Journal of Computational Design and Engineering, 2020, 7(3), 323–336

doi: 10.1093/jcde/qwaa027
Journal homepage: www.jcde.org
Advance Access Publication Date: 9 April 2020

RESEARCH ARTICLE

A review of smart manufacturing reference models based on the skeleton meta-model

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Abstract

Standards will allow interoperability among stakeholders in the upcoming super-connected world. A smart manufacturing reference model (SMRM) is under development inside JWG21 between ISO and IEC. Based on a dimensionality analysis and the skeleton meta-model, the eight proposed SMRMs are reviewed and compared. The SMRMs are classified according to the number of lifecycle axes and the number of dimensional axes. Also, how the concept of a digital twin can be accommodated in an SMRM is investigated.

Keywords: smart manufacturing; reference model; skeleton meta-model; lifecycle; dimensionality analysis; digital twin

1. Background

There are increasing needs for standards because the increased scope and speed of connectivity is expected in the industry 4.0 developments. Thanks to the smartphones and IoT (internet of things), more things are connected and the speed of information flow among them is high through the 5G services of wireless internet. The standards are to help interchangeability or interfaces among heterogeneous things.

For the progress of smart manufacturing, it is found that there are gaps and duplications among international standards. To make things clear, it is nice to have a reference model for standards of smart manufacturing or industry 4.0. ISO-IEC JWG21, a joint working group between ISO TC184 and IEC TC65, started in July 2017, is working to make an international reference model for smart manufacturing. Figure 1 shows the organizational structure of JWG21 (Kimura, 2018).

2. Skeleton Meta-model

Based on the needs for a smart manufacturing reference model (SMRM) and activities of JWG21, there are several reference models (RM) being proposed from different countries and organizations. Among proposed RMs, eight are analysed and the dimensionality of each model is the focus of the analysis.

2.1 Number of dimensions

2.1.1 *Dimensional analysis and dimensionality reduction*

"In engineering and science, dimensional analysis is the analysis of the relationships between different physical quantities by identifying their base quantities (such as length, mass, time, and electric charge) and units of measure (such as miles vs. kilometers, or pounds vs. kilograms vs. grams) and tracking these dimensions as calculations or comparisons are performed" [Dimensional analysis].

The Froude number *Fn* and the Reynolds number *Re* are examples of non-dimensionalized numbers identified through the dimensional analysis in the domain of hydrodynamics. Here a dimension means the monotonical increase of one base quantity. Whereas in machine learning, *dimensionality* simply refers to the number of features (i.e. input variables) in a dataset. There are 2 primary methods for reducing dimensionality: *feature selection* and *feature extraction* (Maaten, Postma, & Herik, 2007).

Received: 20 March 2019; **Revised:** 6 June 2019; **Accepted:** 7 December 2019

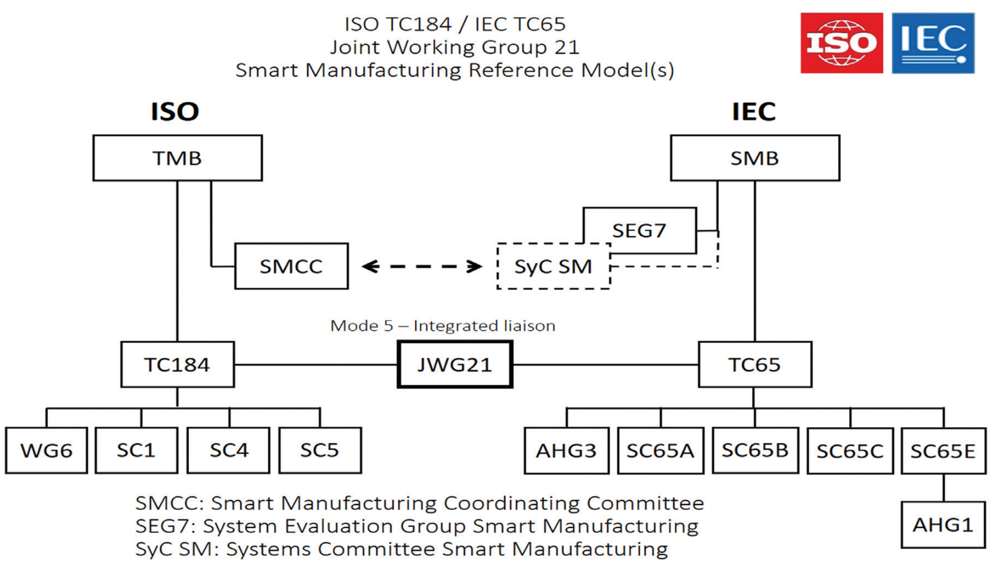

Figure 1: Organizational structure of ISO-IEC JWG21 (Kimura, 2018).

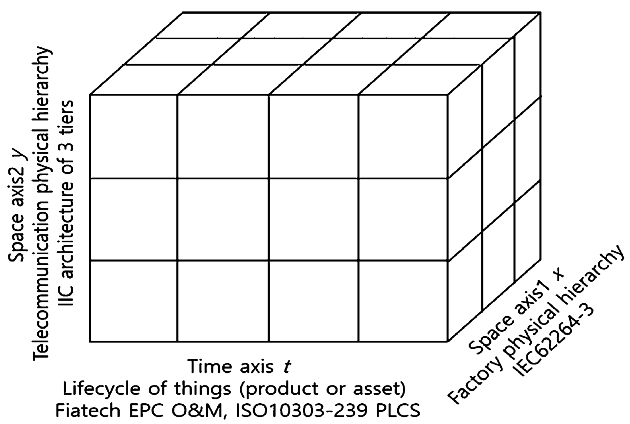

Figure 2: Three axes of the KSTEP cube framework (Korea STEP, 2018; Han, 2019).

A SMRM may need tens of dimensional axes to fully describe the complexity of smart manufacturing. Because it is not easy to visualize more than 3 dimensions for an ordinary human, it is better to limit the maximum dimensions as three. A cube framework is preferred among eight proposed SMRMs If the cube framework is adopted, then the smart manufacturing description needs to be simplified because of this limited dimension of three. The KSTEP cube model (Korea STEP, 2018; Han, 2019) is shown in Fig. 2 as an example. Only two base quantities of space (or size) and time are used in the model.

2.1.2 *Mixing different units along one axis (dimensional homogeneity)*

If one axis of a reference model is used simply as a collection of different members of a set, the axis cannot be used to represent a hierarchy or a progress, along which one quantity monotonically increases its value. The smart grid architecture model (SGAM [Smart grid], Fig. 3), for example, uses the *Domains* axis as a collection of industry domains.

By mixing two or more different base quantities along one axis, the axis cannot be used as a dimensional axis where things can be differentiated only by the value of one quantity (space or time). A set is a finite collection of members whereas a linear dimension is continuous. The linear dimension can differentiate an infinite number of members only by choosing a value of the unit of measure whereas a set cannot represent non-members.

Along the hierarchy axis of RAMI4.0 (IEC PAS, 2017), the *product* is mixed with facilities of a factory as shown in Fig. 4-Left. The *product* is the output of a factory so that *product* is better to be an independent quantity from the facilities of a factory.

Also, along the layers axis of RAMI4.0, the *asset* is mixed with *communication* or control layers above as shown in Fig. 4-Right. *Asset* should be the target object of the communication or control layers rather than a family member of the communication or control layers.

The reasons why different quantities or items (*product* in the hierarchy axis and *asset* in the layers axis) are mixed along one axis are understood as follows. The *product* is mixed with facilities of a factory along the *hierarchy* axis because it may allow better representation of tight (or seamless) connectivity between products and their producing facilities which is a new development in the smart factory research. The *asset* is mixed with *communication* or control layers along the *layers* axis because it may allow better representation of the digital twin concept. The physical *asset* is transformed into a digital item so that the physical *asset* can co-exist with the digital counterpart where they are paired into a digital twin set.

There is a need to find out ways to represent tight or seamless connectivity between products and their producing facilities, and also to represent the digital twin concept inside smart manufacturing. But it will be better if we adopt the original *hierarchy* or *layers* of respective reference model (*Hierarchy* of IEC 62 264 (IEC62264, 2013) or *Layer* axis of SGAM [Smart grid]) because they can represent the monotonical increase of one base quantity (space quantity) and then the dimensional homogeneity can be maintained. Otherwise, the axis cannot be used as one independent dimensional axis which can differentiate many items only by the value of the base quantity.

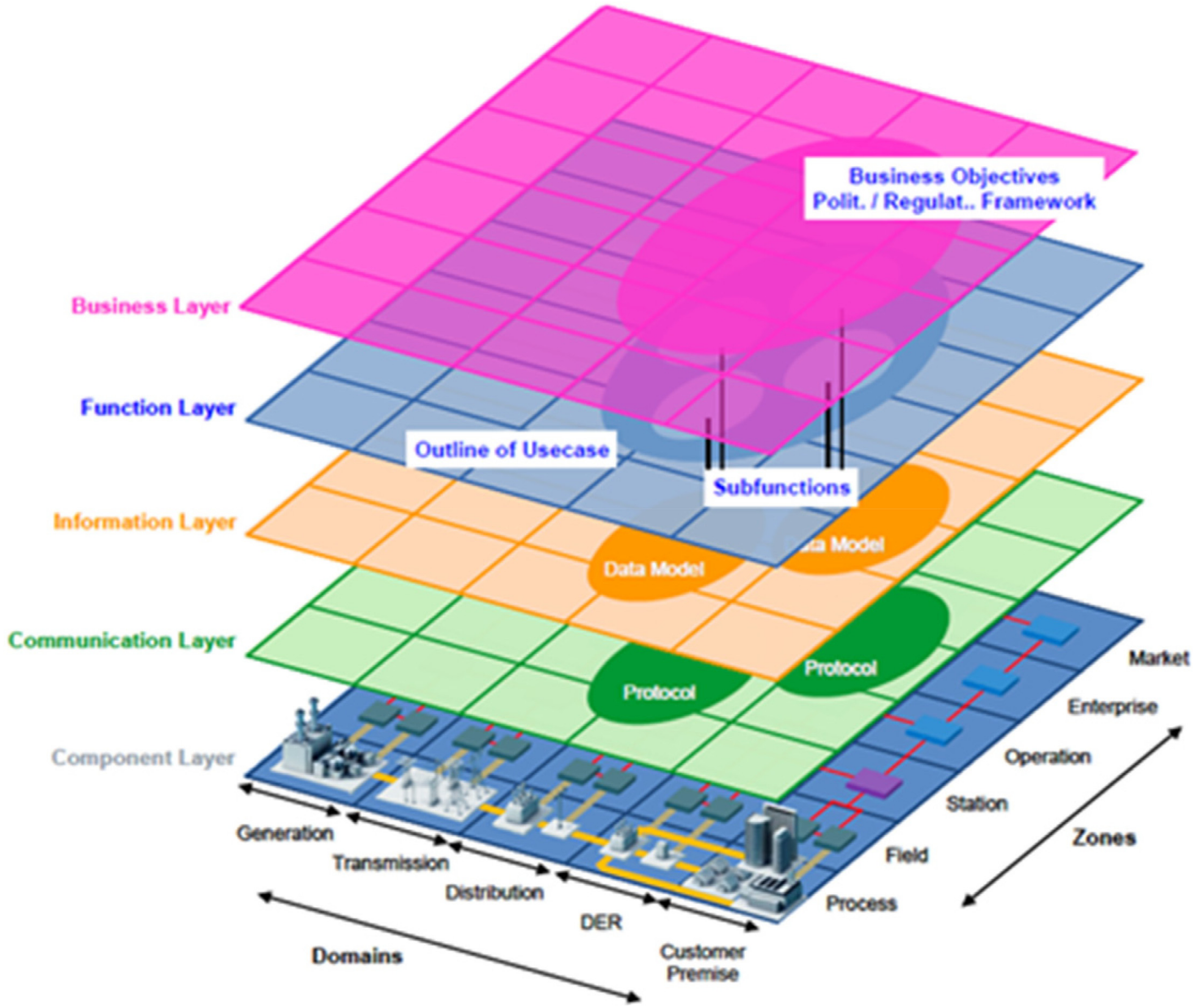

Figure 3: SGAM (smart grid architecture model) [Smart grid] DER (distributed energy resource).

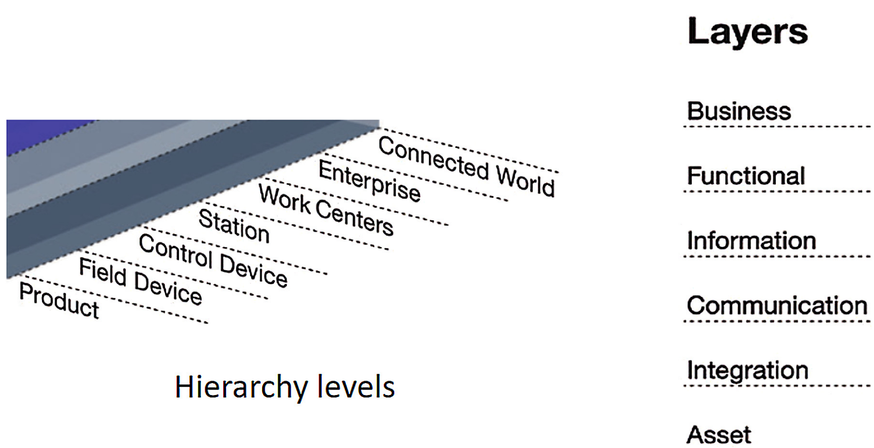

Figure 4: Mix of *product* with facilities of a factory and mix of *asset* with communication layers in RAMI4.0 (IEC PAS, 2017).

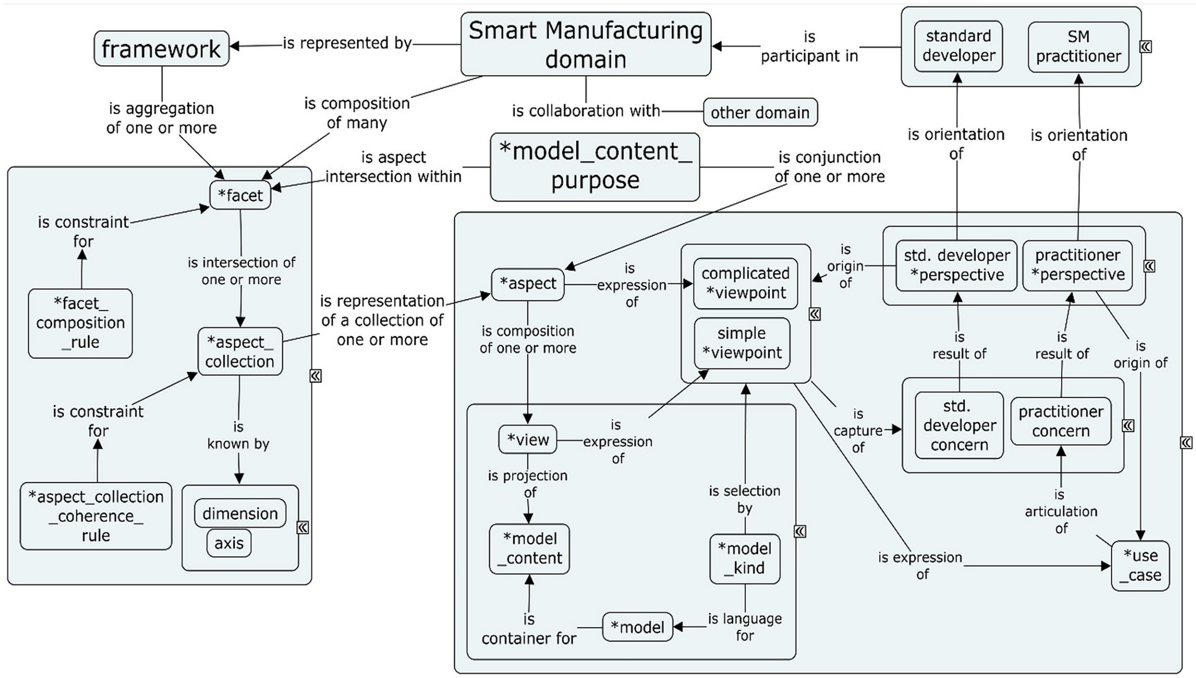

Figure 5: JWG21 meta-model [ISO/TC 2019].

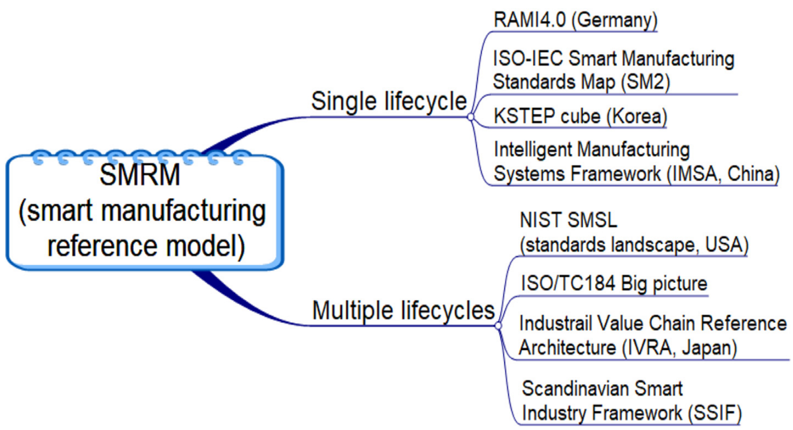

Figure 6: A classification of national SMRM contributions.

Table 1: Comparison of existing reference models.

# of life cycles	Ref. Model	# of axis	Time axis (occurent SPANing)			Space axis (continuant SNAPshot)		
Single life cycle	RAMI4.0	3		Life cycle and value stream		Hierarchy levels		Layers
	SM2	3		Production systems life cycle		Functional hierarchy		Interoperability layers
	KSTEP	3		Lifecycle of things		Factory hierarchy		Telecommunication hierarchy
	IMSA	3		Lifecycle		Systems hierarchy		Intelligent characteristics
Multiple life cycles (LC)	NIST	4	Product LC	Production LC	Business LC	Manufacturing pyramid		
	TC184	3	Lifecycle		Value chain			Interoperability layers
	IVRA	3	Product axis		Service axis		Knowledge axis	
	SSIF	6	Product LC	Production LC	Business LC	Product	Production	Business

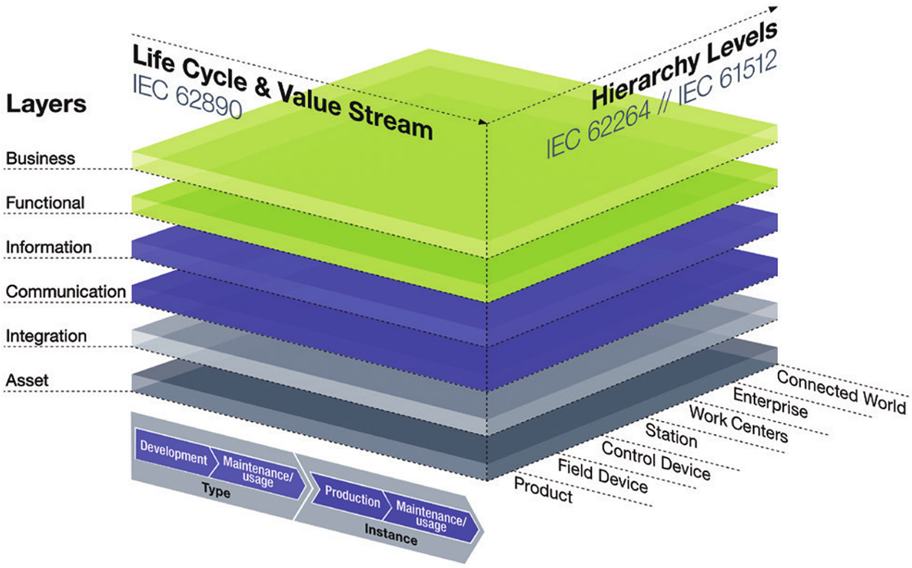

Figure 7: Reference Architecture Model Industrie 4.0 (RAMI 4.0) (IEC PAS, 2017).

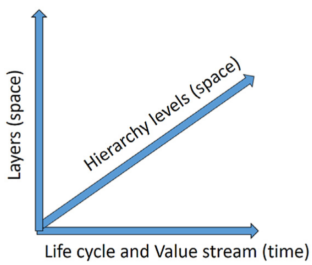

Figure 8: Skeleton of the RAMI4.0 framework.

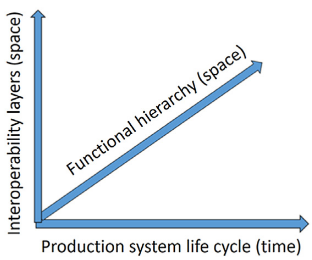

Figure 10: Skeleton of ISO-IEC SM2.

2.2 Meta-models

2.2.1 *JWG21 meta-model*

ISO-IEC JWG21 is producing versions of working draft of SMRM. Current version is titled as “Technical Report, A meta-modeling analysis approach to Smart Manufacturing Reference Models (SMRM)” [ISO/TC 2019]. One of the objectives of JWG21 is to harmonize various contributions of SMRMs which are provided by different countries and organizations.

It is worthwhile to integrate the SMRMs while 5G smartphones are poised to enable the super connectivity. However, fragmented technology standards make it hard to exploit that to connect facilities and products in the smart manufacturing vision. An integrated reference model is sought among experts

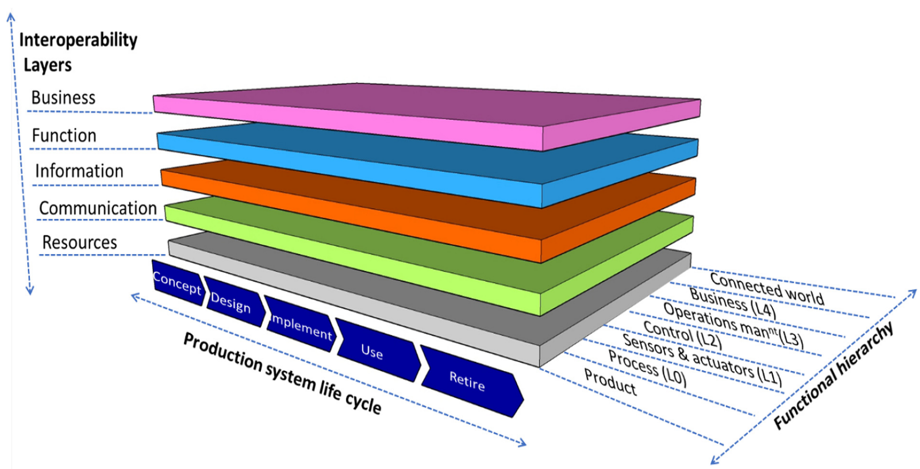

Figure 9: ISO-IEC Smart Manufacturing Standards Landscape (SM2) (ISO-IEC, 2018).

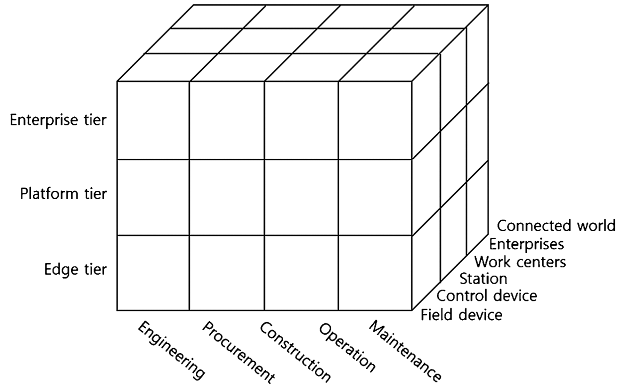

Figure 11: KSTEP cube framework (Korea STEP, 2018; Han 2019).

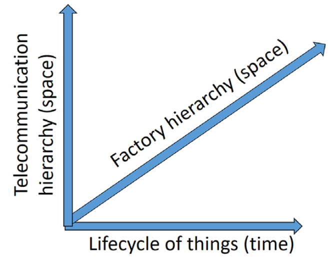

Figure 13: Skeleton of the KSTEP model.

of JWG21 to arrive at common understandings of terminologies and frameworks for smart manufacturing.

A meta-modeling approach had been adopted and mappings of the proposed SMRMs to the JWG21 meta-model have been published in the technical report of JWG21. The JWG21 meta-model shown in Fig. 5 has been developed based on international standards (ISO15704 2000; ISO/IEC/IEEE, 2011). The mapping process, however, is not simple because the JWG21 meta-model has the concept of superset which can accommodate all the key concepts of each proposed reference model.

2.2.2 *Skeleton meta-model*

Toward the opposite direction of the superset approach, there can be the minimal set, the dominating set, or the common intersection approach. The skeleton can be seen as the simplified representation of the complex human body. The skeleton meta-model (Lee, Kashyap & Chu, 1994; Mun, Hwang & Han, 2009) is applied to capture the core elements of each reference model by simplifying the complexities of smart manufacturing. To simplify existing reference models, one can classify each of their axes to either a *space* axis or a *time* axis.

2.3 A classification of SMRMs

Figure 6 shows a classification of eight proposed SMRMs. This classification focuses on the number of lifecycle axis. Four reference models have single axis of lifecycle whereas others have multiple lifecycle axes. To harmonize different SMRMs the number of lifecycles should be harmonized first. One suggestion for the harmonization of lifecycles is explained in Section 4.1.

Number of dimensional axes and their names are compared to further classify the reference models. Table 1 shows a summary of comparison among different reference models. The focus is on the number of dimensional axes. Similarities or differences of each dimensional axis are grouped and compared. More details of each reference model are explained in the Section 3 together with its skeleton model.

The Basic Formal Ontology (BFO) has *Occurent* and *Continuant* (or SPANing and SNAPshot) (Galton, 2016) which can represent time dimension and space dimension, respectively. The time axis and the space axis are the basic quantities of physics and the world. Although the space axis of some SMRMs contains non-spatial items, the hard-simplification of the skeleton

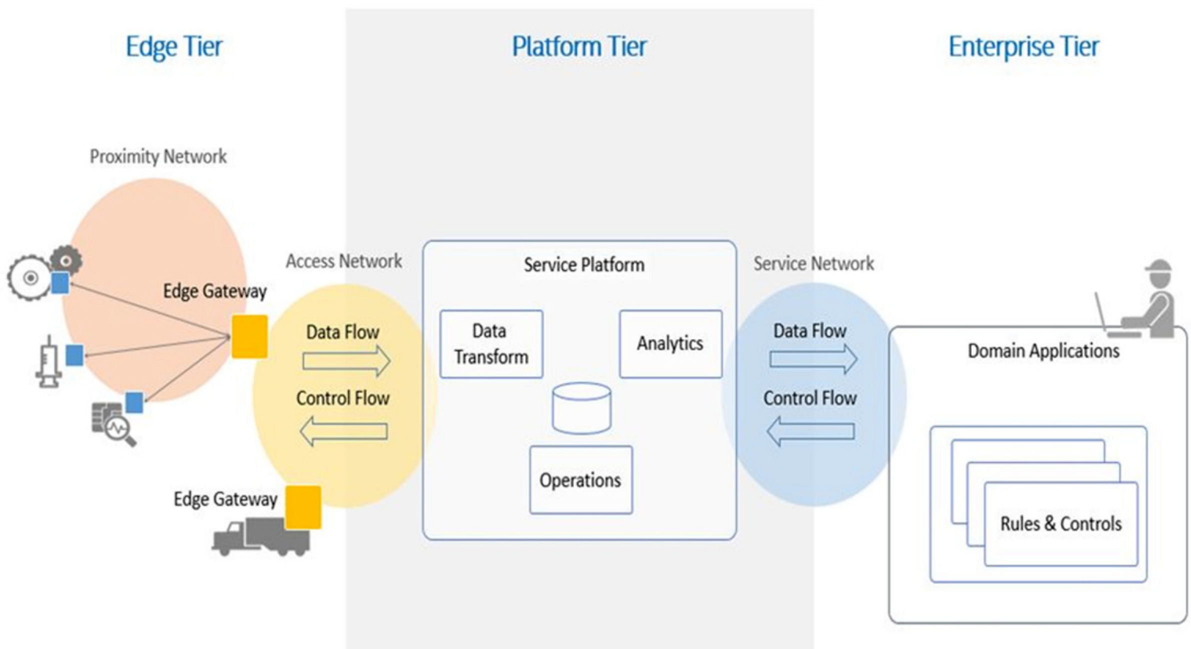

Figure 12: Three-tier IIoT system architecture [IIC].

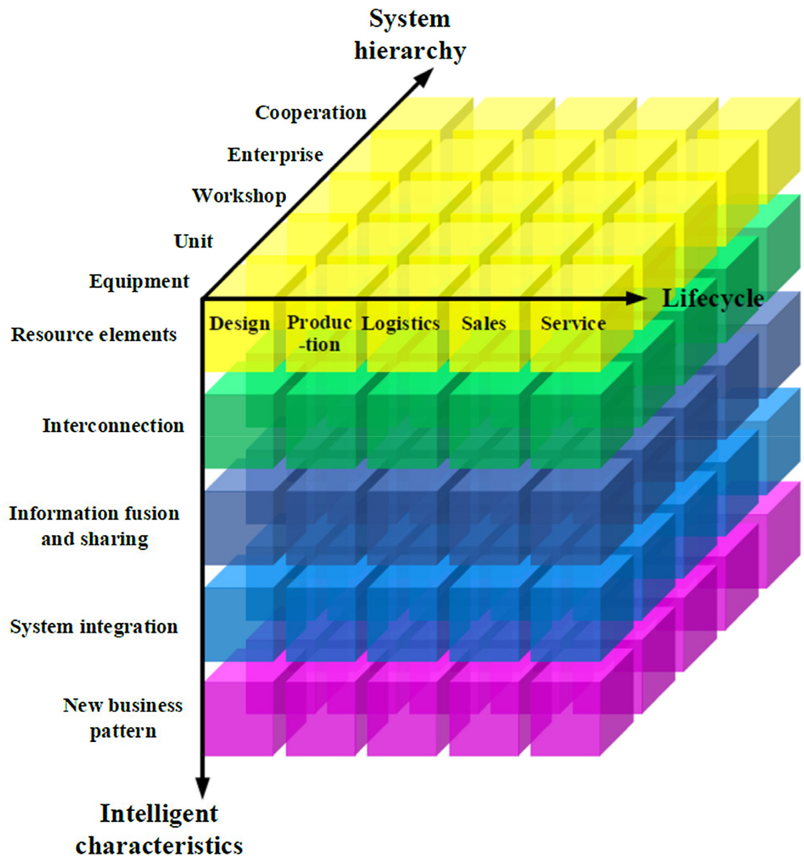

Figure 14: IMSA (Sino-German, 2018).

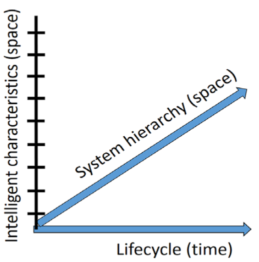

Figure 15: Skeleton of IMSA.

meta-model can help to find the core elements of the complex structure of the smart manufacturing.

Many of reference models adopt three axes model so that they can be easily represented as a box or a cube. *Interoperability*, *telecommunication*, or *connectivity* are highlighted as a separate axis in many reference models. Also the procurement process (or supply chains) of parts are named as *business lifecycle*, *value chain*, or *service axis*.

3. Analysis of Existing Reference Models with Skeleton Meta-models

For each of eight SMRMs which are classified in Fig. 6, a skeleton meta-model is drawn to see the core conceptual dimensions of the reference model.

3.1 SMRMs with single lifecycle

"RAMI4.0" (Reference Architecture Model Industrie 4.0) can be regarded as a 3D map of Industrie 4.0 solutions. It provides an orientation for plotting the requirements of sectors together with national and international standards in order to define and further develop Industrie 4.0. Overlapping standards and gaps can thus be identified and resolved (IEC PAS, 2017).

RAMI4.0 is proposed by Christian Mosch of VDMA (Verband Deutscher. Maschinen-und Anlagenbau. German Machine & Plant Engineering Association) and registered as the PAS (publicly available specification) 63 088 of IEC in 2017. It is a box (or cube) model as shown in Fig. 7 where three axes are layers, lifecycle and value stream, and hierarchy levels.

The *layers* axis consists of layers of asset, integration, communication, information, functional, business. The *asset* layer is to represent a physical facility, a device, or a product. The *integration* layer represents the *administration shell*, which allows the digital transformation of a physical asset (see also Fig. 26), since then the transformed asset can be identified as a digital item (Wagner et al. 2017; ZEVI, 2017). Once converted into a digital thing, the above layers of RAMI4.0 expand toward communication, information, functional, and business layers which can utilize the digitalized asset. The *layers* axis of RAMI4.0 is a variant of the layers axis of the SGAM.

The *lifecycle and value stream* axis consists of stages of *type* and *instance*, where the *type* stage is further divided into *development* and its *maintenance/usage*, and the *instance* stage is further divided into *production* and its *maintenance/usage*. The division of

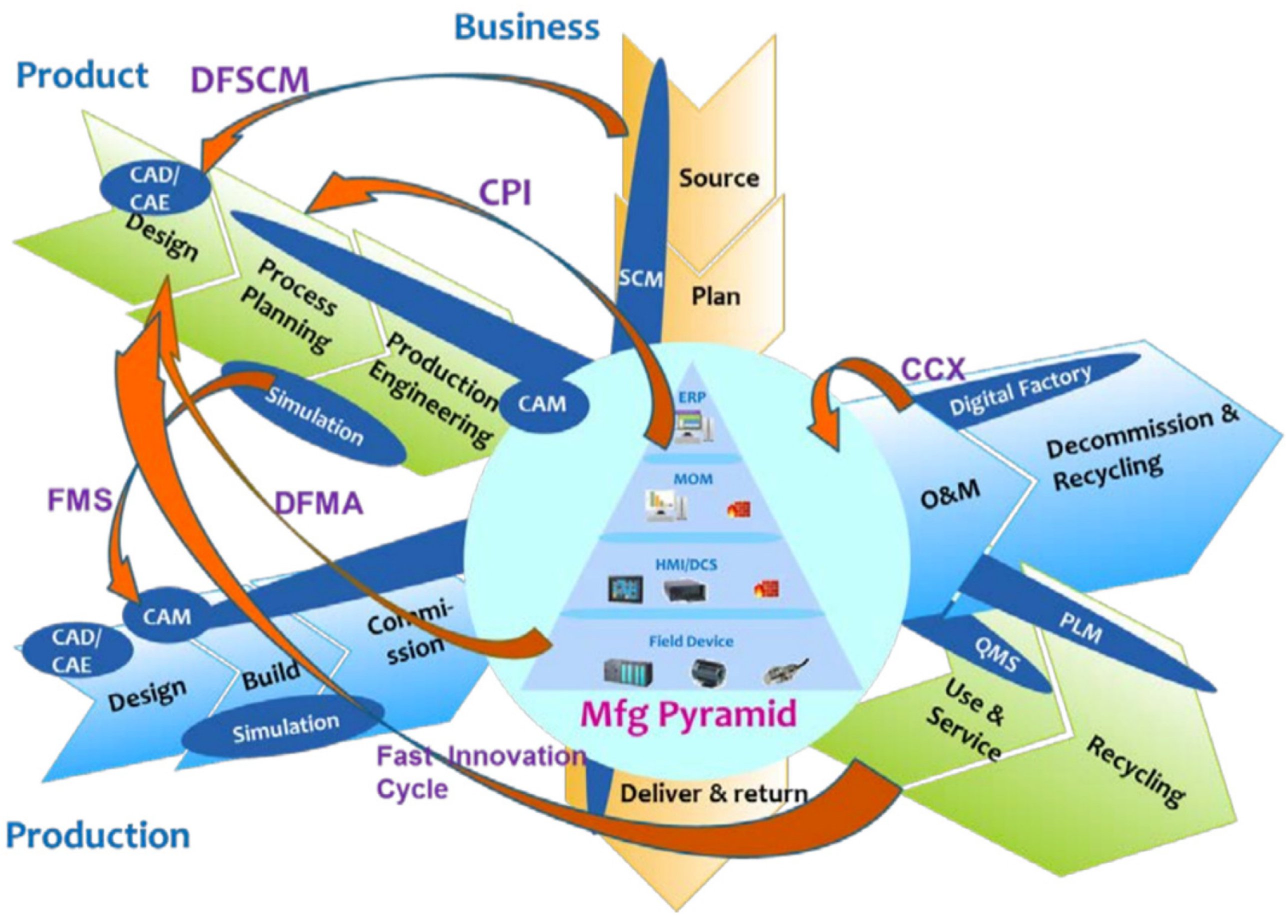

Figure 16: Smart manufacturing ecosystem of NIST [24].

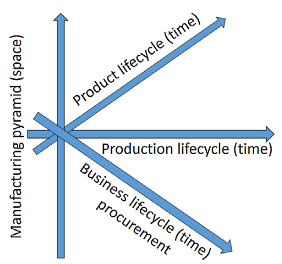

Figure 17: Skeleton of the NIST framework.

type and *instance* can be regarded as the division of *class* and *instance* in an object-oriented software development. However, it does not well represent the lifecycle and value stream of a manufacturing plant (or factory) or a product.

The axis of *lifecycle and value stream* is based on *IEC 62 890 Life-cycle management for systems and products used in industrial-process measurement, control and automation* (IEC62890, 2016). IEC 62 890 standardizes lifecycles of automotive production plants or chemical plants. It focuses on the maintenance of a plant where automation devices are used for the plant operation. Because the life span of a plant is much longer than that of an automation device, upgrades of devices are expected during the lifecycle of the plant itself and this characteristic needs to be accommodated in an SMRM.

The third axis of *hierarchy levels* consists of product, field device, station, work centers, enterprise, and connected world. It shows expansion in space along the hierarchy of physical plant facilities. However, the *product* level is an output of a production plant, so that it is different from the remaining levels of the production plant. The *field device* level collects sensor data of manufacturing operation as the bottom level of the production hierarchy, and report them to a control device in the *station* level.

The *station* level is a grouping of devices which works as a manufacturing function. The *work centers* are groups of connected stations which perform several manufacturing functions in sequence. A collection of work centers can be a factory (or a production plant). A collection of factories can be an *enterprise*, and enterprises are connected via internet to construct the *connected world* where they may collaborate or compete.

The axis of hierarchy levels is a variant of IEC 62 264 or IEC 61 512. *IEC 62 264 enterprise-control system integration* consists of six sub-parts of standards, and is being developed in parallel with ANSI/ISA 95. In the ISA 95 standard, the equipment hierarchy is divided into *work unit, work centers, area, site*, or *enterprise*. *IEC 61 512 Batch control* consists of four sub-parts of standards, and is being developed in parallel with ANSI/ISA 88. In the ISA 88 standard, the physical model has the hierarchy of *control module, equipment modules, unit, process cell, area, site*, or *enterprise*.

Figure 8 shows the skeleton of RAM4.0 where three axes are simplified as one of base quantities of time or space. Although the *layers* axis and *hierarchy levels* axis respectively contain a

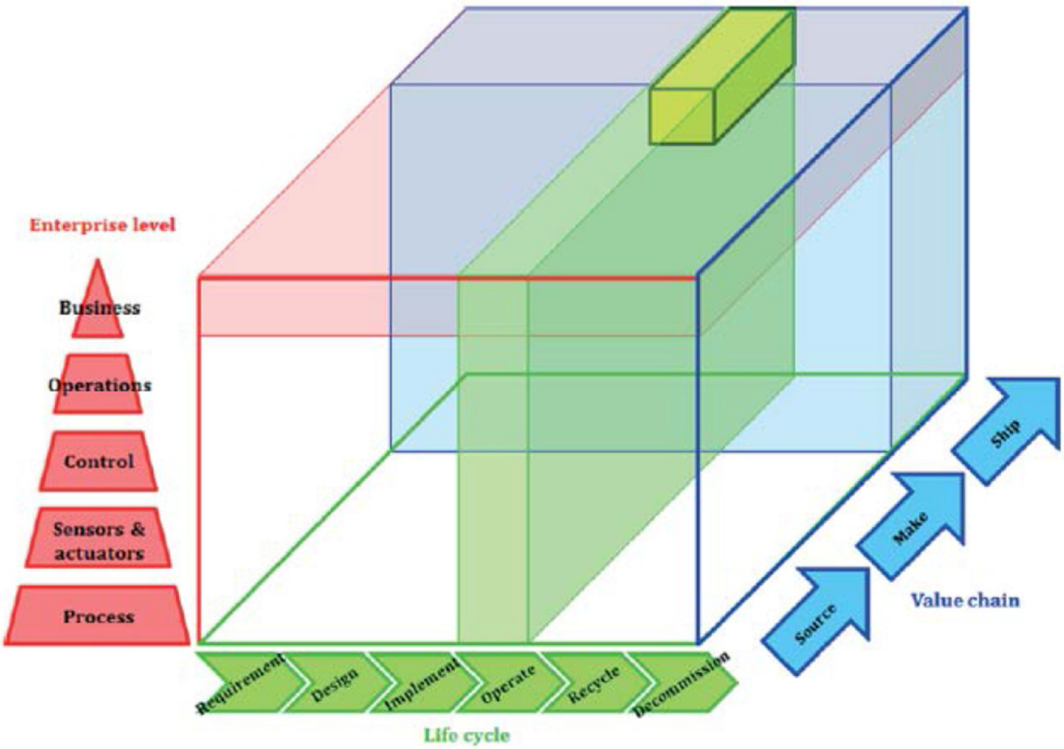

Figure 18: ISO/TC 184 Big Picture [ISO/TR 2018].

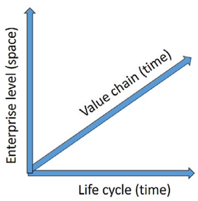

Figure 19: Skeleton of the ISO/TC184 Big Picture.

dissimilar member which are different from their base standards, both axes can be classified as the space axes rather than the time axis.

The limitations of RAMI 4.0 are found as follows:

(1) The model shows only IEC standards. However, a joint working group 5 between the IEC/ISO SC65E and the ISO TC184/SC5 technical subcommittees is actively developing a multi-part IEC 62 264 standard based on the ISA-95 specifications.
(2) The relationship between two space axes of *Layers* and *Level* is not clear.

Improvement ideas for RAMI4.0 are as follows:

(1) Inclusion of ISO and other standards in addition to IEC standards.
(2) Relationship between two space axes of *Layer* and *Level* can be clarified, in terms of differences or resemblances.
(3) Because the interests on the digital twin increase, RAMI4.0 may provide how to accommodate the digital twin concept in addition to the administration shell concept (see also Fig. 26), which simply transforms a physical asset into a digital thing.
(4) The lifecycle of a production plant (or a factory) or a product can be better represented by adopting models from other standards such as the FIATECH model [FIATECH] or ISO 10 303–239 PLCS (product lifecycle support) (ISO10303, 2005). The FIATECH model is a variant of the PLCS model for the plant industry or the construction industry.

Every object has a life so that anything has its own lifecycle. A car is said to be made of about 20 000 parts. Any part of them is a product of a factory. If all the lifecycles of all parts are considered, it is hard to represent or manage all lifecycles of them. It is better to have the generic lifecycle of any part similarly to Fig. 2 *Generic Life-Cycle-Model of a product type* of IEC 62 890.

The Fiatech model or ISO 10 303–239 lifecycle model is better as the generic lifecycle because it accommodates more stages than IEC 62 890 and also covers broader kinds of product categories including a factory. Although the generic lifecycle model of IEC 62 890 can be applied to anything, the explanation about Fig. 2 *of IEC 62 890* shows that the main target products are electronic parts with short-life which are used for automation or control.

Figure 9 shows the ISO-IEC Smart Manufacturing Standards Landscape (SM2) which is prepared by the Smart Manufacturing Standards Map (or SM2) Task Force of ISO and IEC (ISO-IEC, 2018). The cube model looks similar with the RAMI4.0 model with some variations. One noticeable variation is the *production system life cycle*. It is similar to the “product” lifecycle of PLCS. It is reasonable because the *production system* can be seen as a “product” of the *production system* builder.

Figure 10 shows the skeleton of the Smart Manufacturing Standards Landscape (SM2). It has two space axes and one time axis. Although the name of each axis is different from that of RAMI4.0, the contents are similar.

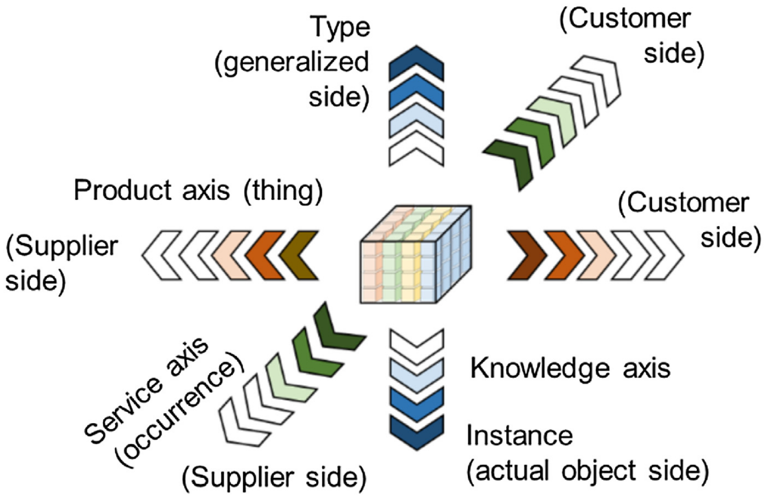

Figure 20: IVRA (Industrial, 2018).

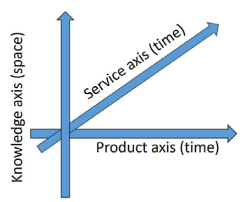

Figure 21: Skeleton of IVRA.

The *layer* axis of the SM Standards Landscape is similar to that of RAMI4.0 whereas the *layer* axis of RAMI4.0 is a variant of the vertical axis of SGAM. There is non-monotonic element(s) along the axis but it can be classified as a space axis because the axis contains elements of spatial hierarchy.

Figures 2 and 11 show the KSTEP cube framework which also has two space axes and one time axis. The core dimensions of the KSTEP framework (Korea STEP, 2018; Han 2019) is same as those of RAMI4.0, but the KSTEP framework adopts different available standards for the lifecycle axis and also for the telecommunication axis. The *factory physical hierarchy* axis is almost same as RAMI4.0 but KSTEP adopts the original IEC62264-3 hierarchy (IEC62264, 2013). The *lifecycle* axis of the KSTEP framework adopts the FIATECH lifecycle [FIATECH] which is a variant of ISO 10 303-239 PLCS (product lifecycle support) (ISO10303, 2005). The *telecommunication physical hierarchy* axis of the KSTEP framework adopts the three-tier IIoT system architecture [IIC].

The *lifecycle* axis of the KSTEP cube framework is composed of *engineering*, *procurement*, *construction* (or manufacturing), *operation*, and *maintenance*. It represents the lifecycle of a *thing* which can represent a *product* or an *asset*. The *factory physical hierarchy* is composed of *field device*, *control device*, *station*, *work centers*, *enterprises*, and *connected world*. The *telecommunication physical hierarchy* is composed of the *edge tier*, the *platform tier*, and the *enterprise tier*.

The space axis2 of the KSTEP model (see also Fig. 2) can be used to represent the physical hierarchy of the telecommunication space such as communication cables or wireless network. Three candidate models considered were the three-tier IIoT system architecture [IIC], the (original) layers axis of SGAM [SGAM], and the OSI 7 layers [OSI]. The three-tier IIoT system architecture as shown in Fig. 12 has been adopted in the KSTEP reference model.

Telecommunication is getting more important as IoT and 5G are progressing in the smart manufacturing. The KSTEP reference model adopts the IIoT system architecture to accommodate this trend of the telecommunication development for the axis of *telecommunication physical hierarchy*.

Figure 13 shows the skeleton of KSTEP model which has two space axes and one time axis of lifecycle. It is similar to RAMI4.0, but it adopts different existing standards for better harmonization.

Figure 14 shows the IMSA (intelligent manufacturing system architecture) of China (Sino-German, 2018) which is again similar to RAMI4.0 model. The axis of *intelligent characteristics* enumerates new technologies for Industry 4.0. The *lifecycle* axis is for a *product* rather than a *production system*. The *system hierarchy* axis does not include the *product* as one level, which is different from RAMI4.0.

Figure 15 shows the skeleton model of IMSA. Because the *intelligent characteristics* axis does not show any structure or hierarchy, the axis is represented as a collection of enumerated items instead of an arrow style axis. The *Intelligent Characteristics* axis of the IMSA reference model from China is a variant of the *layer* axis of RAMI4.0 but it is hard to see a spatial hierarchy.

3.2 SMRMs with multiple lifecycles

'The NIST report provides a review of the body of pertinent standards—a standards landscape—upon which future smart manufacturing systems will rely. It discusses opportunities and challenges for new standards (Lu, Morris & Frechette, 2016).

There are three lifecycle axes (see Fig. 16): the *product* lifecycle, the *production* lifecycle, and the *business* lifecycle. At the center (at the crossing point of three lifecycle axes) of the NIST model, there is the *manufacturing* pyramid. Lifecycles are timelines whereas the pyramid is a space representation or a spatial hierarchy.

The *product* lifecycle consists of *product design, process planning, production engineering, use and service, recycling* along the timeline. It is similar to the engineering lifecycle. Software systems such as CAD (computer aided design), CAE (CA engineering), Simulation, CAM (CA manufacturing), QMS (quality

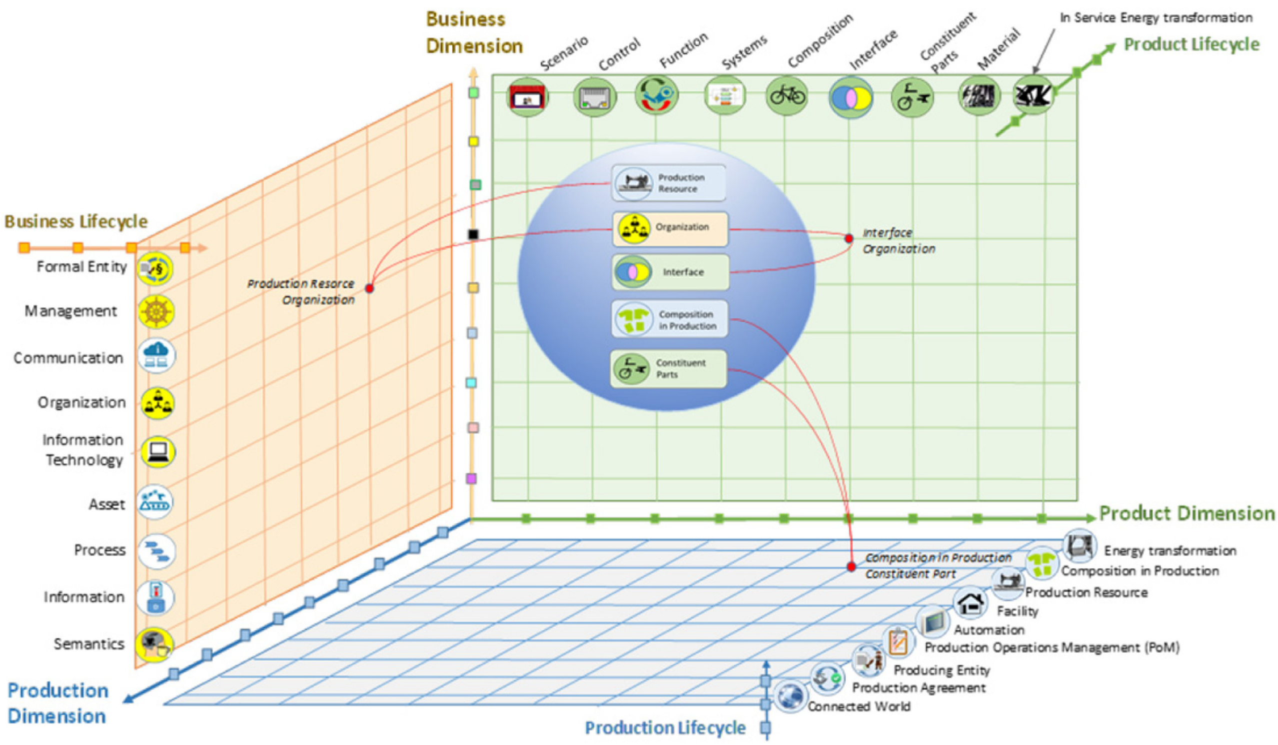

Figure 22: SSIF Semantic Cube (U. Carlsson, personal communication, March 2019).

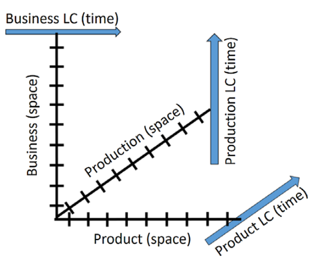

Figure 23: Skeleton of the Scandinavian model.

management system), and PLM (product lifecycle management) are shown together, which correspond to each stage of engineering.

The *production* lifecycle consists of *production design, build, commission, O&M* (operation and maintenance), *decommissioning, and recycling* along the timeline. The *build* stage meets the manufacturing pyramid. The *production* lifecycle is similar to the *product* lifecycle where two are interact with each other.

The *business* lifecycle consists of *source, plan, delivery, return* along the timeline. SCM (supply chain management) is the software for this lifecycle. The procurement stage is to purchase parts usually for assembly of a product. As the modern manufacturing outsources more parts than before, the stage is getting more important so that it is a separate stage of the plant lifecycle of FIATECH. The NIST model has a separate lifecycle to accommodate this trend of outsourcing or procurement as the *business* lifecycle.

The *manufacturing* pyramid consists of *ERP* (enterprise resource planning) at the top, *MOM* (manufacturing operations management), *HMI* (human machine interface), *DCS* (distributed control system), and the *field device* at the bottom level.

Figure 17 shows the skeleton model of the NIST framework where three *time* axes represent three different lifecycles, and one *space* axis represents the manufacturing pyramid. The NIST model has four dimensions.

Figure 18 shows the cube model of the ISO/TC 184 Big Picture where two axes are used to represent different lifecycles [ISO/TR 2018]. One lifecycle (*life cycle*) is for product and the other (*value chain*) is for outsourcing of components of the product. The *enterprise level* represents the spatial hierarchy inside the enterprise. The model is similar to that of NIST.

Figure 19 shows the skeleton model of ISO/TC184 big picture. It is a cube model where two axes represent timelines of two lifecycles and one axis is for the space hierarchy. It looks like a simplified version of the NIST model where two lifecycles of *product* and *production* of the NIST model are collapsed into one *life cycle*.

Figure 20 shows the IVRA (industrial value chain initiative) model from Japan (Industrial, 2018) where two axes represent time lines of *product* and *service*, and the third axis represents space of type and instance hierarchy.

Figure 21 shows the skeleton model of IVRA where two time axes represent *product* lifecycle, *service* (operation and maintenance) lifecycle, respectively, and one space axis represents *knowledge* (type(class) – instance) hierarchy. The knowledge axis of IVRA can be seen as a variation of the lifecycle axis of RAMI4.0, but it does not show any stages of product development. The *type* and *instance* are similar to the *class–instance* relation of the object-oriented programming. That is the reason why it is classified as a space axis.

Figure 22 shows the SSIF (Scandinavian Smart Industry Framework) Semantic Cube where three space axes represent *product*, *production*, and *business* (U. Carlsson, personal communication, March 2019). Each space axis enumerate a good selection of items of each category. There are also three

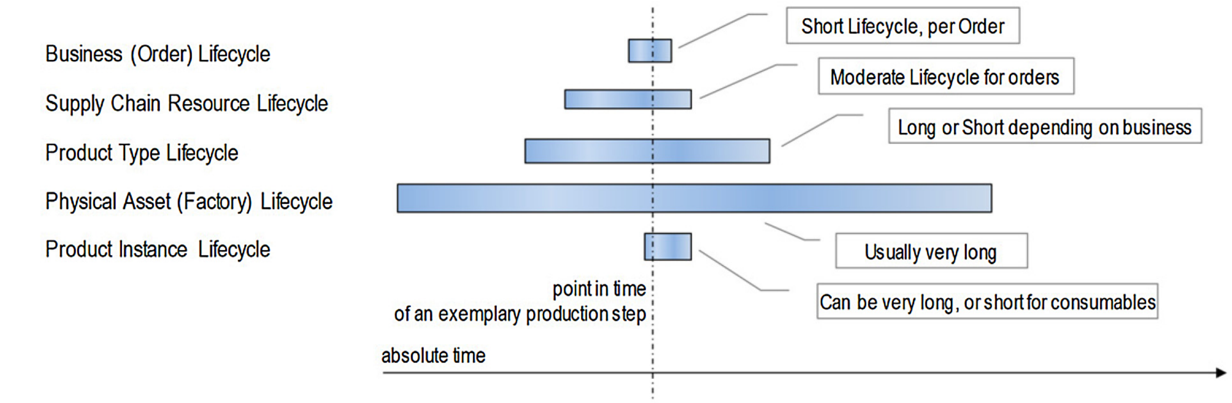

Figure 24: Exemplary lifecycles over time of JWG21 SMRM TR [ISO/TC 2019].

Figure 25: Digital twin of a wind power system (Raut, 2017).

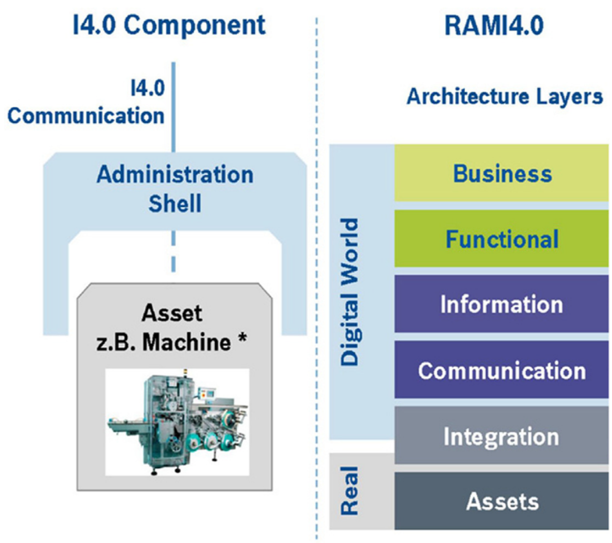

Figure 26: Administration shell for digitalization (ZEVI, 2017).

lifecycle time axes which correspond to each of the three space axes.

Figure 23 shows the skeleton model of the Scandinavian model. Although each space axis elaborates a good collection of key items, there is not clear structure or hierarchy so that the space axes are drawn with enumeration symbols instead of an arrow type axis. For each of the space axis there is a corresponding lifecycle (LC) time axis.

4. Possible Harmonization of SMRMs

ISO-IEC JWG21 is trying to harmonize various contributions from countries and organizations to produce an international reference model. The current approach is to use a meta-model to harmonize differences. The current JWG21 meta-model takes the superset approach where most of key concepts are collected to arrive at a big reference model, whereas the skeleton meta-model can simplify contributions to find core base quantities. In addition to the meta-model approach, two possible approaches are introduced in this section. (1) Multiple lifecycles can be harmonized into single generic lifecycle. (2) The concept of digital twin can be accommodated in the SMRM.

4.1 Bundling of lifecycle axis

Figure 24 shows different lifecycles which can appear during the process of smart manufacturing [ISO/TC 2019]. They have different time durations. The starting point and terminal point of each lifecycle are different. The NIST model [Lu 2016] has three lifecycles and there are more SMRMs which have multiple lifecycles. Lifecycles within the scope of smart manufacturing can be either the *product* lifecycle, the *factory (manufacturing system)* lifecycle, the *parts* lifecycle, or the *facility* lifecycle.

Although the KSTEP cube model and a few other models have only one time axis, the lifecycle can represent multiple lifecycles. It can represent a generic lifecycle which can accommodate various lifecycles of Fig. 24. IEC 62 890 (IEC62890, 2016) also standardized a generic lifecycle which can be used to represent various lifecycles of *product versions*, individual lifecycles of the *integrated components*, *end of warranty period*, *abandonment of the product type*.

The *lifecycle* axis of the KSTEP cube framework can represent the lifecycle of a generic *thing*. A *thing* can represent a *product*, an *asset*, a *plant*, a *factory*, a *manufacturing system*, or a *part* (*component*) of a product. For example, a device or a facility (e.g. a robot or a crane) of a factory is a *product* of another factory which produces the item. Various lifecycles can be represented by this lifecycle of a generic *thing*. The term *thing* is borrowed from IoT (internet of things).

The EPCO&M (engineering, procurement, construction, operation, maintenance) model of the FIATECH Capital Projects Technology Roadmap [FIATECH] is adopted by the KSTEP model. It is a modification of PLCS (product lifecycle support) of ISO 10 303-239 (ISO10303, 2005) for the plant industry. In the EPCO&M model, *Engineering* corresponds to the design and *Procurement*

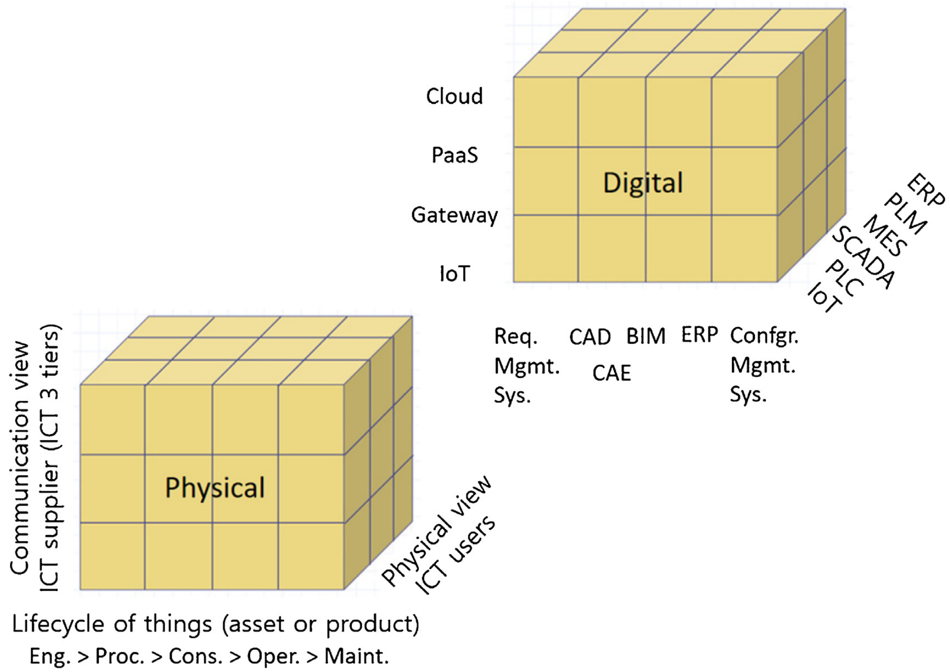

Figure 27: Digital twin of the KSTEP cube framework (Korea STEP, 2018; Han 2019).

corresponds to the purchase of components. *Manufacturing* is usually used for realization of a product and *Construction* is usually used for realization of a factory. The *Operation* stage in a product lifecycle is the stage of *usage* (see also, Operation and Maintenance: O&M) rather than the stage of *making* the product.

A factory (or a plant, an asset) is also a *product* of another company such as a construction company or an engineering company. A shipyard builds an ocean plant such as FPSO (floating, production, storage, and offloading) which is a floating type of oil & gas processing plant. Again, a manufacturing equipment such as a robot or a crane in a factory is a *product* of another company which makes the equipment. The same logic applies to parts (or components such as a bolt or a motor) of a *product*, which once again are *products* of manufacturers of that parts (or components). The lifecycle of a generic *thing* can represent the corresponding lifecycle of a product, an asset, a plant, a factory, or a part (component) of a product. By adopting the EPCO&M lifecycle as the generic lifecycle, lifecycles of many *things* can be represented.

4.2 Accommodation of digital twin

"A digital twin is a digital replica of a living or non-living physical entity" (Raut, 2017). Figure 25 shows a representative figure of the digital twin concept which has two twin parts. Usually there are gaps or mismatches between the physical entity and the digital counterpart. Along the lifecycle of a *product* (or a *thing*), there are different versions of digital models – from the concept design to the production design or the laser scanned model of the realized product. There are also several upgrades and aging degradation of the physical thing after the realization (or production) of the *product*.

Fidelity or LoD (level of detail) is to represent these mismatches. The objective of concept design is to idealize the product so the representation is simple (usually represented as a 2D diagram or a sketch), while the production design is close to the realized product in three dimensions so that the levels of detail are different. The physical *product* changes along the lifecycle of upgrades, aging, and decommissioning. Big data collected through IoT or laser scanners help to reduce the gap between the two twins.

An SMRM should clearly differentiate between physical (tangible) product and digital (virtual, functional, logical, or intangible) model to better accommodate the digital twin concept. There are mixture of physical model and digital model along one-dimensional *layer* axis in RAMI4.0. The *asset* in RAMI4.0 is used to represent both the physical thing and the digital model. An SMRM may differentiate tangible items from intangible items by using the notions of the physical asset and the digital asset. In RAMI4.0, the physical asset is transformed into a logical asset through the *administration shell*. Asset Administration Shell (AAS) is a bridge between a tangible asset and IoT world (Wagner 2017; ZEVI, 2017).

Figure 26 shows that the *administration shell* of RAMI4.0 is for digitalization of an asset or an equipment (ZEVI, 2017). By converting a physical thing into a digital twin by wrapping the physical *thing* with the administration shell, the physical asset can be harmonized into the cyber systems. One possible problem of the *administration shell* is that it can be a heavy implementation to accommodate all the detail of a physical thing.

A reference model should take into account the digital twin notion because the digital twin gets more important in smart manufacturing. The *administration shell* of RAMI4.0 takes into account the digital twin notion even though the administration shell is not shown on the RAMI4.0 cube. Other reference models do not take into account the digital twin notion. As the *administration shell* can be heavy to accommodate the digital twin concept, there can be a better method to accommodate the digital twin concept.

The KSTEP cube framework of SMRM has two cubes as Fig. 27 similar to the digital twin of a wind power system of Fig. 25. One cube is for the physical reference model and the other is for the digital reference model. By twining two reference models it may better accommodate the digital twin concept.

5. Summary

Standards will allow interoperability among stakeholders in the upcoming super-connected world. But there are gaps and overlaps of existing (international) standards. An SMRM is under development inside JWG21 between ISO and IEC. However the development process of an international standard is not simple. It usually takes several years to harmonize different thoughts and understandings of participating countries.

The skeleton meta-models of eight proposed SMRMs are investigated. Number of dimensional axes are compared and eight SMRMs are classified based on the number of lifecycle axes.

- The skeleton meta-model is used to find out the core elements of each reference model by simplifying the complexities of smart manufacturing.
- The number of lifecycle axes is used to classify eight proposed reference models into two groups. Number of dimensional axes and their meanings are compared to further classify the reference models.
- An SMRM needs to accommodate the fidelity differences between the physical twin and the digital twin.

Because the smart manufacturing will evolve together with the technology evolution, the reference model should be flexible enough and simple to understand.

Conflict of interest statement

Declarations of interest: none.

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