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Industry 4.0 Reference Architectural Models: Critical Review and Opportunities

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Abstract: *Technological development is pushing industry towards the Fourth Industrial Revolution. Organizations would need to recognize the importance of adopting the different types of technology as an enabler to ensure their survival in this new paradigm shift. Industrial 4.0 will change organizations and business models particularly in the manufacturing sector. Recognizing the importance of Industry 4.0, many countries, such as the USA, China, Japan, Singapore, Malaysia and others, have begun deriving national policies, plans and strategies to accelerate digital transformation in the manufacturing value chain through various information technology enablers. Supporting such policies are also the various technical reference models which attempt to provide a set of standard and guideline of technology adoption particularly in the area of assets and organisational integration. This paper evaluates the common reference models for Industrial 4.0. These reference models share commonality and differences with the aim for national or local adoption albeit the desire to strive for global emulation and acceptance. While localisation of reference models is logical, these models lack the consideration of social-technical focus, including further research needed on asset integration with security and data interface standard, method to mitigate high cost of adoption, and in the areas of workforce and business process readiness.*

Keywords: Industry 4.0, RAMI 4.0, IIRA, IMSA, IVRA, digital transformation

1. Introduction

The First Industrial Revolution started with the usage of steam and waterpower, enabling mechanisation of production processes, while the Second Industrial Revolution was driven by electric power and mass manufacturing techniques. In the Third Industrial Revolution, information technology led the way. This has led to the subsequent phase of evolution, which is referred to as the Fourth Industrial Revolution, i.e., Industry 4.0 (I4.0) (Neugebauer et al., 2016).

According to European Commission, 99.8% of businesses in the European Union belong to the Small and Medium-sized Enterprise (SME) sector (Safar, et al., 2018). In Malaysia, according to the Ministry of International Trade and Industry's *National Policy on Industry 4.0* (2018), the manufacturing industry is an important economic sector contributing about 22% to the GDP between 2014 to 2018. The manufacturing sector in Malaysia is expected to grow about 5.1% under the 11th Malaysia Plan and this sector made up of the 98.5% of SMEs and form a major part the country's employment at 42%. Realizing the importance of the manufacturing sector and SMEs, Malaysia has derived the National Policy on Industry 4.0, i.e., Industry 4WRD. The aim of this policy is to establish a more cohesive national agenda with initiatives to accelerate Malaysia's transformation into a smart and modern manufacturing system in Industry 4.0.

Similarly, Germany has also setup its High-Tech Strategy 2020 Plan, and in the USA, the Advanced Manufacturing Partnership (AMP) and National Advanced Manufacturing Strategic Plan. EU Commission had also seeded the Factories of the Future Program (2008-2020) for the same purpose while the UK has their own Industrial 2050 Strategy.

In the Asian region, China derived the Made in China 2025 strategy, while the Republic of Korea with their Strategy for Innovation in manufacturing industry 3.0, and Productivity 4.0 by Taiwan (Kuo, et al., 2019). Japan on the other hand concocted the Industrial 4.1J and Revitalization Strategy, including setting up the Science and Technology Industry Alliance to spearhead the I4.0. Singapore, through the Agency of Science, Technology and Research (A*STAR), came up with the Future of Manufacturing (FoM) via Advanced Remanufacturing and Technology Centre (ARTC) and Singapore Institute of Manufacturing Technology (SIMTech).

Supporting the various policies and strategic plans, several countries' institutions proposed models which are aimed to guide the industry to navigate the complexity of creating digital twins and adopt CPS and IT enablers in their quest for digital transformation in I4.0. The following sections evaluate the main reference models available in the market and conclude that while these models are prescribed with matching ISO/IEC supporting standards, there are gaps which adopters would need to be aware of particularly on the lack of focus on the initial high cost of implementation, cybersecurity concerns, workforce readiness and the change management aspects of adoption.

2. Evaluation of Architectural Models

Reference Architecture Model of Industrie 4.0 (RAMI 4.0)

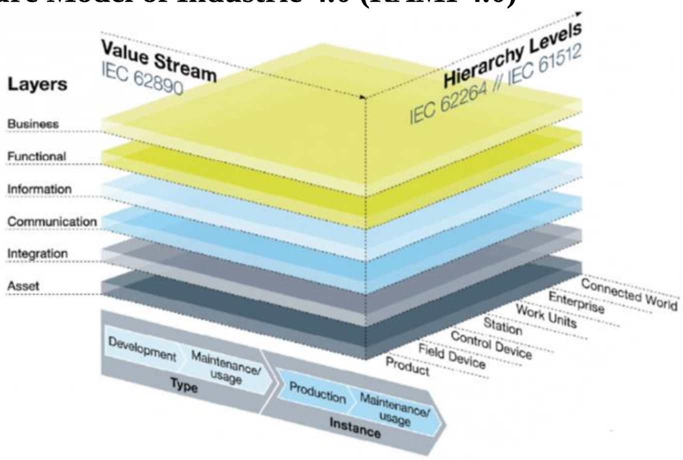

Figure 1: Reference Architecture Model for Industrie 4.0 (RAMI 4.0)

RAMI 4.0, developed in the Germany consists of 3 dimensions:

a) Hierarchy level – where product, field devices, control devices, station, work units, enterprise to connected world are interfaced through standards defined by ISO/IEC62264 International Standard: Enterprise-control System Integration and ISO/IEC61512 where it is made up of 4 concerted standard documentations

b) Lifecycle and value stream – where product development to post product production activities standard is defined by ISO/IEC62890 Industrial-process Measurement, Control and Automation
c) Architectural layer – where assets are represented in the physical world with a digital twin and denote how integration of assets up to the functional and business layer would bring benefits to the manufacturing entities in a value chain. Asset Administration Shell (AAS) provides a guiding principle on assets' digital representation (Grangel-Gonzalez, et al. 2016).

While RAMI 4.0 model extensively incorporates the different IEC standards in its 3-dimensional representation including IEC62264 and IEC62890, there is a gap in the model recommending the common standard for architectural layer integration between the asset layer to the highest level of business layer. There is yet a common set of standards governing the architectural layer.

Furthermore, standard such as IEC62264 as defined in the hierarchical layer of RAMI 4.0 needs to take into consideration of the localisation and execution phase of real-world application rather than just the design phase (Al-Qutais, 2009). This is echoed in the research by Acatech Study from the National Academy of Science and Engineering, Germany in 2016, in which among the 150 respondents from six countries comprising Germany, UK, the USA, China, Japan and South Korea, agreed that there will be no single I4.0 standard for adoption due to the complexity of I4.0 nature. However, the report also added that an *open standard* would encourage a more successful integration ecosystem for different manufacturers at different countries and regions. A dominant closed standard would render organizations to be in the risk of technological lock-in, rendering relatively high costs of choosing a different integration solution due to technological dependency. Therefore, open systems allow small and medium-sized organizations with limited market influence can rely on the interoperable platforms, allowing them access to a relatively large market of manufacturing value chain. This is predominantly valid for small and medium-sized organizations.

Birtel et al. (2019) argued that RAMI 4.0 and AAS lack the principles guiding a flexible human-machine interaction in the production environment where workers form part of the shopfloor and backbone of organizations. They further proposed a FutureFit model which includes a strategy to encompass human aspects and its specific characteristics in the architecture of I4.0. This human-centred AAS suggests a set of requirements for human-AAS-interaction to further complement I4.0 success via the adoption of RAMI 4.0 and AAS framework.

Fraunhofer, a major European Research and Technology Organizations (RTO) went further to develop the 'Fraunhofer layer model' to complement the RAMI 4.0. It argues that RAMI 4.0, albeit being a comprehensive framework of standard, it lacks the focus on major themes to enable a successful adoption (Neugebauer, et al., 2016). The essence of the Fraunhofer Industries 4.0 layer-model lies in the depiction of a 3 layers architecture, with an inner, middle and outer layer. At the heart of the inner layer is the production principles, supported by the middle layer of information and communication technology (ICT) enablers. These are further supported by the outer most layer of business models, business planning and cases, human resource management, as well as transformations and change management. The outer most layer here reflects the dependency with the inner two layers i.e., between technologies and processes (Neugebauer, et al., 2016).

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Industrial Internet of Things: Refence Architecture (IIRA)

The Industrial Internet Consortium (IIC) was established in April 2014 by GE, IBM, Cisco, Intel, and AT&T. IIC is the world's leading organisation dedicated to accelerating the adoption of Industrial Internet of Things (IIoT) in various industries and society. It does so by enabling dependable industrial internet systems, in which systems and devices are securely linked and managed to achieve transformational results across multiple industries (IIC, 2019).

Industrial Internet Reference Architecture (IIRA) was published in June 2015, and Industrial Internet of Things – Volume G1: Reference Architecture, was published in January 2017. Viewpoints, Lifecycle Phase, and Industrial Sectors are the three dimensions of IIRA, as shown in the figure below.

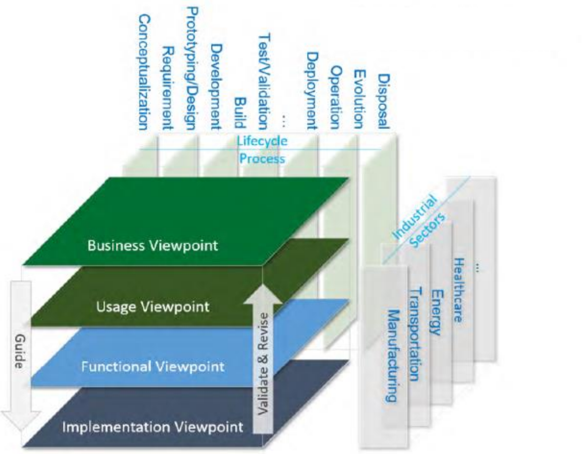


Figure 2: Viewpoints, lifecycle process and industrial sectors in IIRA.

The IIRA is decomposed into four layers, each with its own focus (Monteiro, et al., 2018):

a) Business - focuses on defining stakeholders, their visions, and priorities for establishing IIoT systems, as well as deciding how to accomplish those goals by mapping them to system capabilities.
b) Usage - focus on system's user requirements by highlighting the tasks that should be performed in order to achieve the desired business outcomes.
c) Functional - explains the hierarchy of functional elements, as well as their interactions and relationships with other structures.
d) Implementation - Identifying the technologies needed to incorporate into the functional components.

IIRA is an open architecture for IIoT systems built on a set of specifications. It has a wide range of business applications, which increases its appeal. It offers an architecture framework for designing industrial internet systems, including methods and models, without making clear recommendations for specifications or technologies that make up these systems (Weyrich & Ebert, 2016). Core to IIRA are the different business and technical perspectives are the viewpoints of identifying and addressing architectural concerns.

IIC is concerned with IIoT across sectors, with an emphasis on cross-industry commonality and interoperability, whereas RAMI 4.0 is specifically concerned with manufacturing in detail (Patel, et al., 2019). As a result, enabling interoperability between IIoT systems built on these reference architectures is critical and valuable for IIRA and RAMI 4.0.

Assets in RAMI 4.0 refer to anything that is of value that participates in the business processes such as machines, human resource, commodity, raw material, and software programmes; whereas assets in IIRA refer to the physical object that being monitored and controlled.

Both the IRA and RAMI 4.0 models were developed with the same intention of connecting the physical and digital worlds. Industry 4.0 is referred to smart manufacturing of things, while the Industrial internet is referred to smart working of things. To put it another way, RAMI 4.0 is about producing goods by overseeing the whole value chain and product lifecycle, while the IIRA is all about designing, deploying, and managing broad connected networks. Since manufacturing is one of the sectors covered by the industrial internet, both the IIRA and RAMI 4.0 are relevant for manufacturing. IIC stresses the comprehensive applicability and interoperability of its IIoT systems across industries - with its reference model whereas RAMI 4.0 focuses more in terms of digitalization and manufacturing interoperability (Li, et al., 2018).

Intelligent Manufacturing System Architecture (IMSA)

The Ministry of Industry and Information technology of China (MIIT) and Standardization Administration of China (SAC) published a joint report entitled National Intelligent Manufacturing Standards Architecture Construction Guidance, providing reference model, terminology, evaluation indicators, and technology standards for intelligent manufacturing. The report announces that standardization should be taken as the top priority to steer away from traditional manufacturing to smart manufacturing. Intelligent manufacturing is named as the Chinese Industry 4.0 (Wang, 2015).

The main contribution of the corresponding report is the establishment of a 3-dimensional Intelligent Manufacturing System Architecture (IMSA) shown in the figure below. According to the model, the scope of every smart manufacturing related technology can be determined in terms of dimensions of Life Cycle, System Level, and Smart Functioning. For instance, the scope of industrial robot within the model is presented in the building block formed by resource factors, equipment, and manufacture of the figure below, indicating that industrial robot technology affects production process within the product lifecycle dimension.

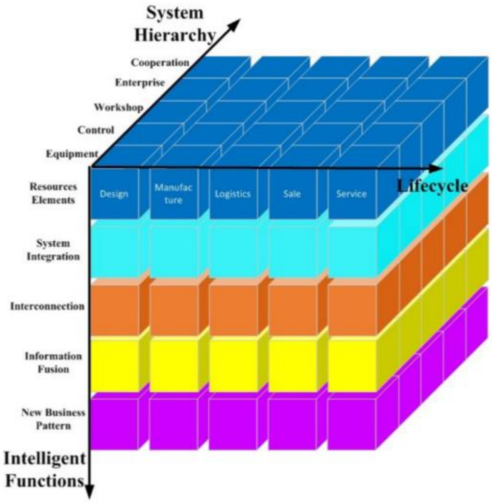


Figure 3: Intelligent Manufacturing System Architecture (IMSA)

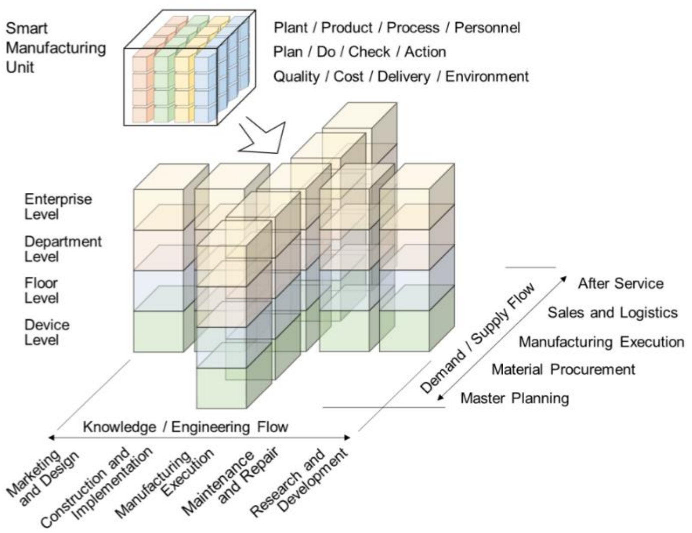
In IMSA, a landscape of intelligent manufacturing standardization architecture is proposed to assist in standards classification. The landscape covers groups of five basic standard type. The National Intelligent Manufacturing Standards Architecture Construction Guidance took the first step in proposing the overall standardization process in the area of smart manufacturing by providing a basic landscape of different categories of standards needed to be derived to support smart manufacturing. However, standardization of smart manufacturing in China is still in its infancy and there is much should be investigated in a broader and deeper extent (Li, 2018).

Comparing IMSA to RAMI 4.0, the latter lacks the focus on the business sales activity in the product lifecycle or value stream horizontal layer, including the focus deficiency in logistics and waste management in the model as compared to IMSA (Wei, et al., 2017). The RAMI 4.0's lifecycle and value stream axis does not provide focus on the importance of post manufacturing activities including post product manufacturing services. IMSA model argues that such activities do play an important role in ensuring the benefits of products leaving the factory would also influence the next product lifecycle development, which forms a continuous feedback loop for manufacturing process improvements.

Industrial Value Chain Reference Architecture (IVRA)

The Industrial Value Chain Initiative, which is a voluntary organization in Japan, is made up 600 member organizations, mainly comprises of manufacturers, was founded in 2015 in Japan. The main aim of this entity is to promote smart manufacturing with its derivation of a reference model known as Smart Manufacturing Unit (SMU) (Nishioka, 2018). It is a 3-dimensional model consisting of the Asset View as the vertical layer, Management View at the hierarchical layer and the Activity View being at the horizontal layer. The asset view consists of the personnel, process, product and the plant itself, all of which are valuable to the organization. These assets can take different roles in the SMU to execute any activities.

The activity view describes the various actions being executed in SMUs and represented with the cycle of 'Plan', 'Do', 'Check' and 'Action'. This cycle of aims to achieve continuous improvement with the control from the management view, comprising the variables of quality, cost, delivery accuracy and the environment.



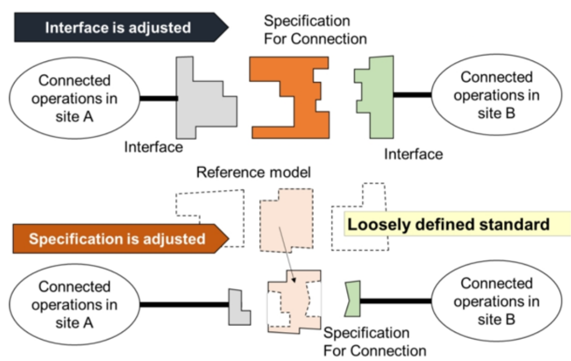


Figure 4: Smart Manufacturing Unit (SMU) with General Function Block (GFB) for smart manufacturing and Loosely Defined Standard (LDS) concept.

While one of the callings of RAMI 4.0 is to allow mass customization of production and IIRA focuses on the notion of data creating values in the value chain via IIoT, IVRA focuses on the efficient migration of current manufacturing practices towards connected manufacturing enterprises across the value chain via human knowledge in creating value as depicted in the SMU. System designers and engineers, as well as factory operators remains the key element in the production to realize digital twin among enterprises (Nishioka, 2018).

According to the Industrial Value Chain Initiative Report (2016), the heart of the IVRA is the concept of Loosely Defined Standard (LDS). It does not aim to prescribe what other existing architectural reference models tend to achieve through a universal global acceptable standard, but LDS means that standardization process is loosened to adjust to the industrial diversity of the actual operating model of organizations along the value chain. IVRA argues that, in smart manufacturing, it is important to find a common ground in which different entities are able to connect based on each unique set of interfaces among the related connected entities, rather than basing on a predefined strict set of standards.

Data models, according to IVRA, should be defined, nevertheless. The entities which would like to be connected can decide on a common set of rules based on their unique factory setting. IVRA argues that organizations if forced to comply with a common model may result in significant changes in the operational, business processes and technology. IVRA strives for a working model of entity-to-entity connection in real life based on each unique integration needs compared to other reference models such as RAMI 4.0, IMSA and IIRA.

3. Discussion

All the reference architecture models are made up with 3-dimensional representations, concocted by different countries' institutions, with the aim of guiding the standards of interoperability. They share a set of commonalities and differences. This paper illustrates the comparison of the functional mapping between the different reference architectural models with a view to the operability of systems as shown in Table 1.

Table 1: Relations between RAMI 4.0, IIRA, IMSA and IVRA domain and viewpoints.

Attribute	RAMI 4.0	IIRA	IMSA	IVRA
Asset	Physical components, documents, software, human resource	Machines, devices, nodes	Personnel, raw materials, equipment, strategy, knowledge and market	Personnel, process, products, plants
Integration	Representing the assets in a digital form	Methods and models, without making clear recommendations for specifications or technologies.	Representing the assets in a digital form	SMU & GFB do not formally define integration (standard) for this attribute
Communication	Establishes communication protocols	Not formally defined.	Mapped to Interconnection layer, i.e., realizing mutual connection among assets	SMU & GFB do not formally define integration (standard) for this attribute
Information	Describes the information being used and exchanged in the I4.0 system	Gather, transform and analyse information in order to obtain an intelligent system.	Describes the information being used and exchanged in the I4.0 system	SMU & GFB do not formally define integration (standard) for this attribute
Functional	Platform for horizontal integration of several functions	Not formally defined	Not formally defined	Mapped to Department level of GFB, evaluated by business function performance
Business	Create connections between different entities along the manufacturing value chain through data brokers	Refers to the value of IIoT provides to the business through assets integration.	Mapped to New Business Pattern layer; means service manufacturing mode such as personal customization	Refers to the Enterprise layer of the GFB overseeing company-wide strategy

Consolidation of literature review on the cons of I4.0 by Sony (2020) also indicated initial high cost of implementation, cybersecurity concerns, workforce readiness, labour and trade unions' apprehensions and the negativity of data sharing in a competitive environment would pose a challenge to a successful reference architectural models adoption.

While Alcacer and Cruz-Machado (2019) points to the benefits of Industry 4.0 through the technical aspects of it, the consideration of social-technical approach is also imperative to ensure successful implementation of the technology enablers. Davis, et al. (2017) posit that organizational culture, roles and responsibilities of workers and management structure should also be given due consideration albeit there is a 'Business' layer within the reference models. Organizations should focus beyond the potential cost and efficiency benefits from RAMI 4.0 technical adoption.

This is further echoed by Furjan et al. (2020) that digital transformation runs a high risk of technology implementation failure if the business processes and ecosystem are neglected. This opens opportunity for future research to cite real-world use cases for repeatable and successful adoption of these reference models which could further provide a valuable feedback-loop to the evolution and improvements of the reference models.

While RAMI 4.0 is partially supported by ISO/IEC standards and IMSA by GB/T China Institute of Standardization, the other reference models lack thorough reference to any similar standards. Even with RAMI and IMSA being supported by standards, there is a lack of detail documentation in guiding the industry to build solutions to enable actual real-world application of these models and this is reverberated by the lack of one agreeable reference model or standard for adoption across the different countries. This may be a challenge when manufacturing entities would like to interface with other entities in different countries when they adopt different standards or architecture of interface.

The high level of abstraction of these reference models coupled with different countries trying to establish their own reference models from the readily available models provides further challenge for manufacturing entities to confidently embark the journey of I4.0. This challenge can be more apparent if a particular country's government does not spearhead and support any reference model for the country's adoption, leading manufacturing entities susceptible in investing any I4.0 infrastructure and initiatives.

4. Conclusion

This paper has outlined the common reference models in the market with an assessment and comparison made between them. Successful adoption of these models is dependent on continuous government and institutional support, the need for consideration of other variables such as social-technical aspects of adoption, completeness of proper guiding documentation, continuous solutioning on cybersecurity concerns, interoperability standardisation within the global community and more real-world success of use cases, amongst others, to convince the manufacturing entities, be it relatively large or small and medium sized, to take the journey of I4.0 forward.

Future research should consider illuminating other critical success factors for reference models adoption and how challenges of such adoption can be further mitigated.

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