WHITE PAPER

Interoperability between IIC Architecture & Industry 4.0 Reference Architecture for Industrial Assets

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EXECUTIVE SUMMARY

- The industrial internet is ushering in an era of connected industrial ecosystems.
- Engineering organizations comprising stakeholders from a spectrum of industries are laying out guidelines and standards that would enable an interoperable, safe and secure industrial internet.
- Two organizations in particular, namely the Industrial Internet Consortium (IIC) and the Working Group for Industry 4.0, have provided recommendations and guidelines in the form of the Industrial Internet Reference Architecture (IIRA) and the Reference Architecture Model for Industry 4.0 (RAMI 4.0), respectively.
- IIRA and RAMI4.0 articulate the creation of industrial internet systems (IISs) and cyber physical systems (CPSs) as fundamental building blocks for the industrial internet.
- Since the essence of both IIRA and RAMI4.0 is to serve as a guide for building a smart connected industrial internet ecosystem, it is natural to expect similarities and intersections between the two frameworks, and therefore discussions on interoperability are gaining prominence.
- We ascertain interoperability using two Infosys IIC testbed solutions, namely the industrial digital thread testbed and the asset efficiency testbed.
- The three-tier architectural pattern, which is the basis for the IIC testbeds, share distinctive features associated with the RAMI4.0 layered architecture, thereby ensuring interoperability at the functional level.
- Fundamental to the discussed IIC testbed solutions is the concept of a 'digital twin' which consists of a virtual representation of the asset along with the asset history. This is analogous to the administration shell in RAMI4.0. This observation indicates that the assets in the discussed IIC testbed solutions share distinctive features of I4.0 components and are therefore I4.0 compliant.
- RAMI4.0 is primarily focused on creating smart manufacturing value chains, whereas IIC has broader focus areas – including energy, healthcare, and transportation.
- Beyond interoperability, a notion of complementarity will result in IIoT solutions that will borrow from both I4.0 and IIC guidelines and architectural paradigms. This will lead to comprehensive end-to-end IIoT ecosystems. For example, an end-to-end energy IIoT ecosystem would comprise multiple levels of manufacturing facilities for the energy assets, which would in turn be connected seamlessly to a network of smart energy assets at a power plant. Models such as the digital twin and digital thread would serve as a bridge providing seamless connectivity among the various layers in the value chain.

INTRODUCTION

Industries across the globe are poised to reap the benefits of the industrial internet by actively leveraging the availability of ubiquitous sensing, intelligent connected machines and products, and advanced analytics. These major shifts in connected thinking and digitalization that are enabling the convergence of information technologies (IT) and operations technologies (OT) are leading to profound changes in the industrial landscape. As industries tread the path to IT-OT convergence, engineering organizations have come forth to establish guidelines and standards that will facilitate the transition of traditional industries towards connected industrial value chains. Among these organizations are the Industrial Internet Consortium (IIC) and the Working groups of Industry 4.0 who have worked with multiple industrial stakeholders and academicians to establish reference architectural guidelines for deploying connected machines, various moving and stationary assets, and entire factories.

Very recently there have been discussions related to identifying intersections, similarities and differences between the guidelines laid out by IIC – as summarized in the Industrial Internet Reference Architecture (IIRA) document [1] – and the Industry 4.0 or RAMI 4.0 architectural guidelines [2]. Recent online publications [3, 4] have summarized these discussions. The general consensus was that certain aspects of IIRA and RAMI 4.0 intersect with each other, but more work is needed to precisely identify interoperability features between the two architectural paradigm. Discussions around interoperability aid business decision makers from a wide spectrum of industries evaluate if implementations of their products, assets, machines and factories would result in intended higher-level integrated system performance across the two architectures.

> **Why interoperability?**
>
> Discussions around interoperability help business stakeholders ascertain intended higher-level integrated system performance of their products and assets across the IIC and I4.0 architectures.

In this white paper, we ascertain interoperability using two example testbed solutions that are instituted by Infosys under IIC – namely the Industrial Digital Thread (IDT) testbed [5] and the Asset Efficiency (AE) testbed [6] – and assess how they fit into the architectural guidelines provided by IIRA and RAMI 4.0. The testbeds represent specific use-cases where industrial internet technologies are being deployed to realize multiple efficiencies associated with a connected value chain. Testbeds, as instituted under IIC, have proven to be an effective accelerator aiding partners and system integrators from a wide spectrum of the industry in evaluating if and how soon connected technologies will help them realize the promise of the industrial internet. Testbeds also allow participants identify technology needs and best practices associated with the deployment of connected technologies that are relevant to their industry.

We begin by briefly describing the IIRA and RAMI4.0 architectural details, which is followed by a description of the IDT and AE testbeds. This is followed by a discussion on interoperability between IIRA and RAMI4.0 from the purview of the testbeds. Finally, we present our viewpoint on the importance of discussions beyond interoperability and comprehensive end-to-end IIoT solutions that will borrow from both IIRA and RAMI4.0 architectures.

INDUSTRIAL INTERNET REFERENCE ARCHITECTURE (IIRA)

The IIRA is the result of an exercise by multiple industrial stakeholders from energy, healthcare, manufacturing, transportation and public sectors under the IIC to achieve broad consensus in driving device and product interoperability and deploying large industrial control systems. Central to the IIRA is the concept of an industrial internet system (IIS) [1]. IISs are complex, heterogeneous systems with multiple components associated with multiple system characteristics. Consequently, IIRA focuses on only a critical few characteristics – namely safety, security, and resilience. The industrial internet architectural framework adopts general concepts from the ISO/IEC/IEEE 42010:2011 standard which includes concerns, framework and viewpoints.

IISs are characterized by four viewpoints: Business, Usage, Functional, and Implementation (see Figure 1). The business viewpoint is concerned with the identification of business stakeholders, the usage viewpoint is concerned with the expected system usage, the functional viewpoint is concerned with the functional components of an IIS, their interrelationships and external interactions, whereas the implementation viewpoint is concerned with the technologies needed to implement functional components.

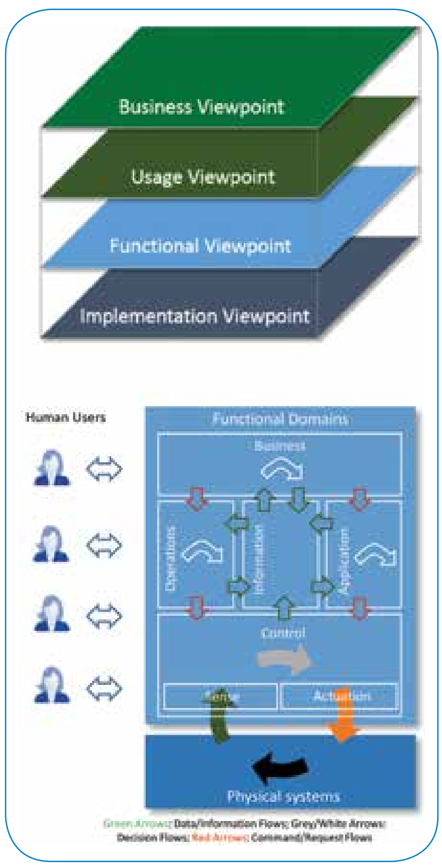

Figure 1 : Viewpoints (above) and functional domains (below) are key building blocks of IISs [1].

For the purposes of the discussion here, we focus on the functional and implementation viewpoints. In the functional viewpoint, the IIS is decomposed into five functional domains: Control, Operations, Information, Application and Business. These domains represent the building blocks of an IIS and illustrate how data and control move among these domains. The implementation viewpoint describes the general architecture, the technological components of an IIS, and the interfaces, protocols and behaviors among them. Certain popular implementations are encapsulated under various architectural patterns, which include the three-tier pattern and gateway-mediated edge connectivity pattern.

The IIRA also addresses a few specific system concerns in detail, such as integrability, interoperability and composability, connectivity, analytics and data management, and automatic integration. IIRA is not a standard, rather it provides guidelines on how a safe, secure and resilient IIS can help realize the vision behind the Industrial Internet.

REFERENCE ARCHITECTURE MODEL FOR INDUSTRY 4.0 (RAMI4.0)

Industry 4.0 or I4.0 focuses on automation, seamless exchange of data, and contemporary manufacturing technologies to realize the vision of a "Smart Factory". I4.0 resulted from joint activity of industrial associations ZVEI, VDMA, and BITKOM, in addition to researchers and VDI, the association of German Engineers. Not only does I4.0 emphasize vertical integration inside a factory setting, but it also lays the foundation for horizontal end-to-end engineering integration across the value chain that goes beyond the factory floor. The ultimate goal of I4.0 is the ability of an interconnected factory to produce highly customizable products that are realized through flexible mass production. Central to I4.0 is the concept of a Cyber Physical System (CPS) [2, 7] – analogous to the IIS in IIRA – where autonomy is localized and participating systems make decisions on their own. The reference architecture model for I4.0, or RAMI 4.0 [2], is the convergence of thinking by multiple stakeholders on how the vision behind I4.0 can be realized. It builds upon existing communication standards and functional descriptions, and discusses modifications that are necessary for I4.0.

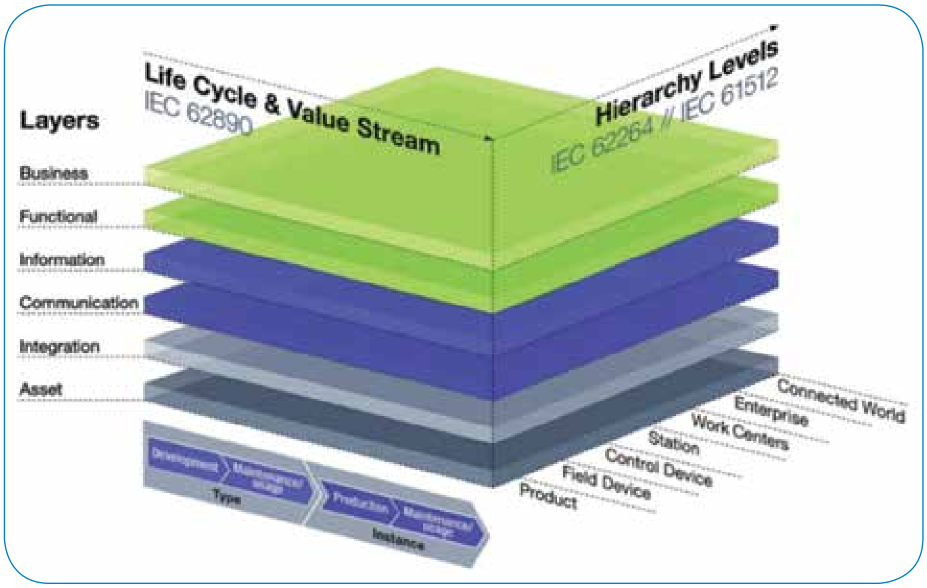

Figure 2 : Reference architecture model for Industrie 4.0 (RAMI4.0). Copyright "Umsetzungsstrategie Industrie 4.0 – Ergebnisbericht, Berlin, April 2015".

Architectural details summarized by RAMI4.0 are captured in a three-dimensional representation of the critical foundational features of I4.0, as shown in Figure 2. The six layers of the vertical axis define the structure of the IT representation of an I4.0 component. This axis therefore represents the business applications, the functional aspects, information handling, communication and integration capability, and ability of the asset to implement I4.0 features. This layered architecture basically breaks the complexity into manageable parts. The life cycle of products, machines, "orders" and factories are captured along the life cycle and value stream axis, whereas the hierarchy levels represent various functions of enterprise IT and control systems.

An important feature of RAMI 4.0 is the identification of an object as either a "type" or "instance". An object can be a product, asset, software, machine, or even a factory. Objects that have the ability to communicate independently using I4.0 compliant communication are called I4.0 compliant components. Non-I4.0 compliant components can be made I4.0 compliant by deploying an administration shell, which essentially provides a virtual representation and a description of the entire life-cycle of the object or asset, in addition to I4.0 compliant communication with the rest of the value chain.

INDUSTRIAL DIGITAL THREAD TESTBED

A paradigm for realizing a connected industrial organization is the Industrial Digital Thread (IDT). When service teams and field engineers perform maintenance and corrective action on large industrial assets, a challenge that they usually face is the lack of data and digital insights that are needed to assess, troubleshoot and evaluate appropriate action. Similarly, quality assurance engineers need to understand why a particular problem occurs frequently or why parts from suppliers do not stack up correctly when assembled. The root cause usually lies somewhere in the design phase, manufacturing phase, associated processes, supply chain logistics and production planning. Availability of data and insights from each stage of the product lifecycle would provide the necessary information for decision makers to take corrective measures. This is the essence behind IDT.

The goal of the IDT testbed [5] is to drive efficiency, speed and flexibility through digitalization, connected workflows, and automation in an industrial context. IDT aims to seamlessly and digitally integrate various phases of the product lifecycle, beginning at the preliminary design all the way to in-service state of the product. Leveraging paradigms such as model-based enterprise and virtual manufacturing, IDT can enable the understanding of various aspects of the part life-cycle, even before the part is manufactured. Coupled with sensor-enabled manufacturing processes, procedures, and machine data, IDT can enable operations and supply chain optimization. It can provide a digital birth certificate of the actual product which can then be compared with the as-designed (intended) part specification through the use of a connected design-manufacturing-supply chain. Data obtained from the connected value chain and associated big-data analytics using IDT can aid in identifying any deviation in product specifications and performance, and trace the root cause of the deviation to the source. Insights from the field and services improve awareness, provide insights and enable targeted changes in the design and manufacturing stages of the product life cycle to improve product efficiencies.

With the goal of realizing the vision behind IDT, a specific use-case of premature wear was chosen to quantify the benefit of a connected life cycle. Premature wear in a product is a prototypical example of a concern that requires investigation across multiple stages of the product lifecycle. Some pertinent questions that stakeholders ask: Where in the product life-cycle does the root cause for premature wear lie?" Can we derive insights and correlations that will allow us to identify the source of the premature wear using 'proactive' data-driven approaches, rather than traditional 'reactive' investigative approaches? The IDT testbed aims to address these questions.

Asset Efficiency Testbed

The term "asset" refers to a product, a part or component of a larger mechanical or electrical system, or the system itself. For example, an asset can be the entire aircraft – or an important sub-component of the aircraft – such as the engine, landing gear or auxiliary power unit. An asset can also refer to the machine on the factory floor that manufactures products. Once an asset is deployed to the field or is in service, data associated with performance and health of the asset can be invaluable to the asset operator, as well as to the original equipment manufacturer. Such data can be used to evaluate efficiencies associated with the asset, help in making decisions regarding design or manufacturing changes, and aid in predictive maintenance of the asset.

Several efficiency benefits can be realized by having connected assets that provide the operator and manufacturer with real-time data [8]:

1. **Energy efficiency:** Aims to reduce consumption of energy, resources (raw material, water and fuels) and waste generation. It saves costs and improves the overall sustainability of an enterprise.
2. **Information efficiency:** Addresses efficient data management with focus on data standards and security for high data quality and interoperability.
3. **Operational efficiency:** Provides integrated view of the entire supply chain by monitoring all levels of asset participation.
4. **Maintenance efficiency:** Planning and execution of maintenance tasks using real-time condition data of production systems coupled with strong predictive analytics to help in improving the overall maintenance efficiency of assets by reducing unexpected breakdowns.
5. **Service efficiency:** Allows for real-time status of assets in the field in order to provide efficient deployment of services, either personnel or parts and labor.

In early 2015, Infosys together with the Institute for Industrial Management (FIR) at RWTH Aachen [8] undertook an effort to understand the competitive benefits of asset efficiency, in addition to the maturity and readiness of I4.0-enabled asset efficiency. FIR and Infosys designed and analyzed responses from over 400 industrial manufacturing executives who were spread across 5 countries – China, France, Germany, UK and US. The principal conclusion from the study was that although there was awareness across industry of the benefits of asset efficiency, this had yet to result in tangible action.

The study also revealed that, by 2020, companies will primarily focus on the following improvements:

1. Data standards and interoperability between modern and legacy shop floor systems in a multi-vendor environment as a precursor for seamless interaction, which enables multiple aspects of efficiency up the value chain.
2. Effective root-cause analysis and corrective actions that build a logical approach in solving problems at their source, rather than just fixing the apparent – a key for any continuous improvement program.
3. Dynamic asset classification based on asset type, relation to other equipment, hierarchy, complexity and criticality which is an important aspect to build the right model that enhances operational and maintenance efficiencies.
4. Real-time production planning and scheduling that can optimize all aspects of operations accurately by minimizing resources consumed and maximizing efficiency.
5. Knowledge capture and management that enables improved operations and maintenance of complex machines, as people and their knowledge are intangible assets in industrial manufacturing.

Aligned with the findings from the Infosys-FIR report, Infosys along with several IIC partners deployed an AE testbed [6] focused on the aircraft landing gear (ALG) (see image below for an example of an asset used in the AE IIC testbed), in addition to other assets.

The goal of this testbed is to efficiently and accurately collect asset information in real time, and leverage analytics to allow stakeholders in making accurate decisions. The AE testbed focuses on failure mode analysis and prediction using engineering knowledge, mapping and modeling of the asset, development of a platform stack for real-time data collection from the asset, and overall system and data analytics. Several commercial benefits are associated with the testbed which include improvement in asset life as quantified by asset utilization, improved return on investment by reducing the downtime of valuable assets, while maximizing production and predictable delivery of service. The testbed focused on data collection which typically includes sensor data, geographic data, categorical data, event data, time data and other system data. Such data is employed for a variety of end goals, such as system health, fault detection, performance analytics, energy utilization, prognostics, asset utilization, and holistic analytics.

Figure 3: Aircraft Landing Gear

INTEROPERABILITY BETWEEN IIRA AND RAMI 4.0

Interoperability is the ability of different information technology systems and software applications to communicate and exchange data, and use the exchanged information to realize a higher-level functional goal of the system (see for example, [9]). Interoperability of systems can be ascertained at various levels, which include *technical interoperability*, which indicates an ability to exchange of information across systems using a communication protocol; *syntactic interoperability,* which indicates an ability to exchange information using specified data formats and communication protocols; *semantic interoperability*, which indicates an ability to not only exchange information across systems, but also automatically interpret the data and produce intended results, and *conceptual interoperability,* which is regarded as the highest form of interoperability where the goal is to have a fully specified but implementation independent model [10]. In the context of industrial IoT solutions, *business interoperability* may also become relevant where the goal is for an enterprise to cooperate with its business partners and to efficiently establish, conduct and develop IT-supported business relationships with the objective to create value [11].

We focus on the implementation viewpoint for the purposes of this discussion. The implementation viewpoint In the IIRA provides an overview of the general architecture of an IIS, its components and how they are interconnected [1]. It provides a map of how the usage viewpoint in IIRA is related to the functional components, and how the functional components maps to the implementation components. It also provides an implementation map for the key system characteristics.

Under the implementation viewpoint, the three-tier architecture is a simplified representation of an IIS and comprises:

(i) Edge Tier

This layer integrates the edge nodes, which comprise assets, edge devices, sensors and control systems. Edge nodes can communicate with the edge gateway that can bridge with other networks. In the IDT testbed, this tier integrates all the assets, firewalls and edge devices that participate in the digital thread. For instance, sensors on a manufacturing asset can provide data on the performance and the health of the asset that will feed through the digital thread to other sites for analysis and insights. In the AE testbed, the asset is integrated with sensors that provide a snapshot of the asset health at regular intervals. The sensor data is usually communicated via an access network to a big data management and analytics platform that provides predictive and prescriptive analytics capabilities.

(ii) Platform Tier

This tier primarily consists of an integration platform that enables the integration of the assets, a data analytics and big data management platform, and an application enablement platform that allows the creation of dashboards, alarms, notifications, mobile apps and graphical user interfaces (GUIs). In the case of the IDT and AE testbeds, the integration platform can be an industrial IoT platform that provides data and asset services, and allows for M2M communication of transactional data. This tier also communicates control data to the edge devices in the edge tier.

(iii) Enterprise Tier

This tier implements enterprise-level systems and domain specific applications that are associated with the particular asset or factory, such as MES, SCM and ERP. It also provides interfaces to end users, business users and other OT users supporting the IDT or AE ecosystem.

The three tiers are presented schematically in Figure 4. As discussed earlier, IIRA specifies a functional viewpoint that tentatively decomposes an IIS into 5 functional domains: Control, Operations, Information, Application and Business. As indicated in IIRA document [1], there is a tentative mapping between the three-tier architecture and the functional domains. The edge tier comprising asset, sensors and gateways implements the control domain; the platform tier comprising the data analytics and big data management implements part of the information domain, and the industrial IoT platform and application enablement platform implements the operations domain. The enterprise tier implements the applications domain

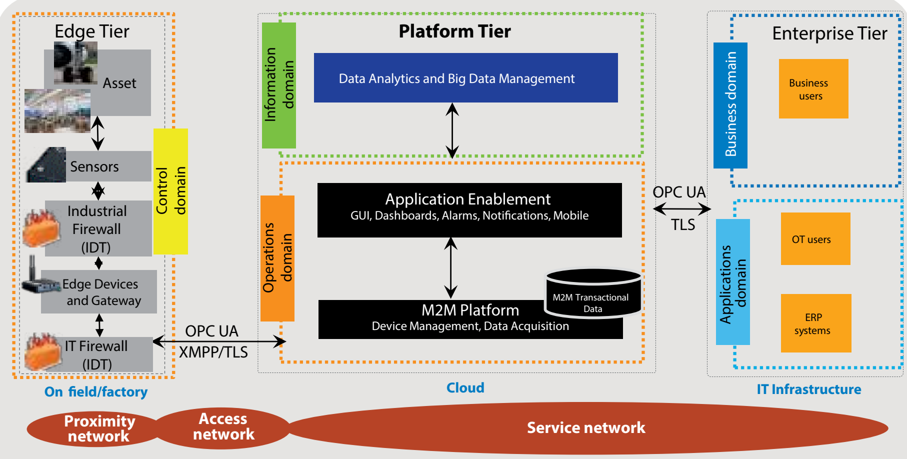

Figure 4 : IIRA 3-tier architecture for the IIC IDT and AE testbeds, along with the functional viewpoint and associated functional domains from IIRA. Also shown are the relevant communication networks associated with each tier [1].

– comprising the web portals and user interfaces that help communicate with the edge and platform tier – and the business domain implements the business layer functions associated with each testbed.

Also shown in Figure 4 are the communication and data transfer networks that are associated with the three-tier architecture. The proximity network connects edge nodes to the gateway; the access network enables data and control flow between the edge and platform tiers using XMPP/TLS communication protocols, and the service network connects the platform services with the enterprise services using TLS protocols. One can conceive of employing the OPC UA communication protocol [12] between various assets and enterprise systems as indicated in the figure.

Figure 5 shows the 3-axis RAMI 4.0 architectural pattern as described by the Working Group for Industry 4.0 [2]. RAMI 4.0 focuses on creating connected factories and supply chains, where every product, machine, order and the factory are a part of a life cycle and value stream. Functionally, the architecture model is decomposed into several hierarchy levels as illustrated in the figure. The question is: can we map the IDT and AE testbeds on the RAMI4.0 three-axis representation?

The colored blocks in Figure 5 indicate an alignment of the testbed in RAMI 4.0 on the 3-axis architectural pattern. The AE testbed focuses on an "instance" or finished product of the ALG "type" that is deployed in the field, whereas the IDT testbed concerns the entire lifecycle of the product from conception to field deployment. Given the scope of the AE testbed, it spans only the "Field Device" and "Product" hierarchy levels. However, the IDT testbed spans the Hierarchy levels from Product to Enterprise, and is therefore most closely aligned with the vision of I4.0.

A mapping between the IT layers in RAMI4.0 and the functional domains under IIRA can be identified as shown in the same figure. A recent blog by IIC [4] indicates a similar mapping between the two architectures. The blog further identifies cross-cutting functions and system characteristics as a means to map the IIRA to the RAMI 4.0 pattern.

Both IIRA and RAMI4.0 stipulate the need for a service oriented architecture (SOA) for encapsulation of functionalities into services. Therefore, IIoT solutions such as the testbeds discussed above that rely on a SOA can be considered to be *semantically interoperable* at a functional level between the two architectures.

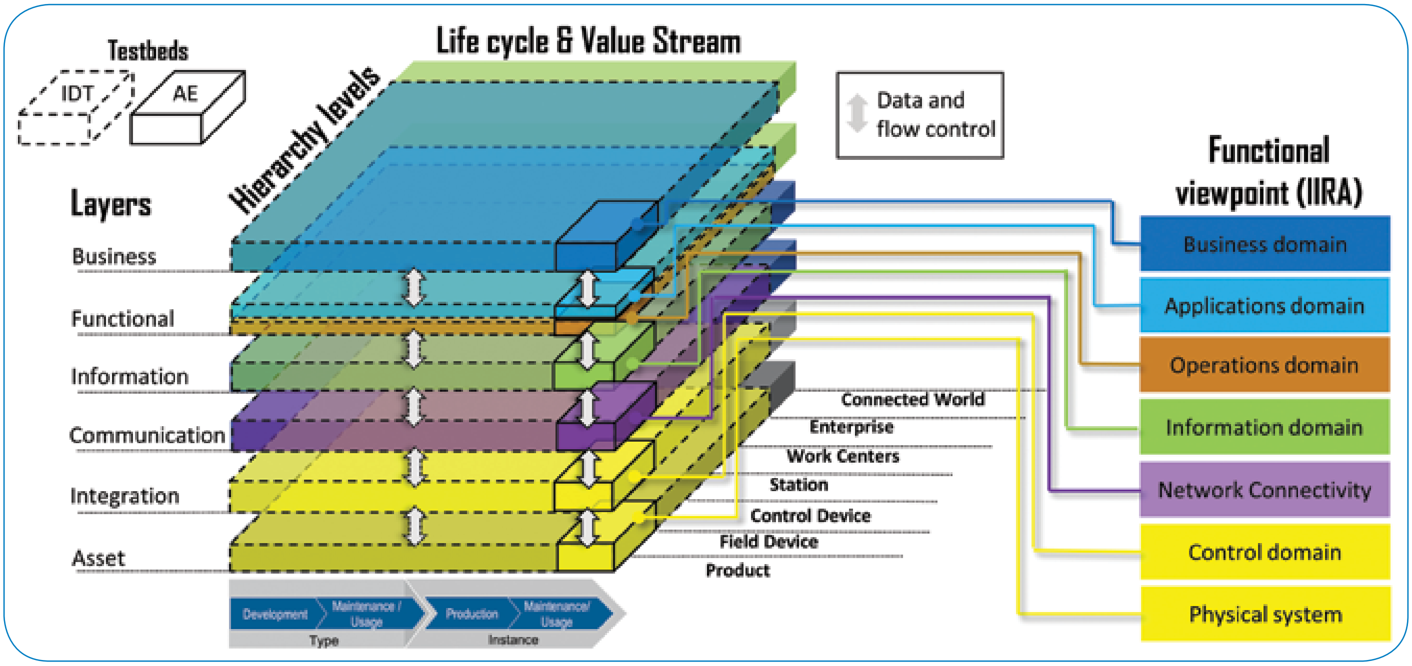

Figure 5 : Mapping between the IIRA 3-tier functional viewpoint with the IT layers associated with the RAMI 4.0 architecture for the IDT and AE testbeds. Both IDT and AE testbeds are focused on the product or the asset. Whereas the AE testbed is concerned with an instance of the ALG that is deployed in the field, the IDT testbed concerns the entire lifecycle of the product from conception to field deployment. In its complete form, the IDT testbed spans the Hierarchy levels from Product to Enterprise, and is therefore most closely aligned with the vision of I4.0 from between the two testbeds.

ASSETS AND I4.0 COMPONENTS

An important highlight of the RAMI 4.0 architectural pattern is the identification of I4.0 compliant components. As per RAMI4.0, an I4.0 component can be a machine, production system, station or an assembly inside a machine that exhibits certain features associated with connectivity, communication and virtual representation. Figure 6 shows the scope of the IDT and AE testbeds superposed on the life-cycle and value stream associated with various I4.0 components. The IDT testbed focuses on providing a digital birth certificate of the product as it moves from the design and development phases to the usage and service phases. Features associated with such a digitalization approach are encapsulated in the concept of a "digital thread." The digital thread also allows relevant stakeholders to compare the 'as-designed' intent to the 'as-built' digital birth certificate of the product. Virtual asset information is captured and resides in a higher level IT system that communicates with each machine producing the asset. This way the manufacturing life cycle is built into the digital birth certificate of each product or asset. Any concerns with product or asset that arises during its life-cycle – either in

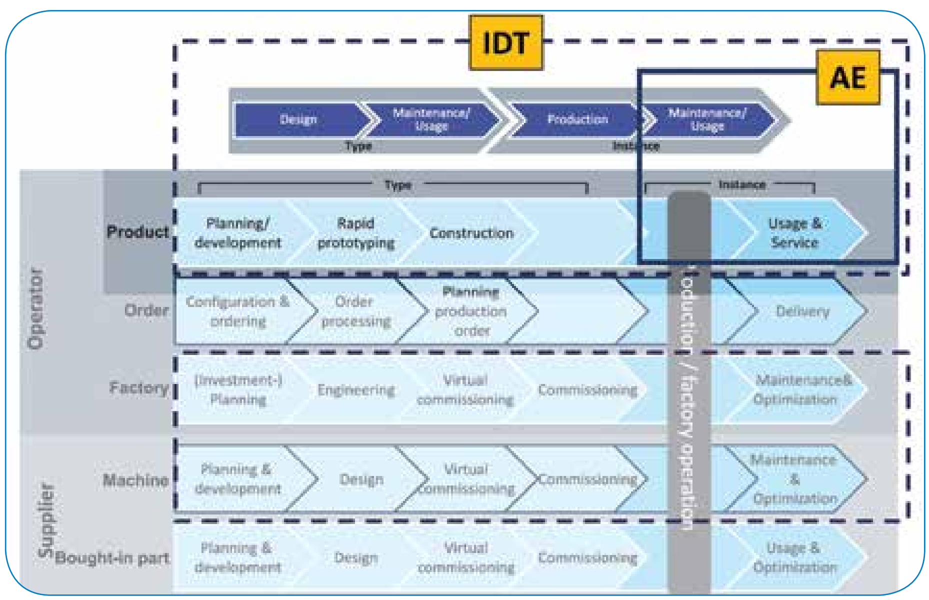

Figure 6 : Various I4.0 components as detailed in the RAMI 4.0 architecture document (Source: M. Hankel, Bosch Rexroth. Based on Plattform Industrie 4.0 WG3. Based on Prof. Bauernhansl, Fraunhofer IPA. Copyright "Umsetzungsstrategie Industrie 4.0 – Ergebnisbericht, Be rlin, April 2015") showing the scope of the IDT and AE testbeds by means of the dashed and solid lines, respectively.

production or in service – can be traced back in time to the origin or cause of the concern.

Similarly, in the AE testbed, each asset consists of a virtual representation of itself in a higher level IT system, such as a cloud-based data services platform. This virtual representation of the asset is sometimes called as the "digital twin" of the asset. The digital twin contains the digital blueprint of the asset which aids in virtually ascertaining its performance, and comparing its 'as-built' version with the 'as-designed' version. Digital twins can also aid in diagnostics, monitoring and prognostics, and efficiently scheduling predictive maintenance of the asset.

RAMI4.0 explains the requirement of an administration shell which can reside in a higher level IT system that converts a non-I4.0 compliant object into a compliant one. This shell contains the virtual representation of the asset, its lifecycle, technical functionality, and can also include procedures to integrate sensor data and condition monitoring capability. Given the architectural implementation in Figure 4, along with the concepts of digital thread and digital twin that are integral to the IDT and AE testbeds, we conclude that the assets and objects that are the focus of these testbeds satisfy the requirements of an I4.0 component. Figure 7 pictorially captures the essence of this compliance.

Figure 7 : I4.0-compliant landing gear (AE testbed) and products manufactured on a factory floor (IDT testbed) showing the administration shell that resides in the platform tier.

An important consideration in the discussion around interoperability is a data exchange model for safe, reliable and platform-independent communication. OPC-UA is the chosen SOA-based protocol by I4.0 for providing scalable and extensible M2M communication in a vertically-integrated factory set up, and for heterogeneous communications and enterprise-wide integration [12]. Both IDT and AE testbeds can leverage OPC UA as the communication protocol thereby making it compliant with I4.0 guidelines. Employing OPC UA as the protocol therefore makes the testbeds *semantically interoperable* across IIRA and RAMI4.0 architectures.

Outlook

The principal features of a connected industrial ecosystem can be summarized as follows:

(i) seamless end-to-end communication from the enterprise level all the way to the edge devices, such as sensors and assets,

(ii) intelligent machines with the ability for decentralized decision making,

(iii) capability to monitor assets, processes or factories using sensors and other edge devices,

(iv) virtual representation of an asset – or a "digital twin", either integrated with the asset or residing in a higher-level IT system,

(v) data assimilation on the asset and comparing it against the asset's virtual (intended) functionality so that any concerns can be addressed efficiently,

(vi) big data analytics to derive insights and optimizing the performance and serviceability of the asset, and

(vii) feeding insights back into the horizontal and vertically-integrated value chain so that multiple efficiencies can be realized at each stage of the asset life-cycle.

Ultimately, the connected industrial ecosystem is expected to drive business return on investment and top-line growth. Both IIRA and I4.0 lay out guidelines and standards to realize this vision. It is not surprising, therefore, that intersections are expected to exist between the two architectures.

A recent joint discussion by teams from the IIC and I4.0 organizations reiterated the focus areas that are associated with each architecture (see Figure 8) [4]. As the figure

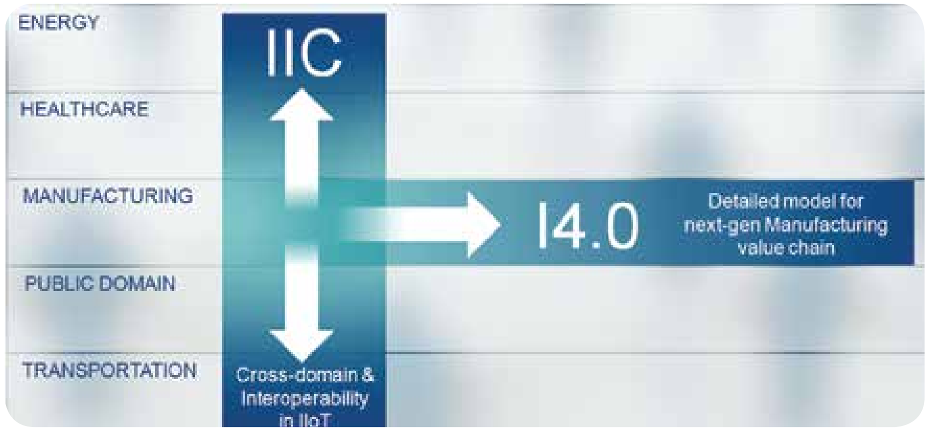

Figure 8: Focus areas of IIC and I4.0 as discussed by a joint group of experts from each organization to identify interoperability requirements [4].

indicates, the focus of IIC spans multiple industrial domains, whereas I4.0 is focused on creating a connected manufacturing value chain. In the face of this observation, we believe that underlying this illustration of focus areas for IIC and I4.0 is a larger, more complex connected ecosystem that will borrow from the vision of both these organizations.

We show one possible manifestation of the multiple connected layers for the case of a hypothetical energy IIoT ecosystem in Figure 9. Industrial IoT deployments in a power plant may not necessarily retain or consider the manufacturing lifecycle of the energy asset as important when creating a connected energy IIoT network. However, the figure illustrates the possibility that in an end-to-end energy IIoT ecosystem, every asset that participates in the IoT connected network at a power generation facility is implicitly connected to its asset lifecycle, which is in turn connected to its digital manufacturing birth certificate. Paradigms such as "digital twin" associated with the energy asset and "digital thread" associated with the asset life-cycle and manufacturing value chain formalize this interconnectivity. This is despite the fact that energy IIoT as portrayed in Figure 8 is not directly associated with the focus area of "manufacturing". Such end-to-end IIoT solutions will borrow from both I4.0 and IIC guidelines. Therefore, beyond interoperability, a discussion on the interplay and a notion of "complementarity" between the two architectures will likely gain prominence.

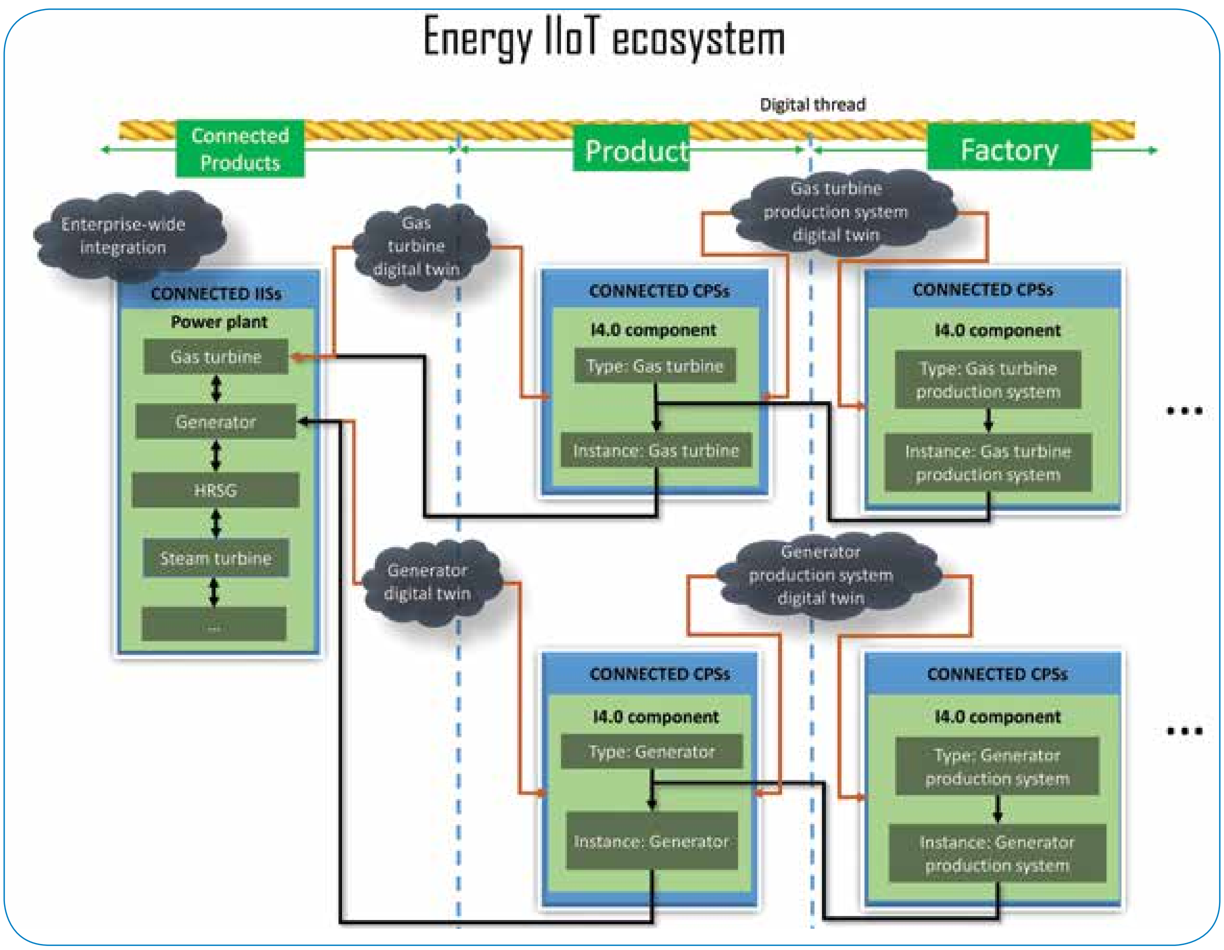

Figure 9 : Snapshot of a possible set of connected layers depicting the overlap between IIC and I4.0 for the case of an end-to-end energy IIoT ecosystem.

Conclusion

Through this white paper, we have shown how certain testbeds deployed under IIC – specifically the Infosys AE and and IDT testbeds – are interoperable with the RAMI 4.0 architectural construct. We conclude this by mapping interrelationships between IIRA and RAMI4.0 architectural guidelines, and by identifying I4.0 compliant components in the testbeds. Standards associated with IIoT ecosystems will continue to evolve and discussions around interoperability are gradually expected to become clearer and more precise. Every industrial sector or domain is implicitly associated with some manufacturing or production scenario at some point in its participating asset lifecycle. We lay out an interpretation of how a combination of IIC and RAMI 4.0 guidelines may find relevance in end-to-end and complementary IIoT solutions going forward. We believe that this observation will spur further discussions on the larger context of integrated IIoT solutions that will borrow from both architectures.

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