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Robot Revolution & Industrial IoT Initiative

PLATTFORM INDUSTRIE 4.0

Digital twin reference model and standardization to realize a sustainable industry

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Content

Abstract

Experts from Plattform Industrie 4.0/SCI 4.0 (Germany) and the Robot Revolution and Industrial IoT Initiative (RRI, Japan) have worked jointly on smart manufacturing and its standardization. They aim to implement a sustainable society and industry by reducing environmental impact and improving Quality of Life (QoL), which are urgent issues for both countries. Visualization and modelling of products and activities, considering the entire life cycle of artifacts, are important to improve sustainability. The digital twin is the basis for this modelling. The interoperability of digital twins also creates various new possibilities. Based on the analysis of use cases in both countries, this paper discusses a reference model of a digital twin and requirements for standardization, with a view to smart manufacturing and its wider application in society.

I. Introduction

There is a prevailing consensus that the planetary boundaries regarding natural resources and climatic conditions must lead to absolute consideration of sustainability [1,2]. All human activities must be taken into full consideration. One possibility for resource-conserving production is the development of intelligent manufacturing processes with comprehensive digitalization [3] and visualization. Today, the importance of the digital twin for ecological sustainability [5,6] can no longer be denied, despite all the problems associated with its introduction [5,6]. Recent trends see digitalized manufacturing as a social infrastructure [4]. Here, social activities can be supported by the manufacturing infrastructure. A sustainable introduction of digitalization concepts naturally requires a common basis, interoperability and global standardization. One basis for this is the long-standing and successful cooperation between Japan and Germany in smart manufacturing and its standardization [7].

II. Digital twin as a part of a social infrastructure toward environmental sustainability

2.1 Urgent issues for environmental sustainability

2.1.1 General trends

Since the First Industrial Revolution in the late 19th century, the human Quality of Life (QoL) has been substantially enhanced by the introduction of higher energy and dynamic power, precise machines and automation, as well as computer and information technology. Nowadays, many kinds of artifacts, including modern household appliances and advanced information technology devices, are used and indispensable in our daily life. Our society is supported by comprehensive infrastructures, such as electricity and water supply, public transportation, commercial goods logistics and so on.

For enjoining the improved QoL, enabled by the advanced science and technology, particularly in the advanced society, a huge amount of natural resources is acquired and consumed with mining of coal, oil, gas, and various kinds of metal and other types of raw materials. At the same time, corresponding amounts of waste and emissions are discharged by the human activities to the natural environment.

In the past years, it was believed that the capacity of the natural environment of the earth is huge, and it is not necessary to consider the influence of human activities on the natural environment.

However, recently, it has been noticed that depletion of oil, gas, metallic and other types of raw materials become evident. Environmental pollution becomes severe due to a lot of waste from industry and daily life of people. Especially global warming effect due to emission of CO2 and other kinds of warming gases is a real threat for our society by causing extreme climate change and natural disaster.

There have been many discussions about causal relations between human activities and climate change. From a scientific viewpoint, the Intergovernmental Panel on Climate Change (IPCC) has concluded in their recent report [8] that “It is unequivocal that human influence has warmed the atmosphere, ocean and land.”

Not only global warming but also depletion of natural resources and environmental pollution are the critical environmental issues for maintaining the sustainability of our society for the future generations. Now the sound scientific and technological basis for the future sustainability is studied as planetary boundaries, where a meteorological environmental model of the earth is considered to evaluate the influence of human activities [1, 2]. By limiting the human activities within the planetary boundaries, QoL of societies can be maintained without harming the future environment. It is called as the absolute sustainability.

The good news by the IPCC report [8] is that, if we change our mind to care about our environment, and change our interactions with the environment, it is still possible to reduce the global warming to maintain the sustainability of our society, as shown in Figure 1. Figure 1 shows the possibility of CO2 emission reduction by taking appropriate scenarios of social life. There are still many ways to go for environmental sustainability, as the message of COP28 [9] advocates.

As our society is supported by many industrial products or artifacts produced and supplied by the manufacturing industry, manufacturing can play an important and critical role for reducing the environmental influence while keeping QoL of the society.

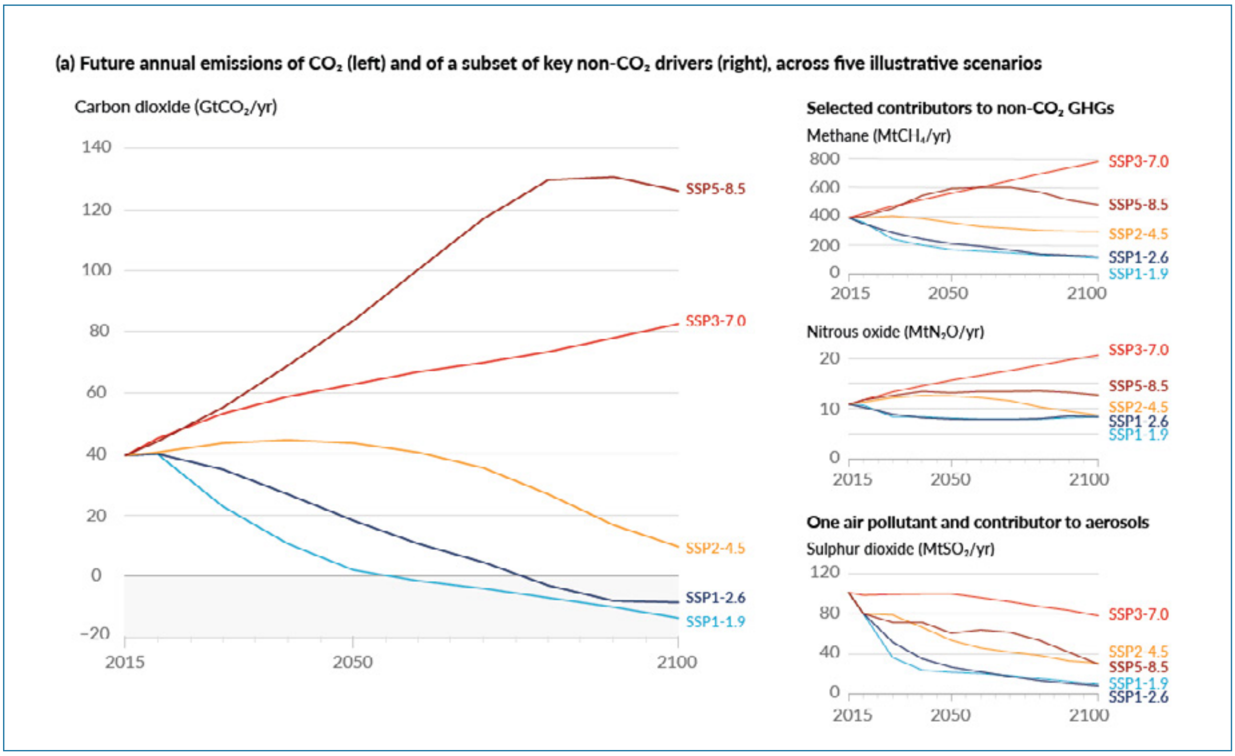

Figure 1: Future annual emissions of CO_2 (left) and of a subset of key non-CO_2 drivers (right), across five illustrative scenarios [8]

2.1.2 Strategy for coping with the environmental issues

Environmental sustainability consists of complicated issues, including political, economic, social, psychological, industrial, technological, scientific, physical and information-related issues. In this paper, we focus on technological issues related to manufacturing. The manufacturing industry supplies all kinds of artifacts and supports our society, including daily-life consumables, to large-scale electric power networks. It is essentially important and effective to re-consider the manufacturing activities from the viewpoint of social sustainability, and to re-organize the technology basis.

Some of the important future strategies can be listed as follows:

- Energy saving
  - Individual technology, system technology → manufacturing

- Circular economy
  - Importance of system aspects [1]
  - No virgin materials, products as materials

- Importance of visualization and quantitative evaluation, e.g., CFP [10]
  - Importance of planning, design, implementation, operation, maintenance, etc.
  - Essential importance of objective evaluation
  - Comprehensive modelling of objects and environment as a basis of evaluation

- Necessity and usefulness of digital twin
  - Common basis of modelling and digitalization of our environment

2.2 Role of smart manufacturing toward environmental sustainability

2.2.1 Importance of modelling

For realizing the strategies described in 2.1.2, manufacturing technology needs to be investigated with the following viewpoints:

- Manufacturing activities should be systematized and modelled to be transparent from the outside for effective interoperability.

- Information about models of manufacturing activities and artifacts should be digitally represented and shared via social information infrastructure.

- Smart technologies shall be systematically integrated to constitute smart manufacturing.

- For utilizing artifacts produced in the manufacturing industry across different social/industry domains, it is required to offer information artifacts for their usage in total life cycle.

For sustainability evaluation, it is essential to evaluate the environmental influence caused by artifacts and manufacturing activities. For this purpose, inclusion of envi¬ronmental aspects in the models is essential. Those aspects are not well modelled in the conventional product and process models. For example, computing a carbon footprint of a product requires information concerning with an amount of CO2 emission related to product information, process operation, status, materials, operation environment, etc. However, such relationship between CO2 emission and manufacturing elements is not well maintained.

2.2.2 Digital twin as a basis of a social infrastructure

For reducing the environmental influence and at the same time supporting the social activities, efficient usage of artifacts is mandatory required. Information infrastructure which represents all the relevant artifact information for social life is effective as shown in Figure 2. A key component is a digital model in the cyber world about a physical or an intangible object in the physical world. By using digital models, necessary objects in the physical world can be flexibly selected and integrated in the application processes for efficient operations.

Traditionally application processes have been sectored into the established domains, such as energy, health, transport, etc. Today new demands are arising to create new value-additive processes across the traditional domains, such as the integration of medical, pharmacy, welfare, food and agriculture domains. If the digital models are available, the newly required application processes can be efficiently configured by combining appropriate digital models. As discussed later in this paper, semantic interoperability across the different domains should be established for flexible integration.

Recently, such digital models are generally called as a digital twin. The definition and technological issues of a digital twin are fully discussed in chapter 3. Here follow some observations about Figure 2.

- Nowadays, all the daily artifacts are manufactured via computer support.

- Naturally, a kind of “digital twin” exists for every artifact by its design and production process.

- It is not difficult to assume a “digital twin” exists for every product.

- It is necessary to reformulate it according to the modelling requirements described in chapter 3.

- If “digital twins” are “interoperable”, they can be used by other industrial/social activities not explicitly intended to be originally used.

- Examples: usage of product information throughout agriculture, food industry, logistics, market, recycling, and so on.

- New businesses adapted to new needs and less resource consuming contribute substantially to sustainability.

- It is important to clarify the requirements of a “digital twin” from use cases. See chapter 3.

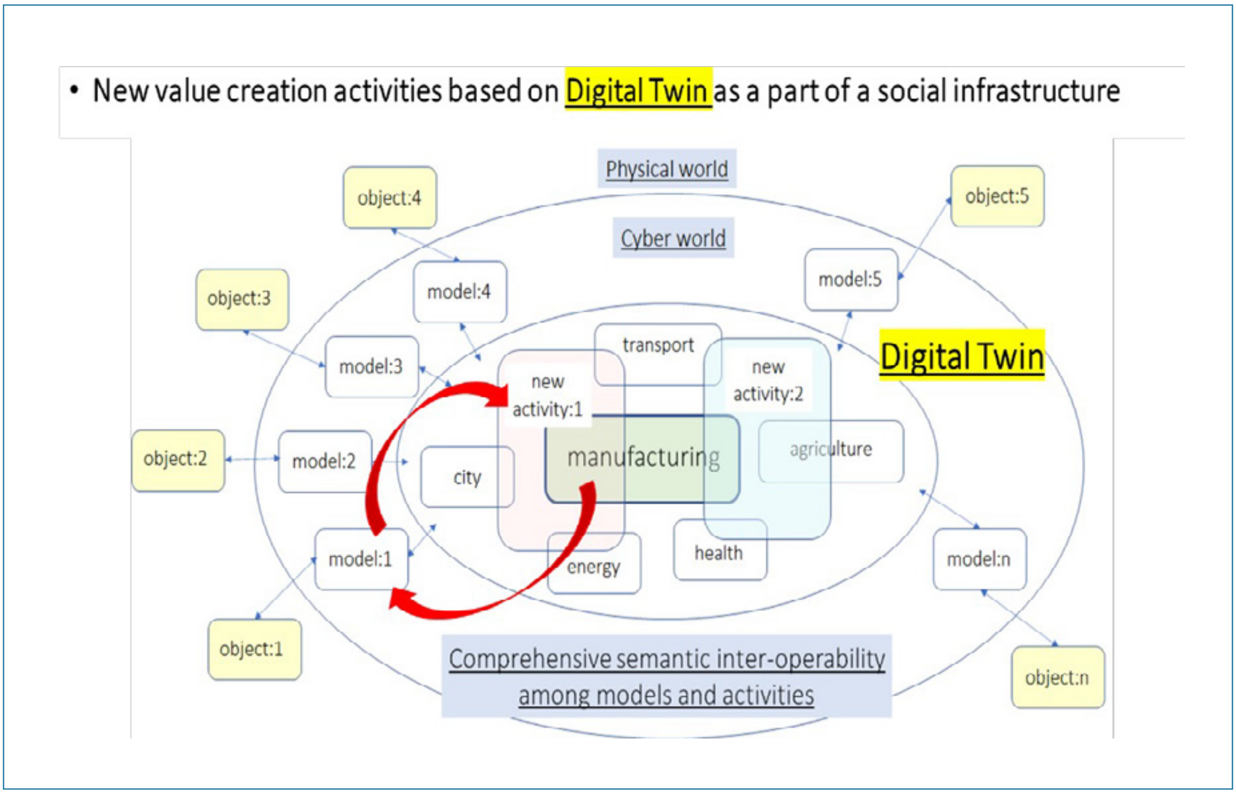

Figure 2: Digital twin as a basis for social infrastructure

2.3 Effective usage of a digital twin in total product life cycle

A digital twin can be considered as a generic modelling framework for representing any kinds of physical or intangible artifacts for supporting to construct social information infrastructure as a basis for creating new application processes toward social sustainability. A digital twin is a comprehensive product life cycle model supporting social activities.

Figure 3 shows a usage view of a digital twin as an introduction of chapter 3 and chapter 4. It shows usage steps of a digital twin for social/industrial applications:

1. Construction of repositories of comprehensive modelling methods and tools, (See Chapter 3.)
2. Construction of repositories of application methods and tools, (See Chapter 3.)
3. Preparation of product life cycle model classes (digital twin model classes),
4. Application of product life cycle model classes for particular industrial productions (digital twin model instances)
5. Application of digital twin models for industrial/social activities
6. Augmentation of repositories of modelling and application methods and tools according to the requirements of step 3, 4 and 5

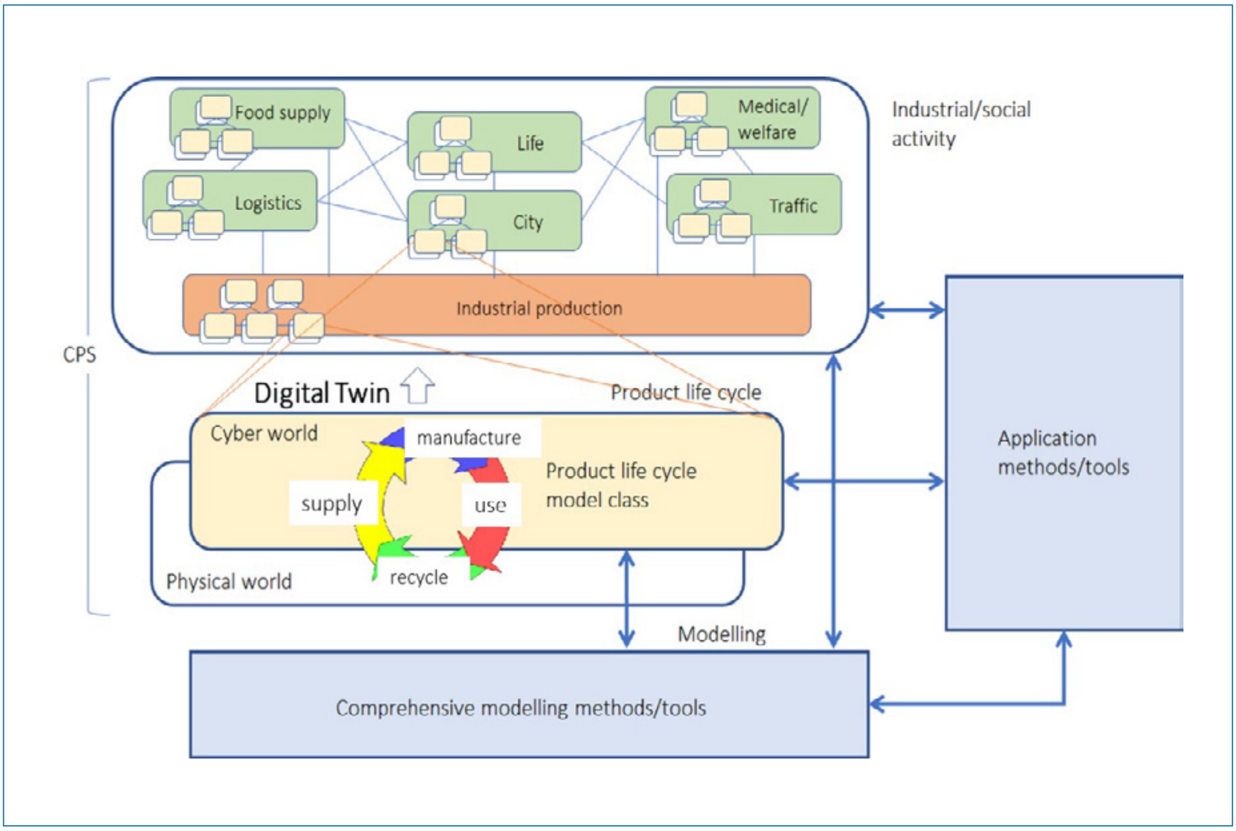

Figure 3: Usage of Digital twin for industrial/social activity

III. Technological basis of digital twin

3.1 Historical review

A concept of a digital twin is not new. From the start of computer-aided design, the concept was discussed, but could not effectively be implemented due to the lack of technology and computing power. After several iterations of revival activities, Grieves re-introduced the concept through a virtual factory context in 2015 [11].

With the movements of smart manufacturing and Industrie 4.0, a digital twin has become an important concept to be applied to a wide range of industrial applications, such as design/manufacturing, production life cycle and supply chain. By recognizing manufacturing as a basis for social infrastructure, application areas of a digital twin have been extended to social applications, including city planning, transportation, disaster protection, etc.

A digital twin is used as a technological enabler for realizing model-based engineering, smart manufacturing, and a social infrastructure. It can be used in combination with technological infrastructures, such as IoT and data spaces [30].

This document focuses on the usage view of a digital twin in the context of social infrastructure applications. There are many references about digital twin research/developments and applications. Detailed literature review and recent industrial/social developments are fully explained in the references [12, 13, 14], and are not elaborated here.

Some of the interesting references include functional requirement discussions with Asset Administration Shell (AAS) [6], digital twin core conceptual models and services [29], and general discussions about the concept of virtual product creation and a digital twin [15].

Many documents about a digital twin exist, but not very much is discussed from the viewpoint of manufacturing infrastructure and about usage view of a digital twin.

3.2 Definition of digital twin

The term “digital twin” has been used in various situations for many years. Its definitions and scopes differ substantially. It may not be easy and not meaningful to try to unify the definitions. Instead, it is useful to clarify a scope and an objective, and to define the term. It may be possible to organize the definitions in a hierarchical way from generic to specific according to their scope descriptions.

The following definition is most appropriate from the viewpoint of manufacturing:

> *“A Digital Twin is a digital representation of an active unique product (real device, object, machine, service or intangible asset) or unique product service system (a system consisting of a product and a related service) that comprises its selected characteristics, properties, conditions and behaviors through models, information and data within a single or even across multiple life cycle phases.” [16]*

Additionally, the following elaboration may be appropriate [11]:

The Digital Twin concept has three constituent parts:

- A physical entity in real space, the “Physical Twin” (PT)
- A virtual entity in virtual space—the actual “Digital Twin” (DT)
- Two-way information and data flow between the physical and the virtual space

Digital thread and other terms and concepts are discussed in [17].

According to [24], digital twins can be divided into different subtypes:

- The "virtual twin" is a physically accurate, realistic digital representation of a plant, facility or product that replicates its real-world counterpart.
- The "connected twin" integrates real-time and right-time data to provide insights into the performance of a facility at specific times, which requires significant human-machine interaction.
- The “predictive twin” utilizes data to predict outcomes for the operation of complex plant and equipment.
- The "prescriptive twin" uses advanced modelling and real-time simulation for potential future scenarios, as well as prescriptive analytics.

This concept can be extended to other subtypes, such as digital twins for sustainability or circular economy. Despite the initially different approach, this concept conceptually comparable to the Industrie 4.0 models based on the Asset Administration Shell.

3.3 Reference model of digital twin

For identifying various usages of digital twins in applications and clarifying their interrelationships, a reference model of a digital twin is effective. By use of an appropriate reference model, use cases of digital twins can be categorized, and relationships among use cases of digital twins can be investigated for interoperability of digital twins in their use cases.

A reference model is generally defined in IEC 63339 [26] as follows:

> *"Abstract description or domain-specific ontology, consisting of an interlinked set of clearly defined concepts produced by an expert or body of experts to encourage clear communication*
>
> *Note: A reference model can represent the components of any consistent idea, from business functions to system components, if it represents a complete set. This frame of reference can then be used to communicate ideas clearly among members of the same community."*

Recently, a unified reference model for smart manufacturing has been studied and standardized in ISO/TC 184 – IEC/TC 65 JWG21. The results are being published as IEC TR 63319 [25] and IEC 63339 [26]. The objective of this model is to unify the various existing reference models of smart manufacturing, including RAMI4.0 [27] and the NIST reference model [28]. Based on perspectives of system designers and system users, appropriate viewpoints and corresponding views are identified with semantic model contents. Views are characterized by aspects, and a set of coherent aspects are collected as a dimension to characterize individual smart manufacturing activities.

The idea of smart manufacturing reference models can be effectively applied for digital twin reference models. Requirements and possible contents of candidate models are being studied extensively in [20] and [21]. Standardization works of digital twin reference models are proceeding in JTC1/SC41/WG6 [18] and ISO/TC184/AG2 [19], and the other groups.

A practical example is proposed as an 8-dimensional model by Rainer Stark [16] as shown in Figure 4. Selected aspects of the eight dimensions are considered appropriate to characterize the capability of a digital twin.

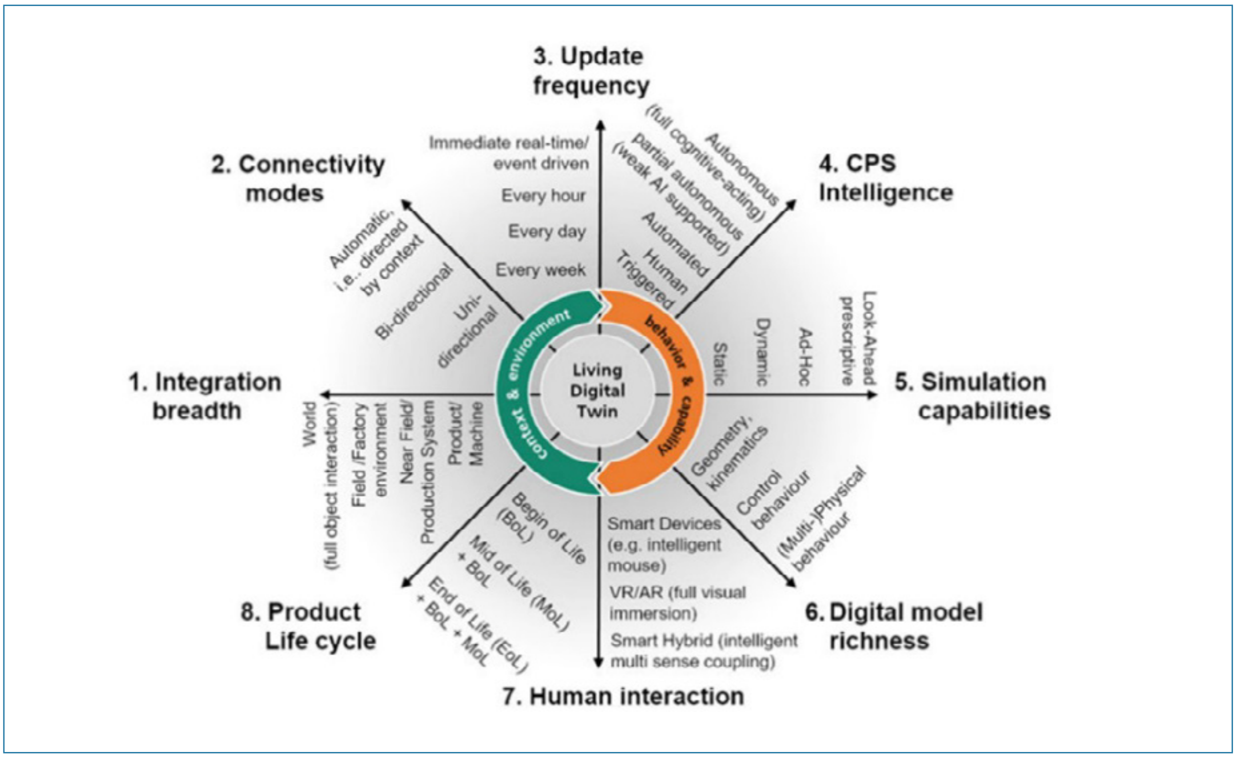

Figure 4: Digital Twin 8-dimension model (R.Stark).

In this paper, based on the analysis of use cases in Japan and Germany collaboration activity and other applications, three fundamental characteristics of digital twins are identified as shown in the table below: "Layer" dimension, extended life cycle dimension and Hierarchical dimension. These dimensions are similar to RAMI4.0, but a reference model of this paper more focuses on interactions among different dimensions, and also interactions among aspects, such as business and usage level viewpoints, and interactions among other different levels. Different sets of dimensions can be selected for effective analysis in response to requirements of other types of applications.

For the "Layer" dimension, this paper focuses on the interactions between usage and functional levels. For the extended life cycle dimension, the whole life cycle exceeding the production activities is considered as discussed in "Life cycle events as aspects of a dimension" (IEC TC65 65E/1028/NP [22]). For the hierarchical dimension, interactions among the different hierarchical levels are the focus.

In the conventional digital twin applications, it appears that the aspects or characteristics marked in red color in the table below are not yet systematically investigated. However, it is considered that digital twins corresponding to those aspects have huge potential benefits of utilizing digital twins in industrial and social applications.

It is interesting to seek digital twin applications in the extended application domains in the table below to create new industrial/social activities with increased service level with reduced environmental influence.

Dimension	Characteristics
"Layer" dimension	
	Business Usage Functional Implementation
Extended life cycle dimension	
product engineering	Supply Chain Manufacturing management/execution Maintenance Reuse/Retirement Material Parts Assembly Usage Reuse/Retirement Engineering Development Design Manufacturing preparation Redesign
Hierarchy	
	Inter-enterprise Enterprise Work-Centre Device (control) Device (physical)
Extended application domain	
	Manufacturing Mobility Food Medical/Welfare Services Logistics Social Infrastructure
• already many examples • still few examples / Huge potential benefits of utilising Digital Twin concepts / Focus area for action items.	

3.4 Classification of digital twin and its usage

As an important application of a reference model, classification of digital twins and their applications are considered. Here the life cycle dimension and the hierarchical dimension are selected as characteristics of classification as shown in Figure 5.

It is considered and should be verified that, according to the life cycle phases, interactions between digital twins and their corresponding physical objects are different regarding the following aspects:

- Application domains
- Functionality levels
- Bi-directional model interactions
  - Cyber/physical object: non-existent, existent, modified, deleted, etc.
  - Bi-directional interaction: semantics

Investigation of typical use cases will clarify beneficial future development directions.

Especially bidirectional model interactions are difficult issues with existing and/or non-existing cyber/physical models/objects. There may be many undetected issues with interesting application possibilities and should be considered as future topics.

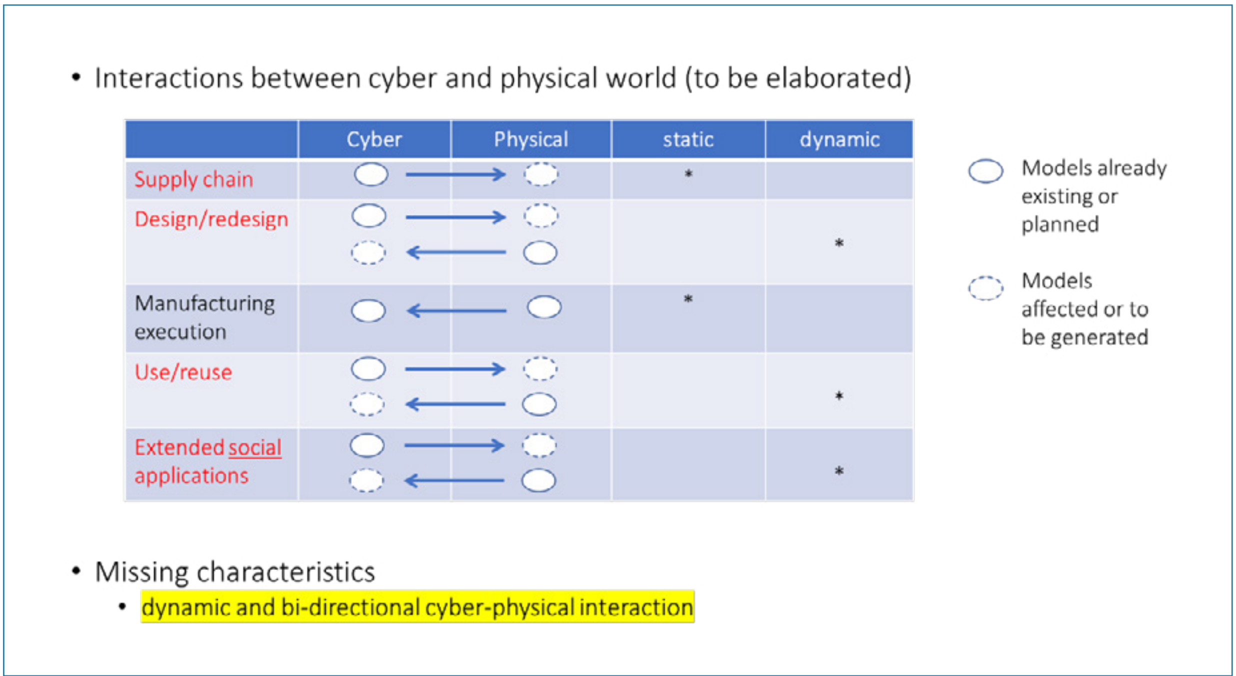

Figure 5: Interactions between cyber and physical world

3.5 Dynamic and bidirectional cyber-physical interaction

As discussed in the previous section, the aspects of dynamic and bidirectional cyber and physical interactions are the most essential characteristics of a digital twin. However, in the traditional applications, these aspects are not fully explored nor explicitly described. When we consider the whole life cycle of digital twin applications, many different aspects have to be investigated to capture the intended objectives of digital twin applications. As some examples are shown in Figure 6, at the respective life cycle phases and hierarchical levels, modes of interactions are different:

- **Modes of interactions**:
  - Design/prototyping: cyber → physical, 1:n,
    {One design model generates many physical objects.}
  - Usage: cyber → physical, n:1,
    {Many usage models are considered for one physical object.}
  - Engineering chain: cyber → physical, n:n, multiple levels/models,
    {Many models and physical objects are created with relations.}
  - Supply chain: cyber → physical, n:n:
    {Many product models correspond to many different physical objects.}
  - Reusing: cyber → physical, n:n,
    {Product models are modified, and corresponding physical objects are produced.}

Correspondences between digital twins and real objects dynamically change from simple 1-to-1 correspondence to complicated n to n correspondence. The semantics of these correspondences must be formally described for intended processing of digital twins and real objects.

Interaction mechanisms for implementing the above requirements are diverse, and it is necessary to investigate systematic and consistent methods for the interoperability across the cross-domain and future applications.

It is important and necessary to explore more use cases to identify the complex situations.

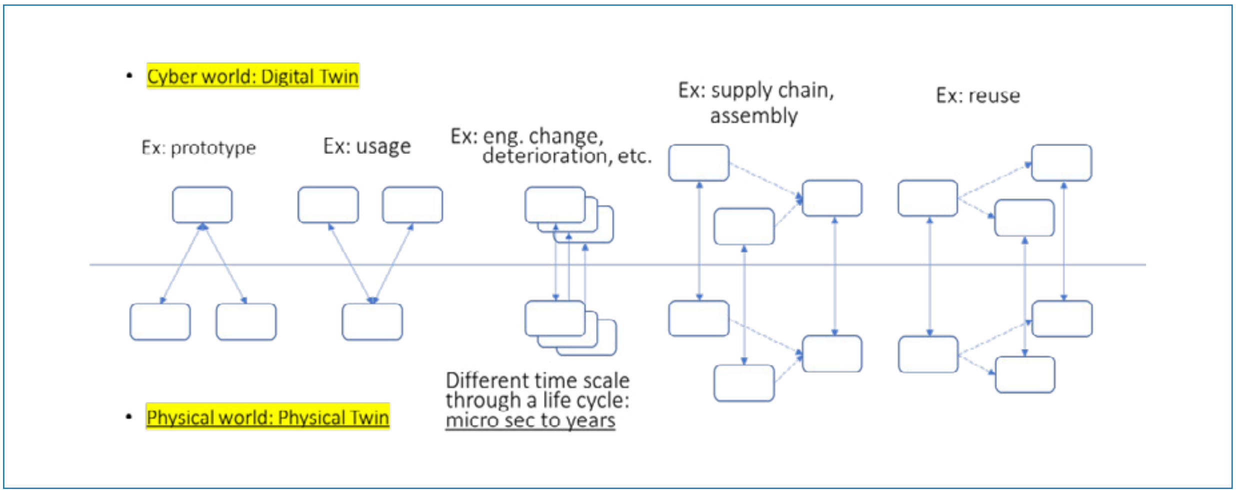

Figure 6: Dynamic and bidirectional cyber and physical interactions

3.6 Semantic interoperability across different domains in total product life cycle

As artifacts are the objects to be paired with digital twins, the manufacturing industry plays a fundamental role in generating and maintaining digital twins. However, many interesting applications are considered which require model information sharing across the industrial and social domains.

Therefore, semantic interoperability across the different domains in total product life cycle is an indispensable requirement for the future applications of digital twins. The following topics should be further considered:

- Basic ontology and common dictionary of engineering information
- Link to the existing activities, e.g., CDD, ECLASS, AAS
- Federation of engineering information in data space
- Practical approach in social applications
  - Dictionary issues
  - Federation approach
  - Existing examples

Typical ways of information federation and integration are shown in Figure 7. Practically, it is difficult to achieve the “to-be” way of interoperability as case (c) shown in Figure 7. It is necessary to plan the long-term development activity to gradually describe the engineering concept/terminology in respective domains, to consolidate the common concept/terminology, and to construct necessary dictionaries in various extents and granularity. It is important to stick to the common methodology, even if the engineering contents are not fully consolidated. In the transition phases, it may be necessary to construct ad-hoc ontologies which are common among related applications, and to standardize gradually those ontologies with a limited scope.

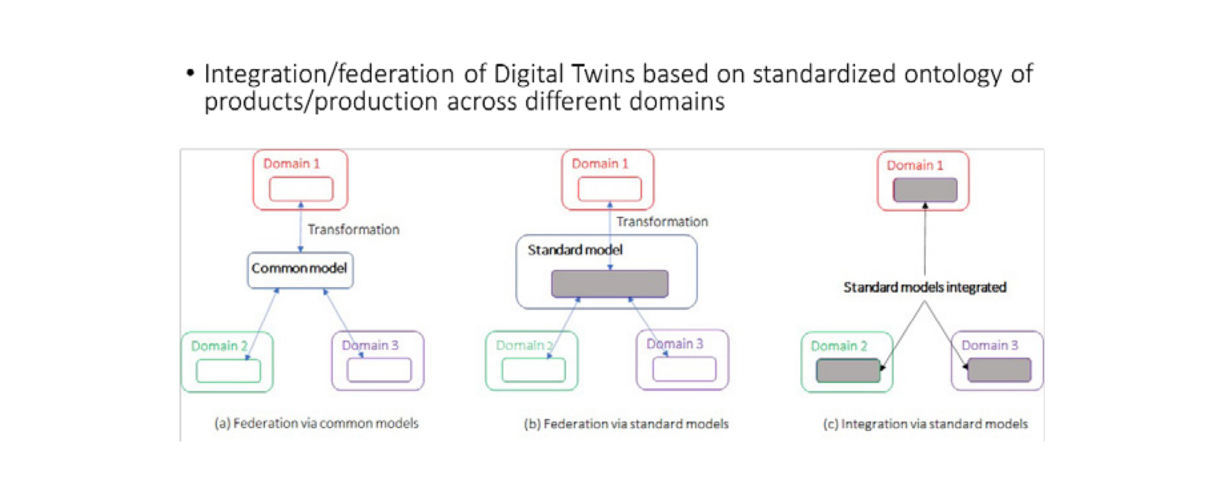

Figure 7: Federation and integration of digital twins across different domains

Figure 8 shows a generic framework to achieve the semantic interoperability of digital twins. Appropriate aspects of engineering contents of activities in digital twins are collected as individual engineering data ontologies. For the common contents of engineering data, individual ontologies are consolidated as a common engineering ontology, and are used for data sharing among related activities as a common dictionary.

There are many engineering ontologies with limited scope and engineering domains. It is practical, as a bottom-up approach, to consolidate such existing ontologies to expand the scope of applications. Appropriate formal description schemes are important long-standing issues.

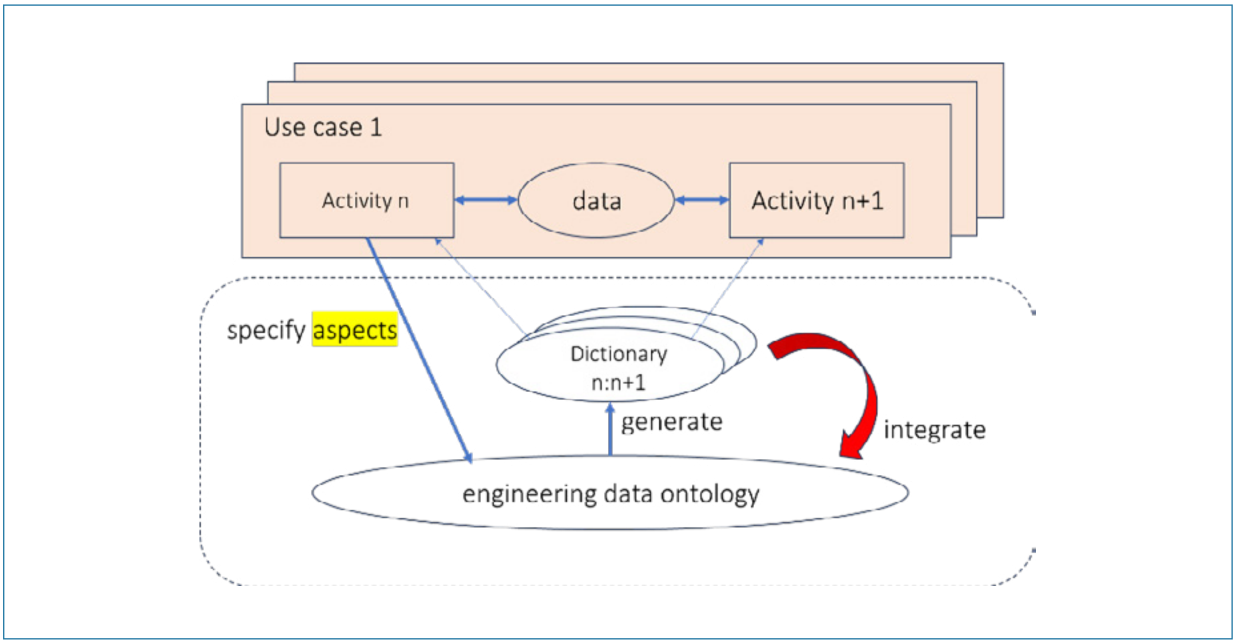

Figure 8: Semantic interoperability based on common ontology and dictionary

IV. Usage of digital twin in total product life cycle

4.1 Importance of information sharing across industries and society

An important key parameter for digital twins is how easily and unambiguously digital features can be exchanged. The two most important points are immediately obvious, as data sharing in the context of:

- Digital twin usage inside manufacturing enterprises

- Digital twin usage across industrial and social activities

This, of course, immediately requires semantic interoperability of data federation in data space applications. The most generic and most widely developed concept is classification of digital twin usage based on the reference architecture model.

Practical and trial implementations of applications supported by digital twin technology are ongoing. However, many of the current works are still confined by the scope and objectives of the applications and individual conditions. Elaboration and specialization aligned with the applications are necessary. But they should be based on the common framework as discussed in chapter 3 as much as possible and maintain the potential to federate future activities. A long-term vision and strategy are required.

In the following sections, the activities in Germany and Japan are introduced to produce easy and clear data exchange and data federation as an infrastructure by use of digital twin. From Germany, the technology is discussed for giving every artifact a digital twin and the legislation as an enabler for it. From Japan, the aspects are discussed to implement federation of data models between different companies and industries.

4.2 Usage of digital twin in product life cycle: German perspective

The German perspective on the usage of digital twin in product life cycle must be viewed from two sides:

- the view of Industrie 4.0

- and Germany's integration into the European Economic Area

The digital twin is very closely related to Industrie 4.0. All these concepts are based directly on the usage of digital twins. Despite the obvious points of overlap and similarities, the terms should not be used synonymously. Many concepts of the digital twin originate from the industry's need to be able to digitally map and model products and processes. It is therefore obvious that the digital twin is a basic framework for Industrie 4.0. At the same time, it has been recognized that these concepts can be used to map not only production processes, but also the entire life cycle of a product. The digital twin is therefore becoming the state of the art for many production processes.

Due to the complexity of digital twins, the standardization strategy must include a bottom-up approach. This naturally starts with unique identifiers and Digital Nameplates for all assets. Further forms of the digital twin can then be easily implemented step by step in a bottom-up process, as shown in Figure 9 to Figure 11. Thus, the Digital Product Passport as a special form of a digital twin must always be recognized as the complete package of Unique Identifier, Digital Nameplate and further digital services.

The second aspect that must be considered is that Germany is part of the European Economic Area. Here, the introduction of a Digital Product Passport will become a legal requirement, which will come into effect with the new Ecodesign Directive [23]. This regulation will oblige manufacturers across Europe to make products more sustainable and environmentally friendly. The Digital Product Passport can be seen as a special version of the digital twin. The EU Product Passport will contain information on the components, ingredients and other properties of products. The high information content and the continuous flow of information will enable all market players and consumers to contribute to the circular economy.

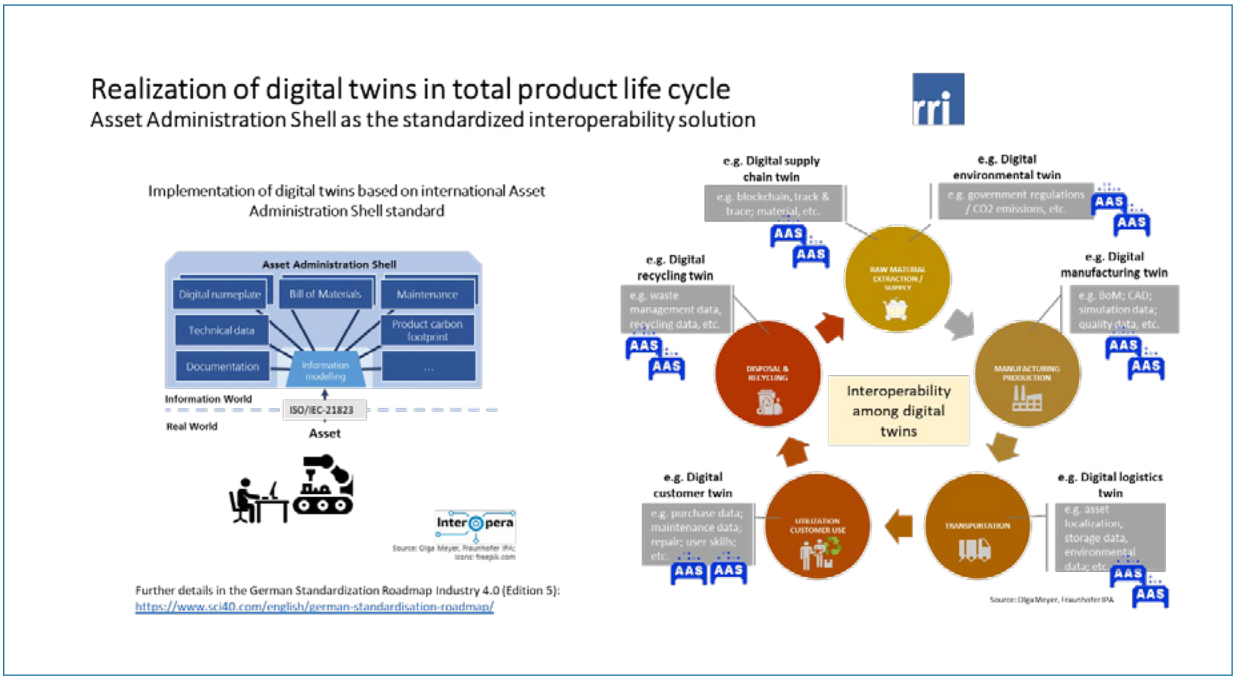

Figure 9: Proposed concept of the Asset Administration Shell is one of the proposed methods for implementing a DPP; this concept is characterized by the fact that the data assigned to the asset/product can be managed generically and dynamically over the life cycle with corresponding Asset Administration Shells.

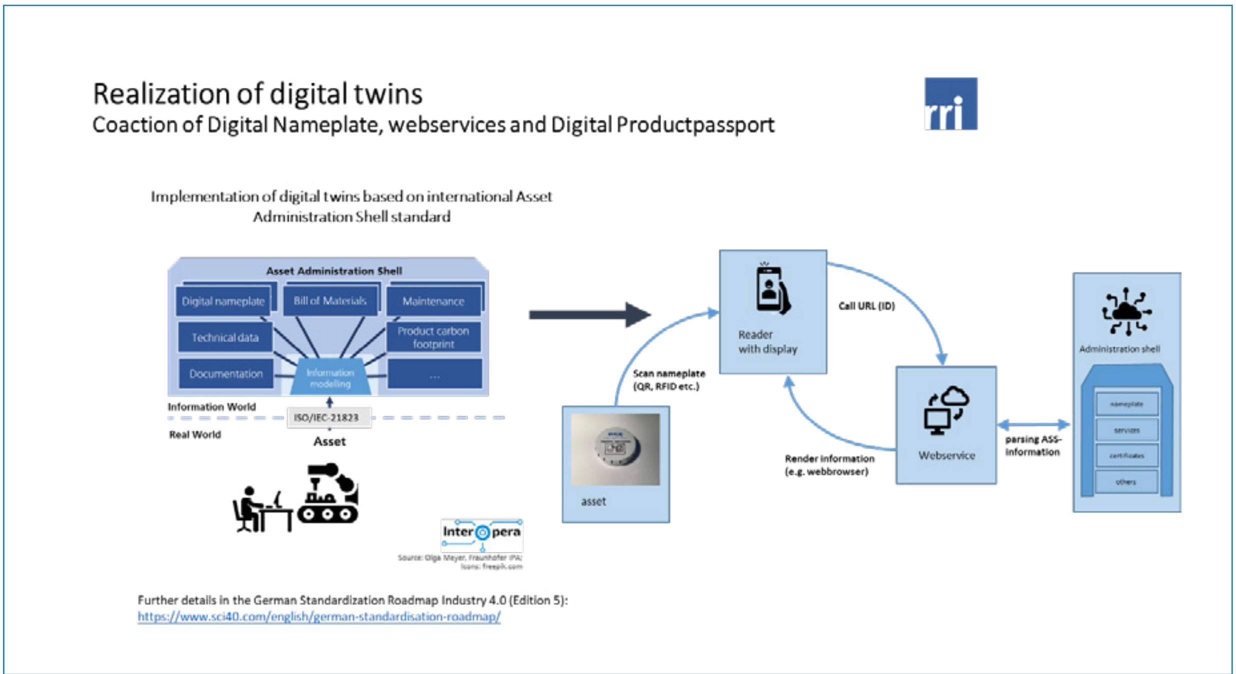

Figure 10: The possible implementation of a digital twin can be achieved by closely interlinking a digital nameplate as a unique identifier with the DPP.

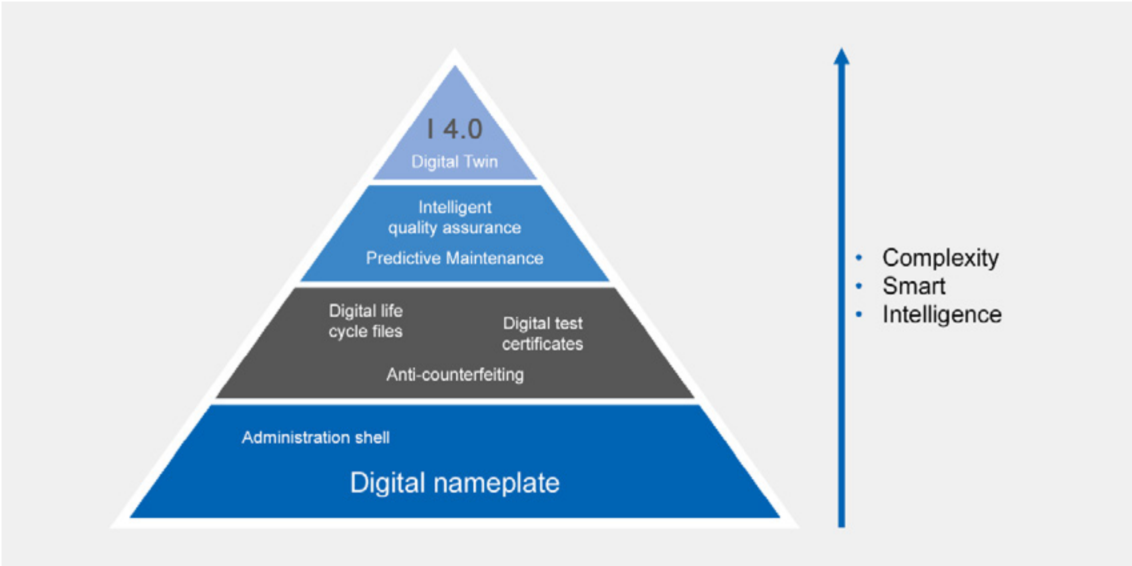

Figure 11: Digital nameplate – foundation for digital twins

4.3 Usage of digital twin in product life cycle: Japanese perspective

Usage of digital twin is investigated, focusing on data federation and integration of industrial and social domains for exploring new applications and identifying missing requirements of a digital twin in conventional applications.

Digital twin enables to integrate various social activities with engineering activities, and to utilize engineering information for enhancing social activities. For example, it is well recognized the importance of digital twin technology in medical diagnosis and surgery with the use of medical equipment. In this example, tight mutual understanding of engineering terminology and medical terminology is essential. Based on the general framework of such mutual understanding, the broader applications of medical equipment can be made possible without starting from scratch. Much effort is still required for effectively reusing the developed information for the more advanced future applications.

It is interesting to see the usage of a digital twin in product life cycle phases where engineering information is not systematically organized in conventional processes. By utilizing the digital twin information effectively, the activities can be made more efficient and create new values.

The followings are some examples of use cases:

- Designing PSS (Product Service System) adapted to customers need
- Feedback of failure phenomena of equipment to design activity for future redesign
- Customized disassembly of EOL (End of Life) products for effective resource reuse
- CFP (Carbon footprint) calculation across global supply chains, including different kinds of industries
- Reuse of products and production systems in long life cycle and across different industries

In the use case of reuse of products and production systems, requirements for digital twin model contents can be identified which are not yet well investigated in the traditional engineering chain. Some of the requirements for model contents are shown below:

- Nominal product information:
  - Functional/usage specification
  - Product configuration/assembly
  - Parts specification including materials for tracing environmental footprint

- Product usage information:
  - Usage environment including dynamic changes
  - Usage history and associated data collected from the physical world including environmental performance data (energy consumption, etc.)

- Used product information:
  - Deterioration of product information including functionalities and materials, etc.
  - Evaluation of quality and reliability

- Product behavior information:
  - Dynamic behavior, including all aspects of physical/logical behavior

- Redesign/reconfiguration information:
  - Redefining functionalities based on product usage data
  - Updating related product information

Long-standing products and production systems may include various kinds of waste in processes and resources for historical reasons. According to the idea of digitalizing the products and production systems based on the "to-be" approach, such existing waste could be identified and eliminated. A digital twin can be effectively utilized for modelling the reality and clarify the transition necessity from "as-is" status to "to-be" status. There are many Japanese industrial cases, where a huge amount of energy and materials can be reduced with small-sized, simple facilities newly designed based on the "to-be" consideration. The examples include a forging and heat treatment system for mass-producing automotive parts, and a precise assembly system for small-sized ceramics-based gas sensors.

V. Requirements for standardization of digital twin

5.1 Requirements for standardization

Firstly, it must be stated that the basic technology is mature with a long history of research and development. But the understanding of the digital twin varies. The smallest common consensus is that it is a dynamic and bidirectional cyber-physical interaction throughout the whole life cycle. Industrial implementations are in progress, but not yet satisfactory and mostly superficial implementations.

The following points therefore emerge for the requirements for standardization:

- Define a common understanding about a digital twin
- Standardize tools for the practical implementation
- Embed existing mature solutions

Overall, a more systematic approach is mandatory for a future sustainable evolution. Furthermore, standardization will be a basis for reducing the complexity and enhancing interoperability.

A critical review and knowledge sharing of the current status and the identification of gaps hindering the practical usefulness are essential requirements for standardization.

5.2 Possible topics of standardization

Regarding digital twins, the following points come into focus for further standardization:

- Reference Model:
  - Scope, domain, viewpoint, etc.

- Architectural framework: Specification of internal interfaces:
  - Dynamic and bidirectional cyber-physical interactions
  - Semantic interoperability across different domains

- Domain-specific ontologies:
  - “Design” information
  - Environmental sustainability
  - Supply chain, circular manufacturing, etc.

- External interfaces for applications

Many standardization activities related to the topics above are already ongoing in international, industrial and domestic standard development organizations, including ISO and IEC. It is mandatory to have a global vision for respective activities based on reference models, to clarify a scope and objectives, and to adapt and reuse the available standards as much as possible, avoiding “re-inventing the wheel”. It must be noted that clarification, systematization and digitalization of common information contents are the key to apply digital twins effectively for sustainable industry and society.

VI. Summary and conclusion

In principle, international standards create a common technical language between trading partners worldwide and form a frame of reference for the global market. They give companies access to new markets and promote free and fair global trade. In the context of global trade and global digitalization, it is obvious that all the concepts presented in this paper require international standardization from the very start.

It is important to emphasize that the technological concepts behind the digital twin are neither fundamentally new nor "rocket science". But the digital twin will only be powerful if everyone involved in and can use it. This therefore requires standardized interfaces, exchange formats, etc. - Thus, standardization matters!

As both countries are strong in the field of smart industry and have been working closely together in standardization for many years, it is only logical that they can act as pacemakers here.

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