Aligning Emerging Technologies onto I4.0 principles: Towards a Novel Architecture for Zero-defect Manufacturing

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***Abstract*—Successful transition of manufacturing enterprises to Industrie 4.0 (I4.0) is highly dependent on the adoption and integration of new technologies, toward making manufacturing processes even smarter and less wasteful. In this paper, we present the OPTIMAI project architecture for zero-defect manufacturing (ZDM), applicable to a variety of industrial verticals. To realise a standards-based approach, we elaborate on the parallels drawn between the presented architectural framework and two leading reference architectures underpinning the "factories of the future" vision (RAMI 4.0 and IIRA). System specifications for ZDM are hence defined according to the perspectives of the two architectural models, allowing us to examine cutting-edge technologies for ZDM (such as blockchain, AI and AR) as both an I4.0 solution, as well as an Industrial Internet of Things system.**

***Index Terms*—Industry 4.0, RAMI 4.0, IIRA, Reference Architectural Models, Zero defect manufacturing**

I. Introduction

Industry 4.0 (I4.0) represents a huge leap in terms of how manufacturing systems have been viewed, primarily because information and communication technologies (ICT) have impacted almost every aspect of the manufacturing ecosystem [1]. At the heart of I4.0 lies the Cyber-Physical Production System (CPPS), a heterarchical architecture of cooperative elements [2], that significantly advances previous, hierarchical models for Dedicated Manufacturing Lines (DML) and Flexible Manufacturing Systems (FMS). Over the past decade, CPPS, in conjunction with the rise of Internet of Things (IoT) and Cloud computing, has significantly propelled the envisioned end-to-end communication paradigm that underpins the need for all production-relevant assets to intercommunicate within the 4th Industrial revolution concept. Despite its clear vision however, I4.0 remains a challenging concept for manufacturing industries to realize [3]. As such, several Reference Architectures (RA) and models have been conceptualised to support research and implementation of future I4.0 technologies, most notably, the Reference Architectural Model Industrie (RAMI) 4.0 [4] and the Industrial Internet Reference Architecture (IIRA) [5]. However, their practical implementation still poses a challenging task for manufacturing companies and small/medium-sized enterprises (SMEs) [6]. Moreover, rapid evolution of technology will continue to break new ground in manufacturing ecosystems, increasing such complexity even further.

As a prime objective of I4.0, zero-defect manufacturing (ZDM) [7] represents a crossroads where innovative technologies, like Artificial Intelligence (AI), Computer Vision, Augmented Reality (AR) and Internet of Things (IoT) meet, to realize smarter quality control and eliminate manufacturing of defective products [8]. While ZDM has drawn attention from the scientific community, its practical application in an actual smart factory shop floor remains a challenging topic. To accelerate such a deployment, an effective alignment to the guiding principles of models such as RAMI 4.0 and the IIRA is warranted. Hence, in this paper, we aim at elaborating on CPPS system design in alignment to I4.0 RA models by presenting an integrated solution targeted at the ZDM concept. We will present a high-level overview of a generic ICT ecosystem for achieving optimal production conditions in a wide range of industrial settings, via a combination of up-and-coming technologies, key to the I4.0 vision, such as multi-sensory data collection and AI analysis [9]; AR [10]; edge computing [11], blockchain [12]; and digital twins (DT) [13]. We proceed to identify guiding RA principles, platforms and technologies that support the overall vision and objectives of an innovative ZDM ecosystem, and contextualise them to highlight which of their features and characteristics best underpin the envisioned concept. A customised, functional architecture is derived, facilitating and maintaining alignment to the specified reference models, as such substantiating an I4.0-compliant approach.

The paper is organised as follows: Section II briefly lists several key I4.0 RA models and provides an overview of their main characteristics and features. Section III presents our own high-level architectural solution for ZDM, capitalising on novel concepts and emerging technologies, as listed before. Section IV specifies how we contextualise this architecture

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to fit prominent I4.0 RA models and principles, highlighting aspects in which the proposed architecture enforces compatibility with the selected I4.0 frameworks. We eventually conclude the paper with a short discussion in Section V.

II. Reference Architectures for Industry 4.0

Over the past decade, several multi-national consortia, as well as independent researchers, identified the need to organise I4.0 guidelines and principles for the design of CPPSs. Their efforts have culminated in several RA models, intended for individual organisations and enterprises to derive and specify concrete ICT solution architectures for addressing a variety of topics in the smart manufacturing environment. In this Section we list the most prominent such models, endorsed by international initiatives, as well as by the academic community.

A. Reference Architectural Model Industry 4.0

RAMI 4.0 is one the oldest (2015) attempts at building a universal understanding of I4.0, with the intent to propose standards, define a common language, and indicate rules for describing requirements and structures for the design of smart factories in different use cases [14]. RAMI 4.0 is a three-dimensional model, comprised of the following axes:

The **hierarchy levels** of a connected manufacturing system axis, represents the layers of automation that are found in a typical factory environment. This dimension of RAMI 4.0 is composed of the following layers (from top to bottom) [15]: (i) **'Product'**, which refers to smart manufactured products communicating with the manufacturing system [16]; (ii) **'Field device'**, which refers to devices that sense and actuate on factory machinery; (iii) **'Control device'**, which includes solutions for optimal production parameters inference, and control of the 'Field device' actuators; (iv) **'Station'**, which relates to Supervisory Control and Data Acquisition (SCADA) [15], taking place in a single integration point providing some kind of User, or Human-Machine Interface (UI/HMI); (v) **'Work Centers'**, which incorporates Manufacturing Execution Systems (MES) capabilities [15], i.e., dealing with acquisition, persistence, analysis and transmission of data, as well as monitoring of the entire manufacturing process; (vi) **'Enterprise'**, which refers to Enterprise Resource Planning (ERP) [15], i.e., management and decision-making based on data evidence and applicable to the entire factory; and (vii) **'Connected World'**, which encapsulates all services provisioned by the factory to the outside world through the Internet [17].

The **life cycle and value stream** axis refers to the lifespan of any element within the manufacturing environment (both obvious, e.g., a product or machine, as well as less obvious, e.g., documentation, etc.). Two distinct phases are defined in this axis, namely **'Type'** and **'Instance'**. The 'Type' Phase corresponds to pre-production, i.e., the initial specification taking place during *'Development'*, and all subsequent design iterations and/or updates occurring at the *'Maintenance Usage'* stage. This Phase is followed by the 'Instance' Phase, where the final design has moved into *'Production'*. *'Maintenance Usage'* at the 'Instance' Phase deals with customer service operations, referring to any individual instance of the object (e.g., maintenance or repairs).

Finally, the **layers** axis is used to describe the different perspectives (or I4.0 components [17]) present in a typical smart factory. From bottom to top, these are: (i) the **'Asset'** layer, i.e., physical resources in the factory, such as equipment, parts, etc.; (ii) the **'Integration'** layer, which defines communication means between Information and Operation Technologies (OT); (iii) the **'Communication'** layer, that further specifies communication protocols and channels that will be used for dispatch of data; (iv) the **'Information'** layer specifies how data will be kept in storage; (v) the **'Functional'** layer relates to the high-level processes for determining what kind of functions each asset should perform; and (vi) the **'Business'** layer includes governance and business operations.

RAMI 4.0 is both widely adopted and extensively researched, providing a reliable reference frame for the ZDM architecture elaborated in this paper. Through an examination of how typical ZDM inspection and production planning use cases relate to the Life Cycle & Value Stream axis, elicited technological functional blocks supporting the solutions' ecosystem can be mapped onto a layer-and-hierarchy RAMI 4.0 layer slice. As a result, our functional components can be aligned in a much more straightforward fashion to RAMI 4.0 Layers and Hierarchy principles, reducing complexity of the three-dimensional model to a 2D map. This exercise constitutes a key contribution of this work, and will be explored in more detail in Section IV.

B. Industrial Internet Reference Architecture

The IIRA [5] is a parallel, evolving initiative led by the Industry IoT Consortium (IIC), targeted at defining a framework for the development of Industrial Internet of Things (IIoT) solutions, systems and applications, that particularly address smart factory needs in various industrial domains. The IIRA hence avoids dictating a concrete implementation architecture (much like RAMI 4.0), instead organising IIoT use cases in four vertically aligned "Viewpoints". These Viewpoints describe principles, needs and requirements that a system should adhere to. The model dictates that top-level Viewpoints essentially guide requirements' elicitation occurring at the Viewpoint directly below. As a result, implementation is driven by decisions made from a business standpoint, and eventually, provides means for upper Viewpoints to validate their processes and/or take corrective action based on the feedback received from the Viewpoints below. The four Viewpoints comprising the core of the IIRA are organised as follows:

The **'Business'** Viewpoint resides at the top of the architectural stack, driving decisions related to business objectives (e.g., costs, return on investment, etc.), that should dictate the capabilities (and limitations) that the IIoT system should satisfy for a specific use case/factory. As a result, decisions in this Viewpoint will have an impact on the designs derived in the 'Usage' viewpoint below.

The **'Usage'** Viewpoint covers use specification of the system based on the requirements imposed by the 'Business'

Viewpoint. It elaborates how the system will work, identifying its parts (both human and IT components), and defines required usages of the system by its foreseen actors. These use cases drive the specification of the functional components in the Viewpoint below.

The **'Functional'** Viewpoint elaborates on the specification of the functional blocks that will deliver on the usage scenarios defined in the Viewpoint above. It further specifies roles and responsibilities of each component, along with foreseen interdependancies between them, essentially describing the concrete system architecture for the selected use case. This architecture drives the activities in the Viewpoint below.

The **'Implementation'** Viewpoint includes the technological details for the implementation and integration of the components defined in the functional architecture from the Viewpoint above. Hence, it deals with aspects, such as communication protocols, deployment to computing nodes, etc.

The IIRA model is extensible, in that it allows system designers to introduce additional Viewpoints in-between the existing ones as needed, in order to satisfy IIoT use case specific needs and requirements.

RAMI 4.0 and IIRA are not competing outlooks on how to achieve the same goals, as the former places strong emphasis in the digital transformation of the entire manufacturing value chain, while the latter focuses on the means to determine proper design of an interconnected platform for a variety of end-user verticals [18]. The two RAs effectively cross paths in the deployment of service-oriented architectures (SOAs) in manufacturing, and hence can be mapped to one another to support the design of highly distributed smart manufacturing solutions. Because of these conceptual similarities, the architecture specified in Section III can indeed be analysed following the Viewpoints-based perspective defined in the IIRA. Indeed, objectives of ZDM in a variety of industrial settings can be analysed following the IIRA business-driven viewpoint guidance. Furthermore, our approach to utilising both cloud and edge computing resources hints at a distributed computing framework for smart manufacturing, thus facilitating substantial alignment of our architecture to the provisions of the IIRA. We highlight this mapping in Section IV, following the guidelines described in [18].

C. Other international consortia

The **Industrial Value Chain Reference Architecture (IVRA)** is a Japanese architecture [3] providing guidelines for smart manufacturing systems. Essentially, this RA is based on the concept of a Smart Manufacturing Unit (SMU), an independent component that connects and collaborates with other SMUs to offer an integrated smart manufacturing system [19]. Each SMU is defined in a three-dimensional viewpoint-based coordinate system, which serves as a building block in the context of a system-of-systems (SoS - where a SMU can be either a component or a SoS in itself).

The **FIWARE4Industry (F4I)** RA constitutes a reference frame for smart factories based on the FIWARE open source framework for interoperable smart solutions [20]. It is a product of the FIWARE4Industry multi-project initiative [21] for combining FIWARE-compliant Generic Enablers (GEs) with the aim to define FIWARE-enabled reference implementations for smart, digital and virtual factories, as well as IIoT systems.

An RA proposed recently for I4.0 solutions has emerged from a multi-partner collaboration initiative led by technology giant IBM and its subordinate company Red Hat, provider of open-source software solutions [22]. The RA is available on IBM's website, where mapping of building blocks to commercially distributed components and systems is shown, inviting stakeholders to build concrete solution architectures for various use cases using IBM and subsidiaries' technology.

D. Notable RAs in the scientific literature

Candidate RAs have also been proposed by academic institutions, supported by several industrial businesses, as an outcome of close cooperation between industries and academia [3]. One example is the Stuttgart IT Architecture for Manufacturing (SITAM) [23], which enables the implementation of data-driven factories through flexible integration of IT systems, manufacturing processes centred in human capabilities and advanced analytics. SITAM differs from the majority of RAs in that it is two-dimensional and comprises three middleware solutions (following a SOA approach) that provide services for creating value for both human operators and machines (provisioned through a desktop/mobile app marketplace).

Another RA worth mentioning is presented in [24]. The LASIM Smart Factory (LASFA) RA describes all the necessary steps for smart factory environment planning. It also adapts the RAMI 4.0 cubic model to a two-dimensional representation with the aim to make abstract concepts included in the current RAMI 4.0 more concrete. LASFA's main advantage in comparison with RAMI 4.0, as stated by the authors, is that the relationship between a production hall (i.e., one or more production lines/cells, warehouses, manual workplaces) and its digital twins (a virtual representation of the real system in digital space - DT) is clearly identified. A DT can be defined for every component of the production hall, as well as the production hall itself, each orchestrated by a digital agent and a local cloud. The primary use of the DT is to improve the effectiveness of visualisation applications that offer human operators the ability to monitor and provide adequate feedback on manufacturing processes at various stages of the production described by the RAMI 4.0 Layers axis (from 'Asset', i.e., managing factory resources, to 'Business', i.e., strategic decision-making at organisational level).

III. OPTIMAI ARCHITECTURE

In this Section, we present the high-level functional, service-oriented architecture for a solutions ecosystem intended to facilitate human-AI collaboration towards optimising production and reducing defects in manufactured goods.

A. The OPTIMAI vision

The architecture is defined and implemented as part of the EU-funded OPTIMAI project [25], a multi-national innovation action striving to achieve high-quality, ZDM through a combination of key enabling technologies. It combines IoT "smart" sensing devices for quality inspection and monitoring at the network edge, with Cloud-based, AI-driven processes and production virtualisation, utilising AR as the HMI. The expected outcome is the development of a context-aware, wearable decision-support system (DSS), meant to provide timely information, and equip human workers (e.g., Production Control Engineers/PCEs, logistics planners, or production managers) with tools to overlook and expedite correctional activities (e.g., firmware updates, software configurations), that will minimise the amount of defective parts (or products) manufactured. Blockchain technology is further leveraged horizontally to verify the integrity of the software and firmware deployed on the various architectural components, enforcing traceability and accountability, and thus, safeguarding the system against outside tampering attempts. The final system follows a human centered design approach for AI [26], putting human-in-the-loop (HITL) in the context of ZDM, capitalising on the benefits of evangelising human-centricity in smart manufacturing [27].

B. *Functional architecture*

The OPTIMAI service-oriented architecture stack segments the envisioned ICT subsystems on a vertical axis, thus allowing for a high-level classification of different technological enablers on the grounds of their properties, relationships and execution environment. Each layer thus comprises a major subsystem, with information flowing through the overall system from top (i.e., the IoT sensing devices) to the bottom (i.e., the actual UI/HMI software). The involved subsystems are: (i) the **Quality Control Sensors Network**; (ii) the **Edge Computing Modules**; (iii) the **Cloud Computing Modules**; and (iv) the **Users' Applications**. The following paragraphs describe each of the identified subsystems and their functional blocks, all of whom comprise the architecture illustrated in Figure 1.

The *Quality Control Sensors (QCS) Network* encapsulates all IoT sensor devices used for production parameters acquisition in the interest of quality inspection. A variety of sensor types/families can be used in support of higher-level functions provisioned by the OPTIMAI architecture (such as the AI routines provided by other components in the architecture, residing on the Edge and on the Cloud). For example, the QCS Network may consist of one or more industrial-grade optical sensors (i.e., 1/2/3D cameras, for e.g., pose estimation or motion segmentation from RGB image data [28]), environmental sensors (e.g., indoor air quality - IAQ), etc. In the case of OPTIMAI, head-mounted/wearable sensors (such as those attached to an AR headset device) are considered to be part of the QCS Network. All sensor/IoT devices should support communication with a Middleware subsystem (see below), based on standardised communication protocols.

Edge computing will unlock significant benefits in industrial IoT scenarios [11], enabling execution of AI-enabled logic on either the sensor devices themselves, or IoT gateways and/or computing stations in close proximity. The proposed architecture incorporates subsystems and modules for deploying

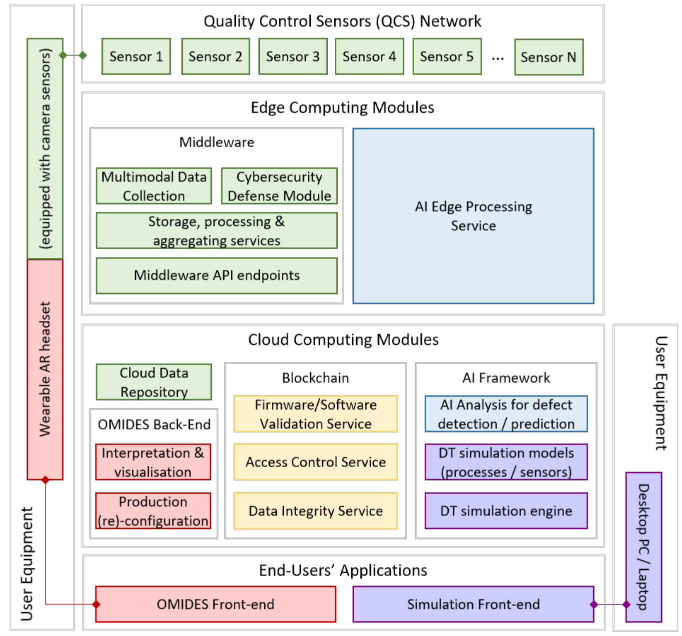

Fig. 1. OPTIMAI generic service-oriented functional architecture for ZDM. Color-coding is used to identify technologies as belonging to an emerging topic in smart manufacturing (green for multi-sensory data acquisition; blue for AI analysis; yellow for distributed ledger technologies; red for context-aware AR; and purple for DT-enabled production optimisation inference).

on-the-edge intelligence with respect to rapidly managing acquisition parameters and re-configuring assets for optimisation of resource usage in real-time. Toward this end, the OPTIMAI *Edge Computing Modules* subsystem is comprised of the **Middleware** platform, which comprises services for the acquisition of the sensors' data; cybersecurity threat detection as soon as data enters the system; (iii) sensor health monitoring; and (iv) coordination of the exchange of information between the Edge and Cloud modules. In addition, an **AI Edge Processing Service** is defined, which is responsible for the orchestration of the deployment and execution of lightweight AI calculations on the Edge nodes (sensors/gateways/PCs).

The *Cloud Computing Modules* subsystem contains all computationally-expensive and data-intensive components that benefit from the provisioned storage and resources in a Cloud environment. The following subsystems and modules are located in this layer:

- The **Cloud Data Repository**, which is the centralised storage point of the entire architecture for the data entered by the Middleware platform.
- A **Blockchain subsystem**, which: (i) comprises a distributed ledger of every critical operation; (ii) triggers the execution of smart contracts to automate a variety of production processes; and (iii) provisions data, software and firmware integrity verification mechanisms. Smart contracts within this architecture operate on top of the elected blockchain platform (e.g., Ethereum), so as to verify transactions with respect to access control (i.e., authorizing users to deploy configurations on top of the

system smart sensors or actuators), the actual application of firmware and software updates on shop floor equipment and keeping track of the AI system responses.

- The **AI Framework**, which executes AI-enabled quality control processes for defect detection and prediction; executes DT virtualisation and simulation routines; and derives optimal production parameters based on predictive analytics methods.
- Finally, the **Operator-Machine Interaction & DEcision Support (OMIDES) Back-end system**, provides all necessary AI routines for processing point of view (PoV) data arriving from employee-worn AR glasses, in order to facilitate interpretation and visualisation of spatial and contextual information regarding defects in the manufacturing line, as well as implementing real-time, user re-configuration of production parameters via natural interaction methods (e.g., gesture-driven).

Finally, the *Users' Applications* Layer contains all user-facing applications, such as the Graphical User Interface (GUI) to the DT simulation engine (mobile, or PC client), or the OMIDES Front-End, a GUI displayed through the AR smart glasses, that also act as sensors in the QCS Network.

IV. OPTIMAI ALIGNMENT TO I4.0 RAS

As specified in Section II, each RA provides a set of guiding principles for concretising the design of smart manufacturing or IIoT solutions and applications. In this Section, the OPTIMAI architecture is aligned with the specifications of the RAMI 4.0, allowing us to address implementation aspects and functions of the various assets, using a uniform framework of I4.0 elements. Our approach reflects the one in [29]. We conclude with a separate mapping of OPTIMAI onto the IIRA, elaborating on how OPTIMAI, as a SOA, supports compatibility with the reference IIoT framework.

A. Alignment with RAMI 4.0

As specified in Section II, RAMI 4.0 is a cubic map encapsulating all things pertinent to the modern I4.0-compliant smart factory. It does not provide a concrete architecture or implementation guidance, but rather presents a structured and simplified approach to addressing challenges and complex processes associated with smart manufacturing use cases. We consider ZDM as such a collection of use cases, e.g., reducing the number of quality defects in the production line and/or improving its efficiency by optimally calibrating machines/robotic cells in a way that decreases interruptions. These use cases are found in the "Instance" phase of the Life Cycle & Value Stream axis of RAMI 4.0. Particularly, such processes refer to the "Production" stage, as they are the actions performed to deal with product deficiencies, and acquiring knowledge for improving the state of the manufacturing environment. Hence, solidifying placement on one of the three RAMI 4.0 axes, our architecture can be layered on top of a 2D slice extracted from the 3D map, as shown in Figure 2, allowing us to present a "layer-and-hierarchy" mapping of the OPTIMAI architecture to RAMI 4.0 in reference to "Production".

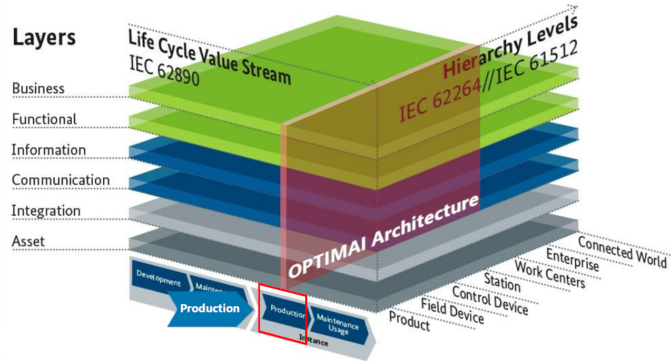

Fig. 2. OPTIMAI RAMI 4.0 "slice" in the 3D RA. Adapted from the original graphic © Plattform Industrie 4.0 and ZVEI, retrieved from [4]

The ensuing mapping of OPTIMAI components and subsystems to the "layer-and-hierarchy" 2D "slice" is shown in Figure 3, illustrating how OPTIMAI interconnected elements and functional blocks align to RAMI 4.0 guiding principles:

1) QCS Network: This subsystem maps at the intersection of the "Field Device" Hierarchy level and the "Asset" Layer, as it comprises all sensor devices physically installed inside the factory premises for data collection and actuation.

2) AI Edge Processing: This service is assigned to the "Control Device" in the Hierarchy-level axis, as it encompasses edge-based calculation and delivery of control parameters in an attempt to optimize the acquisition/actuation cycle. With respect to the "Layer" axis, it maps onto "Integration", as it facilitates direct interaction of measurements from the QCN Network with lightweight AI models.

3) Middleware: The OPTIMAI Middleware solution is responsible for exposing interfaces for communication between shop floor devices and OPTIMAI functional blocks. Hence, this subsystem maps to the "Integration" Layer, as it is responsible for the communication all physical entities in the factory premises with the IT components of the architecture. Pertinent to the exchange of data among architectural functional blocks, sensors and subsystems, the Middleware platform services align with the functional areas that are managed by a MES (given how MES addresses integration and data management in the smart factories concept [30]), e.g., further leveraging application of cybersecurity as early as data is acquired and entered into the system. As such, the Middleware platform aligns with the "Work Centers" Hierarchy level.

4) Cloud Data Repository: This subsystem is responsible for collection and storage of process- and production-related data, thus mapping to the functional responsibilities undertaken by MES (hence mapping to "Work Center" Hierarchy level). With respect to the Layers axis, the repository is directly mapped onto "Information", which describes how data is stored in an organized manner.

5) Blockchain: Components of this subsystem can be mapped to RAMI 4.0 according to their foreseen functions. Blockchain components may be assigned to the "Information" Layer, for managing the distributed ledger infrastructure used

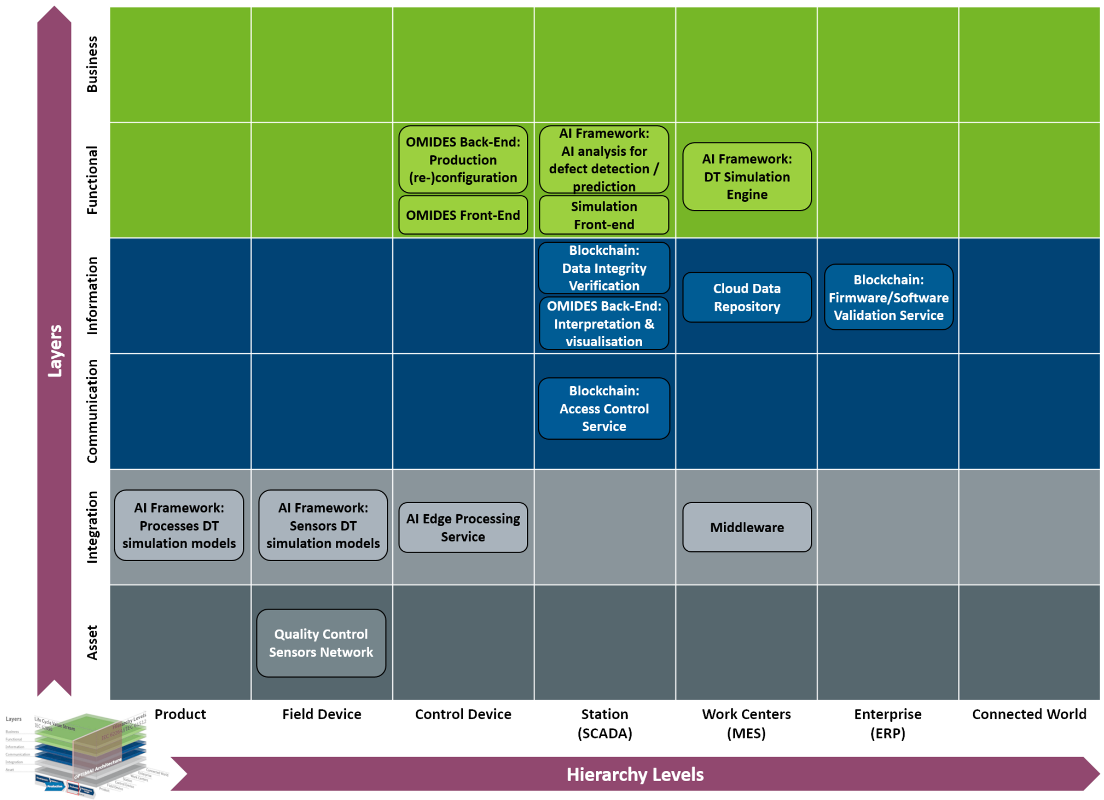

Fig. 3. OPTIMAI Layer-and-Hierarchy mapping to RAMI 4.0.

for record keeping and event processing, where integrity of both data and processes is of key importance [31]. On the other hand, validation of firmware and software installed on sensors and the middleware is reminiscent to the functional capacities provided by an ERP system (i.e., to offer unified and centralised device management), leading to an alignment of these services to the ”Enterprise” Hierarchy-level. Further, data integrity checks are a crucial element in the data acquisition processes that take place in SCADA systems [32], hence placing such services on the ”Station” Hierarchy-level. Finally, for blockchain-based access control, a cybersecurity perspective is implied for resolving security issues related to attack vectors on elected network communication methods [31]. Hence, the functional block also relates to SCADA data routines, and hence maps at the intersection of the ”Communication” Layer and the ”Station” Hierarchy-level.

6) OMIDES Back/Front end: The OMIDES functional components and application relate to information processing for determining both: (i) higher-order information on raw data coming from the AR head-mounted sensors (interpretation and visualisation block); and (ii) information on actions performed by the PCE during supervision of machines via novel natural interaction techniques (production re-configuration block). These attributes place functional block (i) at the intersection of the ”Information” Layer and the ”Station” Hierarchy level. Functional block (ii) on the other hand, along with the OMIDES Front-End components to support HITL decision-making and manual re-configuration of individual machine parameters, are found at the ”Functional” Layer, and relate to processes belonging to the ”Control Device” Hierarchy level.

7) AI Framework: The Cloud Computing Modules of the AI Framework comprise both algorithms for analysis of sensory data toward AI quality control, alongside DT processes. AI analysis components (shown in blue in Figure 1) perform the necessary processing checks, and provide decision support for defect identification and prediction based on real-time data produced by other modules in the OPTIMAI architecture. They are hence a crucial component to the ”brain” of the OPTIMAI ecosystem for ZDM, and are located at the intersection of the ”Functional” Layer and the ”Station” Hierarchy level.

With respect to the OPTIMAI DT components (represented in purple in Figure 1), we acknowledge observations made in [24] regarding ambiguity related to DTs in the framework of RAMI 4.0. We further note the several methods suggested in the literature to facilitate DT architectures conforming to RAMI 4.0. In our approach, we based our mapping in accordance with the Generic Digital Twin Architecture (GDTA) proposed in [33]. Hence, simulation models of processes and/or the QCS network, which generate data that mimics the operation of real-world processes (i.e., as if data was collected by real-world equipment) are found in the ”Integration” Layer, identified as either “Engineering” or “Runtime” data respectively in the context of the GDTA. Cloud-based simulation services are mapped to the ”Functional” Layer, as they represent decision-making instruments based on available (simulated) data. While the GDTA does not align with the "Hierarchy Levels" dimension of RAMI 4.0, on the grounds that DTs can be located at various hierarchical levels, we draw the following mappings to the "Hierarchy Levels" axis based on the foreseen use cases of the final system:

- Simulation models of processes refer to the concept of "Engineering" data, i.e., topological information about the factory (e.g., the distance a worker has to walk from one area to the next in a manual workstation), that should be considered on the grounds of having an impact on the efficiency of the manufacturing process. Such models are hence viewed as originating at the "Product" level, referring to the physical production facilities and the interdependencies they are characterised by [17].
- A Virtualised sensors' array effectively replaces the actual QCS Network for the purposes of simulation, similarly mapping onto the "Field Device" Hierarchy level.
- The DT Simulation Engine is seen as simulating functional areas under the responsibility of a MES, and hence occurs at the "Work Centers" Hierarchy level.
- The Simulation Front-end naturally reflects the UI provisioning of SCADA systems, targeting at supervision of real-time data generated by the simulation engine, and the interaction routines with the DT devices and sensors implemented as part of an emulated HMI solution. The application is hence located at the "Station" level.

B. Alignment with IIRA

As has been mentioned in Section II, IIRA and RAMI 4.0 share many similarities regarding their support of SOAs, driving the decomposition of system functionality into a number of interconnected services. Because of the alignment of OPTIMAI with RAMI 4.0, and the IoT approach taken, the architecture can further be mapped onto the IIRA as well. Regarding the IIRA Viewpoints, OPTIMAI can be described in the following manner:

- *Usage Viewpoint*: refers to the expected usage of the OPTIMAI system as a solution for ZDM. In specifying such use cases prior to the architecture, OPTIMAI aligns with the principle of the IIRA for upper Viewpoints to guide the design of the Viewpoints below.
- *Functional Viewpoint*: this Viewpoint is reflected in the specification of the OPTIMAI components and subsystems, and the functions they execute to support ZDM use cases. Based on the mapping elaborated in [18], parallels can be drawn between the OPTIMAI architecture (as an IIoT solution) and the IIRA, as shown in Figure 4. The RAMI 4.0 Communication layer is mapped to the Connectivity Cross-cutting Function defined in IIRA, reflecting the need for a particular security function to be implemented across communications of the functional components [5] (in OPTIMAI's case, Access Control).
- Finally, elements related to the *Implementation Viewpoint* are related to the technologies' selected technical components (e.g., sensor hardware) and communication schemes (e.g., OPC-UA), while the strategic goals and benefits driving the system implementation and deployment across industrial settings reflect the IIRA *Business Viewpoint*.

V. Conclusion

In this paper, we described the OPTIMAI flexible, modular service-oriented architectural framework, which incorporates key enabling technologies (e.g., AI, AR, Blockcahin, DT, Edge computing, etc.) into a ZDM solutions ecosystem, applicable across various industrial settings and domains. The eventual developed system will be deployed and evaluated in three industrial pilot sites, including varied sets of ZDM use cases including quality inspection, production line setup-calibration and efficient production planning.

A key takeaway of this paper is the alignment exercise to standards-based RAs for realising the I4.0 vision, which delivers a basis for implementing the OPTIMAI framework in accordance with the RAMI 4.0 and IIRA specifications. Through this process, specific cross-cutting system concerns, such as communication between components, integration and interoperability, can be addressed in a more harmonised manner, applying the principles reported in the documentation of the two RAs. Through the demonstration activities planned within the project's timeframe, OPTIMAI further gains the benefit of showcasing a pragmatic implementation of RAMI 4.0 (which is an abstract model) in the context of ZDM and zero-waste production planning, which can extend to other use cases outside the scope of the project.

Over the duration of the second half of the project, use cases in the context of OPTIMAI will be periodically executed to attest to quantitative and qualitative performance indicators in terms of both production efficiency and user acceptance.

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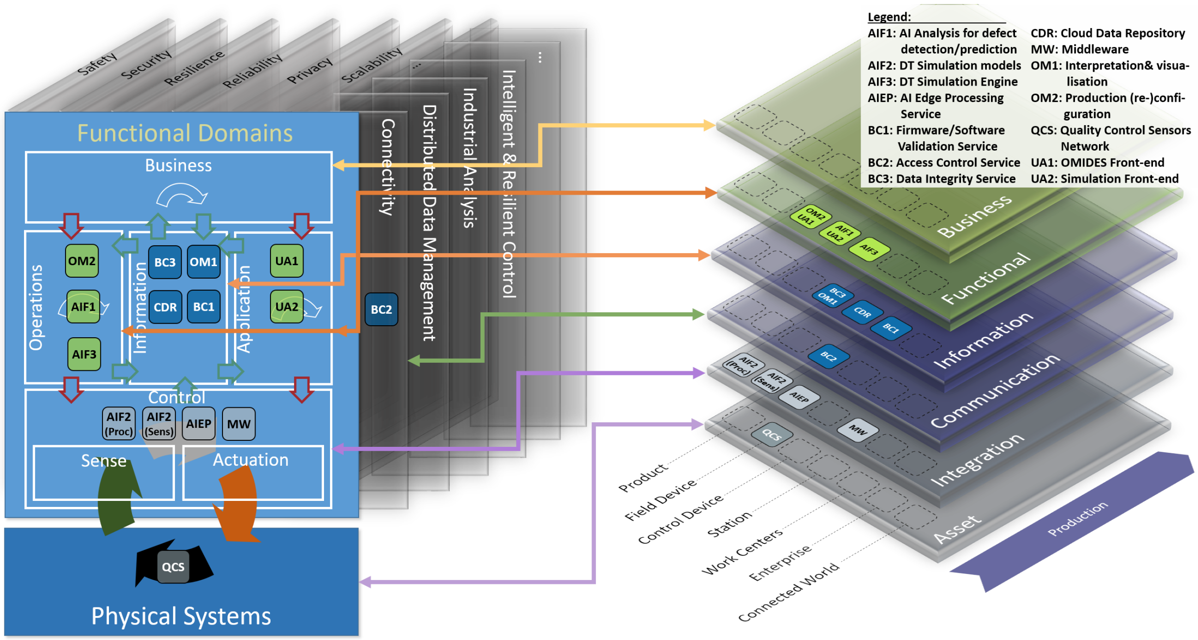

Fig. 4. Functional mapping of the OPTIMAI Architecture to IIRA based on the alignment with RAMI 4.0.

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