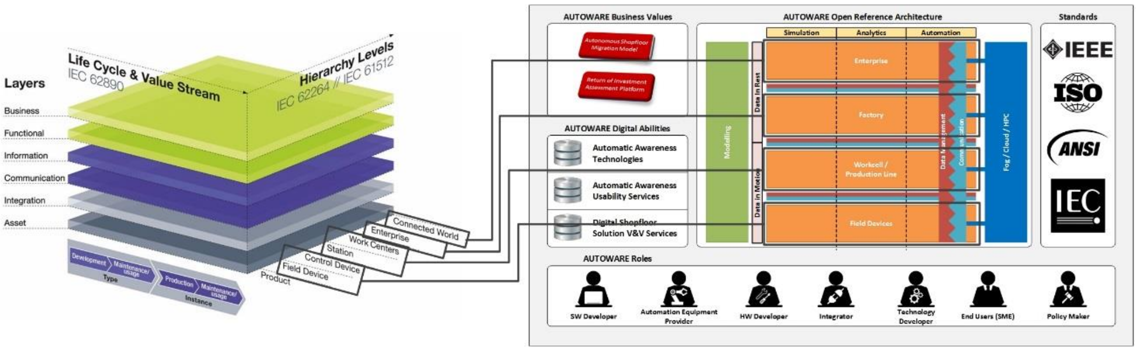

Figure 12: Mapping AUTOWARE – RAMI4.0: Levels

5.2 Related EU Projects

5.2.1 FAR-EDGE

The FAR-EDGE Project (Factory Automation Edge Computing Operating System Reference Implementation) [FAR-EDGE, 2018] is a joint effort of leaders in the field of industrial automation, cyber-physical systems (CPS) for manufacturing and the Industrial Internet-of-Things (IIoT) towards providing a novel edge computing solution for the virtualization of the factory automation. The project researches and explores the application of the edge computing paradigm in factory automation, through design and implementation of reference implementations conformant with recent standards for edge computing in industrial automation applications.

The FAR-EDGE reference architecture (see Figure 13) takes into account the most recent release of some relevant, generic reference architectures for digital industries, industrial IoT and edge computing – namely those from the Platform Industrie 4.0 initiative (RAMI 4.0), the Industrial internet Consortium (IIRA) and the OpenFog Consortium (OpenFog RA). It adopts edge computing principles allowing the execution of automation workflows and data analysis algorithms in close proximity to the target physical process, to the effect of making production systems more flexible and agile. One could image her scalable, fast-configurable production lines to meet the global challenges of masscustomization and reshoring. Additionally, the FAR-EDGE consortium introduces one extra specific layer into the RA, namely the "Ledger Layer". The layer focuses on the permission aspects for virtual automation and analytic processes that is distributed over multiple entities inside the system. This new architectural layer has its background in the Blockchain technology and the FAR-EDGE project wants to demonstrate how specific ledger services can enable decentralized factory automation in an effective, reliable, scalable and secure way.

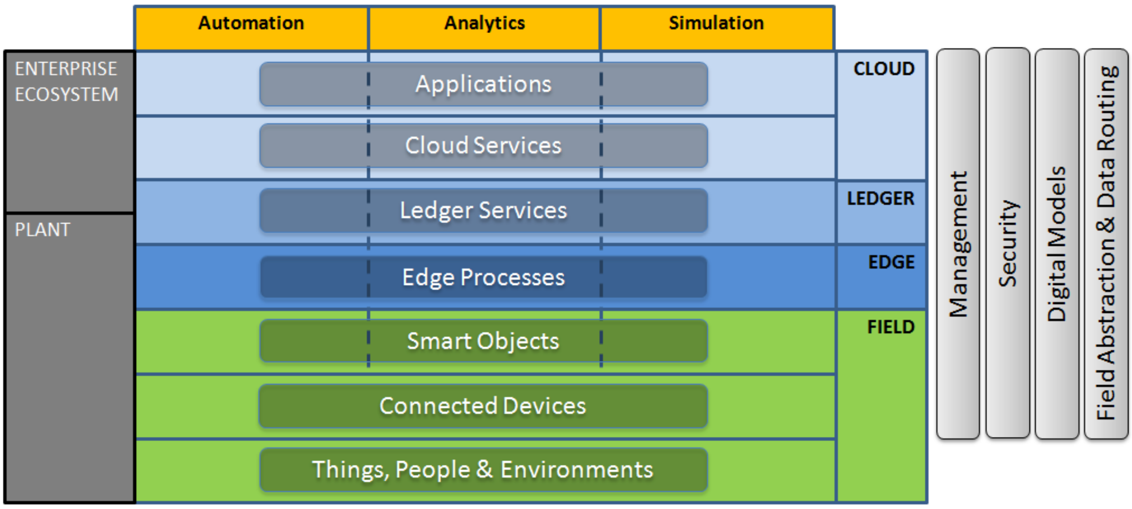

Figure 13: FAR-EDGE Reference Architecture

The FAR-EDGE RA observed from two different viewpoints, namely a "functional viewpoint" and a "structural viewpoint".

The functional viewpoint comprises three high-level functional domains, namely Automation, Analytics and Simulation and four cross-cutting functions (Management, Security, Digital Models and Field Abstraction & Data Routing). On the other hand, the structural viewpoint focuses on the structure of the factory automation based on scopes and tiers. It specifies the plant scope (i.e. the factory) or the enterprise ecosystem scope (i.e. the broader world of corporate IT). The tiers are separated into field, edge, ledge and cloud tier. The field tier is the bottom layer and is populated by the edge nodes (i.e. devices connected to the digital world and to the real world). The edge tier leverages the edge computing model and hosts the edge gateways. The ledger tier comprises ledger services which implement decentralized business logic as smart contracts on top of distributed ledgers (i.e. blockchain). Finally, the cloud tier comprises the cloud servers and is the top layer of the RA.

5.2.2 Daedalus

The Daedalus project (Distributed control and simulation platform on ecosystem of digital automation developers) is a European initiative for industrial automation and targets the full exploitation of the CPS concept of virtualized intelligence, through the adoption of a completely distributed automation platform based on the IEC 61499 standard [IEC61499]. It fosters the creation of a digital automation ecosystem that could go beyond the current limits of manufacturing control systems. It is based on a new generation of distributed intelligent devices (CPS) that are existing both in the real and in the cyber (simulated) world, can be aggregated, orchestrated and re-configured to exhibit complex manufacturing behaviours that optimize the performance of future shop floor.

The Daedalus project will exploit the already existing features of the IEC 61499 international standard for distributed automation to propose a functional model for CPS that merges real-time coordination of the automation tasks with the provision of services to other elements of the automation pyramid (see Figure 14). This extension of the IEC 61499 functionalities adopts the standard's proposed openness and interoperability of implementation, guaranteeing that CPS developed independently will be able to communicate and be orchestrated.

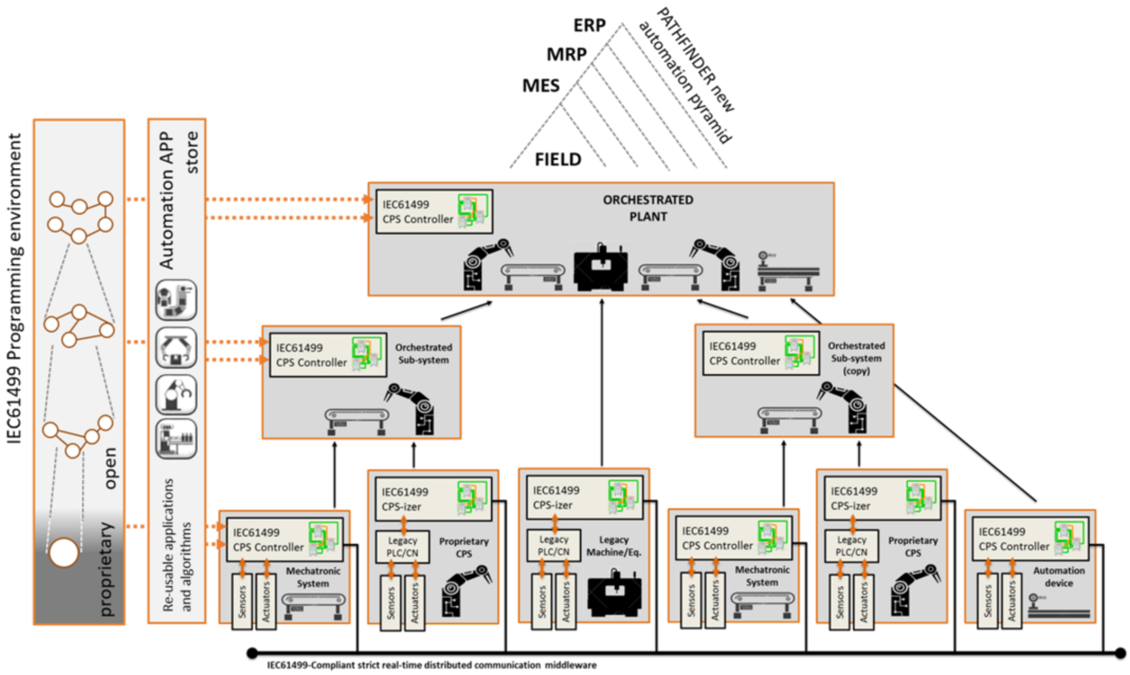

Figure 14: Daedalus Architecture

The Daedalus Initiative set the following goals:

- Ease the conception, development and distribution of intelligence into CPS for real-time execution of orchestrated manufacturing tasks,
- Foster interoperability of CPS from different vendors at orchestration-level,
- Simplify the design, implementation and integration of optimal coordinating control intelligence of CPS,

- Enable near-real-time co-simulation of manufacturing systems as a fully Integrated "service" of a CPS,
- Create a Digital Marketplace to simplify the matchmaking between offer and demand within the Ecosystem,
- Conceive a multi-sided business model for the Automation Ecosystem and the corresponding business plans for its complementors,
- Foster the widespread acceptance of the Ecosystem platform to guarantee success and impact of Daedalus multi-sided market.

5.2.3 Integration FAR-EDGE – Daedalus

Daedalus is particularly focusing on the real-time automation of distributed intelligent devices, based on the IEC 61499 standard, whereas FAR-EDGE considers that type of automation which resides in the edge (or fog), which is positioned between the Factory and the Enterprise/Cloud level (see Figure 15). In addition to this, the characteristic approach of FAR-EDGE of "embedding" station-level automation in a service-oriented interfacing mechanism, is naturally coherent with the object-oriented approach of Daedalus. Additionally, FAR-EDGE will offer a host of functionalities that are not addressed by other implementations, such as IEC 61499 compliant automation and simulation in collaboration with the Daedalus project.

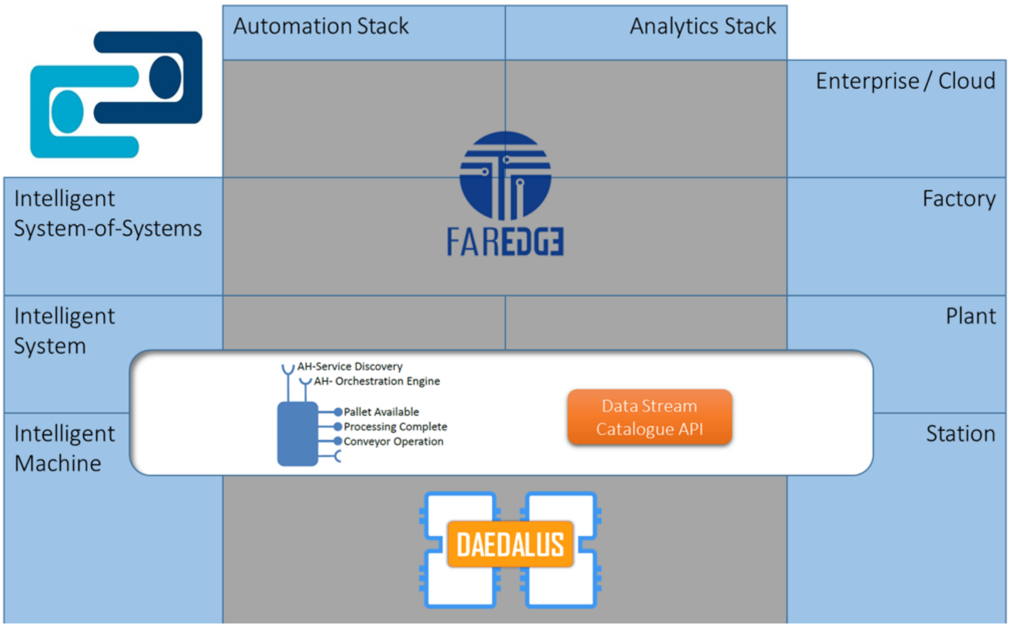

Figure 15: Merging FAR-EDGE and Daedalus

First interaction between the two projects have started. The next step is to look for overlappings between AUTOWARE and the two projects for cooperation. The final goal is to create a general RA and framework that can be applied for manufacturing applications for Industry 4.0. The final RA and framework is beyond the scope of the

AUTOWARE projects. Nevertheless, first cooperation has started and is presented in the following section.

5.3 Mapping of AUTOWARE – FAR-Edge – Daedalus

The aim of the cooperation between the different research projects is to converge to a common reference architecture that covers the most important aspects of all the 3 projects. As mentioned before, the work on the final reference architecture that will arise out of the cooperation is beyond the scope of the AUTOWARE project.

Nevertheless, the architectures from the different projects have been thoroughly considered and investigated and overlapping functionalities identified. The results of this process is presented in the following figures.

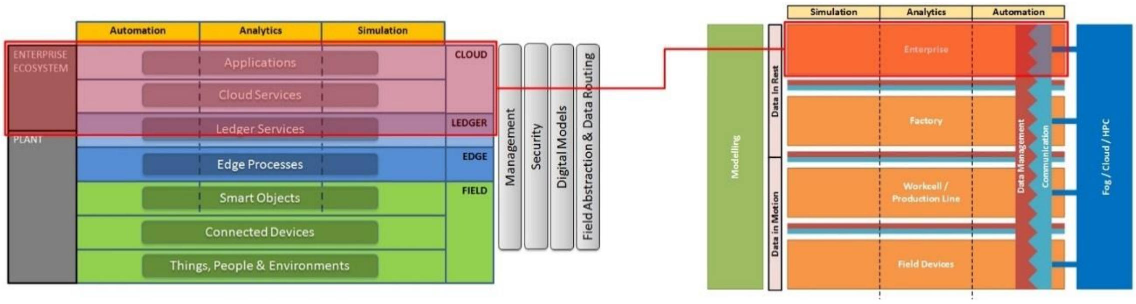

Figure 16: Mapping AUTOWARE – FAR-EDGE: Enterprise level

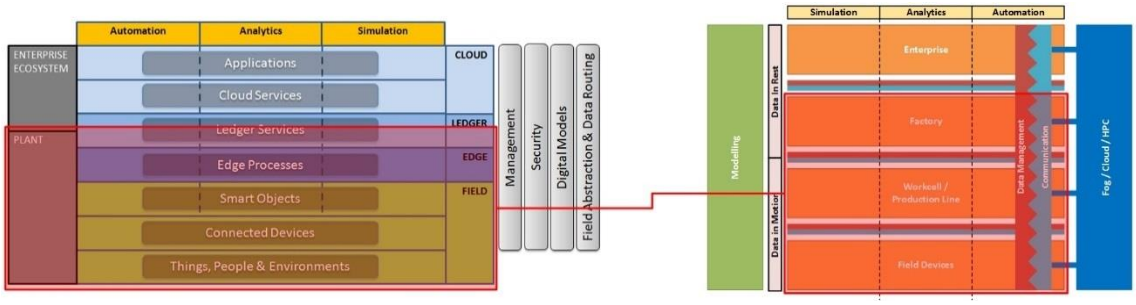

Figure 17: Mapping AUTOWARE – FAR-EDGE: Plant level

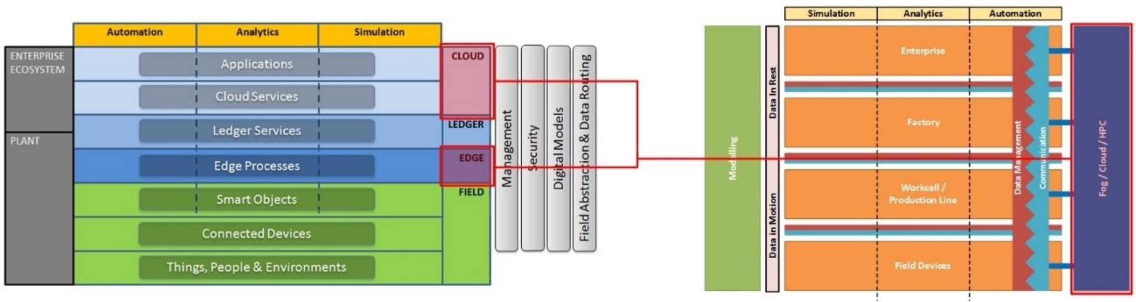

Figure 18: Mapping AUTOWARE – FAR-EDGE: Edge/Cloud level

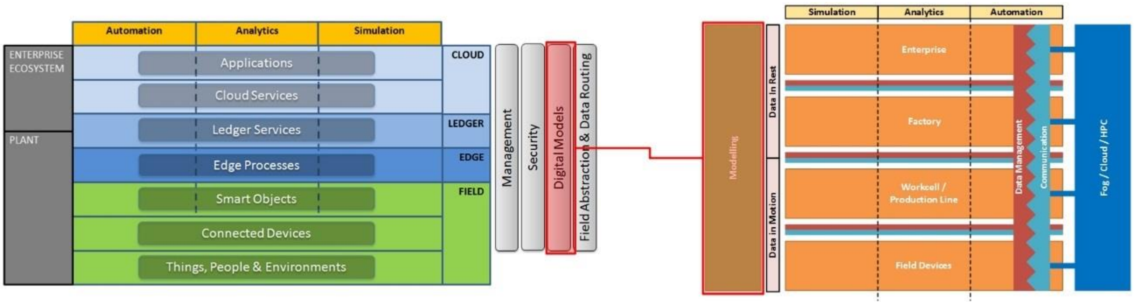

Figure 19: Mapping AUTOWARE – FAR-EDGE: Modelling Approach

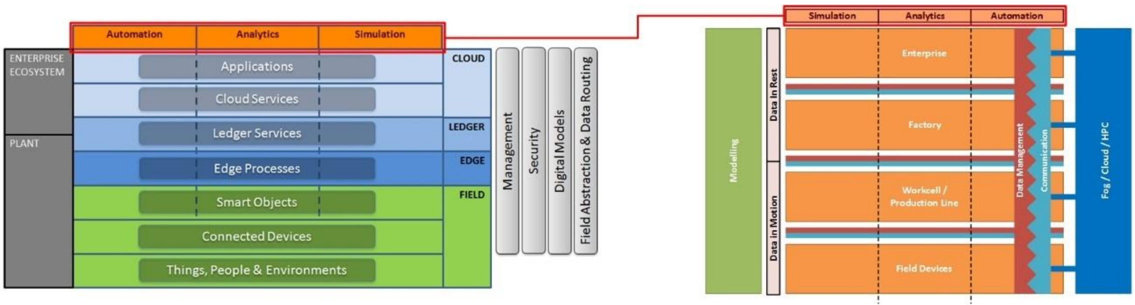

Figure 20: Mapping AUTOWARE – FAR-EDGE: Functional levels

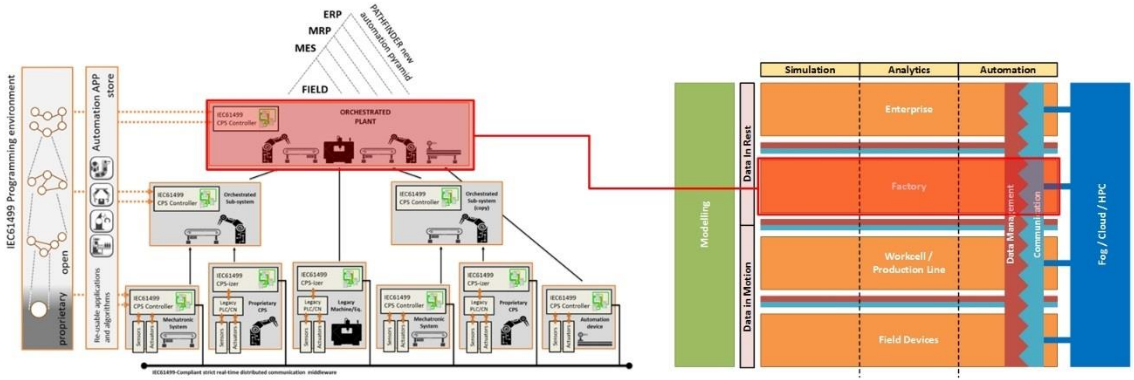

Figure 21: Mapping AUTOWARE – Daedalus: Factory level

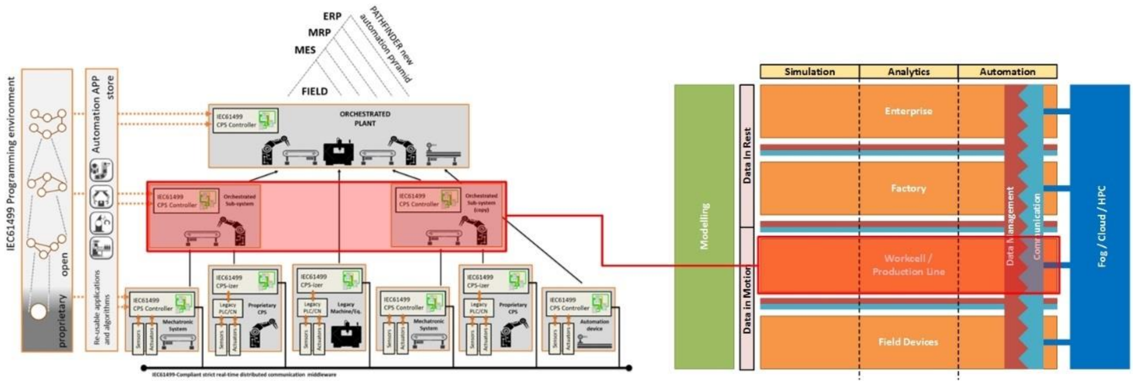

Figure 22: Mapping AUTOWARE – Daedalus: Workcell level

European Commission

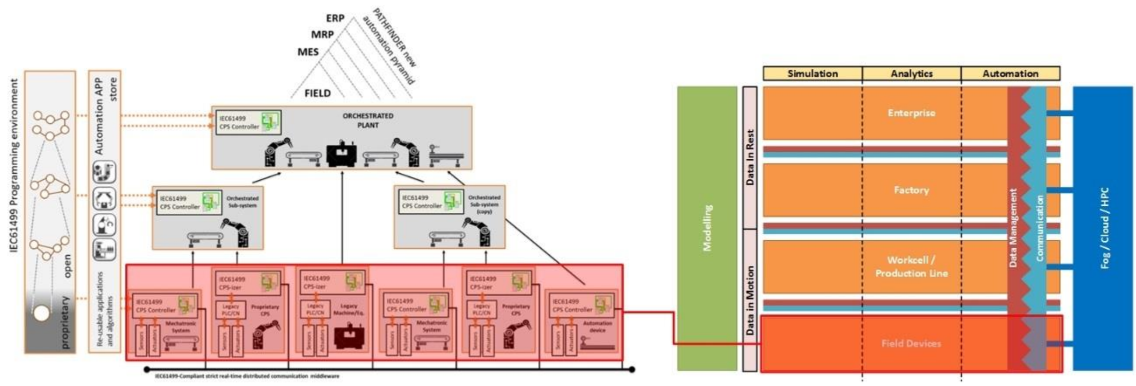

Figure 23: Mapping AUTOWARE – Daedalus: Field Device Level

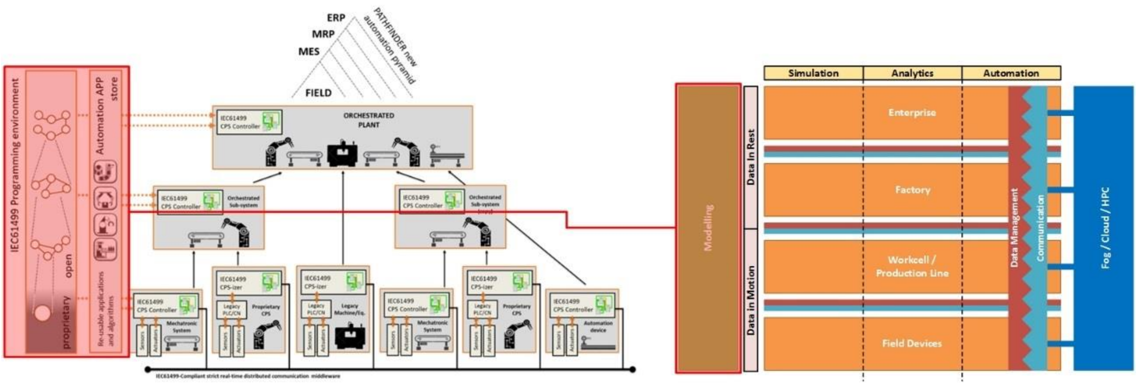

Figure 24: Mapping AUTOWARE – Daedalus: Modelling Approach

6. Conclusions and Next Steps

This deliverable provides the AUTOWARE Framework and Reference Architecture for developing open consolidated ecosystem for CPPS in Small, Medium and Micro-sized Enterprises. The work in this deliverable is an updated and extended version of the previous deliverable D1.3a, where a first version of the AUTOWARE Framework and Reference Architecture has been presented.

The updated content bases on the work performed in the first 20 months of the project and on gathering technical and business requirements from the different technical work packages and potential industrial end users. Based on these updated requirements, changes/modifications to the reference architecture has been performed to provide an architecture where all the AUTOWARE technologies can be mapped to and that can be applied to the industrial use cases. Additionally, the reference architecture is open and flexible so that it can be extended to newly acquired requirements and that it can uphold its conformity to Industry4.0 applications.

In the next steps we will update the technical work packages and use cases definitions, so that they are conform with the updated reference architecture and framework. Fortunately, the modifications have been done in such a way that large modifications to the specifications will not be necessary and that many technologies can still be mapped one-to-one to the reference architecture.

In the final note, , first steps have been initiated for cooperation with related EU projects, namely with the FAR-EDGE and Daedalus projects. These projects are working currently on similar topics and have same partners inside their consortia. First attempts have been made to consolidate their individual approaches, reference architectures and ecosystems into one version that will target the manufacturing market. This is still work in progress and will go beyond the time frame of the AUTOWARE project. Nevertheless, the work performed in this deliverable will form the basis for this process.

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