

Analysis of Relevant Standards for Industrial Systems to Support Zero Defects Manufacturing Process

Abstract: The ongoing 4th industrial revolution is affecting all aspects of traditional industries, including technical and organisational issues. In this context, there is a wide variety of European manufacturing initiatives addressing the challenges related to the implementation of the 4th industrial revolution principles and ideas, including digitalization and Zero-Defects Manufacturing (ZDM). Besides technical and organisational issues, standardization, in the context of next generation manufacturing systems, is a topic requiring better study. In this article we offer an analysis of relevant standards for manufacturing systems which was performed for the Digital Manufacturing Platforms (4DMP) cluster in order to identify those standards that might be relevant for ZDM, as well as for further projects or manufacturing platform designers. The standards covered by this work are aligned with the RAMI 4.0 reference model in order to simplify the design process by interlinking standards with relevant model layers and thus contribute to system's interoperability.

Keywords: Industry 4.0, Zero Defects Manufacturing, Standards, RAMI 4.0.

1. Introduction

The fourth industrial revolution, sometimes also referred as Industry 4.0 or Industrial Internet [1], affects the traditional industries, demanding novel technological and organisational solutions. Typical Industry 4.0 literature provides a set of recommendations on the usage and implementation of existing or emerging technologies, mostly focused on the manufacturing domain [2, 3]. The main emphasis is put on technologies contributing to cyber-physical integration, including remote control and real- or close to real-time data analysis. Among the most popular technologies being part of Industry 4.0 the following can be mentioned: Cyber-Physical Systems (CPS), Smart Systems, Internet of Things (IoT), Digital Twins, Big Data, and Cloud computing [4]. But many other areas are converging to support this revolution, including mobile computing, additive manufacturing, collaborative robotics, and the so-called “exponential technologies” which are strongly based on Artificial Intelligence / Machine Learning [5]. The central point inside the Industry 4.0 paradigm is the digitalisation and smartification of factories and manufacturing processes. In other words, future industrial systems can be seen as a network of distributed autonomous components, with distributed decision making, which are able to interact and collaborate with each other and with human operators [3, 6]. In this perspective, collaborative networks appear as a core enabler for the digital transformation process [7].

The Industry 4.0 paradigm demands an increase in the quality of products, services and processes [4]. In this regard, the concept of Zero Defects or Zero Defects Manufacturing (ZDM) is of particular importance. The main idea behind the ZDM concept is not defects and faults detection, but rather faults and defects prediction and provision of suggestions on how those can be avoided. This can be achieved through a combination of Smart Inspection Tools, CPS, Data Analysis, and Knowledge Management tools [8], as well as Digital Twins (DT). An example of the application of DT for faults and defects mitigation is the Pre-Digital Twin that can be used for quality management before the physical twin deployment [9]. One particular problem of

modern ZDM solutions is that most of them are sequential and narrowly focused on a single production stage instead of multi-stage coverage [10]. Nevertheless, some recent efforts are undertaken to move away from a single stage production, as for instance the GOODMAN project providing a multistage ZDM solution and aggregating data from heterogeneous sources for further processing and decision making [8]. The authors indicate several challenges, one of which is the interoperability and namely the need to integrate data coming from different sources, as well as different engineering domains.

Interoperability remains as one of the basic issues to be considered both in Industry 4.0, as well as in ZDM. According to the definition of interoperability, being relevant in the context of this particular work, it is “the ability of two or more systems or components to exchange and use the exchanged information in a heterogeneous network” [11]. As mentioned earlier, both Industry 4.0 and ZDM imply collaboration of multiply heterogeneous devices or systems that might be built based on different technologies and architectural approaches, making the establishment of interoperability an even harder task. This is directly related to the standardisation activities, although some sources consider them as insufficient [12]. Nevertheless, issues of interoperability and standardisation are tightly coupled and should be considered together.

In fact, interoperability issues can be reduced if we follow a standardized approach from the very beginning of the system/platform design, namely adapt or develop a reference architecture that is in line with the standards and commonly used approaches in the application domain. Significant efforts are undertaken towards establishment of a reference model or reference architecture based on standards for manufacturing supportive platforms. Some notable examples to be mentioned are the Industrial Internet Reference Architecture (IIRA), Reference Architecture Model for Industry 4.0 (RAMI 4.0), Intelligent Manufacturing System Architecture (IMSA), and International Data Space Reference Architecture Model (IDS RAM). IIRA is based on the ISO/IEC 42010 standard aiming at domain-independent representation of Industrial Internet and is developed by the Industrial Internet Consortium [13]. Along with IIRA, the IDS RAM follows the ISO/IEC 42010 standard, possessing a layered structure in conjunction with 3 perspectives [14] being, in fact, a 2-dimensional model. The RAMI 4.0 is a three-dimensional model based on a set of international standards, namely, IEC 62264, IEC 61512 and IEC 62890, developed to support Industry 4.0 platforms design [15]. IEC 62264 is also the basis for the Lifecycle dimension of the IMSA, the architecture developed to support the China 2025 manufacturing strategy [16]. All these models, although representing significant contributions, somehow follow a bottom up approach, being a bit limited when it comes to wider distributed and collaborative manufacturing systems. Nevertheless, they can be complemented with other initiatives such as the ARCON Reference Model for Collaborative Networks [17], which can provide a kind of top-down guide.

In this work we aim at a clarification of the standardisation landscape and proposing a standards alignment framework to improve interoperability in manufacturing systems. The work is conducted as a part of standardization activity for the 4DMP cluster of the projects QUALITY, EFPP, Kyklos 4.0, digiPRIME and SHOP4CF, and, in particular, for the Zero Defects Manufacturing Platform (ZDMP) project. The idea is to collect a portfolio of standards used in the accomplished or ongoing European manufacturing projects and related publications and align them in accordance with the RAMI 4.0 model that is selected for ZDM platform development [15].

The rest of the article is structured as follows: Section 2 introduces the proposed standards alignment framework; Section 3 discusses standards alignment with RAMI 4.0; a discussion and identification of standardization gaps is presented in Section 4; finally, main conclusions are highlighted in Section 5.

2. Standards Alignment Framework

This section introduces the proposed framework for aligning the standards with the RAMI 4.0 (Fig. 1). The main focus is made on standards oriented on computer aided manufacturing systems, either directly like ISO 15531 or IEC 62541, or indirectly, such as assistive standards that are not designed exclusively for regulation of production issues e.g. ISO/IEC 29100, regulating the protection of PII. The RAMI 4.0 reference model has been chosen as the one of the reference models that is used in 4DMP Cluster projects such ZDMP or EFPPF. However, issues of reference models interoperability are highlighted by some other works [13, 15, 18]. This can help to map the standards considered by current research to other solutions based on other reference models such as IMSA or IIRA and thus contribute to the establishment of a modelagnostic standards' pool.

The Alignment Framework consists of 4 main parts: (1) identification of relevant standards, (2) RAMI 4.0 model, as input, (3) the Alignment block itself, and (4) the standards already aligned according to Layers and Hierarchy Levels descriptions of the RAMI 4.0, as output. Standards are extracted from important European projects from the manufacturing domain and corresponding publications. The main source of the relevant standards are the public projects' deliverables. For instance, vf-OS project, one of the considered European initiatives, utilized the RabbitMQ message broker [19, 106], based on the AMQP messaging protocol, to implement the publish/subscribe paradigm. The AMQP protocol is based on the ISO/IEC 19464 international standard. Thus, this standard is considered for the portfolio of the standards that will be analysed and aligned with the RAMI 4.0 inside the "Alignment to RAMI 4.0" block. Another example is the MANTIS project that followed the guidelines of the ISO 13374 standard in terms of "data processing, communication, and presentation of condition monitoring and diagnostics of machines" [20]. The second source to identify relevant standards were some scientific publications, as for instance [21], where the authors address the standardisation in the context of the ARUM European project, e.g. the ISO 15531 for data representation from manufacturing control level and ISO 11898 standing for CAN bus have been mentioned there. Some standards, as for instance OPC-UA represented by IEC 62541 were mentioned in several sources [19, 21].

between the cyber and the physical space, allowing digitalising physical assets as well as human beings through the Human Machine Interface (HMI) [23]. The rest of the Layers are focused on the cyber space. The Communication Layer is responsible for communication technologies and protocols, the Information Layer ensures data integrity, data discovery/querying, and operations on data model [22], and the Functional Layer comprises system administrative tasks, implementing data semantics and semantic discovery mechanisms, as well as providing modelling and runtime environments. For instance, the Enterprise Resource Planning (ERP) Systems are in the scope of the Functional Layer [18]. The Business Layer serves the goal of aligning the business model, internal and external processes, and generic rules for system functioning. Important is to mention that the Business Layer is not so much in the focus of the current research, as it is largely use-case oriented and “does not concern concrete systems” [18].

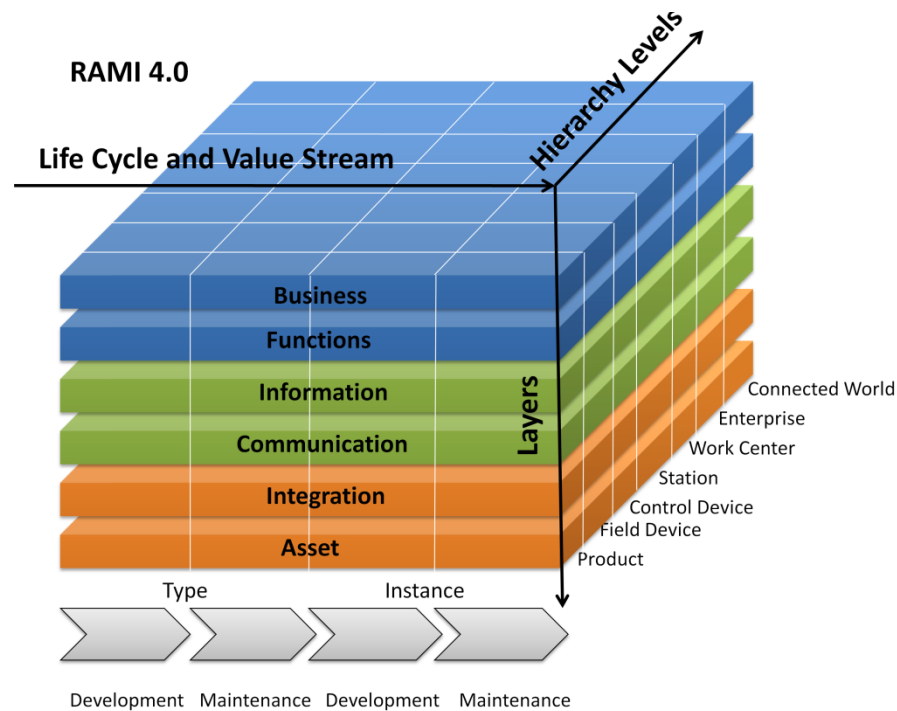


Fig. 2 – RAMI 4.0 Reference Architecture

The second dimension of the RAMI 4.0, that follows principles coined in the IEC 62264 standard, includes 7 Hierarchy Levels indicating the core functional divisions for each Layer [24], namely: (1) Product, (2) Field Device, (3) Control Device, (4) Station, (5) Work Centre, (6) Enterprise, and (7) Connected World. Besides the functionalities related to machines and equipment, these Hierarchy Levels cover the result of the manufacturing process, namely within the “Product” Layer [18]. Most of the remaining functional blocks are focused on different functionalities within the factory while the “Connected World” considers possible inter-factory collaboration (thus related to the horizontal integration dimension of Industry 4.0 [7]). In fact, the RAMI 4.0 expands the IEC 62264 standard, whereas adding the “Product” and “Connected World” levels. Thus, the manufacturing process starts with “Field Device” that participates directly in manufacturing actions within the physical space, as for instance, machine supervised by Programmable Logic Controller (PLC) from “Control Device” layer [25]. Production planning and scheduling for a particular manufacturing cell is defined in the “Station” layer and for a group of manufacturing units in “Work Centre” layer. The “Enterprise” layer is responsible

for coordination of manufacturing activities, as well as strategic planning involving one or more work centres.

Whereas the Hierarchy Levels and Layers give important insights on the manufacturing process itself and its various functional blocks, the Life Cycle and Value Stream dimension enables tracking different stages of product manufacturing from design to recycling according to IEC 62890 guidelines. The Life Cycle and Value Stream consist of two macro-stages: (1) “Type”, covering the period from idea generation to prototype development [26], and (2) “Instance”, covering the phase when the product goes to serial production.

This work focuses on the Layers and Hierarchy Levels for analysis of relevant standards. In other words, RAMI 4.0 reference architecture is used in this work to map and align the identified standards according to the corresponding Layers and Hierarchy Levels. For identifying relevant standards several sources were used, namely: (i) public deliverables of European manufacturing projects, (ii) research articles, (iii) standards’ description linking to other relevant standards, and (iv) Industry 4.0 specifications [23]. Among key projects that were used to identify relevant standards we considered: vf-OS, CREMA, DIGICOR, MANTIS, RestAssured, GOODMAN, BEinCPPS. Another important source, as mentioned, are research articles directly devoted to standardisation issues in manufacturing platforms [21] or to discussing the standardisation in context of the Industry 4.0 [27, 28, 29, 30, 31]. Thus, the next sub-sections are structured according to the RAMI 4.0 Layers: (i) Asset, (ii) Integration, (iii) Communication, (iv) Information, and (v) Functions.

3.1. Asset

The first layer of RAMI 4.0 to be analysed is the Asset Layer. The scope of this layer is focused on the real-world, or in other words, the physical components of CPS possessing at least one passive communication way [32]. In this layer, components are described as real-world units [33]. Some of the considered standards specify various aspects that can be aligned with more than one layer of RAMI 4.0. One example is the IEC 61131 standard for programmable controllers (PLC). This standard covers various aspects of PLCs, for instance part 3 focuses on programming languages for PLCs including the ones used for Human-Machine Interfaces (HMI) design [34], and part 5 focuses on details of PLCs communication and thus belonging to the Communication Layer. Part 1 gives an insight on definitions and basic characteristics, part 2 is related to equipment requirements and tests, and part 4 covers PLCs usage issues for the end-users. Thus, only part 1 and 2 of the standard can be aligned with the Asset Layer. Another closely related standard is IEC 61499 that intends to eliminate the limitations of 61131 regarding distributed control systems [35]. Part 1 of IEC 61499 specifies the architecture for distributed systems using the event driven execution model instead of a cyclic model as in 61131 [36], whereas part 2 sets the requirements for software tools and part 4 contributes to the establishment of a common basis for interoperability and portability of devices.

Issues of security and safety can be addressed in various layers, including the Asset Layer. The IEC 62443 standard specifies the approaches in securing the Industrial Automation Control Systems [37]. This standard matches several Layers, for instance the IEC 62443-3-1 covers both issues related to hardware, i.e. physical instance of the asset, and thus being aligned with Asset Layer, as well as the associated interfaces, being relevant for the Integration Layer, but also

networks and quality assurance issues related to the Communication and Functions Layers respectively [38]. However, the IEC 62443-4.1 and IEC 62443-4.2 are mostly component based parts and thus suit well the Asset Layer [39]. Another closely related standard is the IEC 62453-2:2016, which sets the foundation for designers and developers of field device tools, covering aspects from Field Device to Enterprise Hierarchy Levels of RAMI 4.0. Thus, this standard is aligned with the Asset and Integration Layers of RAMI 4.0, contributing to unification of interfaces and providing common principles of the field device tool concept [40].

In terms of safety, the IEC 61508 standard provides a foundation for programmable electronic systems, fitting the Asset Layer. It addresses a range of measures for faults avoidance, hardware fault tolerance, and modelling techniques to measure failure probability. The IEC 61511 standard complements the IEC 61508 in terms of its relevance to users and integrators working with systems or components [41]. A wide range of requirements and recommendations in the area of field machinery security and safety is set by the ISO 13849 standard [42]. This standard series also provides the verification procedure for machinery safety assessment and can be applied to different types of machines and tools, such as hydraulic, pneumatic, mechanical, electro-mechanical, programmable electronic devices, etc [43]. A similar standard is the IEC 62061, specifying requirements and providing recommendations for the design and validation of electronic and programmable control systems considering safety aspects [44]. Both standards, IEC 62061 and ISO 13849, are complementary, as the IEC 62061 is more suitable for “complex systems without limitations” and the ISO 13849 follows a more classic machine safety approach [45].

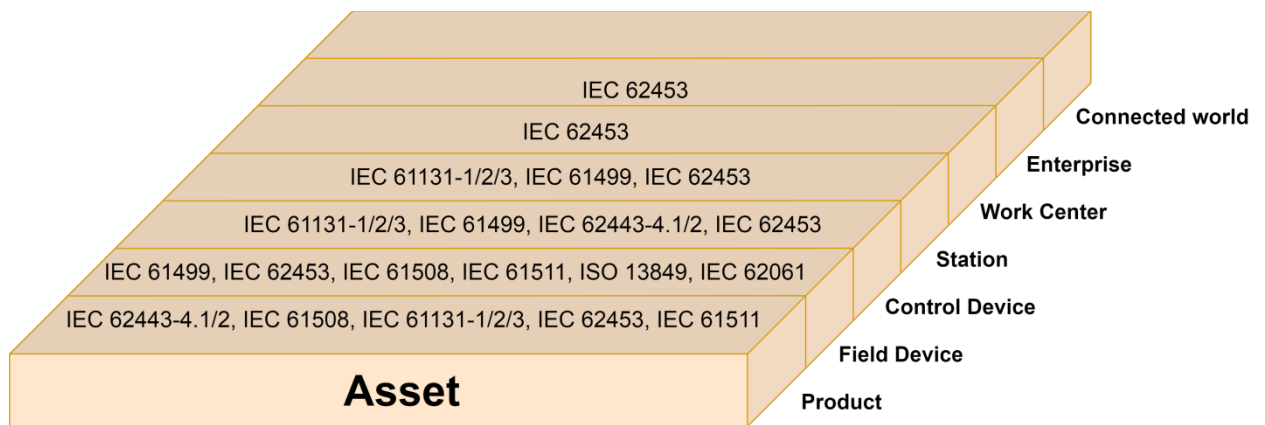


Fig. 3 – Standards matching the Asset Layer of RAMI 4.0

3.2. Integration

In the Integration Layer inputs from the Asset Layer are captured and represented in a form suitable for computer processing, allowing generation of events [46]. In fact, the first stage of Digital Twin generation is accomplished at this stage [33]. Therefore, some components such as sensors and actuators are a part of this Layer. Human-Machine interaction is also considered within the Integration Layer. A relevant standard identifying requirements for the Human-Machine Interfaces is ANSI/ISA-101.01-2015. This standard provides the basis for design, development, operation, and maintenance of the HMI, covering its whole Life Cycle.

One important topic in the context of manufacturing is related to field devices and machines integration. For this purpose, the Electronic Device Description Language (EDDL) is introduced

by IEC 61804-2, being a key support for device integration in process automation [47]. Another complementary issue is addressed in IEC 62543 standard, representing the Field Device Tool (FDT). It offers a basis for accessing device parameters, implementing the interface for its configuration and operation, as well as diagnostics [48]. Both mentioned aspects contribute to integration and low-level management of devices and thus belong to the Integration Layer of RAMI 4.0. Another standard purely focused on Field Devices Integration (FDI) is the IEC 62769. Part 1 of this standard offers an introduction to field device integration in terms of concepts, specifications, and motivation. Part 2 covers the FDI clients; part 3 addresses the FDI server, part 4 and 5 discuss FDI packages, and information model subsequently, whereas part 6 provides the technological map for FDI implementation, including the GUI. This standard is proclaimed to be the most accepted standard for field devices integration [49], creating the common basis for integration of FDT as described by the IEC 62543 and EDDL represented by 61804 [48]. Considering the RAMI 4.0, model the IEC 62769 covers issues from Integration, Communication, and Information Layers.

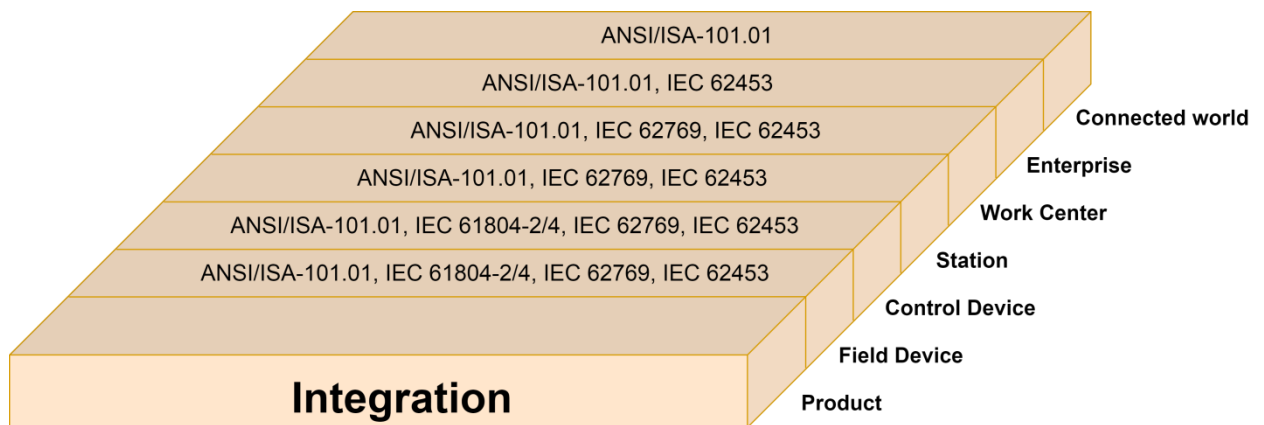


Fig. 4 – Standards matching the Integration Layer of RAMI 4.0

3.3. Communication

The Communication Layer covers the issues related to data transmission, including protocols and corresponding technologies. Modern complex smart systems presume communication of various entities with each other, as well as with control devices. One important standard for communication of distributed components within a vehicle is the ISO 11898. The standard specifies the Controller Area Network (CAN) bus that can serve as vehicle-wide interconnection for controllers and devices comprised from multiple receivers and transmitters [50]. The ISO 11898 is complemented with ISO 16845 standard providing the basis for conformance testing of CAN data link layer and signalling with specification provided by ISO 11898.

Communication protocols for Industrial communication networks (including Fieldbus) are specified by the IEC 61158 standard. This standard has 6 parts detailing: (i) Communication model, (ii) Physical layer, (iii, iv) Data-link Layer, and (v, vi) Application Layer [51]. It provides a basis for a set of other standards such as IEC 61784, specifying the Communication Profile Families (CPF) – set of instructions and guidelines for implementation of IEC 61158. Another example is the IEC 62734, also known as ANSI/ISA 100.11a, being an extension of IEEE 802.15.4 and intended to match the requirements set in IEC 61158 ensuring the distributed

process control for interconnected field devices, avoiding the host system while operating [52]. IEEE 802.15.4 specifies the low-rate wireless personal area networks (LR-WPAN).

One of the key approaches for industrial systems is the Open Platform Communications Unified Architecture (OPC-UA), defined by the IEC 62541 standard, which contributes to both the Communication and the Information Layers of RAMI 4.0 [33]. It allows for applications to communicate under the client-server manner and is considered as one of the core enabling technologies for machine-to-machine communication [53]. Considering RAMI 4.0, it fits both the Communication, and the Information Layers. The reason for this is that besides communication issues, some parts of the standard, such as Part 8 – data access, part 5 – information model, are devoted to issues that are covered by the Information Layer of RAMI 4.0. Another standard contributing to the publish-subscribe messaging paradigm is the ISO/IEC 20922, standing for MQTT messaging transport protocol. It is often described as a lightweight and simple tool for interconnection of edge devices being out of the “*reach of utility telecommunications network infrastructure*” [54]. MQTT possesses several important characteristics, such as: (i) implemented over TCP/IP, (ii) follows publish/subscribe pattern, (iii) does not require excessive information about the content of payload (also called “agnostic to payload context”) [55], and supports asynchronous working regime and different types of message delivery. In fact, there are 3 types of message delivery supported by MQTT: “at most once” – presuming message losses, “at least once” – when the same message can be delivered several times, and “exactly once” – the message is delivered, but duplicates are excluded. It is important to mention that OPC UA is rather a framework providing information models for assets interoperability [56], whereas MQTT is a communication protocol that does not define the data types and thus belongs only to the Communication Layer of RAMI 4.0. Another important protocol for business messaging is defined by the IEC 19464 standard: The Advanced Message Queuing Protocol (AMQP), which has one particular implementation within the RabbitMQ message broker that allows message queuing and distribution among multiply recipients. This protocol belongs to the Application Layer of the OSI model [57]. In reference to RAMI 4.0, it belongs to the Communication Layer and covers the Hierarchical Levels from Station to Connected World.

Issues of IoT systems interoperability are considered by the ISO/IEC 21823 standard consisting of three parts: (i) Framework, (ii) Network Connectivity, and (iii) Semantic Interoperability [58]. Thereby, the standard is covering the Communication, Information, and Functional Layers of RAMI 4.0. Communication of Smart Devices is addressed by a set of standards, such as IEC/TR 61850 or IEEE 1451. IEC/TR 61850 is a standard providing regulations for Intelligent Electronic Device communication. Some authors consider this standard as the most relevant one for the modern power systems communication [59]. In terms of the RAMI 4.0 model it is placed both into the Communication and Information Layers, as the series targets not only the communication protocol itself, but also the information models and some platform-independent semantics [59]. The standard is also aligned with the older ISO 9506 standard, providing Manufacturing Messaging Specification regulating the access to remote devices, controllers, and various manufacturing machines [60]. As for the IEEE 1451 series, it is devoted to smart transducers. In particular, the IEEE 1451.1 specifies network services such as: discovery, access, event notification, and transducer management. Moreover, 3 core communication models are supported: client-server, publish-subscribe, and notifications [61]. The following standard series

is the ISO/IEC/IEEE 21451.x aiming at development of a standardized approach for intelligent devices, such as smart transducers, to access a network [62].

Aspects related to condition monitoring and diagnostics of manufacturing devices and machines are covered by the ISO 13374 standard. It has 4 parts defining (i) general guidelines and requirements, (ii) reference information and processing models, (iii) communication requirements for information exchange, and (iv) requirements for information representation and decision support [63]. Thus, this standard covers three Layers of the RAMI 4.0 model, namely part 3 relates to the Communication Layer, part 2 and 4 discuss the approaches for data processing and representation, issues that are part of the Information and Functions Layers. As for Hierarchical Levels, this standard addresses field devices, whereas detecting deviations and performing signal analysis and other tasks such as problems diagnostics, failure predictions and generation of corresponding recommendations for mitigation performed on the Hierarchy Levels from Control Device to Work Center [64].

Network security of Cyber-Physical Systems is addressed by the ISO/IEC 27033 standard [65], which provides guidelines for implementation of network security controls defined by ISO/IEC 27002 [66]. The part 1 complements and, in fact replaces, the ISO/IEC 18028-1 standard discussing the roadmap, core concepts, and principles used as a basis for further parts of the standard. The following parts are devoted to: (ii) guidelines for design and implementation of network security, (iii) reference networking scenarios, (iv) secure communication using gateways, (v) secure communication using Virtual Private Networks (VPN), and (vi) securing wireless IP network access.

Cloud Computing is also partially addressed by the Communication Layer of RAMI 4.0. One example standard can be found in the IEC 19831 specifying a Cloud Infrastructure Management Interface (CIMI) and a protocol of a REST type. The goal of this standard is to bridge the cloud Infrastructure as a Service (IaaS) providers to IaaS service consumers [67] having limited application to PaaS and SaaS. It also introduces a modelling approach for basic IaaS resources, such as machines, storage, and networks, whereas contributing to interoperability presuming portability among cloud implementations aligned with the standard. The standard covers both the Communication, as well as the Information Layers, as it presents the REST alike protocol fitting the Communication Layer, as well as a logical model for IaaS resources management.

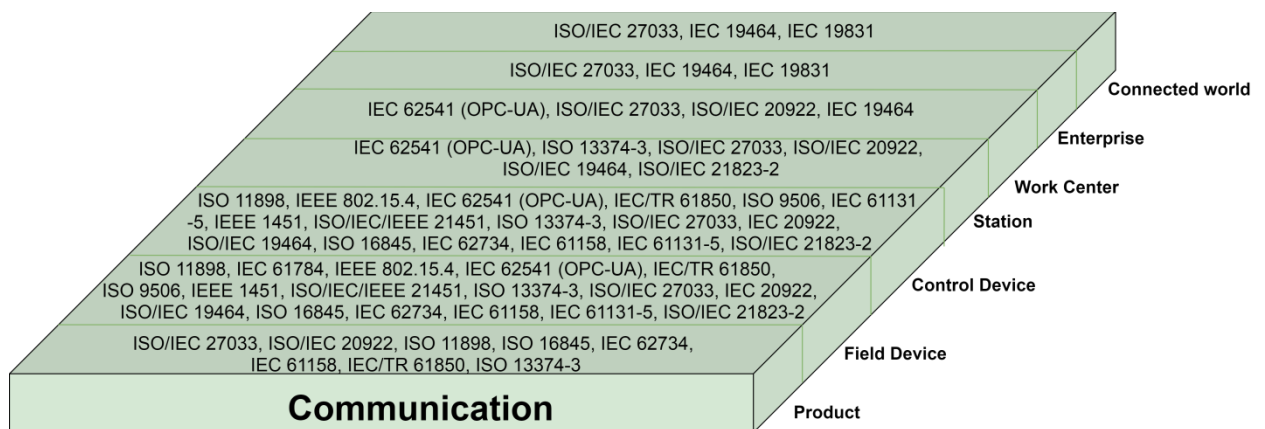


Fig. 5 – Standards matching the Communication Layer of RAMI 4.0

3.4. Information

Events generated in the Integration Layer and transmitted through the Communication Layer are processed in Information Layer, where event-related rules are executed [46]. Moreover, the Information Layer is in charge of data models, persistence, provisioning, integration, transformation, and integrity [15]. Representation and exchange of industrial manufacturing management data is regulated by an international ISO 15531 standard [68]. It is partially based on other international standards such as ISO 10303, ISO 13584 or 14258, whereas using some of the previously coined definitions. Some examples of data definitions re-used from the mentioned standards are: data, data exchange, information, product, product data, and entity derived from ISO 10303, basic semantic unit from ISO 13584, and definitions of enterprise and enterprise model acquired from ISO 14258. The ISO 15531 covers the whole industrial cycle to enable data sharing, exchange, and modelling [69] within the factory, as well as with other enterprises or manufacturing locations. In this regard, another relevant standard is the ISO/IEC 21778, defining the JavaScript Object Notation (JSON) data interchange syntax. This standard belongs purely to the Information Layer, as it only specifies the JSON syntax, without any semantics or text interpretation [70]. Thus, parties using JSON require additional efforts and agreements about semantics, which is an open direction for further standardisation and specification efforts.

Interoperability, in terms of data exchange, appears also in the scope of the Information Layer. An example of related standard is the IEC 18629 that contributes to applications interoperability in terms of data processing and exchange. It offers a common framework for processes descriptions from various domains, emphasising the automatic reasoning, whereas checking the compliance with the pre-defined rules [71]. According to RAMI 4.0, this standard is aligned with the Information and Functions Layers. Another relevant standard addressing interoperability is the ISO/IEC/IEEE 21450 – an umbrella standard for the IEEE 1451 series. This standard represents the data format for Transducer Electronic Data Sheets (TEDS) and descriptions of “*sensor and actuator channels in terms of physical quantities, data representation, measurement range, uncertainty, calibration, etc*” [72]. Data Exchange between industrial facilities and Smart Grid, for instance, is regulated by the IEC TS 62872 standard. This standard presents the interface for managing data needed to support planning, management, and control of energy flows between the industrial facilities and smart grid [73].

Data models and formats are addressed by a set of international standards such as ISO 14306 or IEC 62714. ISO 14306 presents the Jupiter Tessellation (JT) format for 3D data capturing and visualisation in the manufacturing context [74]. The standard defines semantics and syntax of the data format for 3D visualisation of data acquired from the CAD systems, thus complementing the ISO 10303 in terms of adding the 3D visualisation capabilities [75]. The COLLADA (Collaborative Design Activity) schema, specifying the exchange of the digital assets between 3D applications, is described by the ISO/PAS 17506 standard. It is supposed to target the import/export activities from 3D applications or CAD systems [76]. On the other hand, the IEC 62714 standard defines a data exchange format for “semantic description of plant information” [77]. The Automation Markup Language (AML) presented in this standard is used for bringing together various engineering tools from different domains, such as mechanical, electrical, or process engineering, PLCs, etc. [78]. The data format that can be used for data exchange between manufacturing assets is defined by the IEC 62424 standard. This standard defines the semantics for information integration and interoperability as Computer Aided Engineering

Exchange (CAEX) format [79]. The format is closely related to the AML language and can be utilised, for instance, to represent the logical structure of products or production facilities [80]. This standard fits both into the Information and Functions Layers.

Data transformation and mapping are covered by some parts of the IEC 61580 standard that also contributes to the Communication Layer of RAMI 4.0. For instance, the following parts: IEC TS 61850-80-1:2016 – describing the data mapping of device-oriented data models [81], IEC TR 61850-90-7:2013 – information models for information exchange between power converters [82], and IEC TR 61850-90-8:2016 – object model for Electric Road Vehicles, can be considered as sub-chapters fitting into the Information Layer.

An important standard regulating the cloud ecosystem and data flows between the cloud infrastructure and cloud service users and their devices is ISO/IEC 19944. In the context of manufacturing, this standard can be of a great use as it specifies: (i) various types of data flowing between devices and cloud ecosystems, (ii) the impact of connected devices on the data flow, and (iii) data taxonomy and data categories for data circulating between cloud service customer devices and cloud services [83].

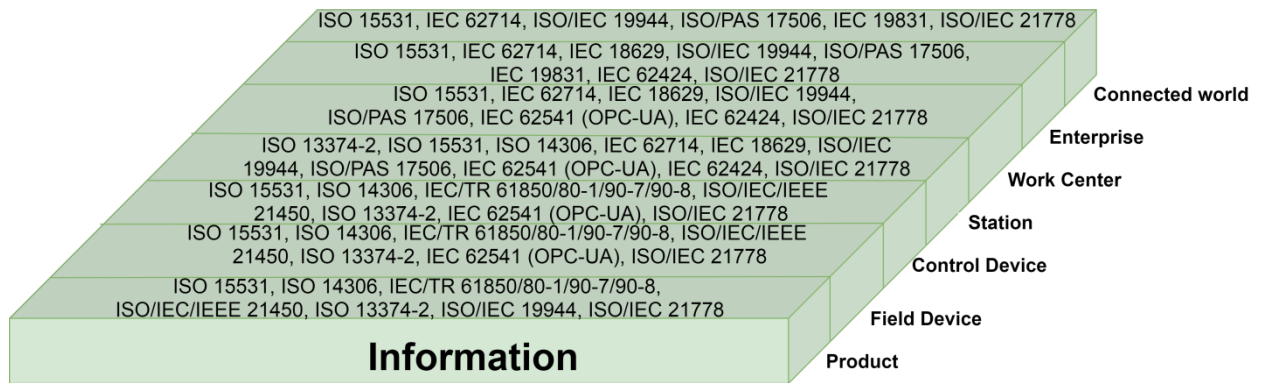


Fig. 6 – Standards matching the Information Layer of RAMI 4.0

3.5. Functions

The Functions Layer is responsible for rules and decision-making logic supporting the Business Layer [18]. Core functionalities of this layer are: (i) formal description of the functions, (ii) horizontal integration, (iii) modelling, and (iv) run-time environment for services supporting business layer [15]. Message Authentication is also placed on the Functional Layer of the RAMI 4.0 model. In this regard, a related standard devoted to message authentication is ISO 16609:2012, specifying the Message Authentication Code (MAC). MAC is the field containing the key that is transmitted with the message and used to analyse, if the message was changed. It only supports symmetric algorithms, in other words, the key is the same for recipient and sender. The standard is specifically focused on banking operations supporting algorithms specified by ISO 9797 [84]. Another standard complementing the ISO 9797 is the ISO/IEC 29192-6, which introduces lightweight MAC authentication algorithms. Moreover, the ISO/IEC 29192 series addresses a set of issues related to cryptography and cyber security mechanisms for RDIFs, Smart Cards, health-care systems, sensor networks, etc. Some topics covered are: hash functions, block ciphers, stream ciphers [85], but also the asymmetric techniques are considered, as opposed to ISO 16609.

Issues related to high-level data processing, semantic analyses, and service logic are the part of Functions Layer. In this regard Collaborative Information Processing (CIP), specified by the ISO/IEC 20005:2013 standard, is of particular importance. CIP is a combination of both processing and collaborative mechanisms for management of data retrieved from sensor networks, whereas focused on services provided by CIP, service interfaces, CIP functionalities, and CIP functional model [86]. Aspects related to data presentation for technical analysis, as well as generation of recommendations on how to cope with different sorts of failures are covered by the ISO 13374-4:2015 standard [87]. The part 4 of the ISO 13374 is intended to provide specifications for condition monitoring and diagnostics (CM&D) to system designers and on how to manage and represent the recommendations within the manufacturing domain [88]. Thus, ISO 13374 is in line with the tasks which are part of the Functions Layer of RAMI 4.0. A closely related standard, stating the key performance indicators to assess manufacturing activities and more specifically contributing to Manufacturing Operations Management, is the ISO 22400. This standard belongs to the third level of the model specified by the IEC 62264 standard [89] that corresponds to the functional Layer of the RAMI 4.0 reference model. Some KPIs provided by this standard, namely the ones related to business planning and logistics [90], match the fourth level of IEC 62264 that is equal to the Business Layer of RAMI 4.0.

An IoT Reference architecture is described by ISO/IEC 30141. This standard introduces the core characteristics of IoT summarized in the IoT conceptual model. According to some authors, e.g. [91], it is the only standard clearly identifying core IoT architectural building blocks. Some of the building blocks to be mentioned are: IoT Device, Sensors, Actuators, Services, IoT Gateway, etc. Moreover, the standard represents an IoT architecture from five different views: (i) *system view*, including physical components, their behaviour, and interconnections, (ii) *communication view*, mentioning some IoT communication networks, (iii) *functional view* (technology agnostic view), (iv) *information view*, considering the data flows among entities, and (v) *usage view*, considering the IoT system from the user perspective [92]. The standard is related mostly to the Functional Layer of RAMI 4.0, although covering some issues from the underlying layers, such as the Information and Communication Layers. Digitalization or digital representation of manufacturing assets is reflected in the IEC 62832 standard. The standard provides a reference model for representation of production system [93], as well as general principles of the Digital Factory Framework and elements, and rules required for production system modelling [94]. The standard is still in its infancy, as only the first part has been published. Other parts, including the data model related to the Information Layer, are under development. However, as the standard covers topics of the Functional Layer, such as a modelling basis for production systems, including production system elements and relationships, it also relates to the Functional Layer.

The Knowledge Discovery Meta-model (KDM) is introduced by the ISO/IEC 19506 standard. KDM is intended to represent the software assets and their associations within the operational environment contributing to Software Assurance (SwA) and Architecture-Driven Modernisation (ADM). In terms of outdated software systems' modernisation, the standard covers all ADM stages: reverse engineering, restructuring, and forward engineering [95]. Moreover, it addresses the interoperability issues for data exchange among different tools developed by different vendors [96].

Table 1 – Analyzed standards related to appropriate Layers and Hierarchy Levels

RAMI 4.0		Layers				
		Asset	Integration	Communication	Information	Functions
Hierarchy Levels	Product	IEC 62443-4.1/2, IEC 61508, IEC 61131-1/2/3, IEC 62453, IEC 61511		ISO/IEC 27033, ISO/IEC 20922, ISO 11898, ISO 16845, IEC 62734, IEC 61158, IEC/TR 61850, ISO 13374-3	ISO 15531, ISO 14306, IEC/TR 61850/80-1/90-7/90-8, ISO/IEC/IEEE 21450, ISO 13374-2, ISO/IEC 19944, ISO/IEC 21778	ISO 13374-4, ISO 16609, ISO/IEC 29192, ISO/IEC 29100
	Field Device	IEC 61499, IEC 62453, IEC 61508, IEC 61511, ISO 13849, IEC 62061	ANSI/ISA-101.01, IEC 61804-2/4, IEC 62769, IEC 62453	ISO 11898, IEC 61784, IEEE 802.15.4, IEC 62541 (OPC-UA), IEC/TR 61850, ISO 9506, IEEE 1451, ISO/IEC/IEEE 21451, ISO 13374-3, ISO/IEC 27033, ISO/IEC 20922, ISO/IEC 19464, ISO 16845, IEC 62734, IEC 61158, IEC 61131-5, ISO/IEC 21823-2	ISO 15531, ISO 14306, IEC/TR 61850/80-1/90-7/90-8, ISO/IEC/IEEE 21450, ISO 13374-2, IEC 62541 (OPC-UA), ISO/IEC 21778	ISO 13374-4, ISO/IEC 20005, ISO/IEC 29192, ISO/IEC 21823-3, ISO/IEC 30141, IEC 62832
	Control Device	IEC 61131-1/2/3, IEC 61499, IEC 62443-4.1/2, IEC 62453	ANSI/ISA-101.01, IEC 61804-2/4, IEC 62769, IEC 62453	ISO 11898, IEEE 802.15.4, IEC 62541 (OPC-UA), IEC/TR 61850, ISO 9506, IEC 61131-5, IEEE 1451, ISO/IEC/IEEE 21451, ISO 13374-3, ISO/IEC 27033, ISO/IEC 20922, ISO/IEC 19464, ISO 16845, IEC 62734, IEC 61158, IEC 61131-5, ISO/IEC 21823-2	ISO 15531, ISO 14306, IEC/TR 61850/80-1/90-7/90-8, ISO/IEC/IEEE 21450, ISO 13374-2, IEC 62541 (OPC-UA), ISO/IEC 21778	ISO 13374-4, ISO/IEC 20005, ISO/IEC 21823-3, IEC 62872, ISO/IEC 30141, IEC 62832
	Station	IEC 61131-1/2/3, IEC 61499, IEC 62453	ANSI/ISA-101.01, IEC 62769, IEC 62453	IEC 62541 (OPC-UA), ISO 13374-3, ISO/IEC 27033, ISO/IEC 20922, ISO/IEC 19464, ISO/IEC 21823-2	ISO 13374-2, ISO 15531, ISO 14306, IEC 62714, IEC 18629, ISO/IEC 19944, ISO/PAS 17506, IEC 62541 (OPC-UA); IEC 62424, ISO/IEC 21778	ISO 13374-4, ISO/IEC 19506, ISO/IEC 29100, IEC 62714, IEC 62872, ISO/IEC 30141, IEC 62832
	Work Center	IEC 62453	ANSI/ISA-101.01, IEC 62769, IEC 62453	IEC 62541 (OPC-UA), ISO/IEC 27033, ISO/IEC 20922, IEC 19464	ISO 15531, IEC 62714, IEC 18629, ISO/IEC 19944, ISO/PAS 17506, IEC 62541 (OPC-UA), IEC 62424, ISO/IEC 21778	ISO/IEC 19506, ISO/IEC 29100, ISO 22400, IEC 18629, IEC 62714, IEC 62872, ISO/IEC 30141, IEC 62832
	Enterprise	IEC 62453	ANSI/ISA-101.01, IEC 62453	ISO/IEC 27033, IEC 19464, IEC 19831	ISO 15531, IEC 62714, IEC 18629, ISO/IEC 19944, ISO/PAS 17506, IEC 19831, IEC 62424, ISO/IEC 21778	ISO 16609, ISO/IEC 19506, ISO/IEC 29100, ISO 27018, ISO 22400, IEC 18629, IEC 62714, IEC 62872, ISO/IEC 30141
	Connected World		ANSI/ISA-101.01	ISO/IEC 27033, IEC 19464, IEC 19831	ISO 15531, IEC 62714, ISO/IEC 19944, ISO/PAS 17506, IEC 19831, ISO/IEC 21778	ISO 16609, ISO/IEC 29100, ISO 27018, IEC 18629

In terms of privacy requirements, an important standard is ISO/IEC 29100, which represents a high-level framework addressing the protection of personally identifiable information (PII) [97]. The scope of the standard covers organisations and companies involved in management, maintenance, or processing of systems requiring personal data for functioning. Some essential privacy aspects identified by the standards include: (i) consent and choice, (ii) purpose legitimacy and specification, (iii) data collection restrictions, (iv) minimization of personal data amount, (v) use, retention and disclosure limitation, (vi) openness and notice, (vii) information security controls, and (viii) accountability [98]. Another important PII focused standard is the ISO 27018, particularly addressing the cloud providers and giving the basis for compliance with EU Data Protection Directive [99].

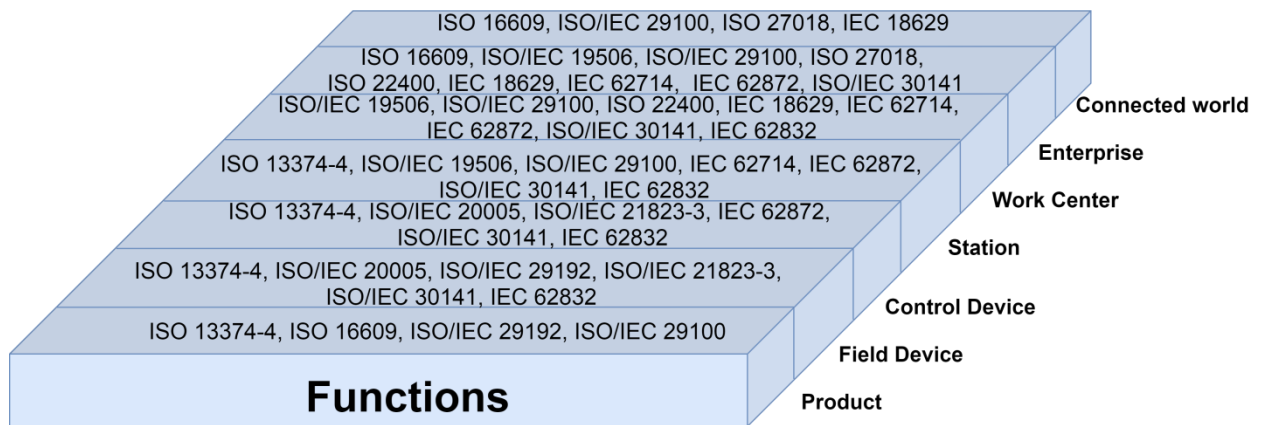


Fig. 7 – Standards matching the Functions Layer of RAMI 4.0

4. Discussion and standardization gaps

Even if the existing number of standards is not showing a gap in the sense that every function layer of the RAMI 4.0 model has at least one standard that can be related to it, the use and need of standards is permanently evolving. Thus, the 4DMP Cluster of projects is contributing to standards as well. This is done in several ways. The use and priority of standards in the 4DMP cluster is regularly updated by relevant project partners coming from industry and academic institutes. This is covering the majority of the standards listed here. After reviewing the available standards we identified a set of topics that are promising for further development in the context of standardization. This includes:

Standardization efforts towards establishment of well defined interfaces to integrate various manufacturing services inside a single platform or marketplace are of crucial importance. Among the key directions we can mention the identification of common formats for user and application data, including specification of mandatory, as well as optional data fields. For instance, it should be clear what data and in which format are to be requested from the user side, so that the developer is aware that platform supports a certain standard or a set of standards and the designed application can be easily integrated into the platform. In relation to this particular issue another challenge is middleware interoperability. Middleware supposed to bridge various platforms, marketplaces, or applications should be easily extensible to incorporate new entities, providing transparent interfaces.

Another promising direction for standardization efforts is the “Plug and Produce” aim to decrease the time of new assets deployment. The “Plug and Produce” principle, by analogy with the Plug-and-Play, is based on the idea of simple integration of new devices into the manufacturing ecosystem, including simplified data exchange mechanisms. “Plug and Produce”, as identified in [100], involves 3 main stages: (i) physical attachment of a device (e.g. smart object) to the ecosystem, (ii) communication establishment to the device or the representative entity, and (iii) integration of device on logical level. The standardisation should encompass each stage of the “Plug and Produce” process. Thus, when the asset is attached to an ecosystem, it becomes visible for all authorised users within the ecosystem, thus sharing its configuration and high-level logical model, being ready to be utilized without extensive efforts.

Another big standardisation challenge is related to security and privacy of the manufacturing systems and assets. Some important characteristics of the manufacturing ecosystems and CPS in particular are modularity, heterogeneity, distributed nature, and physical, as well as virtual dimensions [101]. Some issues of security and privacy are partially or sufficiently covered by existing standards, e.g. authentication issues or cryptographic algorithms. Talking about security and privacy in the context of manufacturing ecosystems it is crucial to distinguish various types of security: (i) security of data, (ii) security of components/assets, and (iii) security of the production processes. The manufacturing data undergoing the biggest threat while being transferred or shared with other partners within or from outside of the manufacturing ecosystem / collaborative network. Thus, efforts need to be focused not only on technological mitigation approaches, but also on administrative aspects through the combination of various access schemas. Another vector for standardisation efforts in security domain, especially in the context of ZDM, is the development of strategies and techniques to maintain integrity of manufacturing devices, preventing ascending and descending data flows modification [102]. Also the ways to avoid unauthorised modification of manufacturing process that can cause higher defects rate has to be the subject of additional standardisation efforts.

Despite the significant number of standards for communication technologies and protocols, some of them such as MQTT and AMQP publish-subscribe protocols are presented in this paper. However, there are still some challenges related to vendor-specific protocols implementations. For instance, there are more than 25 available industrial Ethernet protocols implemented on vendor-specific basis [103]. This adds more complexity and reduces flexibility [30] to the process of integration requiring additional interfaces and adapters for managing data flows.

Collaboration mechanisms are playing significant role in Industry 4.0 [7]. Collaboration challenges for manufacturing ecosystems can be divided into technological, organisational/business or mixed. Modern manufacturing ecosystems generate large amounts of data coming from sensors and controllers deployed on various stages of the production chain, from the shop floor to the logistics network, which creates a big interdependence among components. This has also led to appearance of data-rich environments requiring new orchestration and collaboration approaches [5]. Moreover, growing intelligence and autonomy of components sets new challenges for the organisational structures of the manufacturing ecosystems, allowing to move away from the production-centric to the user-centric paradigm. Development of novel Human-Machine Interfaces creates a basis for human-machine collaboration, e.g. machine helping the worker to perform tasks that could not be accomplished

by the worker alone and vice-versa, in other words integration of human and machine capabilities.

For the very specific field of Zero Defects Manufacturing, only few standards can be found. This is surely due to the fact that ZDM makes use of standards from different sectors like quality management and smart manufacturing. Nevertheless, it seems that ZDM specific gaps could still be filled. Zero Defects Manufacturing specific terms are very scarcely or not defined in current standards. As a common definition of terms forms a basis for a common understanding and fosters a clear communication, the 4DMP cluster of projects engages in the definition of terms, specific for ZDM. Another idea for a standard relates to the process of transforming a manufacturing unit into a ZDM unit, so that matches certain quality criteria with the right use of digital manufacturing tools. For instance, for predictive maintenance, a common process for the monitoring of tools and machines would be useful. This process could not only predict the failure of machines, but also predict if the machine produces a part which does not meet the specs.

As a part of further work, three other topics have been identified by the 4DMP cluster. As such, recommendations to standards are expected to be planned and formulated via conducting CEN-CENELEC Workshops in which CEN-CENELEC Workshop Agreements (CWA) will be created. The creation of a CWA follows a streamlined standardisation process and may therefore take less than a year. However, the CWA does not have the status of a full standard, but can well serve as a template for a future standard, which then goes through the full standardization process. [104]. Those CWAs will be prepared for three topics: (i) Zero Defects in Digital Manufacturing Terminology, (ii) Marketplace Requirements, and (iii) Data Exchange Guidance. As for Data Exchange, other initiatives can be observed claiming to create new European-driven standards especially for cloud based solutions. For instance, the project Gaia-X [105] has the goal to establish a federated, open data infrastructure. Based on a Franco-German initiative, this project is open for contributions from all European countries. Thus, it might be the case that the current development of the project might be taken into account also for the 4DMP Cluster standardization initiatives. All three topics will be connected to digital manufacturing platforms.

To give an insight on the ongoing efforts, the work of 3 standardisation groups, namely *IEC TC 65*, *ISO/IEC JTC 1/SC 41*, and *ISO/IEC JTC 1/SC 27* of the IEC and ISO standardisation bodies is presented in the Table 2. These groups were selected as an illustrative example of the ongoing work on relevant standards for the manufacturing domain. Nevertheless, some other groups are also working on computer aided manufacturing relevant standards, as for instance *ISO/TC 108/SC 5* (condition monitoring of machine systems) or *ISO/IEC JTC 1* (Information technology general). The *IEC TC 65* group is focused on standards and specifications for systems and components for industrial process measurement, control, and automation. Some of the standards produced by this group were considered in the current work, such as IEC 62443. New editions of parts 2-1 and 2-2 of this standard are being prepared and considered in Table 2. Most of the standards coming from *IEC TC 65* are intended for the Asset and Integration Layers of RAMI 4.0. As for the *ISO/IEC JTC 1/SC 41*, the group is addressing issues related IoT and auxiliary technologies. Examples of considered topics are: trustworthiness of IoT services, real-time IoT frameworks, modelling requirement for IoT components, issues related to data management, etc. Another mentioned standardisation group is the *ISO/IEC JTC 1/SC 27* that considers the standards related to protection of Information and ICT in general, whereas covering both security

and privacy issues. Among the considered topics it is worth mentioning: identity management, integrity and confidentiality of information, security management systems, security services, and security requirements. Some standards developed within this group, such as ISO/IEC 28003 and 27033 were considered by our work.

Table 2. Manufacturing related standards under development

IoT related standards under development ISO/IEC JTC 1/SC 41	
ISO/IEC AWI 30147	Information technology – Internet of things – Methodology for trustworthiness of IoT system/service
ISO/IEC AWI 30144	Information technology – Sensor network system architecture for power substations
ISO/IEC WD 30162	Internet of Things (IoT) – Compatibility requirements and model for devices within industrial IoT systems
ISO/IEC AWI 30165	Internet of Things (IoT) – Real-time IoT framework
ISO/IEC AWI 30161	Internet of Things (IoT) – Requirements of IoT data exchange platform for various IoT services
ISO/IEC AWI 30163	Internet of Things (IoT) – System requirements of IoT/SN technology-based integrated platform for chattel asset monitoring supporting financial services
ISO/IEC AWI 30149	Internet of things (IoT) – Trustworthiness framework
Computer aided Manufacturing standards under development IEC TC 65	
IEC 62832-1/2/3 ED1	Industrial-process measurement, control and automation - Digital Factory framework - Part 1: General principles / Part 2: Model elements / Part 3: Application of Digital Factory for life cycle management of production systems
IEC PAS 63325 ED1	Lifecycle requirements for Functional Safety and Security for IACS
IEC TR 63319 ED1	A meta-modelling analysis approach to smart manufacturing reference models
IEC TR 63283-1/2/3 ED1	Industrial-process measurement, control and automation – Smart Manufacturing – Part 1: Terms and definitions / Part 2: Use cases / Part 3: Recommendations for cybersecurity
IEC 62872-2 ED1	Internet of Things (IoT) – Application framework for industrial facility demand response energy management
IEC 62443-2-1 ED2	Security for industrial automation and control systems - Part 2-1: Security program requirements for IACS asset owners
IEC 62443-2-2 ED1	Security for industrial automation and control systems – Part 2-2: IACS Security Program Ratings
IEC 63278-1 ED1	Asset administration shell for industrial applications – Part 1: Administration shell structure
PNW 65-815	Unified reference model for smart manufacturing
Security and Privacy Standards (general considering potential importance for Manufacturing domain) under development ISO/IEC JTC 1/SC 27	
ISO/IEC WD 27071.3	Information technology — Security techniques — Security recommendations for establishing trusted connection between device and service
ISO/IEC WD 24392.2	Information technology — Security techniques — Security reference model for Industrial Internet Platform (IIP)
ISO/IEC WD 27557	Organizational privacy risk management
ISO/IEC WD 27035-1.3/2.3	Information technology — Security techniques — Information security incident management — Part 1: Principles of incident management / Part 2: Guidelines to plan and prepare for incident management
ISO/IEC CD 27030	Information technology — Security techniques — Guidelines for security and privacy in Internet of Things (IoT)
ISO/IEC WD 27402	Cybersecurity — IoT security and privacy — Device baseline requirements
ISO/IEC DIS 11770-7	Information security — Key management — Part 7: Cross-domain password-based authenticated key exchange
ISO/IEC FDIS 20547-4	Information technology — Big data reference architecture — Part 4: Security and privacy
ISO/IEC WD 27046.2	Information technology — Big data security and privacy — Implementation guidelines
ISO/IEC WD 27045	Information technology — Big data security and privacy — Processes

5. Conclusion

Zero Defects Manufacturing concept is an important part of the Industry 4.0 paradigm aiming at minimisation of the production cost as well as making it more sustainable, whereas reducing the number of faults, failures, and defect parts. Several European initiatives, such as ZDMP, are targeting this important topic. The ZDMP project is part of the 4DMP Cluster that is group of European manufacturing initiatives focused on several key development challenges, including: establishment of a common digital marketplace for manufacturing services, platforms interoperability and subsequently standardisation efforts. Standardisation efforts are directed towards creation of a common basis for further manufacturing solutions to be developed, not from the scratch, but based on already elaborated elements.

However, as extensively discussed in previous sections, there is an extremely large number of standards, many of them partially overlapping, which makes the task of any systems' designer very hard. This article targets the standardisation and interoperability issues, representing a step towards the establishment of a common portfolio of standards. In conjunction with RAMI 4.0 this should provide a common vision for the platforms' designers, integrators, as well as service developers, while offering them a kind of "navigation guide" through the multitude of existing standards.

In spite of the large number of discussed standards, there are still areas needing further standardization efforts in this domain. Thus, several topics were identified as needing special attention, namely: applications metadata, user metadata, security, and privacy. Moreover, another important challenge is to move towards federation of various platforms and marketplaces coming from different European industrial projects. The level of integration / federation of platforms and marketplaces is still to be determined during execution of the CWA initiative. To fulfil this task, the common interoperability principles including the standardisation aspects are analyzed. In this regard, this particular work also aims at alignment of standards with the RAMI 4.0 reference model to improve the interoperability. Thus, grouping of standards based on their relation to certain Layers and Hierarchy Levels is of crucial importance. In this way, third-party platforms that do not follow the RAMI 4.0 reference model will be able to assess the best way to integrate their solutions based on the standards or technologies used. Thus, the established portfolio of standards can be useful not only for the 4DMP Cluster members, but also for other initiatives in the manufacturing domain. Even, if the designers of manufacturing platform are not aware of RAMI 4.0, but they are using some standards from the standards' portfolio, it is possible to interrelate the developed components to the corresponding layer and thus more easily integrate the third-party solution with the 4DMP Cluster platforms or other platforms following the RAMI 4.0.

Future activities will be connected with enrichment of the portfolio of standards with relevant up-to-date standards and improvement of the navigation guide. Another research direction is to develop a framework that will integrate several reference models or architectures for further improvement of interoperability. Moreover, an important activity has to consider the third dimension of the RAMI 4.0, besides the Layers and Hierarchy Levels, namely the Life Cycle and Value Stream.

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