REFERENCE ARCHITECTURE MODELS FOR INDUSTRY 4.0, SMART MANUFACTURING AND IOT

AN INTRODUCTION

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1 Introduction

The digitalisation of industrial production makes it more and more important to present the entire life cycle of a product as a comprehensive model. Models reduce complex realities to the essentials and therefore allow for functional representations of complex structures and processes to be created. The complexity of product life cycles is increasing mainly because developers, manufacturers, suppliers and customers will be even more connected in the future – both in product development and production. This means that it will no longer be enough to model connections in pairs only. Industrial production needs to be modelled as a complete system because most system components are indirectly connected. The aim of such comprehensive modelling is to ultimately increase flexibility in the production process to potentially reduce the minimum quantity of a product to one (cf. Heidel et al. 2017).

In the past decade, various terms have been coined and used in connection with the digitalisation of industrial production: Smart Manufacturing, Industry 4.0, IoT (Internet of Things) and IIoT (Industrial Internet of Things) (cf. Li et al. 2018). In recent years, various reference models for system architectures, called reference architecture models, have been published for Industry 4.0, Smart Manufacturing, IoT and IIoT. How are these models related? And what is the benefit of using a reference architecture model?

A reference model is a common and useful model, on the basis of which specific models can be derived (cf. DIN SPEC 91345:2016-04). Based on this definition, specific models for system architectures can be derived from a (general) reference architecture model. But what value does presenting its own processes in such a model create for a company, consortium or research project? A reference model helps to effectively derive system architectures. System architectures provide a common terminology and structure between different stakeholders (developers, manufacturers, suppliers and operators etc.) for different technical systems, some of which have very different nomenclatures. The architectures achieve this by creating a uniform virtual representation of technical objects (assets). The condition for this is that the reference model is generally applicable to all relevant assets and processes in the implementation project. A reference architecture model also provides a better overview of relevant standards which can also be included in this model.

In chapter 2, we will look at current reference architecture models for Industry 4.0 or Smart Manufacturing, and for IoT/IIoT. The term Industry 4.0 is mainly used in Germany in connection with the digitalisation of industrial production.[1] In other countries, the term Smart Manufacturing has become more established.

When industrial components form large IoT/IIoT systems, reliable communication or seamless and cost-effective interaction between the individual parts is crucial (cf. Lin et al. 2017). IoT/IIoT are therefore the basis for a fully digitalised industrial production. Nevertheless, there are significant differences between the reference architecture models for Industry 4.0 and those for IoT/IIoT. These differences are due to the fact that IoT/IIoT also cover the fields of energy, healthcare, industrial production and transport as well as the public sector, among other things. This means that interoperability plays a more important role. The concept of Industry 4.0, on the other hand, focuses more on effective industrial production (cf. Lin et al. 2017).

This paper presents those reference architecture models for Industry 4.0 and IIoT that are internationally known and used. However, it is very difficult to determine how widespread the individual models actually are. The rule of thumb is that the models are more widespread in the country in which they were developed or proposed than elsewhere. This means that the internationally familiar RAMI 4.0 Reference Architecture Model is probably the best known reference architecture model for Industry 4.0 in Germany. Due to the fact that the Industrial Internet Consortium (IIC) now also includes some German companies, the IIC IIoT Reference Model developed there is increasingly being considered in Germany.

Chapter 3 presents three important industry and consortium standards which are frequently discussed in connection with reference architecture models: the administration shell, OPC Unified Architecture (OPC UA) and AutomationML.

Chapter 4 provides answers to the questions of why the reference models differ so much and which model is best suited for which purpose.

1 Industry 4.0 was originally set up as a project of the German government’s high-tech strategy in 2012. In 2013, the BITKOM, VDMA and ZVEI associations founded the Industry 4.0 platform, which is now under the direction of BMWi and BMBF and in which numerous stakeholders from business, science, trade unions and associations are taking part.

2 Reference Architecture Models for Industry 4.0

Most of the reference architecture models for Industry 4.0 described in this paper are based on the “automation pyramid” which illustrates the different levels of information technology in industrial production (cf. IEC 62264). First, there is the company level at which ERP software (Enterprise Resource Planning) plans and controls the basic processes in purchasing, production and sales. Then there is the operations management level where the use of personnel, machines and materials is managed in Manufacturing Execution Systems (MES). And last, there are the process management and control levels where the machines are actually monitored and controlled (see figure 1).

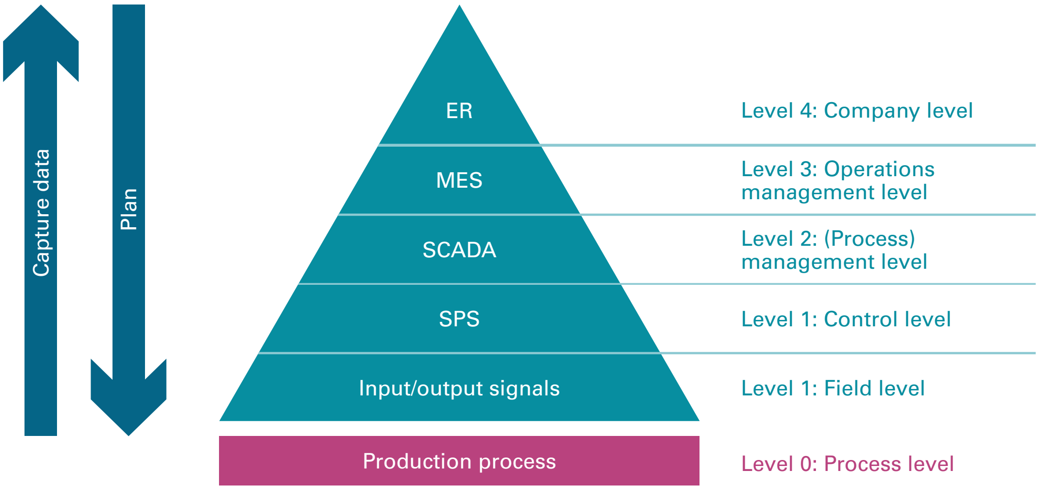

Figure 1 The automation pyramid allows for IT systems to be assigned to the various levels of industrial production (according to Gunther Reinhart (ed.): Handbuch Industrie 4.0: Geschäftsmodelle, Prozesse, Technik, Hanser: Munich 2017)

2.1 RAMI 4.0

Reference Architecture Industry 4.0 (RAMI 4.0) is a reference architecture model which was developed mainly by members of the Industry 4.0 platform and was introduced into standardisation nationally through DIN SPEC 91345:2016 and internationally through IEC/PAS 63088:2017. It describes a reference model for the architecture of technical components (assets) which enables their description and life cycle as well as their assignment to technical and organisational hierarchies to be defined (cf. DIN SPEC 91345:2016-04). Any asset that is used in a company as part of its manufacturing process can therefore be classified in RAMI 4.0. The classification of all relevant assets in the model allows both a virtual representation of these assets and a uniform, virtual, efficient description of all relevant processes and standards and therefore ultimately provides the basis for Industry 4.0.

The model comprises three dimensions for describing the assets through

- the different levels (layers) of their digital representation: from the level of physical devices to the level of business models,
- their classification in the functional hierarchy of a production plant or company (hierarchy levels) and
- their classification in a simple life cycle model consisting of the development (type) and the production (instance) of an asset.

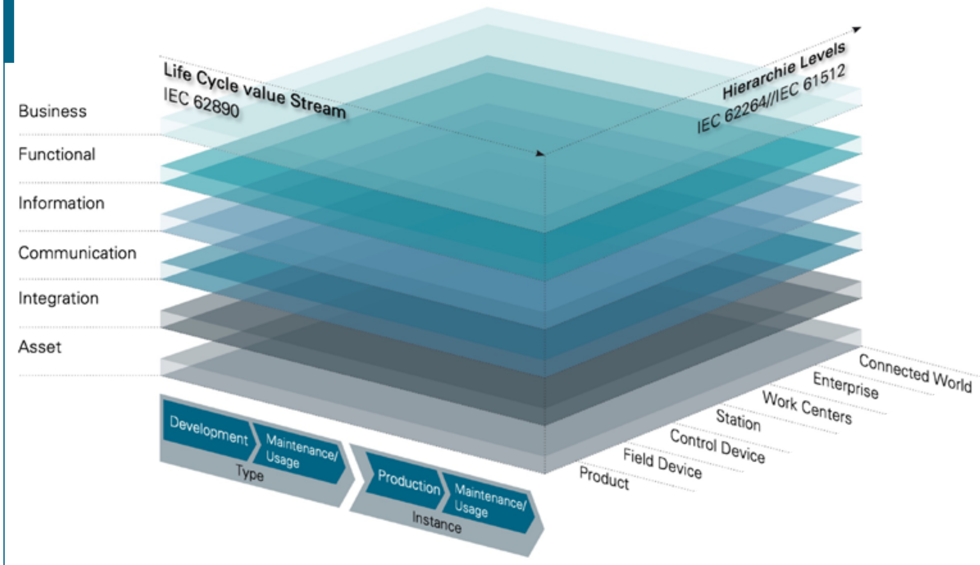

Figure 2 Representation of Reference Architecture Industry 4.0 as a “RAMI cube” (source: Industry 4.0 platform)

Three-dimensional layer models such as RAMI 4.0 allow each asset classified in the model, in other words each technical component, to be linked to its direct neighbours in three dimensions.

RAMI 4.0 follows international standards both along the hierarchy axis (cf. IEC 62264 and IEC 61512) and the life cycle axis (cf. IEC 62890 ED1:2016). Here, any combination of assets can be an asset again which means that the composite asset is then “higher” on the hierarchy axis. For example, the components of a machine are assets, and the machine composed of them is an asset. So, a CNC milling machine with a ball screw is an asset, but the ball screw itself is also an asset.

In principle, each asset of a company can be classified in the hierarchy/life cycle level according to the stage in its life cycle. Along the architecture axis, the layers form the six levels of the three-dimensional layer model. The various layers – Asset, Integration, Communication, Information, Functional and Business – each handles information relevant to it. The Asset layer comprises the elements of the physical world, while the other five layers represent the virtual world. The Integration layer essentially contains information about the conditions and states of the physical world as well as digital information relevant for the asset (e.g. firmware). The Communication layer describes an asset's ability to exchange information. Important information for the functions of an asset is represented in the Information layer, while the Functional layer includes the functionalities themselves. The Business layer ultimately represents all the business aspects of an asset.

An asset to be included in the model is classified in the hierarchy/life cycle level depending on its hierarchy level and life cycle, i.e. in a comparatively simple, rough discrete model. The description of the asset in the administration shell (in which the real and virtual worlds are linked; see Section 0 for more detailed information) can then be very detailed depending on the asset (cf. DIN SPEC 91345:2016-04). The structure of RAMI 4.0 itself is very general so it can be used for all conceivable assets in Industry 4.0, if possible.

RAMI 4.0 is a reference architecture model that is also known outside Germany, which is why it is used as a reference below.

2.2 NIST Smart Manufacturing Ecosystem

The National Institute of Standards and Technology (NIST), a federal agency in the United States, has developed and published reference architectures on a wide range of information technology topics, from cloud computing to big data. The Smart Manufacturing Ecosystem published by NIST (August 2015) already contains the idea of a multidimensional representation of Industry 4.0, but there are great differences to RAMI 4.0 and the three-dimensional layer models described below (cf. Lu et al. 2015). In the NIST model, the product, production and business dimensions have their own life cycles and meet in the (one-dimensional) automation pyramid. See figure 3. In fact, the NIST model can be mapped to the three-dimensional layer models (RAMI 4.0 already contains the NIST model in the Asset and Business layers). Vice versa, the three-dimensional layer models cannot be fully mapped to the NIST model because they contain more levels of description (Integration, Communication, etc.).

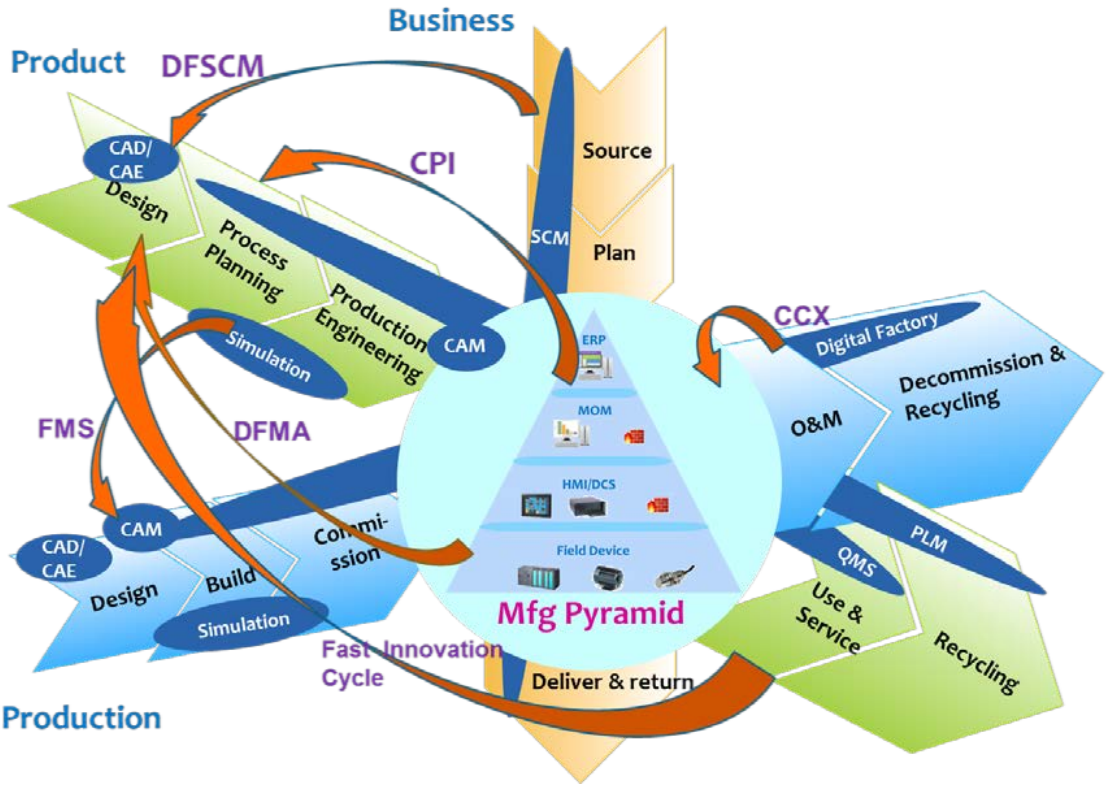

Figure 3 The NIST Smart Manufacturing Ecosystem (Source: NIST)

2.3 IMSA

The development of the IMSA (China Intelligent Manufacturing System Architecture) model followed the "Made in China 2025" strategic plan developed by the Chinese government. The objective of this plan, which was inspired by the German Industry 4.0 project, is a comprehensive enhancement of Chinese industry (cf. Kennedy 2015).

IMSA was published on December 30, 2015. It is also a three-dimensional layer model that includes the life cycle, system hierarchy and intelligent functions dimensions (cf. Wie et al. 2017).

IMSA is strongly reminiscent of RAMI 4.0 in its structure. The main difference is that RAMI 4.0 divides the life cycle axis into development and production, allowing these two phases to be considered independently of each other. This is not the case in IMSA. The two models can nevertheless be mapped very well to each other. (Cf. BMWi 2018)

2.4 Big Picture

The TR 23087 Technical Report (cf. ISO/TR 23087:2018-03) of the International Organization for Standardization (ISO) provides a complete overview of the standards (The Big Picture of Standards) for automation systems and integration. French standardisation organisation AFNOR and French electricity company EDF (Électricité de France) were particularly involved in preparing this technical report. This document essentially classifies standards which were prepared by the TC 184 (Automation Systems and Integration) technical committee of ISO and TC 65 (Control Technology for Industrial Processes) of the IEC (International Electrotechnical Commission) standardisation organisation.

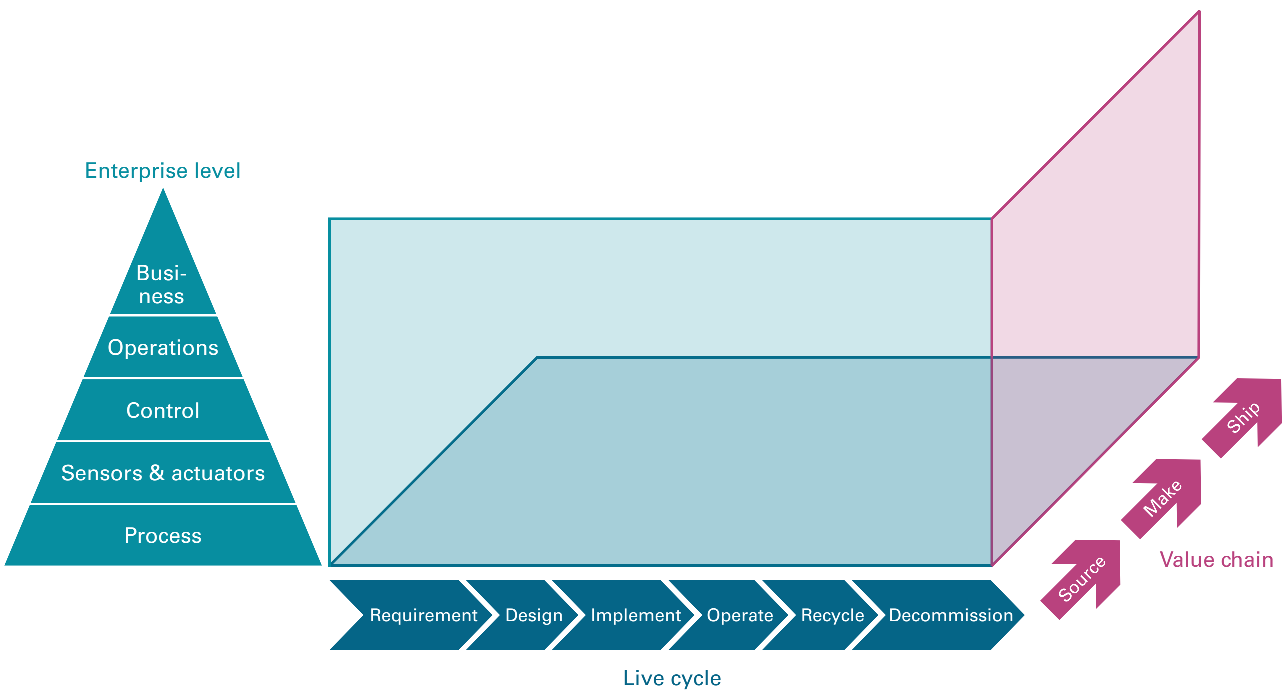

Figure 4 The description axes in the Big Picture (source: ISO/TR 23087)

The Big Picture is a three-dimensional layer model that includes the enterprise level (comparable to the levels of the automation pyramid), value chain and life cycle axes (see figure 4). The life cycle axis is comparable to that of RAMI 4.0. The enterprise level is similar to the layers (architecture axis) and the hierarchy level in RAMI 4.0. This means that there is a business enterprise level, but also a sensors and actuators enterprise level. The value chain axis comprises the Source (supply chain), Make (production), Ship (sales) and Whole (all three) values. These values are also similar to both the individual layers of the architecture axis and the hierarchy level in RAMI 4.0. The model level of the enterprise level/value chain axes in The Big Picture can therefore be mapped to the model level of the architecture/

hierarchy axes in RAMI 4.0. Since the life cycle axis is common to both models, the models can be mapped completely to each other. This is particularly interesting when dealing with a possible meta model of the existing reference architecture models for Smart Manufacturing. So The Big Picture can describe the same assets and processes as RAMI 4.0, but looks at them from a different perspective. It would therefore be extremely worthwhile to classify the standards from ISO/TR 23087:2018 in RAMI 4.0 because placing current standards in the reference architecture model of choice is an important step that has already been taken in The Big Picture (cf. ISO/TR 23087:2018-03).

2.5 IVRA

The Industrial Value Chain Reference Architecture (IVRA) was published in 2016 by the Industrial Value Chain Initiative (IVI), a consortium of major Japanese companies such as Mitsubishi Electric, Fujitsu, Nissan Motor and Panasonic (cf. IVI 2016). IVRA is also a three-dimensional reference architecture model. At the heart of IVRA is the three-dimensional model of a Smart Manufacturing Unit. It contains the Activity View, Management View and Asset View axes. This classification shows that information is arranged differently in IVRA than in RAMI 4.0. IVRA's successor, IVRA Next, which is still based on the Smart Manufacturing Unit, was presented at the Hanover Fair in 2018 (cf. IVI 2018).

2.6 ISO and IEC meta model

Since 2017, an ISO and IEC Joint Working Group 21 (JWG 21) has aimed to harmonise existing reference models for Industry 4.0 or Smart Manufacturing. Representatives from numerous nations including the major industrialised nations of USA, China, Japan, Germany and France sit on the JWG 21. The two chairmen of the JWG 21 come from the USA and Japan. Given the time scales in international standardisation, publication of a first draft of findings can be expected in 2020.

2.7 IIRA/IIC IIoT

The Industrial Internet Consortium (IIC) has developed a reference architecture model for the Industrial Internet of Things (IIoT). The IIC was founded in 2014 by AT&T, Cisco, General Electric, IBM and Intel with the aim of simplifying the integration of the physical and virtual worlds and has more than 200 members today including some major German companies. The members of the IIC come from healthcare, transport, energy, public infrastructure and production (cf. Lin et al. 2017). The wide background of the IIC members also reflects the meaning of the term industry in English, which can also refer to economic sectors.

Initially, the IIC published the Industrial Internet Reference Architecture (IIRA) in June 2015; see (cf. IIC 2015). In January 2017, the IIRA was then re-published as the Industrial Internet Consortium: Industrial Internet of Things (IIC IIoT) (cf. Lin et al. 2017).

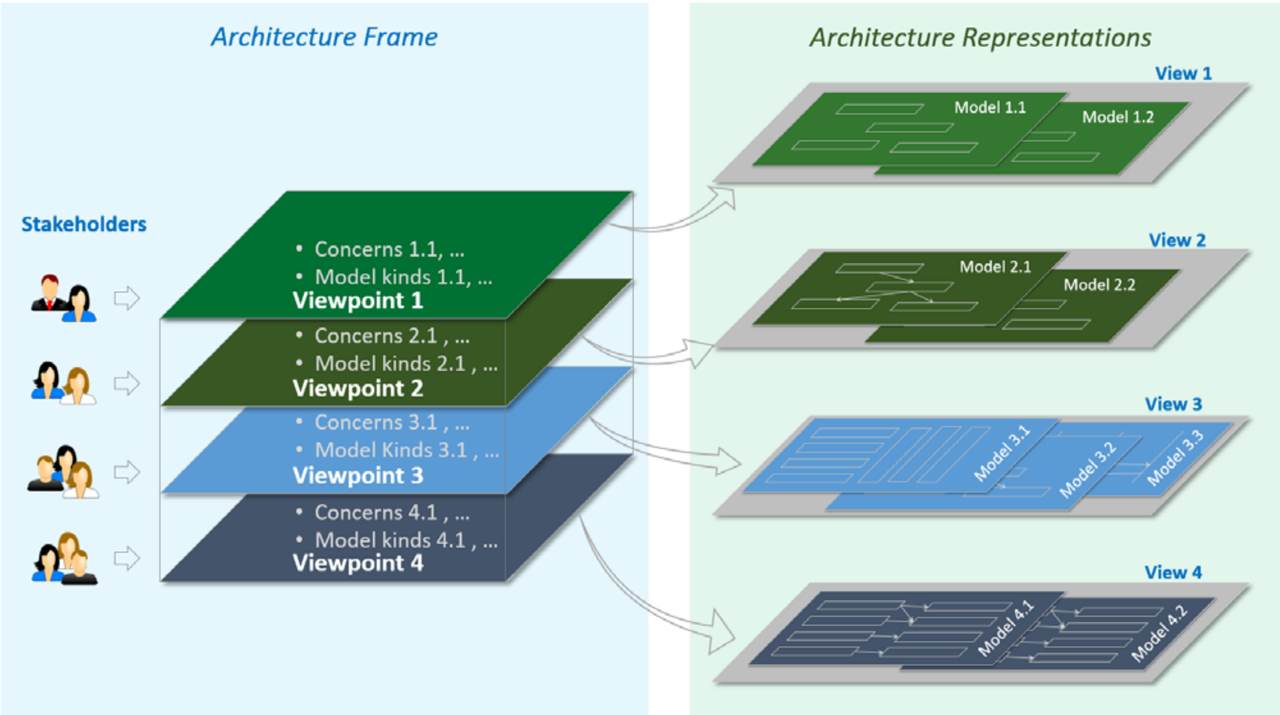

Figure 5 The viewpoints in the IIC IIoT (source: IIC)

IIC IIoT has certain similarities to the three-dimensional layer models used in Industry 4.0 or Smart Manufacturing. But there are also very significant differences. First, the viewpoints can be mapped well to the layers of the architecture axis in RAMI 4.0; see figure 5. IIC IIoT has four viewpoints: business viewpoint, usage viewpoint, functional viewpoint and implementation viewpoint. The structure of the individual viewpoints within IIC IIOT differs considerably. The viewpoints themselves are implicitly linked via system characteristics on reliability and what are known as cross-cutting (cross-functional) functions. Examples of cross-cutting functions are connectivity and data management which affect all viewpoints and link them. According to IIC IIoT, a separate life cycle needs to be defined for each industrial sector (19).

2.8 IoT Reference Architecture

Since 2018, the international standards organisations ISO and IEC have developed the IoT Reference Architecture (IoT RA) in the ISO/IEC 30141 standard within the Joint Technical Committee JCT 1, subcommittee 41, Internet of Things and related technologies (cf. ISO/IEC 30141:2018-08). The IoT RA contains an IoT Reference Model which is not to be confused with the model of the standardisation department of the International Telecommunications Union (ITU-T) (see next section).

The views of IoT RA can be mapped to the views of IIC IIoT. The views of IoT RA are (IIC-IIoT views in brackets): functional view (functional viewpoint), system deployment view (implementation viewpoint), networking view (business viewpoint) and usage view (usage viewpoint).

The characteristics of IoT systems of IoT RA can be mapped to the cross-cutting functions, or the system characteristics of IIC IIoT. The viewpoints on functionality are also very similar in both models.

2.9 General reference models for the Internet of Things

Other reference models that are also mentioned frequently have a much wider application focus and are therefore only marginally interesting for Industry 4.0 or Smart Manufacturing: the IoT-A architectural Reference Model, developed by the IoT-A project from the 7th Research Framework Program of the European Commission; the AIOTI Reference Architecture of the Alliance for Internet of Things Innovation (AIOTI), an initiative of the European Commission; and the ARVIDA Reference Architecture of the BMBF-funded ARVIDA project (cf. Leukert et al. 2016 and ARVIDA 2020).

The International Telecommunication Union's Telecommunication Standardization Sector (ITU-T), which primarily deals with telecommunications, has produced the document "Overview of the Internet of Things" in its Study Group 13 (cf. ITU-T Y.2060:2012-06). Among other things, the standard defines the IoT Reference Model (IoT RM) which obviously focuses on communication aspects.

3 Important industry and consortium standards for Industry 4.0

In the current discussion on Industry 4.0 there are several standards that are currently being developed and are essential for connecting machines and components.

3.1 Administration shell

From the beginning, an important element in the context of RAMI 4.0 was the Industry 4.0 component which was developed at the same time as RAMI 4.0 by the Industry 4.0 platform and was standardised itself alongside the RAMI 4.0 Reference Architecture Model (cf. DIN SPEC 91345:2016-04). This Industry 4.0 component consists of the asset of the physical world and what is known as the administration shell, which provides the physical world with the features that characterise the asset for the information world. Standardisation of the administration shell is driven by the Industry 4.0 platform and ZVEI. The administration shell itself consists of a header and body (see Figure 6).

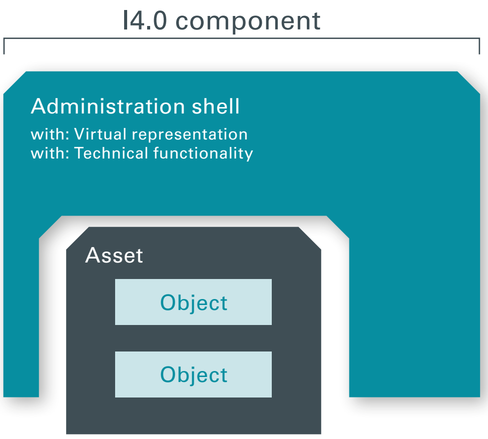

Figure 6 The structure of the administration shell (source: DIN)

A list of features in the header enables the identification and designation of the administration shell as well as concrete objects and, if necessary, refers to selected capabilities of the objects.

In the body, individual submodels are managed within the administration shell. These submodels describe content-related, descriptive or functional aspects (e.g. identification or information security). Each submodel has a structured number of features that reference individual data and functions.

Administration shells, objects, submodels and features must be clearly identified to ensure binding semantics. ISO 29002-5 (e.g. eCl@ss and IEC Common Data Dictionaries) and URIs (Unique Resource Identifiers) are approved as global identifiers (cf. DIN SPEC 91345:2016-04).

3.2 OPC UA

In 1996, the OPC Foundation, an industrial consortium of American companies, first published the OPC standard which was initially limited to Windows systems (cf. OPC 2020). The abbreviation originally referred to the OLE (Object Linking and Embedding) system and protocol developed by Windows; as a result, OPC referred to object linking and embedding in process control. Today, OPC stands for Open Platform Communication.

With the introduction of service-oriented architectures, new requirements were created for IT systems in production with regard to information security and data modelling which the OPC Foundation met with the development of the OPC UA standard (OPC Unified Architecture). OPC UA is an open, platform-independent interface standard that is becoming increasingly established for Industry 4.0 communication (cf. DIN EN IEC 62541). In addition, OPC UA comprises data models and interaction concepts and allows the creation of device and capability descriptions in the form of information models (cf. Angeli, Carsten et al. 2019). Industry-specific, standardised information models are referred to as Companion Specifications (cf. VDMA / Fraunhofer IOSB-INA 2017).

OPC UA Companion Specification Robotics which aims to integrate robotics into Industry 4.0 concepts is particularly relevant for Smart Manufacturing. A draft for the first part of the series – the VDMA Companion Specification 40010-1 – has already been produced (VDMA 40010-1:2019-07). It covers condition management, asset management, predictive maintenance and vertical integration. Basic specifications are defined; in concrete terms, an information model is defined which needs to cover all robotic systems (service robots, mobile robots, etc.).

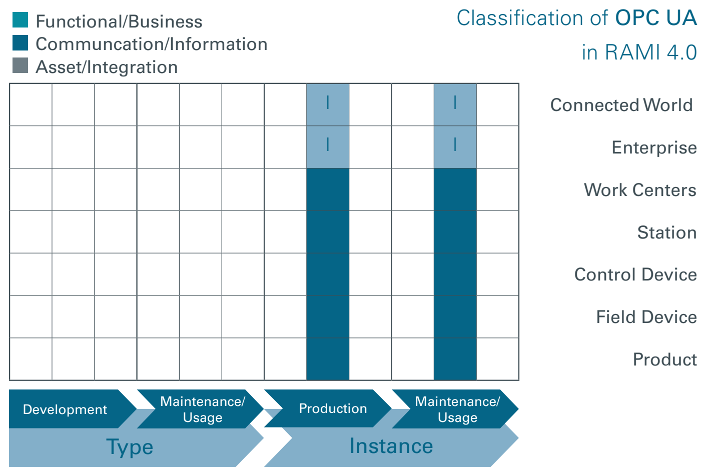

Figure 7 Classification of OPC UA in RAMI 4.0

OPC UA needs to be classified in the Communication Layer at all levels of the hierarchy axis of RAMI 4.0 because OPC UA can be used both in tiny sensors and for cross-factory communication (connected world) (cf. VDMA / Fraunhofer IOSB-INA 2017). Extended information models and OPC UA Companion Specifications, on the other hand, need to be assigned to the Information Layer. Since OPC UA is used both for communication between Industry 4.0 components and for connecting devices (assets) to their administration shells, it can in future be placed in the Integration Layer of RAMI 4.0.

3.3 AutomationML

Although OPC UA provides the framework for meta models, it does not define their contents for data exchange (cf. OPC 2017). This is where the neutral, XML-based AutomationML data format (Automation Markup Language) defined in IEC 62714 is used to describe precisely those contents (DIN EN IEC 62714 and Fraunhofer IOSB n.d.), thereby enabling cross-industry and cross-company exchange of engineering data (such as computer-aided design data).

AutomationML was founded in 2006 as an industrial consortium of German and US companies from the automation technology sector with the aim of standardising data exchange during the engineering process in production. No new data format was developed, but existing formats were taken and extended, adapted or combined. Since 2009, AutomationML has been recognised as a registered association, AutomationML e.V. (cf. AutomationML 2020).

The AutomationML data format offers the possibility of integrating internal and external submodels (ISA95, eCl@ss properties, PDF documents). Rules that describe the transformation of AutomationML into the OPC UA information model and therefore enable the synthesis of both standards are shown in the AutomationML Companion Specification for OPC UA. Based on the contents of the Companion Specification, the transformation rules are detailed and extended in DIN SPEC 16592 (cf. DIN SPEC 16592:2016-12). In addition, possible use cases for the combination of AutomationML and OPC UA are provided, and ways shown in which further standards (CANopen, STEP) could be integrated.

The IIC has published "The Industrial Internet Connectivity Framework" (IICF) which presents communications in all areas of the IIoT (cf. Lin et al. 2017 and Joshi et al. 2018). Similar to the old well-known ISO/IEC 7498-1:1994 OSI model, several communication layers are defined here: physical, link, network, transport, framework, and distributed data interoperability and management (cf. ISO/IEC 7498-1:1994). IICF, like IIC IIoT, refers to all areas of IoT/IIoT. For manufacturing, OPC UA is also recommended with regard to the transport and framework layers (cf. Joshi et al. 2018).

4 Discussion and outlook

When comparing the different reference architecture models, it is clear that the three-dimensional layer models are formulated in more general terms. In comparison, the individual viewpoints of the IoT/IIoT reference architecture models are described in more detail. Industry standards such as OPC UA contain the most details. The higher the level of detail of a standard the more the standards differ in different areas. For example, there are different Companion Specifications for different industrial sectors in OPC UA.

The three-dimensional layer models for Industry 4.0, such as RAMI 4.0, describe all aspects of the life cycles in the development and production of a product, along the entire hierarchy of any company and from all required viewpoints.

The IoT/IIoT reference architecture models focus on interconnectivity and are therefore described in more detail. At the same time, IoT/IIoT reference architecture models describe more industries than just manufacturing. What is crucial, however, is that the description of interconnectivity in different areas requires a more detailed model.

In this context, the question of why IoT/IIoT models are not designed as three-dimensional layer models can also be answered. The life cycles in different IoT/IIoT-relevant areas (energy, healthcare, manufacturing, etc.) differ significantly as described above. It is therefore difficult to decide on a life cycle axis, as in the three-dimensional layer models on manufacturing, which is why less elegant but more detailed models have to be used. In the IoT/IIoT models, the connection of the individual viewpoints or layers is ensured by means of cross-cutting functions and, in the three-dimensional layer models, is naturally made by means of a vertical connection along the vertical architecture axis.

In many cases, it may be worthwhile to use the different model types together. For example, RAMI 4.0 and IIC IIoT can complement each other, since the challenges affecting IIoT are considered from different perspectives (cf. Lin et al. 2017). Which model is more suitable in individual cases always depends on the individual perspective of a company, but often the consideration of both models provides added value. Projects from the former Autonomik für Industrie 4.0 technology programme have provided similar arguments; in "Software architectures for Industry 4.0 – RAMI and IIRA from the perspective of projects in the technology programme", the applicability of RAMI 4.0 and IIRA (the predecessor of IIC IIoT) to the projects of the programme was analysed (cf. Anderl et al. 2016). Among other things, it was found that IIRA particularly supports developers and system integrators dealing with the concrete design and architecture of an industrial internet system, while the RAMI 4.0 cube allows an easy-to-understand, compact representation of complex systems.

In principle, it can be said that RAMI 4.0 or a related reference architecture model is often the appropriate choice for companies focusing on production. For organisations that require interoperability, the use of IIC IIoT or a comparable reference architecture model for IIoT is recommended.

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