PART I

2

Open Automation Framework for Cognitive Manufacturing

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The successful introduction of flexible, reconfigurable and self-adaptive manufacturing processes relies on evolving traditional automation ISA-95 automation solutions to adopt innovative automation pyramids proposed by CPS vision building efforts behind projects such as PathFinder, ScorpiuS and RAMI 4.0 IEC 62443/ISA99. These evolved automation pyramids demand approaches for the successful integration of data-intensive cloud and fog-based edge computing and communication digital manufacturing processes from the shopfloor to the factory to the cloud. This chapter presents an insight into the business and operational processes and technologies, which motivate the development of a digital cognitive automation framework for collaborative robotics and modular manufacturing systems particularly tailored to SME operations and needs, i.e. the AUTOWARE Operative System (OS).

To meet the requirements of both large and small firms, this chapter elaborates on the proposal of a holistic framework for smart integration of well-established SME-friendly digital frameworks such as the ROS-supported robotic Reconcell framework, FIWARE-enabled data-driven BEinCPPS/MIDIH Cyber Physical Production frameworks and OpenFog [3] compliant open-control hardware frameworks. The chapter demonstrates how AUTOWARE digital abilities are able to support automatic awareness; a first step in the support of autonomous manufacturing capabilities in the digital shopfloor. This chapter also demonstrates how the framework can be populated with additional digital abilities to support the development of advanced predictive maintenance strategies as those proposed by the Zbre4k project.

2.1 Introduction

SMEs are a pillar of the European economy and key stakeholder for a successful digital transformation of the European industry. In fact, manufacturing is the second most important sector in terms of small and medium-sized enterprises' (SMEs) employment and value added in Europe [1]. Over 80% of the total number of manufacturing companies is constituted by SMEs, which represent 59% of total employment in this sector.

In an increasingly global competition arena, companies need to respond quickly and economically feasible to the market requirements. In terms of market trends, a growing product variety and mass customization are leading to demand-driven approaches. Industry, in general, and SMEs, in particular, face significant challenges to deal with the evolution of automation solutions (equipment, instrumentation and manufacturing processes) they should support to respond to demand-driven approaches, i.e. increasing and abrupt changes in market demands intensified by the manufacturing trends of mass customization and individualization, which needs to be coupled with pressure on reduction of production costs, imply that manufacturing configurations need to change more frequently and dynamically.

Current practice is such that a production system is designed and optimized to execute the exact same process over and over again. Regarding the growing dynamics and these major driving trends, the planning and control of production systems has become increasingly complex regarding flexibility and productivity as well as the **decreasing predictability of processes**. It is well accepted that every production system should pursue the following three main objectives: (1) providing capability for rapid responsiveness,

(2) enhancement of product quality and (3) production at low cost. On the one hand, these requirements have been traditionally satisfied through highly stable and repeatable processes with the support of **traditional automation pyramids**. On the other hand, these requirements can be achieved by creating short response times to deviations in the production system, the production process, or the configuration of the product in coherence to overall performance targets. In order to obtain short response times, a high process transparency and reliable provisioning of the required information to the point of need at the correct time and without human intervention are essential.

However, the success of those adaptive and responsive production systems highly depends on real-time and operation-synchronous information from the production system, the production process and the individual product. Nevertheless, it can be stated that the concept of fully automated production systems is no longer a viable vision, as it has been shown that the conventional automation is not able to deal with the ever-rising complexity of modern production systems. Especially, a high reactivity, agility and adaptability required by modern production systems can only be reached by human operators with their immense cognitive capabilities, which enable them to react to unpredictable situations, to plan their further actions, to learn and to gain experience and to communicate with others. Thus, new concepts are required, which apply these cognitive principles to support autonomy in the planning processes and control systems of production systems. Open and smart cyber-physical systems (CPS) are considered to be the next (r)evolution in industrial automation linked to Industry 4.0 manufacturing transformation, with enormous business potential enabling novel business models for integrated services and products. Today, the trend goes towards open CPS devices and we see a strong request for open platforms, which act as computational basis that can be extended during manufacturing operation. **However, the full potential of open CPS has yet to be fully realized in the context of cognitive autonomous production systems.**

In fact, in particular to SMEs, it still seems difficult to understand the driving forces and most suitable strategies behind shopfloor digitalization and how they can increase their competitiveness making use of the vast variety of individualized products and solutions to digitize their manufacturing process, making them cognitive and smart and compliant with Industry 4.0 reference architecture RAMI 4.0 IEC 62443/ISA99. Moreover, as SMEs intend to adopt data-intensive collaborative robotics and modular manufacturing systems, making their advanced manufacturing processes more competitive, they face additional challenges to the implementation of “cloudified” automation processes. While the building blocks for digital automation are available, it is up to the SMEs to align, connect and integrate them to meet the needs of their individual advanced manufacturing processes, leading to difficult and costly digital automation platform adoption.

This chapter presents the AUTOWARE architecture, a concerted effort of a group of European companies under the Digital Shopfloor Alliance (DSA) [12] to provide an open consolidated architecture that aligns currently disconnected open architectural approaches with the European reference architecture for Industry 4.0 (RAMI 4.0) to lower the barrier of small, medium- and micro-sized enterprises (SMMEs) in the development and incremental deployment of cognitive digital automation solutions for next-generation autonomous manufacturing processes. This chapter is organized as follows. Section 2.2 presents the background and state of the art on open digital manufacturing platforms, with a particular focus on European initiatives. Section 2.3 introduces the AUTOWARE open OS building blocks and discusses their mapping to RAMI 4.0, the Reference Architecture for Manufacturing Industry 4.0. Then, Section 2.4 exemplifies how AUTOWARE platform can be tailored and customized to advanced predictive maintenance services. Finally, the chapter concludes with the main features of the AUTOWARE open automation framework.

2.2 State of the Play: Digital Manufacturing Platforms

Industry 4.0 started as a digital transformation initiative with a focus on the digital transformation of European factories towards smart digital production systems through intense vertical and horizontal integration. This resulted in the development by European industry of the RAMI 4.0 reference model built on the strong foundations of the automation European industry. As a consequence, Asian and American countries have also put efforts to define their reference model for the digitization of their manufacturing processes with stronger influences from IT and IoT industries. This has resulted in the development of the IVRA (Industrial Value Chain Reference Architecture) by the Industrial Value Chain Initiative (IVI) in Asia and the Industrial Internet Reference Architecture (IIRA) by the US IIC initiative; see Figure 2.1 below. These initiatives clearly showed the need to consider in the digitalization of European industry not only the Smart Production dimension, but also Smart Product and Smart Supply Chain dimensions.

As a consequence, European industry kicked off complementary efforts to ensure on the one hand RAMI 4.0, IVRA and IIRA interoperability, mapping

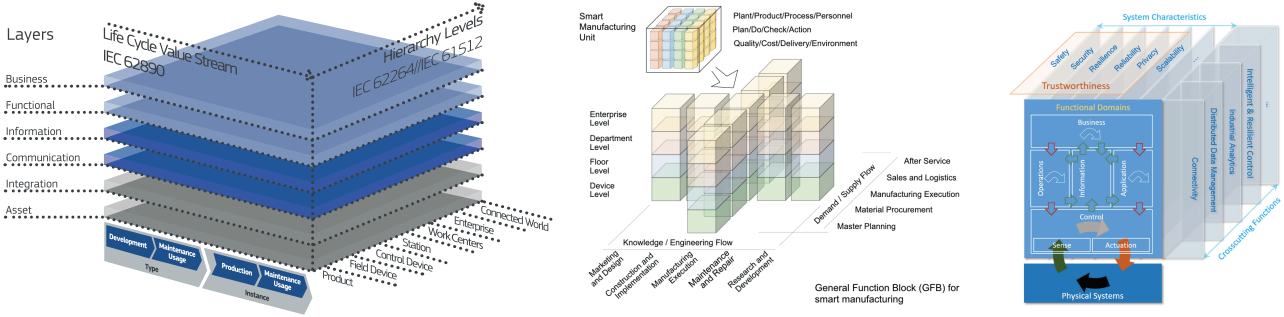


Figure 2.1 RAMI 4.0, IVRA and IIRA reference models for Industry 4.0.

and alignment for global operation of digital manufacturing processes. On the other hand, it has also triggered the need to extend the RAMI 4.0 model with an additional data-driven and digital smart service dimension beyond factory IT/OT integration. This resulted in the development of initiatives such as the Smart Service Welt and the Industrial Data Space to promote the development of smart data spaces as the basis for trusted industrial data exchange. This also derived in a more recent development of a need to support an increased autonomous operation shopfloors in the context of smart data-driven manufacturing processes.

This section provides a state-of-the-art revision of the reference models for factories 4.0 with a focus on RAMI 4.0 and the state of play of digital platforms initiatives developed to address the needs of data-driven operations within Industry 4.0, as the basis and context for the development of a framework for digital automation in industrial SMEs aiming at implementing cognitive and autonomous manufacturing processes.

2.2.1 RAMI 4.0 (Reference Architecture Model Industry 4.0)

The RAMI 4.0 (Reference Architecture Model for Industry 4.0 [34]) specification was published in July 2015. It provided a reference architecture initially for the Industrie 4.0 initiative and later for alignment of European activities and international ones. RAMI 4.0 groups different aspects in a common model and assures the end-to-end consistency of *"…technical, administrative and commercial data created in the ambit of a means of production of the workpiece"* across the entire value stream and their accessibility at all times. Although the RAMI 4.0 is essentially focused on the manufacturing process and production facilities, it tries to focus on all essential aspects of Industry 4.0. The participants (a field device, a machine, a system or a whole factory) can be logically classified in this model and relevant Industry 4.0 concepts are described and implemented.

The RAMI 4.0 3D model (see Figure 2.2) summarizes its objectives and different perspectives and provides relations between individual components. The model adopts the basic ideas of the Smart Grid Architecture Model (SGAM), which was defined by the European Smart Grid Coordination Group (SG-CG) and is worldwide accepted. The SGAM was adapted and modified according to the Industry 4.0 requirements.

The RAMI 4.0 model aims at supporting a common view among different industrial branches like automation, engineering and process engineering. The 3D model combines:

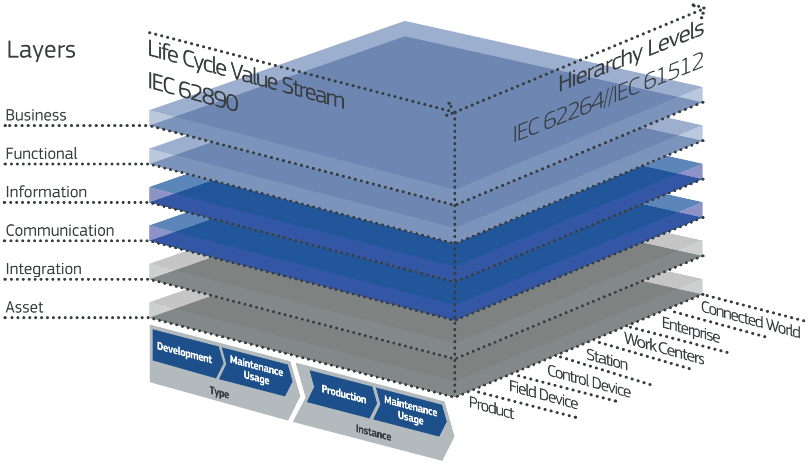


Figure 2.2 RAMI 4.0 3D Model.

- **Hierarchical Levels (Y Axis):** this axis collects the hierarchy levels envisaged by the IEC 62264 international standards on the integration of company computing and control systems;
- **Cycle & Value Stream (X Axis):** the second axis represents the life cycle of facilities and products. The RAMI 4.0 takes the IEC 62890 standard for life cycle management as a reference point to structure the life cycle. This axis focuses on features able to provide a consistent data model during the whole life cycle of an entity.
- **Layers (Z Axis):** the vertical axis, finally, represents the various perspectives from the assets up to the business processes.

The combination of the elements on these three axes represented a quite innovative management of product manufacturing, especially the elements on the X axis. Indeed, the RAMI 4.0 is the only reference architecture to explicitly analyze and take into account entities' life cycles at their time of proposal. Later, other models such as IVRA have also adopted that view.

One of the main objectives of RAMI 4.0 is to provide an end-to-end (i.e. since the inception of the product's idea, until its dismantling or recycling) framework able to connect and consistently correlate all technical, administrative and commercial data so as to create value streams providing added value to the manufacturer.

Many elements are available in RAMI 4.0, e.g. models, types, instances, production lines, factories, etc.). They differentiate between objects, which are elements that have a life cycle and data associated with it. On the other hand, there are the so-called “active” elements inside the different layers and are called Industry 4.0 components (I4.0 component). I4.0 components are also objects, but they have the ability to interact with other elements and can be summarized as follows: (1) they provide data and functions within an information system about an even complex object; (2) they expose one or more end-points through which their data and functions can be accessed and (3) they have to follow a common semantic model.

Therefore, the RAMI 4.0 framework goal is to define how I4.0 components communicate and interact with each other and how they can be coordinated to achieve the objectives set by the manufacturing companies.

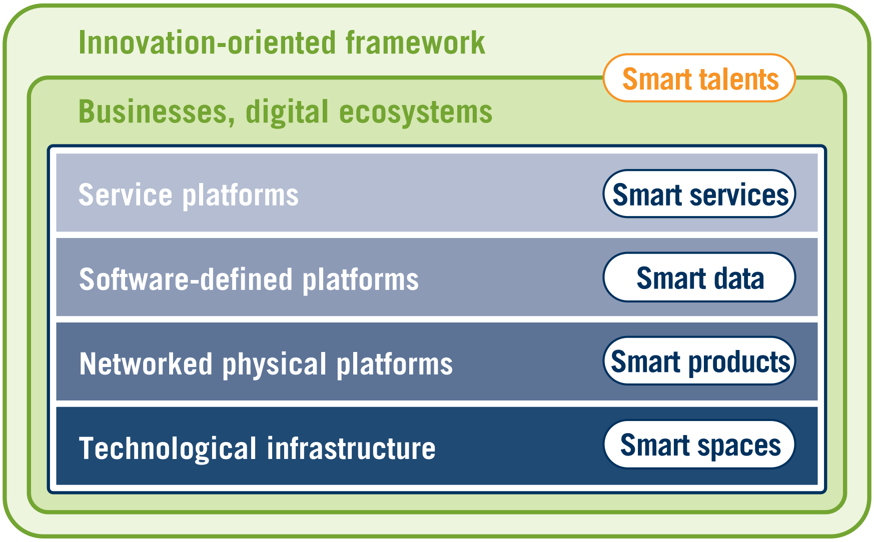
2.2.2 Data-driven Digital Manufacturing Platforms for Industry 4.0

The digital convergence of traditional industries is increasingly causing the boundaries between the industrial and service sectors to disappear. In March 2015, Acatech, through the Industry-Science Research Alliance’s strategic initiative *“Web-based Services for Businesses”,* has proposed a layered architecture (see Figure 2.3), to facilitate a shift from product-centric to user-centric business models, which extends the Industry 4.0 perspective.

At a technical level, these new forms of cooperation and collaboration will be enabled by new digital infrastructures. **Smart spaces** are the smart environments where smart, Internet-enabled objects, devices and machines (smart products) connect to each other. The term **“smart products”** refers to actual production machines but also encompasses their virtual representations (CPS digital twins). These products are described as “smart” because they know their own manufacturing and usage history and are able to act autonomously. Data generated on networked physical platforms are consolidated and processed on **software-defined platforms**. Providers connect to each other via these service platforms to form **digital ecosystems**.

Digital industrial platforms integrate the different digital technologies into real-world applications, processes, products and services; while new business models re-shuffle value chains and blur boundaries between products and services [16].

In the last few years, a number of initiatives have been announced by the public and private sectors globally dealing with the development of digital manufacturing platforms and multi-sided ecosystems for Industry 4.0 (see Figure 2.4). Vertical initiatives such as AUTOSAR [29] and ISOBUS [28], for instance, in the smart product dimension aim at



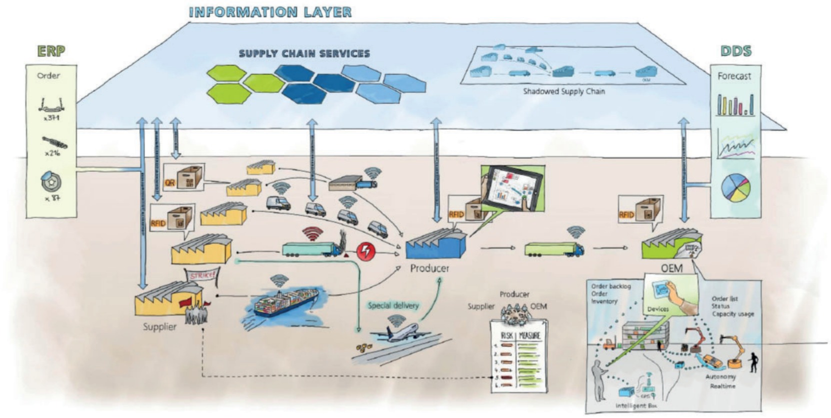


Figure 2.3 Smart Service Welt Reference Model & Vision.

enabling smart products in the automotive and smart agrifood sectors, whereas initiatives such as OPC-UA [31] intend to address manufacturing equipment universal access to a large extent. Similarly, more horizontal open (source) platform initiatives dealing with embedded systems (S3P [27]) or local automation clouds (Arrowhead [26], Productive 4.0 [32]) deal with networked physical product control across vertical industries, e.g. transport, manufacturing, health, energy and agrifood.

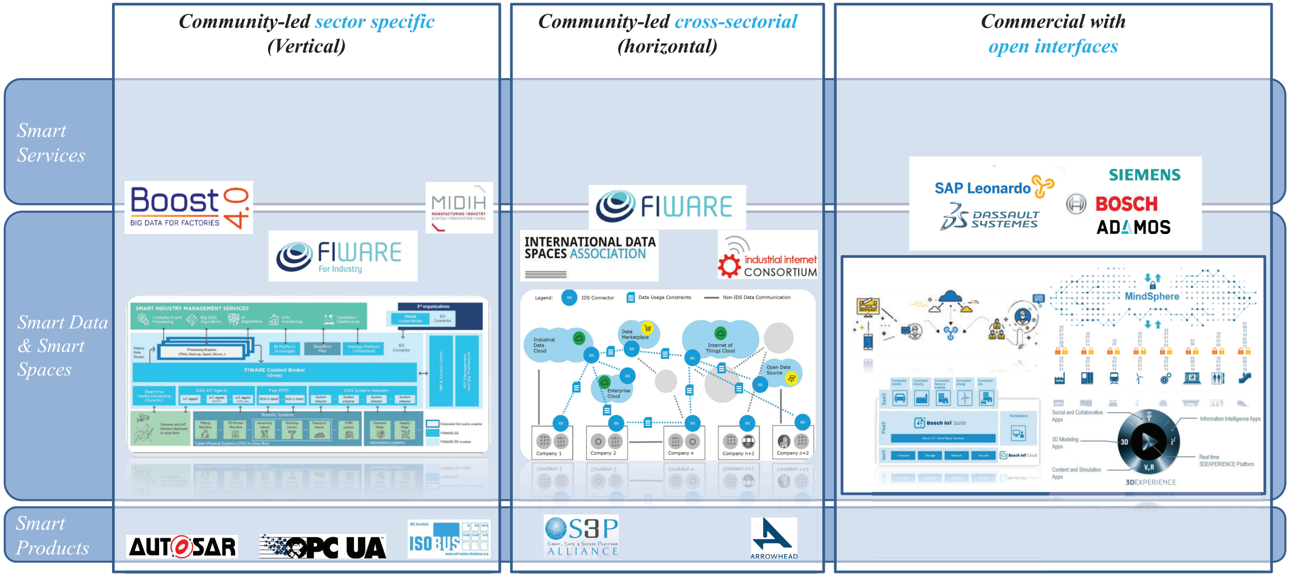


Figure 2.4 Digital manufacturing platform landscape. Adapted from [14] and [15].

However, the largest investment of industry so far has focused on the development of software-defined platforms to leverage smart spaces for smart data; either for vertical industries or for more horizontal approaches. Initiatives such as FIWARE for Smart Industry [22], MIDIH [21] or Boost 4.0 [24] are working to pave the way for the implementation of data-driven smart connected factories. On the other hand, more cross-domain initiatives for smart Internet services (FIWARE [23]), data-sharing sovereignty (International Data Spaces [25]) or Industrial IoT (IIC [30]) are both providing critical general software foundations for the development of vertical solutions such as those mentioned before (FIWARE Smart Industry, Boost 4.0 or MIDIH) and ensuring that interoperability across domains is properly developed as part of the digital transformation supporting the breakup of inter-domain information silos.

Along this line is also worth noting the recent efforts from large industrial software companies to provide commercial solutions with open APIs to respond to the challenge of leveraging digital infrastructures and smart data platforms to support the next generation of digital services. In this area are very relevant initiatives such as Mindsphere by SIEMENS [17], Leonardo by SAP [18], Bosch IoT suite [19] or 3DExperience [20] by Dassault Systems.

2.2.3 International Data Spaces

The **Industrial Data Space initiative** is an initiative driven forward by Fraunhofer together with over 90 key industrial players such as ATOS, Bayer, Boehringer Ingelheim, KOMSA, PricewaterhouseCoopers, REWE, SICK, Thyssen-Krupp, TÜV Nord, Volkswagen, ZVEI, SAP. BOSCH, Audi, Deutche Telekom, Huawei, Rittal and a network of European multipliers (INNOVALIA, TNO, VTT, SINTEF, POLIMI, etc.). **Digital sovereignty over industrial data and trust in data sharing** are key issues in the Industrial Data Space. Data will be shared between certified partners only when it is truly required by the user of that data for a value-added service. The basic principles that form the framework for the technological concept of the Industrial Data Space are summarized as (1) securely sharing data along the entire data supply chain and easily combining own data with publicly available data (such as weather and traffic information, geodata, etc.) and semi-public data, such as from a specific value chain. (2) Sovereignty over data, that is, control over who has what rights in which context, is just as important as legal certainty, to be ensured by certifying participants, data sources and data services. The reference architecture model should be

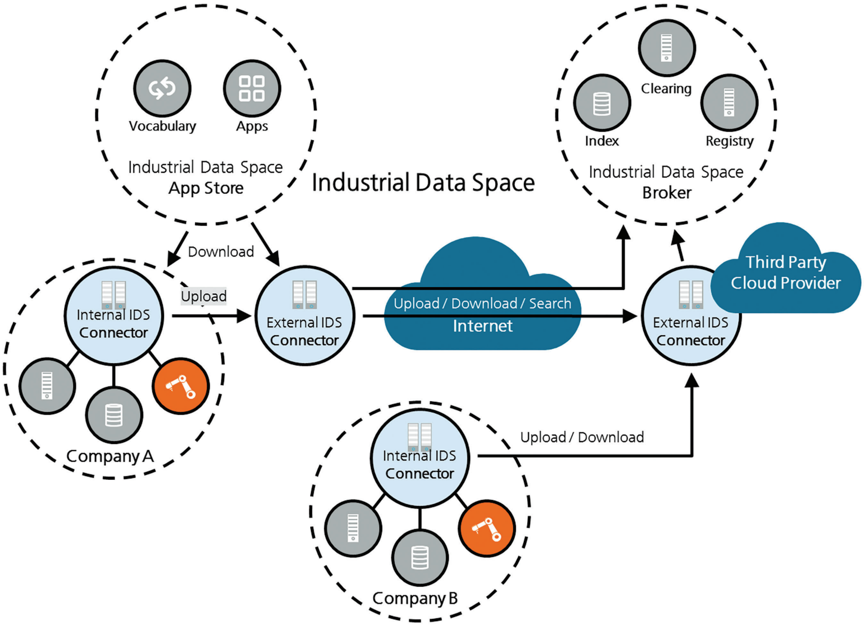


Figure 2.5 Industrial Data Space reference model.

seen as a blueprint for secure data exchange and efficient data combination. Figure 2.5 illustrates the technical architecture of the Industrial Data Space.

The Industrial Data Space fosters secure data exchange among its participants, while at the same time ensures data sovereignty for the participating data owners. The Industrial Data Space Association defines the framework and governance principles for the Reference Architecture Model, as well as interfaces aiming at establishing an international standard which considers the following user requirements: (1) data sovereignty; (2) data usage control; (3) decentralized approach; (4) multiple implementations; (5) standardized interfaces; (6) certification; (7) data economy and (8) secure data supply chains.

In compliance with common system architecture models and standards (such as ISO 42010, 4+1 view model, etc.), the Reference Architecture Model uses a five-layer structure expressing stakeholder concerns and viewpoints at different levels of granularity (see Figure 2.6).

The IDS reference architecture consists of the following layers:

- The **business layer** specifies and categorizes the different stakeholders (namely the roles) of the Industrial Data Space, including their activities and the interactions among them.

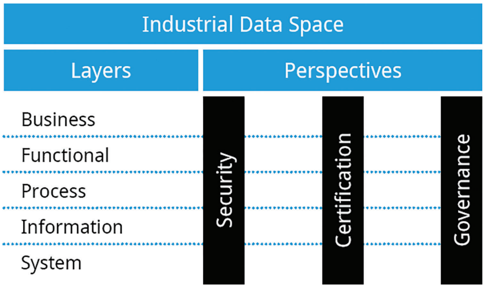


Figure 2.6 General structure of Reference Architecture Model [36].

- The **functional layer** comprises the functional requirements of the Industrial Data Space and the concrete features derived from them (in terms of abstract, technology-agnostic functionalities of logical software components).
- The **process layer** provides a dynamic view of the architecture; using the BPMN notation, it describes the interactions among the different components of the Industrial Data Space.
- The **information layer** defines a conceptual model, which makes use of “linked data” principles for describing both the static and dynamic aspects of the Industrial Data Space’s constituents (e.g. participants active, Data Endpoints deployed, Data Apps advertised or datasets exchanged).
- The **system layer** is concerned with the decomposition of the logical software components, considering aspects such as integration, configuration, deployment and extensibility of these components.

In addition, the Reference Architecture Model contains three cross-sectional perspectives:

- **Security:** It provides means to identify participants, protect data communication and control the usage of data.
- **Certification:** It defines the processes, roles, objects and criteria involved in the certification of hardware and software artifacts as well as organizations in IDS.
- **Governance:** It defines the roles, functions and processes from a governance and compliance point of view, defining the requirements to be met by an innovative data ecosystem to achieve corporate interoperability.

System layer: technical components

The most interesting layer for the IDS framework is the system layer, where the roles defined in other layers (business and functional Layers) are now mapped onto a concrete data and service architecture in order to meet the requirements, resulting in what is the technical core of the IDS. From the requirements identified, three major technical components can be derived:

- Connector
- Broker
- App Store

These are supported by four additional components, which are not specific to the IDS:

- Identity provider
- Vocabulary hub
- Update repository (source for updates of deployed connectors)
- Trust repository (source for trustworthy software stacks and fingerprints as well as remote attestation checks).

IDS open source implementation using FIWARE

The most interesting aspect about the IDS business reference architecture is the opportunity to support multiple implementations and to combine it with open source enablers. It is a common goal that a valid open source implementation of the IDS Architecture can be based on FIWARE software components, compatible also with FIWARE architecture principles.

The FIWARE foundation is working towards making sure that core FIWARE Generic Enablers can be integrated together to build a valid open source implementation of the IDS architecture. Both organizations are collaborating on the development of domain data models and communicating about the development of their respective specifications and architectures to keep them compatible.

The way FIWARE software components can be combined to support the implementation of the main IDS architecture components is shown in Figure 2.7. FIWARE technology offers the following features to support IDS implementation:

1. Docker-based tools relying on Docker Hub Services enabling automated deployment and configuration of Data Apps.
2. Standard vocabularies are being proposed at https://www.fiware.org/data-models

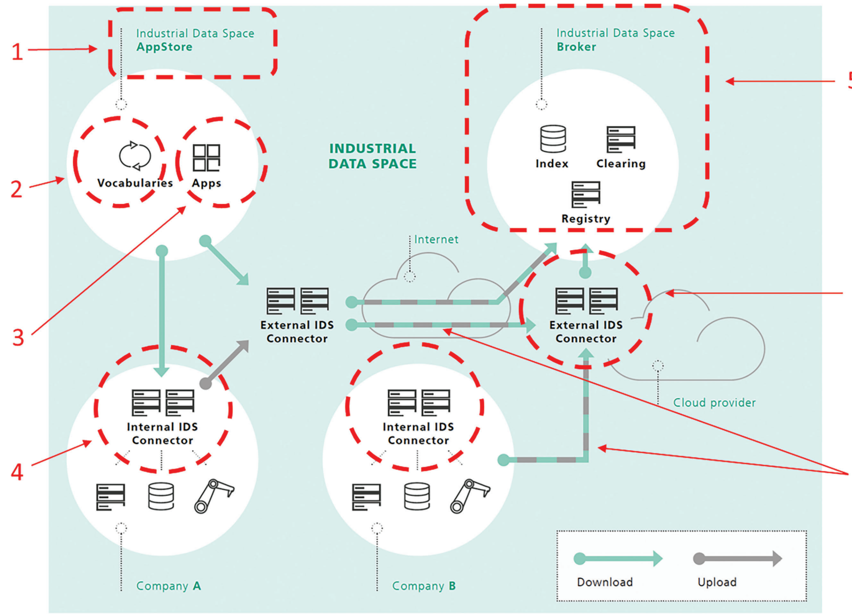


Figure 2.7 Materializing the IDS Architecture using FIWARE.

3. Data Apps map to NGSI adapters or Apps processing context information.
4. Both External and Internal IDS Connectors are implemented using FIWARE Context Broker components.
5. Extended CKAN Data Publication Platform.
6. FIWARE Context Broker components will be used as core component of IDS Connectors.
7. Interface between IDS connectors based on FIWARE NGSI.

2.3 Autoware Framework for Digital Shopfloor Automation

2.3.1 Digital Shopfloor Evolution: Trends & Challenges

The previous section presented the main digital platform and reference architecture work currently in place to deal with data-driven digital transformation in manufacturing. The industrial digitalization supported by Industry 4.0 and its vision of the intelligent networked factory of the future are major talking points as mobile technologies like cloud computing are revolutionizing industrial processes. With embedded systems, components and machines can now talk to one another and self-optimize, self-configure and self-diagnose processes and their current state, providing intelligent support for workers in their increasingly complex decision-making. Today's centrally organized enterprise is turning into a decentralized, dynamically controlled factory whose production is defined by individuality, flexibility and rapidity. As a consequence, see Figure 2.8 below, the digital shopfloor vision is increasingly evolving towards more flexible plug & produce modular assembly islands moving away from more rigid production lines with the ambition of real-time actuation and adaptation **(cognition and autonomy)** of production with an aim of reaching zero defect manufacturing. Equally, manufacturing processes are increasingly collaborative among humans, robots and autonomous mobile systems that come together as needed for mission-oriented tasks.

This new scenario is obviously generating that SMEs face difficulties at various levels to make strategic decisions while building a digital shopfloor, i.e. evolution model to adopt, automation technology selection and cost and time of deployment and operation, associated return on investments that will boost their business strategies (quality, efficiency, cost, flexibility, sustainability, innovation).

Since the 1980s, the IT structure of factories has been ordered hierarchically from field level to the level of factory control. Cloud and edge

Figure 2.8 Digital shopfloor visions for autonomous modular manufacturing, assembly and collaborative robotics.

technologies now make it possible to disengage these hierarchies and link up individual components – from computer numerical control CNC and robot control RC to manufacturing execution systems MES and enterprise resource planning ERP – in flexible networks. The core of this new approach is the virtualization of systems in which software functionality (digital abilities) is decoupled from the specific computer hardware (embedded, edge, cloud, HPC) where it runs. In other words, software used to depend on specific computer or control platforms is now separated from it via virtual machines and transferred to the cloud or the edge based on decision/actuation time scales. In a multitude of ways, **transfer of control functions to the cloud** opens up a whole new dimension of flexibility. First of all, the cloud-edge mechanism *"rapid elasticity"* enables the flexible and mostly automatic distribution of computing capacity. This means that the computing power of a whole group of processor cores in a "private cloud" can be allocated in a few seconds – for instance, between the CPU-intensive processes of the five-axis interpolation of a milling machine or the complex axis control of cooperating robots. Consequently, a much more efficient use of available computing power can be made than was possible with the older, purely decentralized control systems for individual machines and robots. At the same time, further gains in flexibility are given when – with adequate computing power – any number of virtual machine controls VMC or virtual robot controls VRC can be generated. The **cloud-based control** opens the way to upgrading or retrofitting high-quality machines and equipment whose control systems are outdated. The main challenge here is meeting the stringent real-time requirements set by state-of-the-art machine and robot control systems.

AUTOWARE [3], a European initiative under the European Commission initiative for digitizing European Industry, supports the deployment of such autonomous digital shopfloor solutions based on the following three pillars:

- **Pillar1: Harmonized open hardware and software digital automation reference architecture.** From a data-driven perspective for cyber physical production systems (smart products), leverage a reference architecture across open ICT technologies for manufacturing SME (I4MS, www.i4ms.eu) digital transformation competence domains (cloud, edge/OpenFog, BeinCPPS/MIDIH, robotics/ROS-ReconCell). For keeping integration time and costs under control, AUTOWARE framework acts as a glue across manufacturing users and digital automation solution developers in a friendly ecosystem for business development, more efficient service development over harmonized architectures (smart machine, cloudified control, cognitive planning-app-ized operation).

- **Pillar 2: Availability of digital ability technology enablers for digital shopfloor automatic awareness and cloud/edge-based control support.** Leverage a number of SME *digital abilities*, e.g. augmented virtuality, reliable wireless communications, smart data distribution and cognitive planning, to ease the development of automatic awareness capabilities in autonomous manufacturing systems. For ensuring digital shopfloor extendibility, the AUTOWARE framework envisions the development of *usability services* (Cyber Physical Production Systems (CPPS) trusted auto-configuration, programming by demonstration) as well as associated standard compliant *validation & verification services* for digital shopfloor solution.
- **Pillar 3: Digital automation business value model to maximize Industry 4.0 return of investment.** Leverage digital automation investments through a shared SME cognitive manufacturing migration model and an investment assessment platform for incremental brownfield cognitive autonomous solution deployment.

As opposed to other manufacturing environments, digital automation faces an increased challenge in terms of the large diversity of technologies involved. This implies that access to digital technologies or digital services is not enough for Industry 4.0 in general, but SMEs in particular, to leverage the Industry 4.0 business value. In the context of digital automation in general and in the context of cognitive and autonomous systems in particular, safe and secure integration of all technologies involved (robotic systems, production systems, computing platforms, cognitive services and mobile information services) into solutions is the real challenge, as illustrated in Figure 2.9.

Based on these three pillars, AUTOWARE has proposed a framework based on other existing frameworks (e.g. MIDIH, BEinCPPS, FIWARE,

Figure 2.9 AUTOWARE digital automation solution-oriented context.

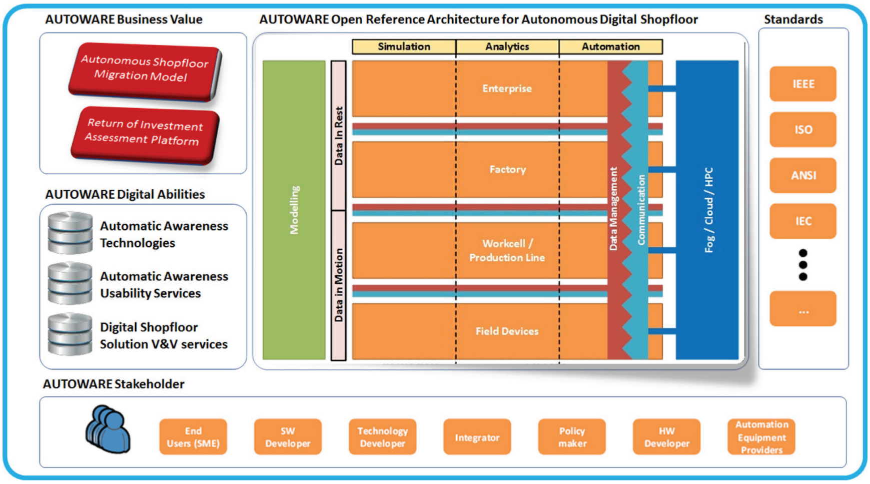


Figure 2.10 AUTOWARE framework.

RAMI 4.0), taking into consideration the industrial requirements from several use cases, aiming to provide a solution-oriented framework for digital shopfloor automation. Figure 2.10 shows the AUTOWARE framework with its main components.

The AUTOWARE framework from a technical perspective offers many features and concepts that are of great importance for cognitive manufacturing 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 CPS services.
- **Reference architecture.** Platforms focused on harmonization of reference models for cloudification of CPS 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 defect manufacturing, energy efficiency.
- **Connectivity to IoT.** Multi-level operation (edge, cloud) and function visualization 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 allows 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 poses new safety and security system requirements; component 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 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.

2.3.1.1 Pillar 1: AUTOWARE open reference architecture for autonomous digital shopfloor

AUTOWARE Reference Architecture (RA) aligns the cognitive manufacturing technical enablers, i.e. robotic systems, smart machines, cloudified control, secure cloud-based planning systems and application platform 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 system control architectures with BEinCPPS and MIDIH data-driven industrial service reference architectures (already fully aligned with ECSEL CRYSTAL and EMC2 CPS design practices) supported by secure and edge-powered reliable industrial (wireless) communication systems (5G, WiFi and OPC-UA TSN) and high-performance cloud computing platforms (CloudFlow) across cognitive manufacturing competence domains (automation, analytics and simulation).

The goal of the AUTOWARE RA is to have a broad industrial applicability, map applicable technologies to different areas and to guide technology and standard 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 (the so-called automatic awareness digital ability usability services).
- **Runtime domain:** it includes all the systems that support the execution and operation of the AUTOWARE autonomous CPPS.

The AUTOWARE RA has four layers/levels (see Figure 2.11), which target all relevant layers for the modeling of autonomous CPPS in the view of AUTOWARE:

- **Enterprise:** The enterprise layer is the top layer of the AUTOWARE reference architecture that encompasses all enterprise's systems, as well as interaction with third parties and other factories.
- **Factory:** At the factory layer, a single factory is depicted. This includes all the various workcells or production lines available for the complete production.
- **Workcell/Production Line:** The workcell layer represents the individual production line of cell within a company. Nowadays, a factory typically contains multiple production lines (or production cells), where individual machines, robots, etc. are located in or become a part of.
- **Field Devices:** The field devices layer is the lowest level of the reference architecture, where the actual machines, robots, conveyer belt, as well as controllers, sensors and actuators are positioned.

To uphold the concept of Industry 4.0 and to move from the old-fashioned automation pyramid (where only communication was mainly possible within a specific layer, and to establish communication between the different layers, complicated interfaces were required), the communication concept is a "pillar" to cover all the mentioned layers. The communication pillar enables direct communication between the different layers. The pillar is named **Fog/Cloud** and uses wired (e.g. IEEE 802.1 TSN) and wireless communication to create direct interaction between the different layers by using Fog/Cloud concepts (blue column in Figure 2.11). In good alignment with this paradigm, this pillar is also responsible for data persistence and potentially distributed transaction management services across the various components of the autonomous digital manufacturing system.

Finally, the last part of the AUTOWARE Reference Architecture focuses on the actual **modeling, programming and configuration** of the different technical components inside the different layers (green column in Figure 2.11). On each layer, different tools or services are applied and

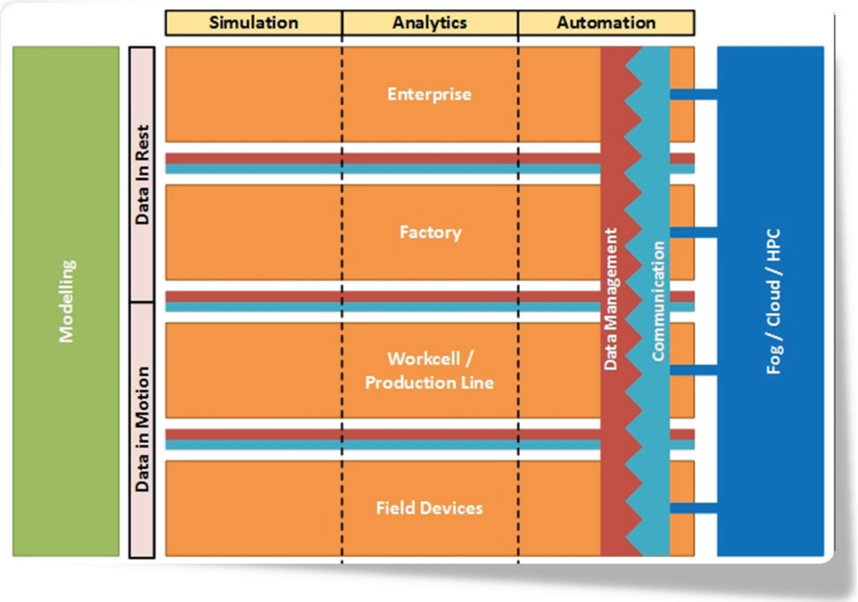


Figure 2.11 AUTOWARE Reference Architecture.

for all of them, different modeling approaches are available. The goal of these modeling approaches is to ease the end user/system developer/system integration developing the tools or technologies for the different levels. Additionally, it could be possible to have modeling 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 reference architecture also represents the two **data domains** that the architecture anticipates, namely the data in motion and data and rest domains. These layers are also matched in the architecture with the **type of services** automation, analysis and learning/simulation that are also pillars of the RA. The model also represents the layers of the RA where such services could be executed with the support of the fog/cloud computing and persistence services (blue pillar in Figure 2.11).

2.3.1.2 Pillar 2: AUTOWARE digital abilities for automatic awareness in the autonomous digital shopfloor

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. In fact, as discussed in [37] and shown in Figure 2.12, openness and interoperability need to be facilitated across all of those in a harmonized manner to ensure future digital shopfloor extendibility as industry gradually adopts digital abilities and services to build their competitive advantage.

For this purpose, the AUTOWARE framework provides three main components. These AUTOWARE components (technologies, usability services and V&V services) provide a collection of enablers that facilitates the different users of the AUTOWARE framework to interact with the system on different levels. Apart from the enablers developed in the AUTOWARE project, there have been several international projects to promote the creation of new open source enablers for such an architecture. The most interesting ones have come from FIWARE Smart Industry, I4MS and IDS communities and have been integrated into the AUTOWARE framework. Within AUTOWARE, there are three different enablers: technology, usability and verification and validation (V&V), which are crucial to ensure that a particular digital ability (in the specific case of AUTOWARE, automatic awareness) can be effectively and efficiently modeled, programmed, configured, deployed and operated in a digital shopfloor.

On the one hand, within the AUTOWARE framework, there is a collection of technology enablers, which can be identified as the technical tools, methods and components developed or provided within the AUTOWARE framework. Examples of technology enablers within the AUTOWARE project are robotic systems, smart machines, cloudified control systems, fog nodes, secure cloud- and fog-based planning systems as solutions to exploit cloud

Figure 2.12 AUTOWARE harmonized automatic awareness open technologies.

and fog technologies and smart machines as a common system. All these conform to a set of **automatic awareness integrated technologies,** which, as shown in Figure 2.12, adopt i-ROS-ready reconfigurable robotic cell and collaborative robotic bi-manipulation technology, smart product memory technology, OpenFog edge computing and virtualization technology, 5G-ready distributed data processing and reliable wireless mobile networking technologies, OPC-UA compliant Time Sensitive Networking (TSN) technology, Deep object recognition technology and ETSI CIM-ready FIWARE Context Brokering technology.

On the other hand, the AUTOWARE digital ability framework additionally provides **automatic awareness usability services** intended for a more cost-effective, fast and usable modeling, programming and configuration of integrated solutions based on the AUTOWARE enabling automatic digital shopfloor awareness technologies. This includes, for instance, augmented virtuality services, CPPS-trusted auto-configuration services or robot programming by training services.

Through its digital abilities, AUTOWARE facilitates the means for the deployment of completely open digital shopfloor automation solutions for fast data connection across factory systems (from shop floor to office floor) and across value chains (in cooperation with component and machine OEM smart services and knowledge). The AUTOWARE added value is not only to deliver a layered model for the four layers of the digital business ecosystem discussed in Section 2.2 for the digital shopfloor (smart space, smart product, smart data and smart service), but more importantly to provide an open and flexible approach with suitable interfaces to commercial platforms that allows the implementation of collective and collaborative services based on trusted information spaces and extensive exploitation of digital twin capabilities and machine models and operational footprints.

The third element in the AUTOWARE digital ability is the provision of **validation and verification (V&V) services** for digital shopfloor solutions, i.e. CPPS. Although CPPS are defined to work correctly under several environmental conditions, in practice, it is enough if it works properly under specific conditions. In this context, certification processes help to guarantee correct operation under certain conditions, making the engineering process easier, cheaper and shorter for SMEs that want to include CPPS in their businesses. In addition, certification can increase the credibility and visibility of CPPS as it guarantees its correct operation under specific standards. If a CPPS is certified to follow some international or European standards or regulation, then it is not necessary to be certified in each country, so the integration complexity, cost and duration are highly reduced.

2.3.1.3 Pillar 3: AUTOWARE business value

On the one hand, around the world, traditional manufacturing industry is in the throes of a digital transformation that is accelerated by exponentially growing technologies (e.g. intelligent robots, autonomous drones, sensors, 3D printing). Indeed, there are several European initiatives (e.g. I4MS initiative) and interesting platforms that are developing digitalization solutions for manufacturing companies in different areas: robotic solutions, cloudification manufacturing initiatives, CPS platforms implementation, reconfigurable cells, etc. However, all these initiatives were developed in isolation and they act as isolated components.

On the other hand, manufacturing SMEs need to digitalize their processes in order to increase their competitiveness through the adoption of ICT technologies. However, the global competition and the individualized products and solutions that currently exist make it difficult for manufacturing SMEs to access all this potential.

For this reason, AUTOWARE defined a new Autonomous Factory Ecosystem around their AUTOWARE Business Value Pillar allowing manufacturing SMEs to gain a clear competitive advantage for the implementation of their manufacturing processes. This pillar provides access to a set of new generation of tools and decision support toolboxes capable of supporting CPPS and digital services cloudification, robotics systems, reconfigurable cells, thanks to a faster and holistic management of several initiatives and tools into an open ecosystem providing a more seamless transfer of information across physical and digital worlds.

Therefore, AUTOWARE provides an ***open CPPS solution hub ecosystem*** that gathers all resources together, thus enabling SMEs to access all the different components in order to develop digital automation cognitive solutions for their manufacturing processes in a controlled manner and quantifiable business impact.

AUTOWARE reduces the complexity of the access to the different isolated tools significantly and speeds up the process by which multi-sided partners can meet and work together. Indeed, AUTOWARE connects several initiatives for strengthening the European SME offer on cognitive autonomous products and leveraging cognitive autonomous production processes and equipment towards manufacturing SMEs. Thus, AUTOWARE leverages the development of open CPPS ecosystem and joins several stakeholders' needs:

- **End Users (SME):** The main target group of the AUTOWARE project is SMEs (small and medium-sized enterprises) that are looking to change their production according to Industry 4.0, CPPS and Internet of Things (IoT). These SMEs are considered the end user of the AUTOWARE developments, whereby they do not have to use all the developed technologies, but can only be interested in a subset of the technologies.
- **Software Developers:** As the AUTOWARE platform is an open platform, software developers can create new applications that can run on the AUTOWARE system. To support these users in their work, the system provides high usability and intuitiveness level, so that software developers can program the system to their wishes.
- **Technology Developers:** The individual technical enablers can be used as a single technology, but being an open technology, they can also be integrated into different technologies by technology developers. The technology must be open and once again be intuitive to re-use in different applications. Technology developers can then easily use the AUTOWARE technology to develop new technologies for their applications and create new markets for the AUTOWARE results.
- **Integrator:** The integrator is responsible for the integration of the technologies into the whole manufacturing chain. To target this user group, the technologies must support open interfaces, so the system can intuitively be integrated into the existing chain. The advantage of the open interfaces is that the integrator is not bound to a certain brand or vendor.
- **Policy Makers:** Policy makers can make or break a technology. To increase the acceptance rate, the exploitation and dissemination of the technology must be at a professional level, and additionally, the technology must be validated, supporting the right standards and targeting the right problems currently present on the market. Policy makers can push technologies further into the market and act as large catalyst for new technologies.
- **HW Developers:** For hardware developers, it is important to know what kind of hardware is required for the usage of the different technologies. In ideal case, all kind of legacy hardware is capable of interacting with new hardware, but unfortunately, this is not always the case.
- **Automation Equipment Providers:** The technologies developed within the AUTOWARE project can be of interest to other automation equipment providers, e.g. robot providers, industrial controller providers, sensor providers, etc.

2.3.2 AUTOWARE Software-Defined Autonomous Service Platform

Once the complete AUTOWARE framework overview has been presented, this section will focus on the detailed presentation of the software-defined service platform for autonomous manufacturing services. This section extends the main technological blocks underlying the AUTOWARE reference architecture.

Due to the recent development of numerous technical enablers (e.g. IoT, cloud, edge, HPC etc.), it is possible to take a service-based approach for many components of production information systems (IS). When using a service-based approach, instead of developing, deploying and running our own implementations for all production IS tasks, an external service provider can be considered and the end user can rent access to the offered services, reducing the cost and knowledge needed.

AUTOWARE focuses on a service-based approach denoted as software-defined autonomous service platform (in the following, also abbreviated as "service platform") based on open protocols and implementing all the functionalities (physical, control, supervision, MES, ERP) as services. As a result, the components can be reused, the solution can be reconfigured and the technological advanced can be easily followed.

Figure 2.13 includes the reference architecture of the AUTOWARE service platform showing also how all the functionalities are positioned in the overall scheme of production IS. There are different functionalities (and therefore, services) on the different layers depending on the scope, but all of them are interconnected.

2.3.2.1 Cloud & Fog computing services enablers and context management

AUTOWARE considers several cloud services enablers for an easier implementation of the different services or functionalities. Context management and service function virtualization is a critical element to be supported in the delivery of automatic awareness abilities in a digital shopfloor. The use of these open source enablers permits the easier exchange of information and interoperability between different components and services, something really useful for future use cases.

AUTOWARE RA considers FIWARE for Smart Industry technology as the basis to meet AUTOWARE needs of context building management for digital automation information systems with extended support to robotic

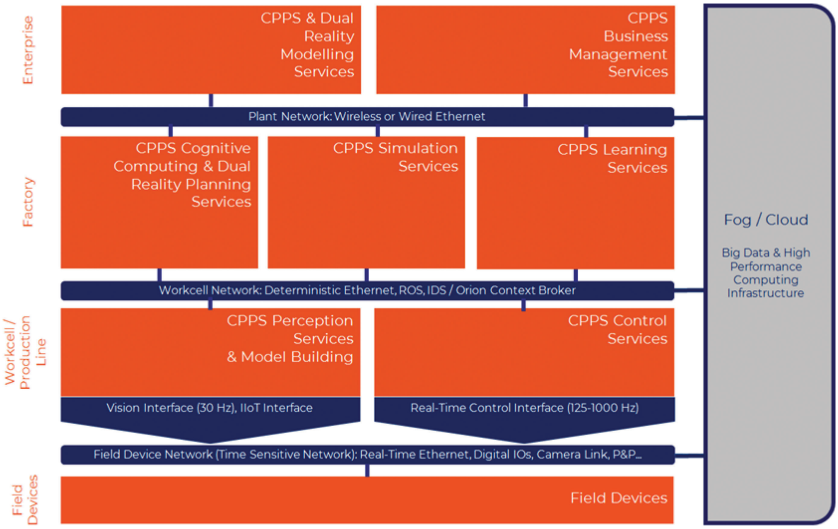


Figure 2.13 AUTOWARE Software-Defined Autonomous Service Platform.

systems. Additionally, AUTOWARE considers OpenFog as the framework for operation of virtualized service functions.

The main features introduced in the cloud & edge computing pillar, beyond those inherent to OpenFog specifications, are the support for automation context information management, processing and visualization. Such functionalities are being provided through edge and cloud support to two main FIWARE components:

- **Backend Device Management – IDAS:** For the translation from IoT-specific protocols to the NGSI context information protocol considered by FIWARE enablers.
- **Orion Context Broker:** It produces, gathers, publishes and consumes context information. This is the main context information communication system throughout the AUTOWARE architecture. It facilitates the exchange of context information between Context Information Producers and Consumers through a Publish/Subscribe methodology (see Figure 2.14). This permits a high decentralized and large-scale context information management and high interoperability between the different components due to the use of a common NGSI protocol. The IDS architecture and connectors permit the use of such a powerful communication tool, making the use of IDS an extension of the AUTOWARE RA through FIWARE support to IDS reference architecture, as described in Section 2.2.

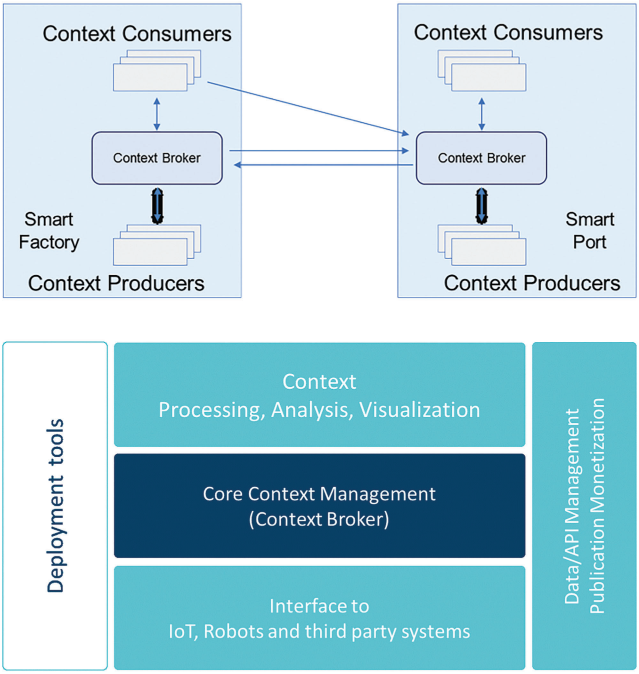


Figure 2.14 Context Broker basic workflow & FIWARE Context Broker Architecture.

- **Backend Device Management – IDAS:** For the translation from IoT-specific protocols to the NGSI context information protocol considered by FIWARE enablers.
- **Cosmos:** For an easier Big Data analysis over context integrated information with most popular Big Data platforms and cloud storage.

AUTOWARE extends a cloud-based architecture to a more flexible and efficient one based on fog computing, which is defined by the OpenFog Consortium as follows: "A horizontal, system-level architecture that distributes computing, storage, control and networking functions closer to the users along a cloud-to-thing continuum". Adding an intermediate layer for data aggregation and computing capabilities at the edge of the network resolves the bottlenecks and disadvantages in complex industrial scenarios: (1) data bottlenecks that occur on the interface between IT and cloud infrastructure; (2) disability to guarantee pre-defined latencies in the communication; (3) sensor data are sent unfiltered to the cloud and (4) limited intelligence on the machine level.

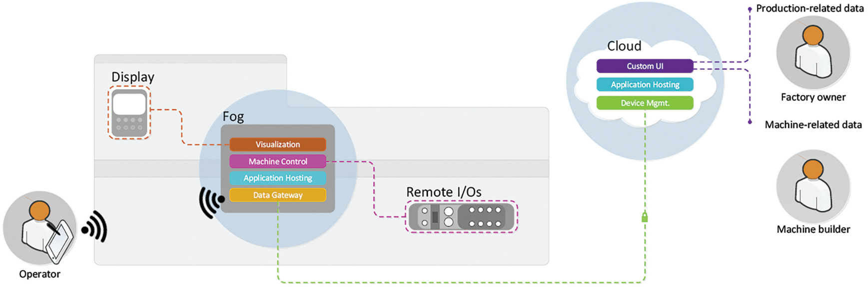


Figure 2.15 Embedding of the fog node into the AUTOWARE software-defined platform as part of the cloud/fog computing & persistence service support.

These drawbacks can be repealed using fog nodes. In addition, strict requirements on timing or even real-time constrains can only be achieved by avoiding long transmission of the data. Thus, the fog computing approach is inherently avoiding the latencies.

Figure 2.15 shows the embedding of the fog node into the AUTOWARE framework. The architecture supports the following aspects:

- **Machine Control Capabilities:** AUTOWARE platform can control the different machines (e.g. robots, machines, etc.) within the plant or the manufacturing cell. It can connect to remote I/Os via an integrated PLC.
- **Device Management Capabilities:** It allows users to perform management of multiple machines in a distributed manner. The device manager is situated in the main office, whereas the devices are distributed over the factories, possible worldwide. The communication between the device manager and the different devices must be implemented over a secure and safe communication channel.
- **Data Gateway:** It enables the communication between other fog nodes, between the fog node and the cloud and with a remote operator.
- **Visualization Capabilities:** The AUTOWARE open platform provides standard interfaces (wired and wireless) to guarantee connectivity via user interfaces to access data via reports, dashboards, etc.
- **Application Hosting Functionality:** It can be located as well in the fog as in the cloud.

The pillars of this architecture, which are common themes of the OpenFog reference architecture, include security, scalability, openness, autonomy, RAS (reliability, availability and serviceability), agility, hierarchy and programmability.

2.3.3 AUTOWARE Framework and RAMI 4.0 Compliance

The overall AUTOWARE Framework and Reference Architecture is also related to the RAMI 4.0, as this is the identified reference architecture for Industry 4.0. The goal of the AUTOWARE project was to keep the developments related to the topics of Industry 4.0 and keep the Reference Architecture and Framework related to the RAMI 4.0 as well as to extend their scope to address the smart service welt data-centric service operations and future autonomous service demands.

To establish this link, the consortium mapped the different concepts and components of the AUTOWARE Framework to the RAMI 4.0 model. In Figure 2.16, the result of such mapping is provided. 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 RAMI 4.0 architecture. On the hierarchical axis, the mapping is provided with the layers of the reference architecture, whereas the lifecycle coverage for type and instance is addressed through the modeling, configuration, programming pillar and the cloud/fog computing and persistence service layers. As discussed in the previous subsection, the data-management services to support at the various layers simulation, learning and knowledge-cognitive capabilities are actually implementing those advanced Industry 4.0 functionalities based on the cloud and edge support. This strict mapping ensures that the AUTOWARE framework not only supports Industry 4.0 scenarios, but also that they can also bring forward more advanced data-driven autonomous operations.

2.4 Autoware Framework for Predictive Maintenance Platform Implementation

In the new Industry 4.0 paradigm, cognitive manufacturing is a fundamental pillar. It transforms manufacturing in three ways:

1. **Intelligent Assets and Equipment:** utilizing interconnected sensors, analytics, and cognitive capabilities to sense, communicate and self-diagnose any type of issues in order to optimize performance and efficiency and reduce unnecessary downtime.
2. **Cognitive Processes and Operations:** analyzing a huge variety of information from workflows, context, process and environment to quality controls, enhance operations and decision-making.

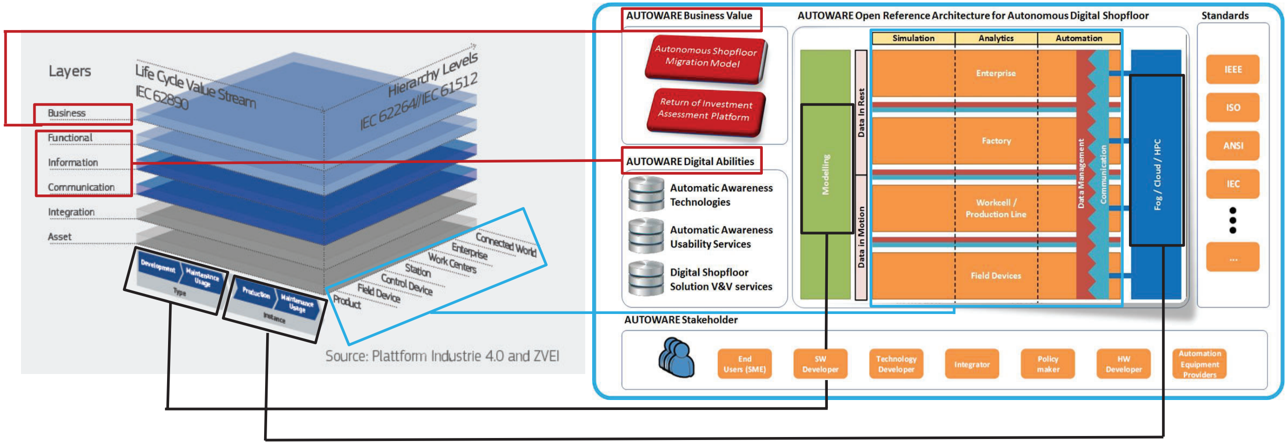


Figure 2.16 Mapping and coverage of RAMI 4.0 by the AUTOWARE framework.

3. **Smarter Resources and Optimization:** combining various forms of data from different individuals, locations, usage and expertise with cognitive insight to optimize and enhance resources such as labor, workforce, and energy, improving in such a way the efficiency of the process.

Predictive maintenance is the prediction of a tool life cycle or other maintenance issues by the use of the information gathered by different sensors and analyzing that information by different types of analytical processes and means. Therefore, predictive maintenance is a clear example of cognitive manufacturing and the focus of the Z-Bre4k project, which employs AUTOWARE Digital Shopfloor reference architecture as its framework for process operation. This section discusses how the AUTOWARE framework can be customized and additional digital abilities and services can be incorporated to implement advanced Industry 4.0 manufacturing processes.

2.4.1 Z-BRE4K: Zero-Unexpected-Breakdowns and Increased Operating Life of Factories

The H2020 project **Z-BRE4K,** https://www.z-bre4k.eu/, looks to implement predictive maintenance strategies to avoid unexpected breakdowns, thus increasing the uptime and overall efficiency of manufacturing scenarios. To this extent, several hardware and software solutions will be implemented in three industrial demonstrators, adapting to the particular needs of each one.

In particular, Z-BRE4K delivers a solution composed of eight scalable strategies at component, machine and system level targeting:

1. **Z-PREDICT.** The prediction occurrence of failure.
2. **Z-DIAGNOSE.** The early detection of current or emerging failure.
3. **Z-PREVENT.** The prevention of failure occurrence, building up or even propagation in the production system.
4. **Z-ESTIMATE.** The estimation of the remaining useful life of assets.
5. **Z-MANAGE.** The management of the strategies through event modeling, KPI monitoring and real-time decision support.
6. **Z-REMEDIATE.** The replacement, reconfiguration, re-use, retirement and recycling of components/assets ().
7. **Z-SYNCHRONISE.** Synchronizing remedy actions, production planning and logistics.
8. **Z-SAFETY.** Preserving the safety, health and comfort of the workers.

The Z-BRE4K solution implementation is expected to have a significant impact, namely (1) increase of the in-service efficiency by 24%, (2) reduced accidents, (3) increased verification according to objectives and (4) 400 new jobs created and over €42M ROI for the consortium.

In order to implement these strategies and reach these impact results, data coming from machine components, industrial lines and shop floors will be fed in the Z-BRE4K platform, which is featured by a communication middleware operative system, a semantic framework module, a dedicated condition monitoring module, a cognitive embedded module, a machine simulator to develop digital twins, an advanced decision support system (DSS), an FMECA module and a predictive maintenance module, together with a cutting-edge vision H/S solution for manufacturing applications associated to advanced HMI.

The General Architecture must be able to support all the components developed under the Z-BRE4K project, which lead to fulfilling the predictive maintenance strategies, being able to keep the information flow constant and well distributed between all the components. At the same time, it must permit an easy implementation in each use case scenario, leading the way towards each particular architecture for each use case and, in the future, different scenarios from other industrial systems. This means that the General Architecture must be highly flexible and easily adapted to new use cases, promoting the predictive maintenance towards its integration in SMEs.

Due to the high flexibility, the architecture requires the main communication middleware operative system to support a high number of different types of data coming from different types of sensors and control software. At the same time, due to the high number of different components, it must also support the need of a continuous communication between all of them, and the interoperability must reach top-notch levels.

2.4.2 Z-Bre4k Architecture Methodology

The Z-Bre4k architecture is designed and developed on the foundations of the AUTOWARE reference architecture and building blocks enabling the convergence of information technology (IT), operational technology (OT), engineering technology (ET) and the leveraging of interoperability of industrial data spaces (IDS), for the support of a factory ecosystem. The objective is to develop a highly adaptive real-time machine (network of components) simulation platform that wraps around the physical equipment for the purpose of predicting uptimes and breakdowns, thus creating intuitive maintenance control and management systems.

The AUTOWARE framework has been selected as open OS for the Z-Bre4k framework for cognitive CPPS service development and strategy implementation. The AUTOWARE open framework is particularly well suited for integration of Z-Bre4k strategies over legacy machines and IT systems with minimum interference and that even SMEs are able to easily integrate advanced predictive maintenance strategies in the very same IT framework used to deal with production optimization or zero defect manufacturing processes.

2.4.3 Z-BRE4K General Architecture Structure

The Z-BRE4K General Architecture will be a combination of the AUTOWARE RA from Figure 2.17 with a vertical separation definition included in the Digital Shopfloor Alliance Reference Architecture and the integration of the IDS General Architecture from Figure 2.6 by using FIWARE Generic Enablers as IDS core components. The main result is shown in Figure 2.18, where the Z-BRE4K Automation, Z-BRE4K Analytics and Z-BRE4K Simulation are presented following the Far-Edge Architecture principles envisioned in the DSA Reference Architecture.

2.4.4 Z-BRE4K General Architecture Information Workflow

Since the predictive maintenance Z-BRE4K is aiming at has been envisioned as a service, the General Architecture will adapt AUTOWARE Service Platform Reference Architecture to the Z-BRE4K structure as shown in Figure 2.19. Figure 2.19 shows the different services divided into the AUTOWARE different blocks and layers, all of them interconnecting through suitable data-buses constructed across information contexts. The main work cell and plant network will be done through the IDS Connector and FIWARE Orion Context Broker principally, but not necessary, so other communication methodologies are also supported, to be able to adapt the architecture to any future use case implementation. The Fog/Cloud interconnection is always available through the fog nodes described in Section 2.3. This will permit the use of storage, HPC and Deep Learning FIWARE Generic Enablers for better computing and calculating processes.

The information captured by the field devices (sensors, machines, etc.) is sent through the Time Sensitive Network (TSN) located in the end users facilities to the Control Services and Perception Services & Model Building components in Real Time.

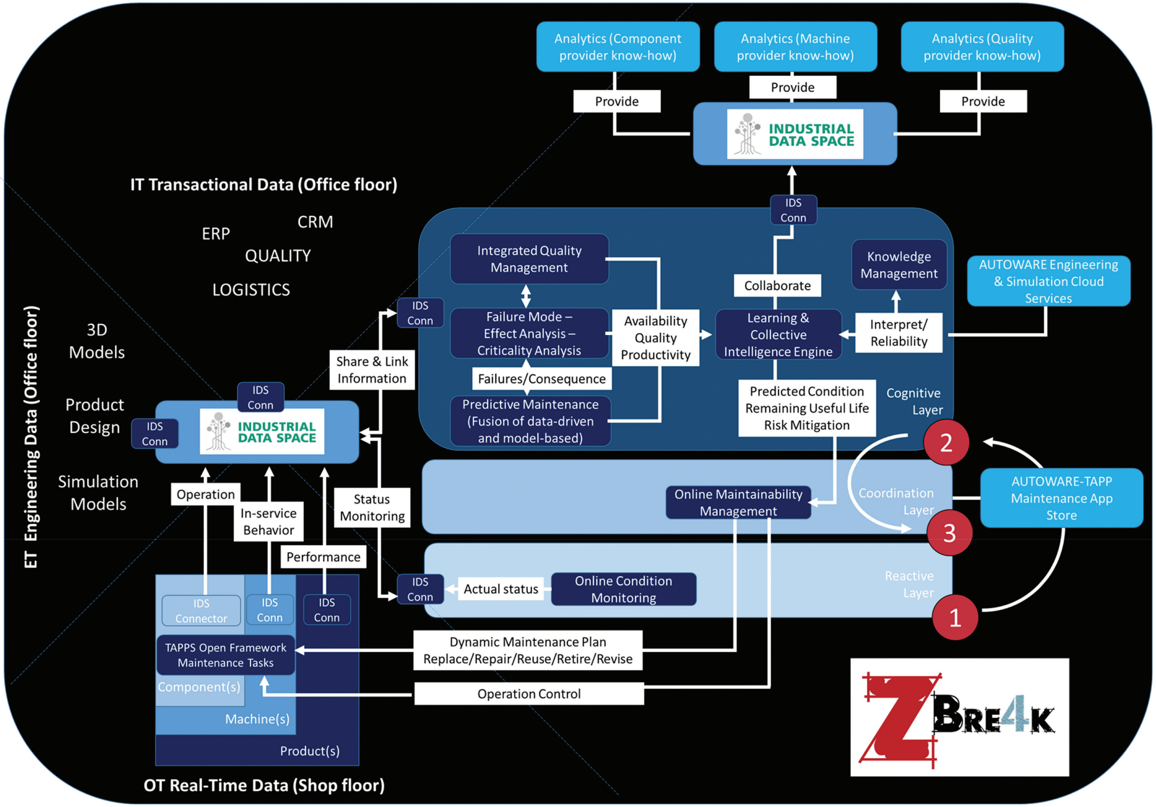


Figure 2.17 Z-Bre4k zero break down workflow & strategies.

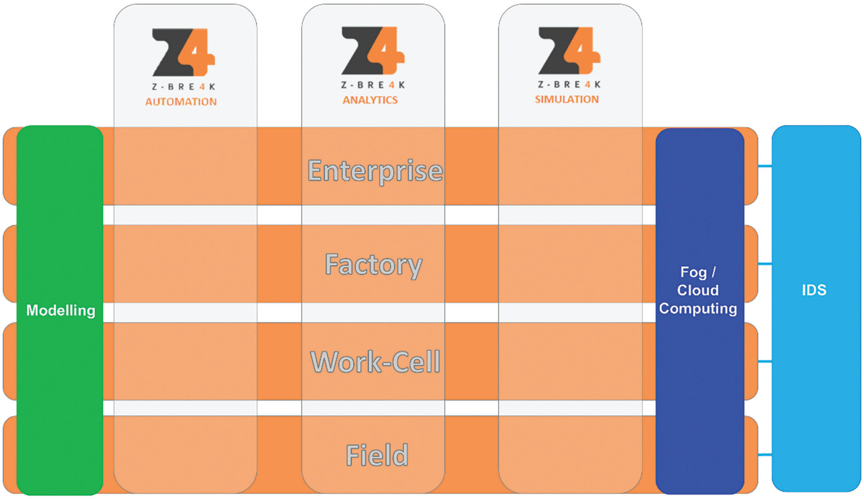


Figure 2.18 Z-BRE4K General Architecture Structure.

The next step is, through the IDS Connectors connected to the Workcell layer components, the data (normally preprocessed by the Workcell components) is sent to (published) the Orion Context Broker. The different components from the factory layer that are subscribed to each data set will receive it for their analysis and processing. The factory services components, which are divided into Learning, Simulating and Cognitive Computing Services, may require processed data from another factory layer service. The outputs from factory layer components that are required as inputs by other factory layer components will be published once again in the Orion Context Broker in the Workcell. The factory layer components that need those outputs as inputs will be subscribed to that data and will receive it. That is how the communication and information flow will be carried out through the different hierarchical levels.

The Learning, Simulating and Cognitive Computing Services will end up creating valuable information as outputs that will be published in the Plant Network's Orion Context Broker. The different Business Management Services will recollect the information required as inputs for their processing and will elaborate reports, actions, alerts, decision support actions, etc. Dual Reality and Modelling Services will also gather information and will process it to give extra support information for business management decision making and user interfaces by publishing it back in the Plant's Orion Context Broker.

The Business Management Services will be able to send information to the Control Services for user interface issues or optimization actions if necessary.

2.4.5 Z-BRE4K General Architecture Component Distribution

Following the Z-BRE4K General Architecture Service Block division from Figure 2.19 and the component for predictive maintenance, the final Z-BRE4K General OS will be as shown in Figure 2.20, where the specific technologies, services and tools to support the required predictive maintenance digital ability are actually illustrated.

The strength of the AUTOWARE RA to serve the Z-Bre4k predictive maintenance lies that once the data has been published in the Orion Context Broker in any of the scenarios considered, they can consider similar information workflows (see Figure 2.21).

The information in the particular use cases, presented in Figure 2.21, for the predictive maintenance will go as follows: (1) The information is gathered by the field devices, pre-processed if necessary by the control and model building services and published in the Orion Context Broker through each use cases' IDS Connector. (2) The data is collected by subscription by the C-03 Semantic Framework, where it is given the semantic structure and stored in a DB (fog/cloud computing most probable). Then, it is published again in the Context Broker. (3) Data is used to feed the C-08 Machine Simulators. (4) Prediction algorithms (from the C-07 Predictive Maintenance) are run through the C-08 outputs. (5) The C-04 DSS gathers information from the C-07 Predictive Maintenance and analyzes it, giving as an output the failure mode. (6) The C-05 FMECA gets the failure mode from the DSS through the context broker. (7) FMECA returns criticality, risk, redundancy, etc. for the specific failure mode to the DSS through the Context Broker. (8) The DSS, based on the Rules set, provides Recommendations to the Technicians through a common User Interface and control services. (9) The Technicians can use the C-06 VRfx for the better understanding of the information. (10) The Technicians take Actions on the assets through the control services based on the recommendations given. (11) The Technicians provide Feedback on the accuracy of the Recommendations given by the DSS. (12) The DSS improves its Rules and Recommendations based on the Feedback received.

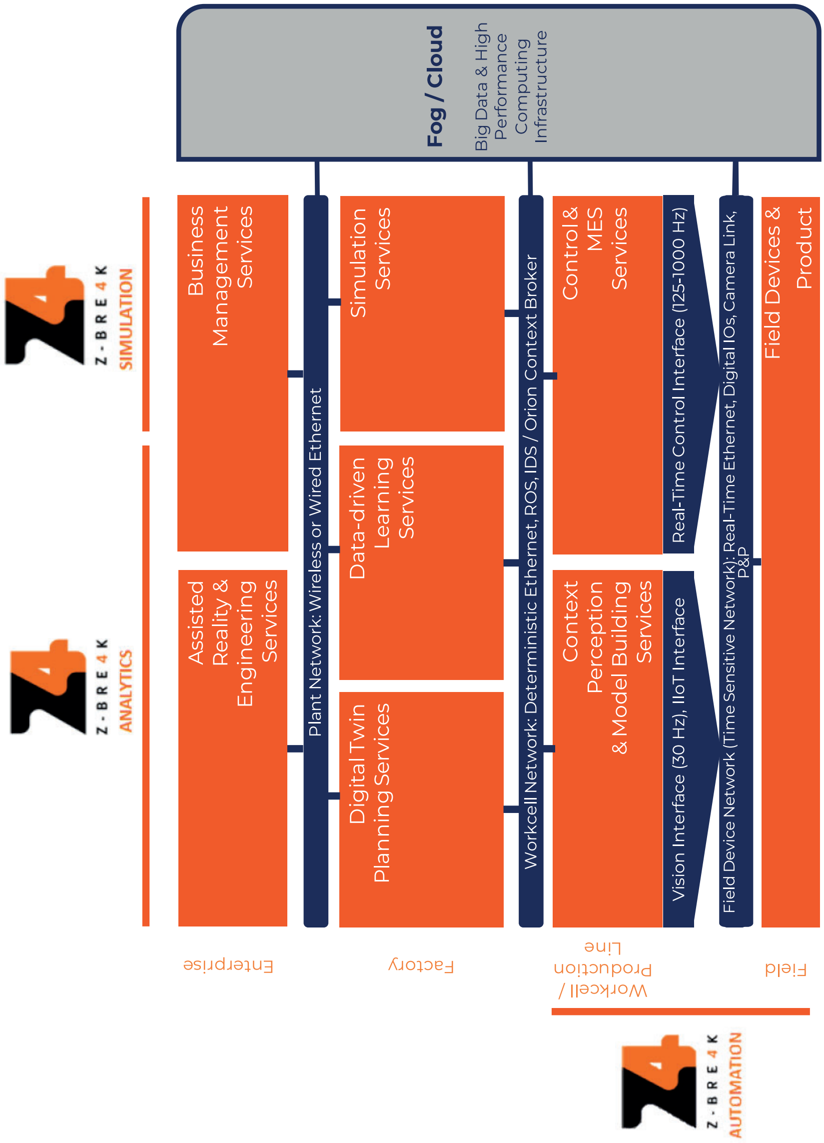


Figure 2.19 Z-BRE4K General Architecture Connections.

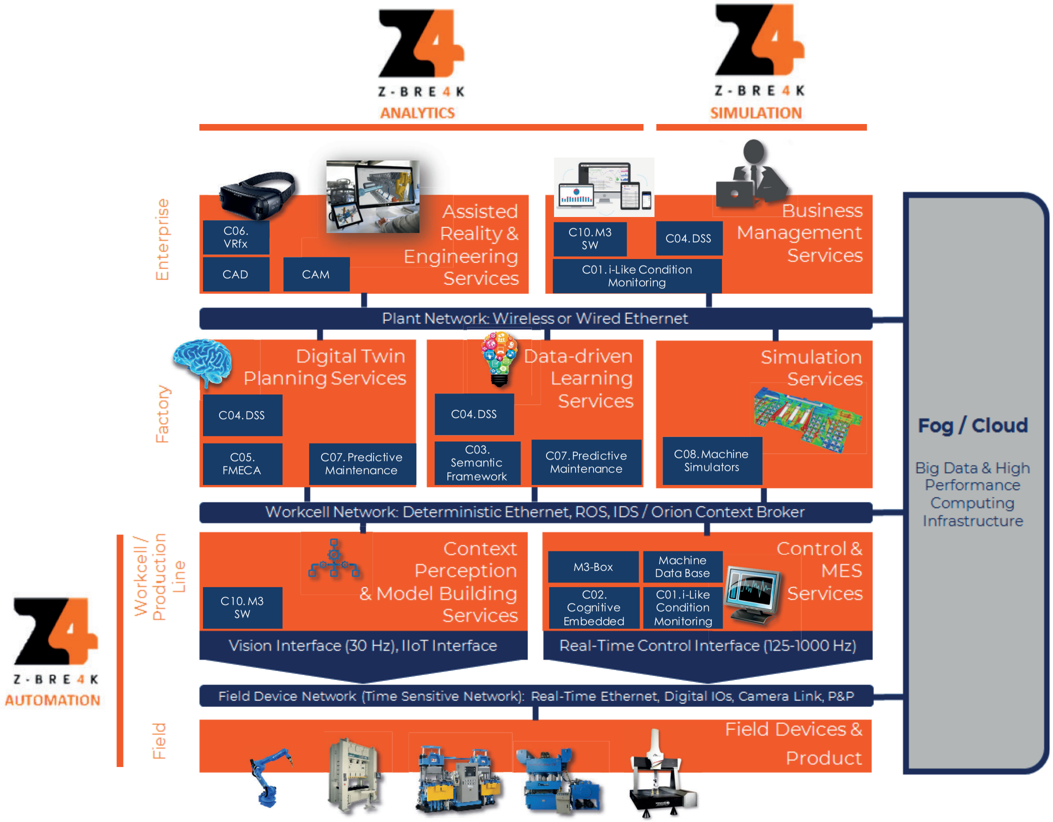


Figure 2.20 Z-BRE4K General OS.

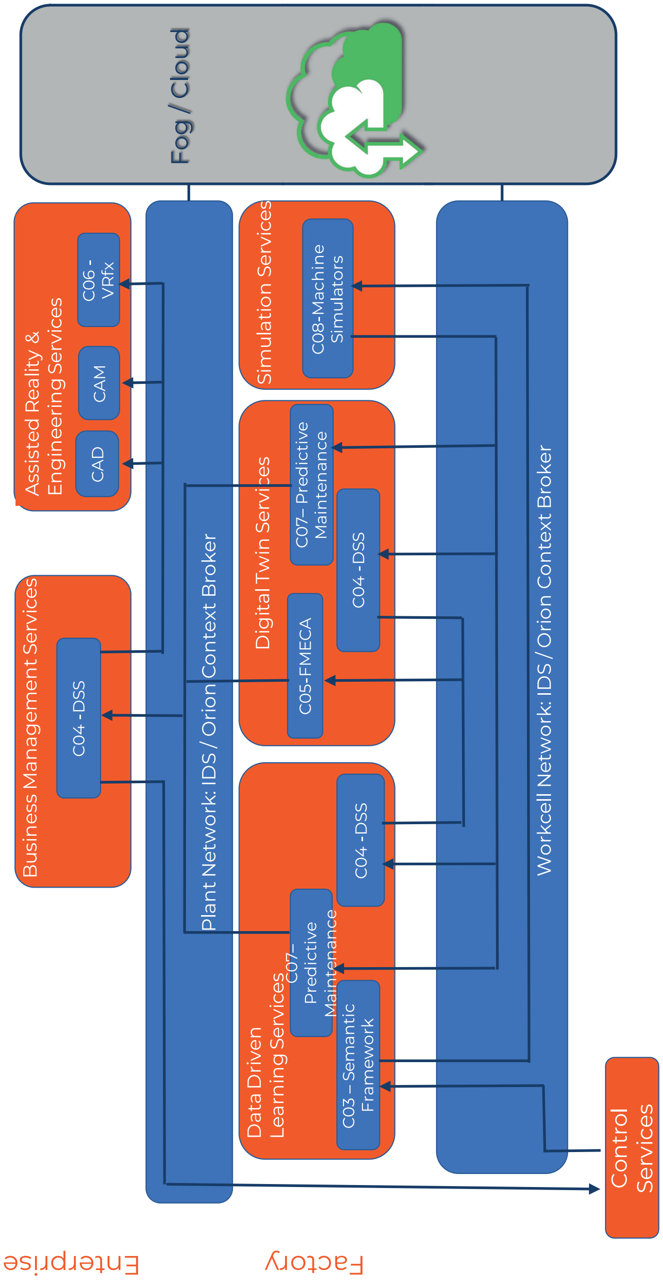


Figure 2.21 Use Cases Particular Information Workflow.

2.5 Conclusions

In this chapter, we have discussed the needs for development of a digital automation framework for the support of autonomous digital manufacturing workflows. We have also presented how various open platforms (i-ROS, OpenFog, IDS, FIWARE, BeinCPPS, MIDIH, ReconCell, Arrowhead, OPC-UA/TSN, 5G) can be harmonized through open APIs to deliver a software-defined digital shopfloor platform enabling a more cost-effective, control and extendable deployment of digital abilities in the shopfloor in close alignment with business strategies and investments available. This chapter has also presented how AUTOWARE is also bringing forward the technology enablers (connectivity, data distribution, edge extension of automation and control equipment for app-ized smart open control hardware (open trusted platforms) operation, deep object recognition), usability services (augmented virutality, CPPS autoconfiguration, robotic programming by training) and verification and validation framework (safety & standard compliant) to the deployment and operation of automatic awareness digital abilities, as a first step in cognitive autonomous digital shopfloor evolution. We have presented how open platforms for fog/edge computing can be combined with cloudified control solutions and open platforms for collaborative robotics, modular manufacturing and reconfigurable cells for delivery of advanced manufacturing capabilities in SMEs. Moreover, we have also presented how the AUTOWARE framework is flexible enough to be adopted and enriched with additional digital capability services to support advanced and collaborative predictive maintenance decision workflows. AUTOWARE is adapted for operation of predictive maintenance strategies in high diversity of machinery (robotic systems, inline quality control equipment, injection molding, stamping press, high-performance smart tooling/dies and fixtures), very challenging and sometimes critical manufacturing processes (highly automated packaging industry, multi-stage zero-defect adaptive manufacturing of structural lightweight component for automotive industry, short-batch mass customized production process for consumer electronics and health sector) and key economic European sectors with the strongest SME presence (automotive, food and beverage, consumer electronics).

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