Digital Twin maturity model

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Survey of Digital Twin maturity models[1]

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[1] *This excerpt is taken from "Characterization of Digital Twin," a publication available on ResearchGate. The document spans 380 pages, as of March 1, 2024. For more details, visit: https://www.researchgate.net/publication/353930234_Characterization_of_Digital_Twin.*

Background and introduction

Motivation

This is a real-life story that inspired the initiation of our maturity model survey and development. The first author participated in a discussion meeting to explore the influence of the Digital Twin concept on smart city visions and related implementations. The meeting gathered participants with diverse expertise across technology domains such as GIS, autonomous delivery vehicles, industrial manufacturing, and transportation. Throughout the discussion, he noticed that participants explained the technical aspects of Digital Twin from various viewpoints, which occasionally led to miscommunications.

NOTE: Standardization experts often exhibit a professional trait. When they are conversing with people, they pay attention to term definitions to clearly convey meaning and intention and often bring out term definitions to others, leading to unfamiliar situations for them. This professional trait makes it easier than anyone else to notice when people aren't on the same page, i.e., there is a lack of mutual understanding or alignment among participants.

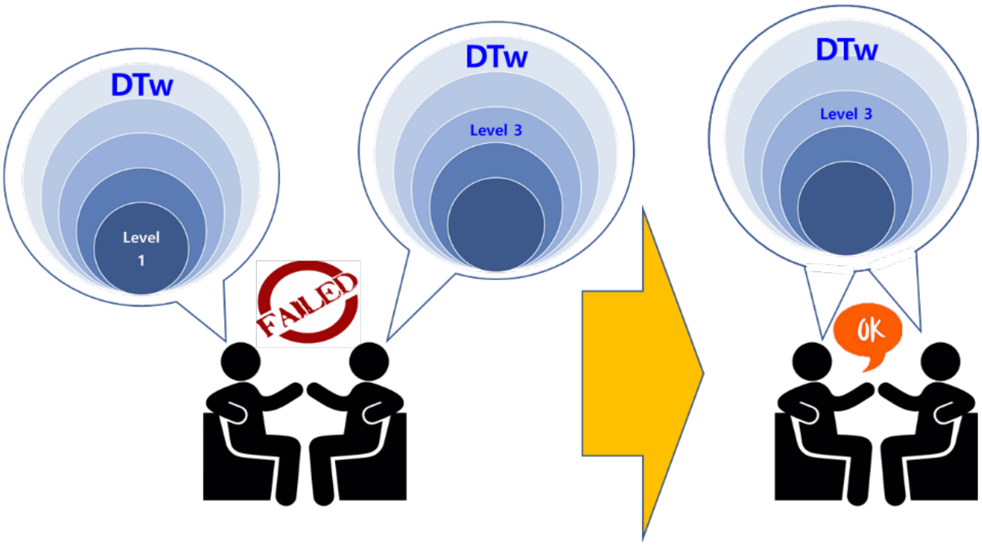

Figure 1 – Communication failure and success

For example, Figure 1 presents two cases of communication, one showing a failure and the other a success. In the failure case, the expert on the left discussed his experiences with geometrical representation and structural simulation, while the other expert focused on behavioral simulation. Despite both addressing modeling and simulation for the same object, they approached modeling and simulation from different perspectives and occasionally delved into different issues.

Similarly, data exchanges can lead to similar situations as they occur across peer-to-peer relationships among distinct computing systems and between layer-to-layer relationships in the same system, each serving a unique communication purpose and driving discussions to different focal points.

As a result, we were motivated to develop a structural hierarchy of associated functions for Digital Twin systems, aiming to facilitate focused discussions among meeting participants at the same level. We created a conceptual sketch of Levels 1, 2, 3, and 4 and later added Level 5 after further deliberations.

However, an expert later informed us of *"Gartner's maturity model (p. 8),"* and we were surprised and concerned about any conflict. Upon comparison, we were pleased to find that both models shared the same conceptual hierarchy, although there was a slight difference in perspective.

Definition of maturity model

Generally speaking, a maturity model is a structured framework that helps assess and improve a target's level of maturity in a particular concern. It provides a roadmap to move from an initial or ad-hoc state to a more advanced, optimized state in terms of processes, practices, capabilities, and performance. The word maturity embeds advancement, improvement, or optimization.

Martin Fowler said, *"A maturity model is a tool that helps people assess the current effectiveness of a person or group and supports figuring out what capabilities they need to acquire next in order to improve their performance. In many circles, maturity models have gained a bad reputation, but although they can easily be misused, in proper hands, they can be helpful [1]."* We interpret the maturity model as a self-assessment tool that helps individuals or groups identify their current state, determine their desired future state, and define the necessary actions to achieve the next step.

The maturity model typically includes a set of maturity level descriptions, which outline the characteristics of target domains at each level and a set of key features or practices necessary to achieve a particular level of maturity. The model may also include an assessment tool or questionnaire to help domain users evaluate their maturity level and identify improvement areas.

Purpose of maturity models

The purpose of maturity models is to provide a structured approach for domain stakeholders to develop or improve their processes, practices, and performance and to establish a roadmap for continuous development or improvement. By following the roadmap, they can identify gaps in their current practices, set goals for development or improvement, and implement a plan to achieve their desired level of maturity in the chosen domain.

Digital Twin maturity models aim to provide an assessment tool for understanding what levels Digital Twin implementations and their functionalities belong to. It can aspire to establish a continuous development roadmap toward higher levels. They can also help technical discussions focus on relevant issues of the same level and identify different level issues.

Nature of maturity models

A maturity model serves as a common framework for a group of stakeholders, fostering a unified understanding and facilitating effective communication. It is crafted from the stakeholders' perspective, reflecting their unique viewpoints and shared understanding. Consequently, different models may be developed, catering to diverse perspectives as illustrated in Figure 2 below. These variations underscore that there's no one-size-fits-all answer; different models simply represent the distinct understanding, interpretations, and needs of various stakeholder groups.

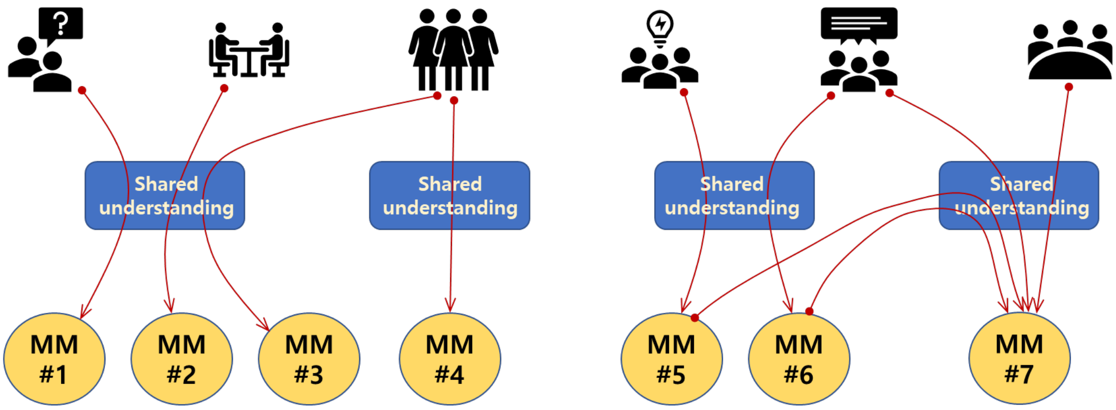

Figure 2 – Different maturity model cases by different ways of understanding

For instance, stakeholders might develop different models based on their focus areas, such as technical advancement, business growth, sustainability, risk management, or user adoption. This diversity allows groups to tailor models to their specific requirements. Furthermore, stakeholders have the flexibility to integrate advantageous aspects of multiple models into a comprehensive, customized model (e.g., MM #7). The DAPA's maturity model exhibits a customization case.

NOTE 1: Ramesh Manickam's team has developed a User Experience-Digital Twin Maturity Model, focusing on enhancing user interaction. This model is built on five fundamental pillars: Understandability, Usability, Convenience, Dependability, and Delight Factors. These components collectively aim to elevate the overall user experience, ensuring that Digital Twin technologies are not only functional but also intuitive and satisfying for users [2].

However, it is important to maintain a consistent view of the maturity assessment. Shifting viewpoints or criteria can lead to inconsistent assessment results, which may sow confusion regarding past assessments, the current state, and future development paths. Therefore, maintaining a stable and consistent assessment framework is key to deriving reliable and actionable insights from maturity models.

Evolution model vs. Maturity model

Evolution does not have a direction. It will be gone if any evolved change isn't appropriate to adapt to the environment. Otherwise, it will survive. Thus, it is a neutral concept.

Alternatively, according to the existing maturity definitions, it means a fully developed state. Martin Fowler's explanation also presents a directional goal for improvement. Because of this kind of meaning, low-level technologies may be considered inefficient or immature.

For example, ISO 22549-2[2] defines a maturity model to help assess the convergence of informatization and industrialization in industrial enterprises. MESA (Manufacturing Enterprise Solutions Association) released its MOM/CMM (Manufacturing Operations Management / Capability Maturity Model) in a questionnaire-based form to assess a particular maturity concern

[2] ISO 22549-2:2020, *"Automation systems and integration — Assessment on convergence of informatization and industrialization for industrial enterprises — Part 2: Maturity model and evaluation methodology"*

from manufacturing operations and management perspectives. Their maturity models are shown above in Table 1.

Table 1 – Maturity models of ISO 22549-2 and MESA MOM

Level	ISO 22549-2	MESA MOM
1	Identified	Initial
2	Measured	Managed
3	Analysed	Defined
4	Optimized	Quantitatively managed
5	Autonomous	Optimizing

These two example cases in point suggest directional goals for improvement. Thus, they can be called maturity models.

However, some capabilities or features of the maturity models that Atkins/IET, Gartner, Rainer & Thomas, IDC, IoT Analytics, Di-Phy Innovations, DAPA, and ETRI developed don't look likely as those improved over other capabilities/features but just as additional supporting or required capabilities. Thus, their maturity models don't imply directional goals for improvement, so they should be called evolution models.

But it is just a theoretical clarification. Actually, the evolution and maturity models don't have to be distinguished because we want to look at the same point, share the same understanding, and have a development roadmap for the next stages, where it should be noted that development is neutral like evolution. Thus, this document refers to the popular term *"maturity model."* However, a proper interpretation of maturity must be explained to avoid misleading and miscommunication.

Interpretation of maturity for Digital Twin assessment

Every technology should meet the necessary functional requirements. More functions than necessary will only increase complexities, costs, and the probability of errors. Engineers often say that *"simple is beautiful."* If traditional and low-level technologies meet functional requirements, they are considered good enough or even perfect. In contrast, high-level and advanced technologies that exceed the necessary requirements can waste valuable resources, such as personnel, budget, and time.

Therefore, a lower level of maturity should not be considered inferior to higher levels. Higher levels encompass a broader range of purposes and technical features, as depicted in Figure 6, showcasing an inclusive representation. Thus, a higher level is intended to support lower-level functionalities together, and the level choice depends on factors such as simplicity, stability, reliability, economy, functionality, and familiarity. It does not necessarily indicate improvement or advancement.

Review of existing ones

Various Digital Twin maturity models exist according to their understanding and analysis views. Here, a few existing ones are introduced.

Atkins/IET's maturity model

Some technical experts of the built environment developed a maturity model from their technical backgrounds, as shown in Table 2 [3]:

Table 2 – Atkins/IET's Digital Twin maturity model [3]

Maturity element (logarithmic scale)	Defining principle	Outline usage
5	Autonomous operations and maintenance	• Complete autonomous operations & maintenance
4	Two-way data integration and interaction	• Remote & immersive operations • Control the physical from the digital
3	Enrich with real-time data *(e.g., from IoT sensors)*	• Operational efficiency
2	Connect model to persistent (static) data, metadata, and BIM Stage 2 *(e.g., documents, drawings, asset management systems)*	• 4D / 5D simulation *(i.e., time and cost, additionally to 3D)* • Design/asset management • BIM Stage 2
1	2D map/system or 3D model *(e.g., object-based, with no metadata or BIM (Building Information Modeling))*	• Design/asset optimization and coordination
0	Reality capture *(e.g., point cloud, drones, photogrammetry)*	• Brownfield (existing) as-built survey

The above maturity model has been tailored for the built environment by referring to specific keywords such as BIM (Building Information Modeling), 2D, 3D, 4D, and 5D. Additional outline usages can be added from other BIM dimensions such as performance aspect; project lifecycle aspect; sustainable, resilient, energy-efficient, and environmental aspects; facility management and maintenance aspects; and risk, safety, and health aspects. Therefore, Atkins/IET's maturity model is more applicable to the built environment.

"Broadly, the spectrum of a twin can be organized into six identifiable elements. Although each element may increase complexity and cost, it's neither a linear nor sequential process, so a twin might possess early or experimental features of higher-order elements before possessing the lower-order, foundational ones.

The lower elements are fundamentally the creation of an accurate, as-built data model of an asset or system. These models can be connected to static data, metadata, and BIM, and then further enriched with real-time data. Finally, with additional sensor and mechanical augmentation, two-way *integration and interaction can begin. This allows a digital twin to alter the state and condition of a physical asset. Ultimately, this system could become completely autonomous in its operations, evolving to manage the asset through total integration between the physical and digital worlds [4]."*

Every maturity model cannot provide the right answers but only guidelines for reference from a specific perspective. Although the maturity levels of Table 2 are somewhat different from those of Table 15, both of them can be complementary to each other and serve as a reference. The following table is given for comparison:

Table 3 – Comparison of Atkins/IET's and ETRI's Digital Twin maturity models

<table>
<tr><th>Atkins/IET's maturity model, Table 2,</th><th>ETRI's maturity model, Table 15</th></tr>
<tr><td>Level 5 – Autonomous operations and maintenance</td><td>Level 5 – Autonomous</td></tr>
<tr><td>Level 4 – Two-way data integration and interaction</td><td rowspan="2">Level 3 – Modeling and simulation
Level 2 – Monitoring and control</td></tr>
<tr><td>Level 3 – Enrich with real-time data</td></tr>
<tr><td>Level 2 – Connect model to persistent (static) data, metadata, and BIM Stage 2</td><td rowspan="3">Level 1 – Mirroring</td></tr>
<tr><td>Level 1 – 2D map/system or 3D model</td></tr>
<tr><td>Level 0 – Reality capture</td></tr>
</table>

Gartner's maturity model

Gartner released a research document, *"Use the IoT Platform Reference Model to Plan Your IoT Business Solutions,"* containing the three levels of Digital Twin realization, as shown in Table 4 [5].

The FunctionBay explained Gartner's maturity levels: *"The difference between Levels 1 and 2 is whether or not online methods are used to collect the data that is to be inputted into the model. Using offline data to conduct simulations in advance, thereby allowing for 3D visualization, is Level 1. Level 2 involves models applying online data obtained from sensors on actual objects through IoT platforms. At this level, the object and model are both subject to the same experiences, so the actual object and digital twin can be seen as a 1-to-1 match. Level 3 involves the use of input data and results to predict results in the future [6]."*

Table 4 – Comparison of Gartner's and ETRI's Digital Twin maturity models

Gartner's maturity model	ETRI's maturity model, Table 15
N/A	Level 5 – Autonomous
N/A	Level 4 – Federated
Level 3 – Analysis, prediction, and optimization	Level 3 – Modeling and simulation
Level 2 – Real-time monitoring	Level 2 – Monitoring and control
Level 1 – 3D visualization and simulation	Level 1 – Mirroring

While Gartner's maturity model consists of three levels, i.e., Levels 1, 2, and 3, our proposed maturity model (referred to as ETRI's model) in Table 15 consists of five levels, i.e., additionally Levels 4 and 5.

Levels 2 and 3 of both maturity models are the same, but Gartner's Level 1 has a different view on *"simulation."* The simulation is said to be the most characterized feature of Digital Twin. It can help ascertain the future of a simulated system according to different input parameters.

A simulation should be considered from three different viewpoints, geometrical, structural, and behavioral, as described in *"Geometrical, structural, and behavioral simulations vs. structural analysis [7]."*

The simulation of Gartner's Level 1 is likely to refer to geometrical and structural simulations from 3D-rendered structures. *"Analysis, prediction, and optimization"* of Gartner's Level 3 can refer to behavioral simulations based on operational behavior models. Thus, simulation activities are performed at both Levels 1 and 3. However, *"simulation"* of Gartner's Level 1 may mislead readers because it appears only at Level 1.

In addition, geometrical simulation only deals with the geometry of shape, size, and appearance. In contrast, structural and behavioral simulations deal with structural and dynamic behaviors, often correlated in a complex way like two sides of a coin, causing them to be difficult to distinguish from each other. Virtual Singapore can be an example case to see this concern.

NOTE 1: Singapore's entire city, including buildings, road networks, trees, and rivers, has been created as structural 3D virtual models. Simulation models for traffic flows, crowd distribution, and pedestrian movement patterns are available for various purposes. Virtual Singapore can simulate how sunlight and ambient temperature change throughout the day over a street, road, or around buildings. City designers can visualize the effect of constructing a new building on the temperature and luminosity of a property. Thermal and noise maps can also be overlaid.

The basic Digital Twin concept is premised on the interaction between a physical object and its virtual object through real-time data communication. However, Virtual Singapore didn't establish real-time data interaction because it is too challenging for a city-scale structure and may cause significant risks of failure.

Some experts said that Virtual Singapore belongs to Gartner's Level 1 because it supports Singapore's 3D models and also various simulation features.

As observed in the above Virtual Singapore case, it is not limited to geometric and structural simulations but supports operational and behavioral simulations such as wind flows, traffic flows, thermal and noise maps, pollution dispersion, crowd distribution, and pedestrian movement patterns. Therefore, distinguishing geometrical, structural, and operational/behavioral simulations is not technically easy.

It can be concluded that the distinction doesn't have to be made because of a lack of benefits to get for a maturity model. Therefore, simulation-related features should be together in one place for easier understanding and reference.

ETRI's model has taken only the visual representation into Level 1 in terms of geometrical and structural representations based on static 2D/3D data and the behavioral representation into Level

3. Therefore, only the 3D visualization of Gartner's Level 1 is identical to the mirroring of ETRI's Level 1. ETRI's maturity model identifies Virtual Singapore as ETRI's Level 3.

Rainer's maturity model

The study paper *"Digital Twin,"* authored by Rainer Stark and Thomas Damerau, introduced the *"Digital Twin 8-dimension model"* for planning Digital Twin system models according to purposes and business contexts, as shown in Figure 3 [8].

1. Integration breadth	2. Connectivity mode	3. Update frequency	4. CPS intelligence	5. Simulation capabilities	6. Digital model richness	7. Human interaction	8. Product lifecycle
Level 0 Product / Machine	**Level 0** Uni-directional	**Level 0** Weekly	**Level 0** Human triggered	**Level 0** Static	**Level 0** Geometry, kinematics	**Level 0** Smart devices (i.e., intelligent mouse)	**Level 0** Begin of Life (BoL)
Level 1 Near field / Production system	**Level 1** Bi-directional	**Level 1** Daily	**Level 1** Automated	**Level 1** Dynamic	**Level 1** Control behavior	**Level 1** Virtual Reality / Augmented Reality	**Level 1** Mid of Life (MoL) + BoL
Level 2 Field / Factory environment	**Level 2** Automatic, i.e., directed by context	**Level 2** Hourly	**Level 2** Partial autonomous (weak AI supported)	**Level 2** Ad-hoc	**Level 2** Multi-Physical behavior	**Level 2** Smart hybrid (intelligent multi-sense coupling)	**Level 2** End-of-Life (EoL) + BoL + MoL
Level 3 World (full object interaction)		**Level 3** Immediate real-time / event driven	**Level 3** Autonomous (full cognitive-acting)	**Level 3** Look-ahead prescriptive			
Digital Twin environment			Digital Twin behavior and capability richness				Digital Twin lifecycle context
Living Digital Twin							

Figure 3 – Digital Twin 8-dimension model [8]

The Digital Twin 8-dimension model provides each layered model of 8 Digital Twin dimensions. Its technical levels can be considered from a maturity perspective and complement ETRI's model because of different analysis perspectives. It aims to provide a structured approach for planning the scope and type of Digital Twin because the Digital Twin concept can be applied in numerous fields and for different purposes [8]. It can also guide people to develop appropriate Digital Twin models through its step-by-step analysis and design methodology.

It consists of eight dimensions in three categories, namely *"Digital Twin environment," "Digital Twin behavior and capability richness,"* and *"Digital Twin lifecycle context,"* in addition to three or four hierarchical levels for each dimension. The Digital Twin environment sets working boundaries and conditions for Digital Twin models. The richness of behavior and capability specify the fidelities of behavioral dynamics of Digital Twin models. It can be said that the *"Digital Twin environment"* represents a horizontal analysis view, and the *"Digital Twin behavior and capability richness"* does a vertical analysis view.

The Digital Twin 8-dimension model is defined as follows [8]:

- Dimension 1, *"integration breadth,"* describes the scope and extensions of the Digital Twin and the environment to be considered within the Digital Twin;
- Dimension 2, *"connectivity mode,"* distinguishes the capabilities needed to realize Digital Twins' communication capabilities;
- Dimension 3, *"update frequency,"* refers to the questions on how often a Digital Twin needs to be updated with data from the digital shadow, i.e., data measured and acquired during the operation and use of physical entities;
- Dimension 4, *"CPS intelligence,"* distinguishes different levels of intelligence through, for example, rule-based algorithms, machine learning, and artificial intelligence;
- Dimension 5, *"simulation capabilities,"* distinguished the fidelity levels of simulation by input parameters, time dependency, behavior, and prediction aspects;
- Dimension 6, *"digital model richness,"* describes which characteristics of a product are mapped to its Digital Twin;
- Dimension 7, *"human interaction"* refers to Digital Twin user interfaces; and,
- Dimension 8, *"product lifecycle,"* is related to the product or system's lifecycle phases in question supported by the Digital Twin.

IDC's maturity model

IDC (International Data Corporation) provided its maturity model from a Digital Twin's collaboration complexity perspective, as shown in Table 5 [9].

Table 5 – IDC's Digital Twin maturity model

Low 🡸 Digital Twin complexity for multiple uses across your value chain 🡺 High				
Digital visualization	**Digital development**	**Digital Twin enterprise**	**Digital Twin ecosystem**	**Digital Twin orchestration**
For ideation and innovation, collaboration with customers and suppliers, visualization of processes	For internal design and development, service and maintenance at a workgroup level	For enterprise-wide, internally-focused visibility and collaboration	For real-time product and asset operation and improvement, extended to customers, partners, suppliers	For real-time visualization, visibility, and decision support across a network of digital twins for products, assets, facilities, and plants

Any group can set up its viewpoints into a structured model, as described in *"Nature of maturity models (p. 4)"* above. Table 5 is designed structurally depending on how many business stakeholders or work people cooperate in developing Digital Twin systems and how complex their cooperation and communication relationship is developed accordingly.

Aidan's maturity model

His research paper didn't explain his model as a maturity model, but the concept can be used as a maturity model, so it is explained. The maturity model is based on the data integration level between physical and virtual objects, consisting of three types of Digital Twin instance systems, as shown in Table 6 and Figure 4 [10][11].

Table 6 – Aidan's data integration-based maturity model

Level	Aidan's maturity model
Level 3	Digital twin
Level 2	Digital shadow
Level 1	Digital model

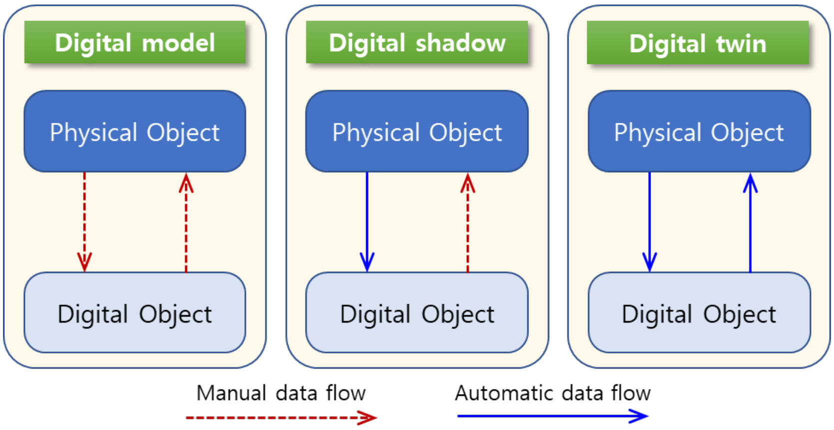

Figure 4 – Data integration types of Digital Twin systems [10][11]

- ***Digital model***: It is a digital representation of a physical object without any automated data exchange between the physical and digital objects. This means that a change in the physical object is not reflected automatically in the digital object and vice versa.

- ***Digital shadow***: It is a digital representation where an automated one-way data exchange exists, meaning that a change in the physical object is reflected automatically into the digital object, not vice versa.

- ***Digital twin***: It is a digital representation where data is fully integrated and flows automatically in both directions between the physical and digital objects.

Aidan's model doesn't encompass the DTP-type Digital Twin system, i.e., a standalone system, but only covers DTI cases. That is, it supports the cases where both sides exist, and their peer data associations are maintained, but it doesn't for the case of digital objects existing solely.

"Consideration of data integration levels (p. 43)" includes additional review results from the data integration perspective.

IoT Analytics' maturity model

It developed a classification framework to identify and categorize Digital Twin model cases across three dimensions, as shown below in Figure 5. The framework encompasses 252 combination cases resulting from the six hierarchical levels, six lifecycle phases, and seven most common uses of Digital Twin models. This classification framework can help identify the current state of a Digital Twin model, determine where it needs to go, and provide guidance on what development actions to take. As a result, it can be used as an effective maturity model.

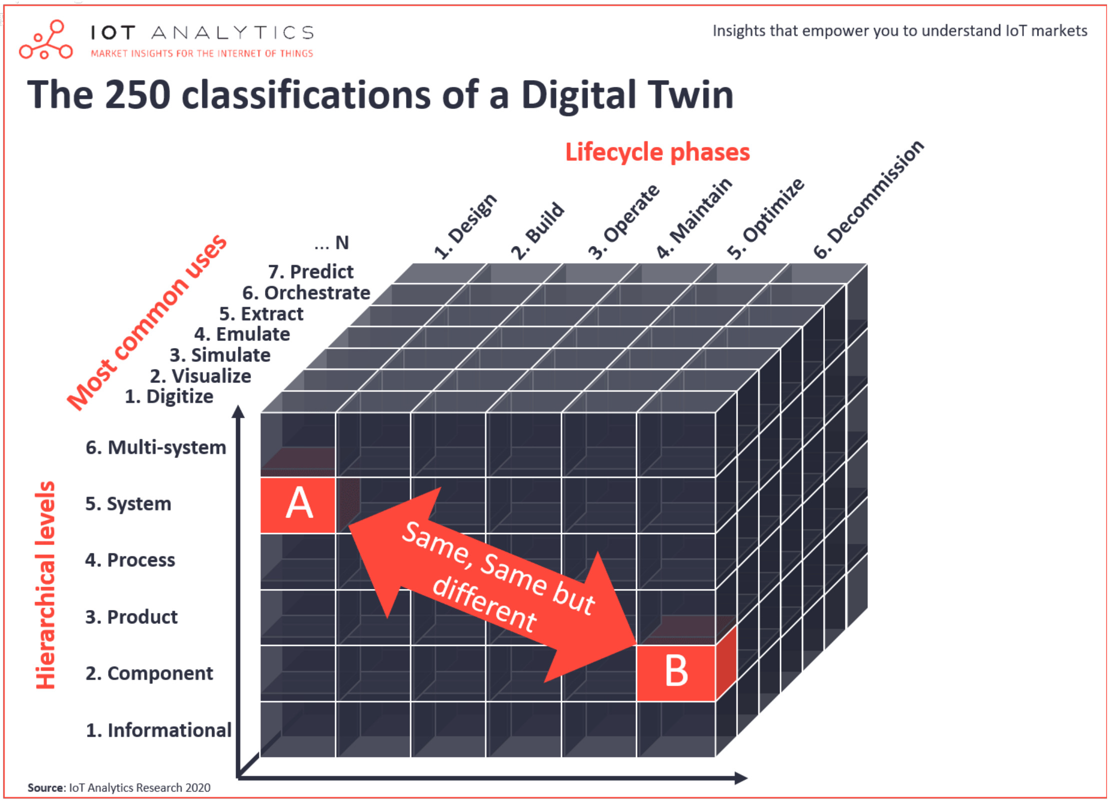

Figure 5 – IoT Analytics' Digital Twin classification framework [12]

Those three dimensions represent:

- ***Hierarchical levels***: it covers the aggregation concept, referring to *"Digital Twin types and scoping [7]"* and *"Digital Twin composition and aggregation [7]."* Its specific levels are the following [12]:
  - ***Informational***: Digital representations of information, e.g., an operation manual in digital format.
  - ***Component***: Digital representations of individual components or parts of a physical object, e.g., a virtual representation of a bolt or a bearing in a robotic arm.
  - ***Product***: Digital representations of the interoperability of components/parts as they work together at a product level, e.g., a virtual representation of a rotating robotic arm.

- ***Process***: Digital representations enabling the operation and maintenance of entire fleets of disparate products that work together to achieve a result at a process level, e.g., a virtual representation of a manufacturing production line process.

- ***System***: Digital representations twinning multiple processes and workflows, not just limited to physical objects, enabling the optimization of operations at a system level, e.g., a virtual representation of an entire manufacturing system.

- ***Multi-system***: Digital representations of multiple systems working together as one unified entity to enable unprecedented insight, testing, and monitoring of key business metrics in a data-driven manner, e.g., a virtual representation of several systems working in unison such as systems for industrial manufacturing, supply chain, traffic control, communication, HR (Human Resources), etc.

- ***Lifecycle phases***: it accommodates time-based changes of stages, states, process steps, etc., related to *"Lifecycle consideration [7]."* Its specific phases are [12]:

  - ***Design***: In the design phase, requirements are gathered, and one or more designs (e.g., for components, products, processes, or systems) are developed, with which the required outcome can apparently be achieved, e.g., using Digital Twins as the source of all data such as object properties and parameter values for which virtual representations can be built on.

  - ***Build***: The build phase takes the code requirements outlined previously and uses those to build the actual software-based Digital Twin. This phase also covers data management, configuration provisioning, repository management, and reporting, e.g., using Digital Twins to virtually build and simulate prototypes without building more cost-intensive physical counterparts for testing.

  - ***Operate***: The operation phase is when actual users start using online Digital Twins in active deployments. Typical operative tasks include extracting sensor data or orchestrating devices remotely, e.g., using Digital Twins to extract real-time sensor data from a rotating robotic arm in a production line or updating the device configuration over the air.

  - ***Maintain***: The maintenance phase involves making changes to hardware, software, and documentation to support its operational effectiveness. It includes making changes to correct problems, enhance security, or address user requirements, e.g., using Digital Twins to do regular maintenance tasks such as sending OTA (Over-the-Air) updates for system configuration or cybersecurity.

  - ***Optimize***: The optimization phase requires the use of existing capability information and a statistical approach to tolerancing. This can be used to improve the development of detailed design elements, predict performance, and optimize operations, e.g., using Digital Twins to run a large number of tests that generate insights to help predict future performance and failures.

  - ***Decommission***: The decommissioning phase involves the removal of a Digital Twin release from use. This activity is also known as system retirement or system sunsetting, e.g., using Digital Twins to remotely decommission devices no longer in use and subsequently retiring the use of that corresponding Digital Twin.

⌖ ***Most common uses***: it deals with how a Digital Twin model is utilized and what it can provide. The goal of this dimension is partially related to *"ETRI's maturity model."* Its specific use items are [12]:

- ***Digitize***: Any digitized information
- ***Visualize***: Basic digital representation of a physical object
- ***Simulate***: Simulation model of a physical system in its environment
- ***Emulate***: Emulation model of the physical system with real software
- ***Extract***: Extraction model of real-time data streams, physical to virtual system
- ***Orchestrate***: Orchestration model for virtual control/updating of physical devices
- ***Predict***: Prediction model to predict the future behavior of the physical system

The resulting Digital Twin cube explains why a digital replica which is used for a *"system digitization during the design phase, (A)"* is completely different from a *"component digitization during the decommissioning activity (B)."* Both are called Digital Twins but only have limited overlap [12].

NOTE 1: Maturity models can be of a 1D, 2D, or 3D type for practical use. The key issue is which analysis or consideration point should be taken to its dimension out of other various points. IoT Analytics suggested another one, "data type," e.g., real-time data, historical data, or test data, additionally to those three dimensions. Other candidates are "data integration" from Aidan's maturity model, "collaboration complexity" from IDC's model, "human engagement types" from "Consideration of human engagement types [7]," and some of Rainer's dimensions, such as "update frequency," "digital model richness," and "human interaction." Therefore, what is/are the first primary one for 1D, the first and second for 2D, or three primary ones for 3D should be carefully considered and determined.

When developing a 3D-type maturity model, we have the same view with IoT Analytics' three dimensions. As various physical objects can be interrelated or even integrated through a systematic aggregation, it is essential to understand which hierarchical level an object belongs to in order to create an effective Digital Twin model. This involves identifying the specific type of object that should be modeled and where it fits into the overall system structure.

Elaborating on time-based process stages is critical in Digital Twin modeling because it enables tracking of historical data in both forward and backward directions. This is important for solving various industrial problems and for innovating current activities.

The question of why to use a Digital Twin model is crucial, as its benefits can justify adopting and deploying a Digital Twin system. This question pertains to the purpose and usage of a Digital Twin and could be considered another dimension in a 3D-type maturity model.

NOTE 2: While the classification framework shares characteristics with maturity models and can be used as a kind of maturity model, there is a certain consideration issue to bear in mind when using it in this capacity.

The problem statement of IoT Analytics reads "The commonality in most definitions is that the Digital Twin is a "digital abstraction or representation of a physical system's attributes and/or *behavior." The devil is in the details because one could still refer to a fully-automated dynamically-recalibrating virtual representation of a physical system or alternatively just one software element of that setup – or something else [12]." A classification framework can be used to resolve such a problem and identify the current state of a case system, which is also a role of maturity models.*

Maturity models can help create a development roadmap, which can then be used to establish a specific implementation plan. However, too many specific items for each dimension of a maturity model can lead to complexity, confusion, and unnecessary debates. Therefore, a simpler structure should be considered to avoid mixing up similar issues and suffering from miscommunication. Specific details can work effectively in classification, but they can rather cause inconvenience and confusion in a maturity assessment.

For example, while various human models, such as 3D shape, skeletal structure, muscle, and blood vessels, can be developed, creating a human model that reflects differences in people's genes may be beyond the needs of medical surgery requirements. This is where a granularity concern comes into play.

Our review results identified granularity concerns regarding two dimensions of the "Hierarchical levels" and "Most common uses." In both cases, there is a concern that they are too much detailed, with a particular focus on the "Informational" level within the "Hierarchical levels" dimension and the "Digitize" item within the "Most common uses" dimension. These specific items may make sense logically and theoretically, but they may not be practical or useful in actual practice because of their level of detail.

Moreover, the development and maintenance of a Digital Twin system often involve activities such as simulation, emulation, and prediction, which are closely related. These activities can be performed together to gain insights into the behavior of the physical system and its digital counterpart. However, when categorizing and assessing the maturity level of a Digital Twin system, the current level of detail related to these activities can be overwhelming and may lead to unnecessary complexity. Thus, simulation, emulation, and prediction should be viewed together in an integrated manner rather than as separate entities to make analysis and design easier. This integration will allow for a more comprehensive and cohesive understanding of the Digital Twin system and its behavior.

When transforming the classification framework into a maturity model, some specific items that may be too detailed can be removed. Furthermore, closely related issues can be converged into an integrated item to avoid unnecessary complexity. This will help streamline the assessment process and allow for a more practical and manageable maturity model. A simpler and more integrated framework with a higher abstraction can enable stakeholders to more effectively evaluate the maturity level of a Digital Twin system.

Di-Phy Innovations' maturity model

A Digital Twin maturity model can help assess and categorize the level of development and implementation of Digital Twins within an organization or industry for which each maturity model phase will represent increasing levels of sophistication and integration into business processes. To determine where an organization stands in terms of Digital Twin maturity, particular measurement points and questions specific to each phase can help conduct its self-assessment to identify areas for improvement and chart a roadmap for growth [13].

The Di-Phy Innovations' maturity model leans more towards addressing the organizational and business development aspects of Digital Twin implementation rather than purely focusing on the technical development milestones. It emphasizes on the integration of Digital Twins into business processes, decision-making, and stakeholder engagement across the various levels of maturity. Each stage described in the model progressively incorporates more sophisticated business-oriented objectives.

By structuring the maturity model around these six stages, the Di-Phy Innovations is highlighting the transformational potential of Digital Twins not just as a technological tool but as a strategic asset that supports business growth, decision-making, and operational efficiency. This approach acknowledges that the true value of Digital Twins extends beyond their technical capabilities to include their impact on business models, organizational structure, and the broader ecosystem of stakeholders and departments.

Table 7 – Di-Phy Innovations' Digital Twin maturity model [13]

Maturity level	Reference name	Description
6	Autonomous Expansion	• In this advanced stage, organizations scale up Digital Twin implementation, achieving comprehensive coverage and integrating them with various stakeholders and departments. • Measurement points: Digital Twin coverage, integration with stakeholders, artificial intelligence integration, real-time decision-making, human intervention reduction • Questions: – To what extent have we expanded the implementation of Digital Twins? – How well integrated are Digital Twins with various stakeholders and departments?
5	Prescriptive / Optimization	• The Digital Twin provides actionable insights and recommendations, enabling data-driven decision-making and resource optimization. • Measurement points: prescriptive analytics utilization, scenario simulation, recommendations implementation, optimization impact, data-driven decision-making • Questions: – To what extent does our Digital Twin leverage prescriptive analytics techniques? – Can the Digital Twin effectively simulate various scenarios? – How often are recommendations and prescriptions from the Digital Twin implemented?
4	Predictive / Analysis	• Organizations leverage historical and real-time data, predictive analytics, and machine learning to forecast future states and the performance of the system.

		• Measurement points: predictive analytics implementation, scenario forecasting, resource optimization, proactive maintenance, decision-making impact • Questions: – To what extent does our Digital Twin utilize predictive analytics techniques? – Can the Digital Twin effectively forecast potential scenarios? – How often are recommendations and prescriptions from the Digital Twin implemented?
3	Integration / Diagnostic	• The Digital Twin has connections with real-time data sources, enabling condition monitoring and troubleshooting. • Measurement points: data source integration, advanced analytics usage, pattern recognition, preventive actions, downtime reduction • Questions: – Have we established robust connections between our Digital Twin and real-time data sources? – Are advanced analytics and machine learning algorithms integrated into our Digital Twin?
2	Development / Descriptive	• This phase involves continuously updating the Digital Twin with real-time sensor data, ensuring an accurate representation of the physical twin's current state. • Measurement points: real-time data integration, frequency of updates, connectivity level, use of real-time insights • Questions: – Are real-time sensor data streams integrated into our Digital Twin? – How frequently is the Digital Twin updated with real-time data? – To what extent is the Digital Twin connected and synchronized with the physical twin?
1	Conceptualization / Stand-Alone	• Organizations have a virtual model of physical assets, even before they exist, serving as a basis for future development and integration. • Measurement points: virtual model development, data sources, use cases • Questions: – Have we developed a comprehensive virtual model of our physical assets or systems, even if the physical twin does not exist or is not fully connected to the real environment? – What are the primary sources of data used to create our Digital Twin, and how complete and reliable are they? – How are we currently utilizing the Digital Twin?

Unity's maturity model

Unity's Digital Twin maturity model presents a structured framework focused on the evolution of Digital Twins from basic digital representations to fully autonomous systems. Its model places a strong emphasis on the technological aspects of Digital Twins, detailing the specific technologies and capabilities at each level. *"Di-Phy Innovations' maturity model (p. 16),"* while also technical, incorporates a broader perspective on how Digital Twins integrate into and evolve with organizational processes and business strategies.

Table 8 – Unity's digital twin maturity model [14]

Maturity level	Reference name	Description	Keywords
5	Autonomous Twin	• The Level 5 twin uses multiple real-time data feeds to learn and make decisions to correct issues automatically and enable predictive and prescriptive analytics.	Autonomous action, Artificial intelligence
4	Prescriptive Twin	• The Level 4 twin leverages advanced modeling and real-time simulation for potential future scenarios as well as prescriptive analytics and recommendations.	What-if simulations, Machine learning, Intelligent recommendations
3	Predictive Twin	• The Level 3 twin leverages data to predict the outcomes and problems for the operations of complex facilities and equipment.	Analytics, Decision-assist, Predictive maintenance
2	Connected Twin	• The Level 2 twin integrates real-time and right-time data to provide insights into the performance of an asset at specific points in time.	Real-time data, Monitoring and reporting, IoT
1	Virtual Twin	• The Level 1 twin is a physically accurate realistic digital representation of an asset, facility, or product that emulates its real-world counterpart.	Spatial awareness, Interaction, Experience, Collaboration

Table 9 – Comparison of Unity's and ETRI's Digital Twin maturity models

Unity's maturity model	ETRI's maturity model, Table 15
Level 5 – Autonomous Twin	Level 5 – Autonomous
	Level 4 – Federated
Level 4 – Prescriptive Twin Level 3 – Predictive Twin	Level 3 – Modeling and simulation
Level 2 – Connected Twin	Level 2 – Monitoring and control
Level 1 – Virtual Twin	Level 1 – Mirroring

- Level 1 (Virtual Twin): This level establishes the foundation with a highly detailed and accurate digital representation of a physical asset. It focuses on creating a realistic simulation environment for interaction, collaboration, and spatial awareness. This stage serves as the groundwork for more complex functionalities by providing a detailed and interactive model of the physical world.

  NOTE 1: It is identical to ETRI's Level 1 (Mirroring, p. 34).

- Level 2 (Connected Twin): At this stage, the twin begins to integrate real-time and right-time data, enhancing the virtual model with live operational insights. This enables monitoring and reporting capabilities, leveraging IoT technology to connect the Digital Twin with its physical counterpart for up-to-date asset performance insights.

  NOTE 2: It shares similarities with ETRI's Level 2 (Monitoring and control, p. 34). ETRI's model explicitly includes control capabilities alongside monitoring, highlighting a significant distinction. Control is a separate function that goes beyond mere monitoring and reporting, necessitating a distinct decision-making process. For example, MTConnect is designed to support monitoring of industrial assets without incorporating control functions. Although control is not explicitly mentioned in the Level 2 stage of Unity's model, this technical report infers its inclusion. The rationale is that the subsequent stage Level 3 (Predictive Twin) is geared towards proactive management. This implies that Level 2 inherently encompasses reactive management, including the ability to reactively control based on real-time data, thus bridging the gap between simple monitoring and active control.

- Level 3 (Predictive Twin): Building on the connected twin (Level 2), this level introduces predictive analytics to forecast potential outcomes and identify problems before they occur. It represents a shift towards proactive management of facilities and equipment, aiding in decision-making and predictive maintenance through advanced analytics.

  NOTE 3: Unity's Level 3, although not directly corresponding to the specifics outlined in ETRI's Level 3 (Modeling and simulation, p. 34), aligns with the broader objectives of ETRI's Level 3. This alignment is because ETRI's Level 2 focuses on employing well-established technologies for monitoring and control, a foundation described in "Design principles (p. 29)." In contrast, Unity's Level 3 advances beyond this foundation by embracing sophisticated data manipulation techniques. It specifically targets predictive analytics, proactive management, and predictive maintenance. This progression signifies a shift towards more advanced functionalities that not only anticipate future conditions but also prepare and adjust operations proactively.

- Level 4 (Prescriptive Twin): This stage advances the digital twin's capabilities with what-if simulations and intelligent recommendations, using machine learning and advanced modeling to explore potential future scenarios and prescribe actions. It enhances decision-making processes by not only predicting future outcomes but also recommending optimal responses.

  NOTE 4: It is identical to ETRI's Level 3 (Mirroring, p. 34).

- Level 5 (Autonomous Twin): The pinnacle of Unity's model is the autonomous twin, which leverages AI and multiple real-time data feeds to make decisions and implement corrective actions without human intervention. This stage embodies the Digital Twin's full potential, enabling predictive and prescriptive analytics to operate dynamically and autonomously, ensuring optimal performance and efficiency.

NOTE 5: Unity's Level 5 shares the same goals with ETRI's Level 5, aiming for a high degree of autonomy in Digital Twin operations. However, it's important to note that the enabling technologies for this level, such as AI and multiple real-time data feeds, are not exclusive to Level 5. These technologies can be, and often are, applied across various levels of maturity as needed to meet the specific objectives of each level.

DAPA's maturity model

On December 28, 2023, the Defense Acquisition Program Administration (DAPA) of Korea issued guidance on utilizing Digital Twins for military weapon systems. This initiative is designed to enhance the reliability and efficiency of both the acquisition and operational phases of weapon systems. It introduces standards and procedures tailored for the pilot application of Digital Twins during the weapon system acquisition process. DAPA has adapted ETRI's maturity model to suit the specific needs and challenges of the defense sector, as illustrated in Table 10 [15].

Table 10 – DAPA's Digital Twin maturity model [15]

Maturity level	Reference name	Description
5	Decision	• Supporting decision-making by integrating information from all weapon systems based on AI and big data
4	Connected	• Interaction by linking information between weapon systems in real time
3	Virtual works	• Predicting results in virtual situations through collected data and dynamics
2	Monitoring	• Collecting simple information (e.g., position and speed) data with sensors attached to prototype systems
1	Shaping design	• Designing and visualizing shapes in 3D (including animation)

- Level 1 (Shaping design): Similar to ETRI's Level 1 (Mirroring), both levels aim for the same objective: the foundational design and 3D visualization of systems. Despite different names, the focus on initial design visualization remains consistent.

- Level 2 (Monitoring): DAPA's Level 2 emphasizes monitoring through sensor data collection, such as position and speed. In contrast, ETRI's Level 2 (Monitoring and control), which combines monitoring and control, highlights that these functions, while often paired in industrial applications, represent distinct capabilities. The choice to support one or both is strategic, underscoring a divergence in focus between the two models.

- Level 3 (Virtual works): Despite the differing terminology from ETRI's Level 3 (Modeling and simulation), both levels pursue the same goal: to predict outcomes based on data and simulations. This highlights a shared commitment to using virtual environments for outcome prediction.

- Level 4 (Connected): DAPA's Level 4 parallels ETRI’s Level 4 (Federated) in its aim, albeit under a different name. Both focus on the real-time linkage and interaction among systems, indicating a convergence in objectives toward integrated Digital Twin ecosystems.

- Level 5 (Decision): DAPA’s Level 5 focuses on supporting decision-making with AI and big data, contrasting with ETRI’s more visionary Level 5 (Autonomous). DAPA’s Level 5 is currently realistic for actual implementations. It’s important to recognize that the technologies enabling this level, such as AI and big data, are versatile and may be applied across various maturity levels to fulfill specific objectives.

Jan-Frederik’s maturity model

Jan-Frederik’s team developed a comprehensive Digital Twin maturity model by conducting a systematic literature review across various databases, including SCOPUS, IEEE Explore, SpringerLink, and Web of Science. Through this extensive research, they identified a wide range of capabilities and features associated with Digital Twins, which they organized into seven key categories: context, data, computing capabilities, model, integration, control, and human-machine interface. This categorization led to the creation of a 30-dimension model, each dimension offering specific scoring characteristics to assess maturity [16].

Their conceptual approach draws parallels to *“Rainer’s maturity model (p. 10),”* focusing on three main aspects: maturity categories, maturity dimensions, and a gradation of maturity levels or scoring characteristics/values, as illustrated in Table 11. Despite having somewhat distinct perspectives and varying levels of detail, their mappings between corresponding dimensions across both models are associated with each other. Corresponding to a kind of maturity levels, scoring characteristics of each dimension of Jan-Frederik’s maturity model is given in Table 12. Specific levels of each dimension of Rainer’s maturity model is depicted in Figure 3 (p. 10).

Table 11 – Jan-Frederik’s Digital Twin maturity model and Rainer’s maturity model

<table>
<tr><th colspan="2">Jan-Frederik’s maturity model [16]</th><th colspan="2">Rainer’s maturity model [8]</th></tr>
<tr><th>Categories</th><th>Dimensions</th><th>Categories</th><th>Dimensions</th></tr>
<tr><td rowspan="4">Context</td><td>Reference object</td><td rowspan="4">Digital Twin lifecycle context</td><td></td></tr>
<tr><td>Tangible product life cycle phases</td><td>8. Product lifecycle</td></tr>
<tr><td>Benefits</td><td></td></tr>
<tr><td>Application domain</td><td></td></tr>
<tr><td rowspan="5">Model</td><td>Digital Twin creation approach</td><td rowspan="5">Digital Twin behavior and capability richness</td><td></td></tr>
<tr><td>Modelled characteristics</td><td>6. Digital model richness</td></tr>
<tr><td>Digital model types</td><td>5. Simulation capabilities</td></tr>
<tr><td>Model authenticity</td><td></td></tr>
<tr><td>Model maintenance</td><td></td></tr>
</table>

	Modularity		
Data	Data storage		
	Data scope		
	Data quality		
	Data sources		
	Data interpretation		
Control	Level of cognition		
	Levels of autonomy		4. CPS intelligence
	Learning capabilities		
Human-Machine Interaction (HMI)	Types of interaction devices		7. Human interaction
	Human interaction capabilities		
Computing capabilities	Trigger types	**Digital Twin environment**	
	Model look-ahead perspective		
	Computing capabilities		
	Update frequency – Input		3. Update frequency
	Update frequency – Output		
Integration	Digital Twin interaction		
	Hierarchy		
	Connection mode		2. Connectivity mode
	User focus		
	Interorganizational integration/collaboration		1. Integration breadth

Table 12 – Scoring characteristics for each dimension of Jan-Frederik's Digital Twin maturity model [16]

NOTE 1: 'n' in the score column denotes scoring values, while '–' denotes no score.

Categories	Dimension and question to identify	Scores and scoring characteristics	
Context	**Reference object** *What is the reference object of our DTw(s)?*	–	Product
		–	Resource (Manufacturing) Asset / Component / Resource
		–	Process / Service
		–	Human / People
	Tangible product life cycle phases *In which product lifecycle phase is the DTw applied?*	–	Begin of Life
		–	Middle of Life
		–	End of Life
	Benefits *How does the DTw provide benefits?*	–	New service innovation
		–	Service optimization

	Application domain *What is the application domain of the DTw?*	–	Manufacturing, Aerospace, Healthcare, Automotive, Maritime, Construction, Smart cities, Logistics, Smart products, Energy, Education, Agriculture, Mining, and so on
Model	**Digital Twin creation approach (0 … 1)** *How is the DTw designed?*	0	Retrofitted-DTw
		1	Design-for-DTw
	Modeled characteristics *Which characteristics of the physical object are modeled?*	–	Geometry-kinematics
		–	Control behavior
		–	Sensor behavior
		–	(Multi-)Physical behavior
		–	Production System behavior
	Digital model types *How are the characteristics of the DTw modeled?*	–	Conceptual models
		–	Physics-based models
		–	Data / Machine learning-based models
		–	Hybrid models
		–	Model is used in simulation *(Option)*
		–	Time is represented in simulation (dynamic / not static) *(Option)*
		–	Simulation calculates with probabilities (stochastic / not deterministic) *(Option)*
		–	Processed values are within an infinite range (continuous / not discrete simulation) *(Option)*
	Model authenticity (0 … 3) *How is the authenticity of the DTw? How good is the representation of reality?*	0	No
		1	Low
		2	Middle
		3	High
	Model maintenance (0 … 5) *How is the model quality observed and controlled?*	0	Model descriptions are not formalized but maintained manually
		1	Models are formalized and periodic maintenance procedures are used
		2	Individual models can detect lacking model quality itself [1]
		3	[1] and reload latest data and code itself
		4	[1] and load additional model plugin or adjust the model parameter itself
		5	[1] and fully maintain themselves by e.g., organizing new sensors and computing capabilities
		0	Unit

	Modularity **(0 … 2)** *How modular and reusable is the DTw modeled?*	1	System
		2	System of Systems
Data	**Data storage** *Where is the data storage located?*	–	Edge-based
		–	Local servers
		–	On-premises cloud
		–	External cloud
	Data scope **(0 … 4)** *How large-scaled is the sourcing of data?*	0	Informal data acquisition of a specific asset
		1	Local-scope data is collected regularly for one asset and its environment
		2	Data of multiple assets
		3	Internal and external data of a supply chain and very numerous assets
		+1	Big data *(Option)*
	Data quality **(0 … 7)** *How is the data quality?*	–	DTw follows the fitness-for-purpose approach
		+1	Accuracy: Low degree of errors
		+1	Completeness: All needed data available
		+1	Semantic consistency: Uniform vocabulary and definitions
		+1	Structural consistency: Uniform format and structure
		+1	Uniqueness: Few irrelevant/duplicate data
		+1	Check for data quality regularly *(Option)*
	Data sources **(0 … 2)** *What is the source of the data?*	+1	Physical data
		+1	Fused data
	Data interpretation **(0 … 1)** *How capable is the DTw to interpret incoming data?*	0	Structured
		1	Unstructured
Control	**Level of cognition** **(0 … 5)** *How intelligent is the DTw?*	+1	Descriptive analytics: What happened?
		+1	Diagnostic analytics: Why did it happen?
		+1	Predictive analytics: What could happen?
		+1	Prescriptive analytics: What should we do?
		+1	Cognitive analytics: Solving complex problems and causing something to happen
	Levels of autonomy **(0 … 5)**	0	No autonomy
		1	User assistance

	What are the levels of autonomy?	2	Partial autonomy
		3	Conditional autonomy
		4	High autonomy
		5	Full autonomy
	Learning capabilities (0 … 4) *How is the learning capability?*	0	No learning
		+1	Reactive learning with user-based control strategies
		+1	Learning from historical data to make decisions by use of (un)supervised learning
		+1	Able to learn new skills with reinforcement learning self-aware with human-like intelligence
		+1	Fast learning *(Option)*
Human-Machine Interaction (HMI)	**Types of interaction devices (0 … 3)** *What types of devices are used?*	1	Traditional, structured reports
		2	Multi-modal interaction devices
		+1	Adaptive assistance system *(Option)*
	Human interaction capabilities (0 … 4) *For which requests can the DTw answer?*	+1	Predefined, structured reports
		+1	Simple questions and answers
		+1	Complex questions and answers
		+1	DTw adjusts to the user *(Option)*
Computing capabilities	**Trigger types (0 … 3)** *How is the DTw triggered?*	+1	Ad-hoc (event-driven)
		+1	Dynamic (continuous)
		+1	Static (once at a time)
	Model look-ahead perspective (0 … 3) *How far ahead does the DTw think?*	+1	Long-term
		+1	Middle-term
		+1	Short-term
	Computing capabilities (0 … 1) *How much is the runtime/response time?*	0	Hours
		0	Minutes
		1	Seconds
		1	Milliseconds
	Update frequency – Input (0 … 2) *How often is new data considered and the DTw models updated?*	0	Every day or less frequent
		1	Every hour
		2	Real-time / event-driven
	Update frequency – Output (0 … 1) *How often is the result of the DTw applied?*	0	Periodic
		1	Instant / real-time
Integration		1	Standalone

	Digital Twin interaction (1 … 4) *Is it only one or are there more DTws?*	2	System of systems with interconnection/network of integrated systems
		3	System of systems with collaboration but independent goals
		4	System of system with one/common goals and optimization
	Hierarchy *Are the DTws in collaboration of equal rank?*	–	Decentral organization and control
		–	Cluster-based organization
		–	Central orchestration and control
	Connection mode (1 … 3) *How is the DTw connected to the real world?*	1	Digital model / Offline
		2	Digital shadow / Uni-directional
		3	Ideal DTw / Bi-directional
	User focus (1 … 4) *Who benefits from the DTw?*	1	Single user
		2	Multiple users in one department
		3	Multiple users across an enterprise
		4	Multiple users across multiple enterprises
	Interorganizational integration/collaboration (0 … 4) *How far is the DTw integrated in the IT-landscape? Options: max. +1*	0	No collaboration: Independent DTws for different stakeholders, No exchange/access of/to DTw elements for other stakeholders
		1	Minimal collaboration: Integration of stakeholders via services / defined interfaces, Basic collaboration between partners
		2	Limited collaboration: Different grades of integration possible, Aligned relationships between stakeholders, Defined area of work for stakeholders
		3	Full collaboration: Different grades of integration possible, High trust between stakeholders, and Collaborative development and usage of DTw
		+1	Platform owns/hosts DTw *(Option)*
		+1	Software as a Service (SaaS) *(Option)*

Short conclusions

This technical report has explored ten existing Digital Twin maturity models, with a forthcoming detailed look at ETRI's maturity model. It's important to recognize that these models represent just a fraction of the myriad approaches to assessing Digital Twin maturity, highlighting the diversity of perspectives in this field. From the analysis of eleven maturity models, we can categorize them into three distinct types based on their primary focus as shown in Table 13:

Table 13 – Classification of Digital Twin maturity models

Types	Maturity assessment methodologies	
	General usage	Domain-specific usage
Organizational and business development perspective	• IDC’s maturity model • Di-Phy Innovations’ maturity model	
Capability and feature perspective	• Gartner’s maturity model • Aidan’s maturity model • IoT Analytics’ maturity model • Unity’s maturity model • ETRI’s maturity model	• Atkins/IET’s maturity model • DAPA’s maturity model
Comprehensive landscape perspective	• Rainer’s maturity model • Jan-Frederik’s maturity model	

Reflecting on the *“Nature of maturity models (p. 4),”* we’re reminded that maturity models are crafted by and for specific groups of stakeholders, including those that reach the status of international standards. This development process ensures that each model acts as a shared framework, enhancing common understanding and effective communication among its users. However, the variability in viewpoints and needs means no single maturity model can universally apply to all assessment scenarios or objectives.

Considering this diversity, users of maturity models are encouraged to select or adapt a maturity model that aligns with their specific assessment goals and requirements. The customization demonstrated by DAPA’s maturity model exemplifies how stakeholders can tailor existing maturity models to suit unique organizational requirements.

Moreover, users have the opportunity to create a dedicated, bespoke model by integrating the most beneficial aspects of various models into a single, comprehensive, and tailored framework, as illustrated by MM #7 in Figure 2. This approach enables a more detailed and effective assessment, uniquely shaped to align with each organization’s objectives and challenges.

In the section *“Nature of maturity models (p. 4),”* a crucial point is underscored: maintaining a consistent perspective throughout the maturity assessment process is essential. Variability in the assessment criteria or viewpoints can lead to discrepancies in results, casting doubt on the reliability of previous evaluations, the understanding of the current state, and the clarity of the path forward. Thus, ensuring a stable and uniform assessment framework is fundamental for obtaining reliable and actionable insights from maturity models.

Design principles and market situations

Because of our motivation explained in *"Motivation (p. 3),"* we prepared the following design principles and reviewed current market situations to model specific maturity levels.

Design principles

As explained in *"Motivation (p. 3),"* ETRI's maturity model was initially designed as a way to share a common understanding and baseline to facilitate effective communication among meeting attendees from diverse backgrounds. In its initial development, sophisticated design principles and a comprehensive landscape were not considered; rather, the model was constructed without following a systematic development methodology. The design principles outlined below reflect the piecemeal criteria that were kept in mind during the initial development.

NOTE 1: When developing new maturity models, it would be beneficial to utilize a structured development methodology for maturity models to take advantage of more organized, systematic, and step-by-step guidance. A maturity model development methodology for reference is introduced in the accompanying memo box.

- A maturity model must not be used for competitive evaluation and certification purposes but for a self-assessment to figure out where one is, where one should go, and what one should do for a particular development.

- As shown in Figure 6, the five-level maturity model is more appropriate because this type is very popular and familiar in various industry fields.

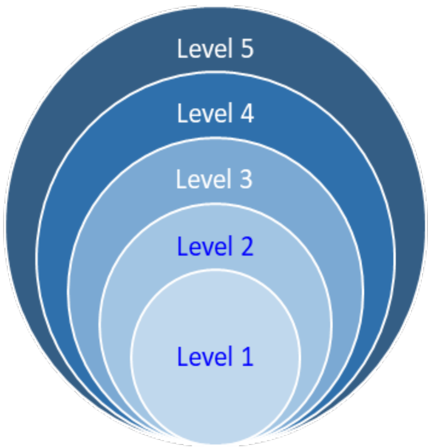

Figure 6 – Layered maturity model

- A Digital Twin system can incorporate various enabling technologies that can be organized into different levels. Levels 1 and 2 encompass past achievements related to Digital Twin systems, while Level 3 represents current and near-future technical features. Levels 4 and 5 cover future technology functions. It's important to note that past technologies are not necessarily obsolete or inefficient but rather are still working and long-standing proven technologies that have been adopted so far. Time is not an absolute condition for the levels, so advanced technologies can be located at Levels 1 and 2.

- Higher levels must be inclusive of their lower levels, as illustrated in Figure 6.

- A maturity model should accommodate as many market voices as possible. Because there are no technical specifications and standard usages for a Digital Twin instance system, no judging for *"Yes"* or *"No"* can be technically possible in terms of conformance.

Maturity model development methodology: General design principles for maturity models [17]

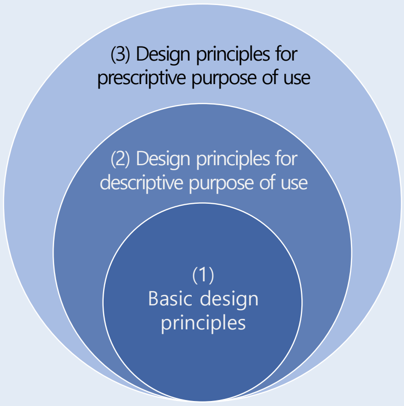

Figure 7 – Organization of the design principle framework [17]

Figure 7 shows the organization of the groups of design principles (DPs): basic principles, principles for a descriptive purpose of use, and principles for a prescriptive purpose of use. Basic DPs should be addressed independently of a specific purpose of use. Descriptive maturity models should also comply with the basic DPs. Prescriptive maturity models should fulfill the DPs for descriptive maturity models and the basic DPs [17].

Table 14 illustrates an overall framework of general design principles for reference when developing maturity models. Jens's paper (refer to [17]) provides their details for understanding.

Table 14 – A framework of general design principles for maturity models [17]

Group		***Design principles***
(1) Basic	***1.1***	***Basic information*** *a) Application domain and prerequisites for applicability* *b) Purpose of use* *c) Target group* *d) Class of entities under investigation* *e) Differentiation from related maturity models* *f) Design process and extent of empirical validation*
	1.2	***Definition of central constructs related to maturity and maturation*** *a) Maturity and dimensions of maturity* *b) Maturity levels and maturation paths* *c) Available levels of granularity of maturation* *d) Underpinning theoretical foundations with respect to evolution and change*
	1.3	***Definition of central constructs related to the application domain***
	1.4	***Target group-oriented documentation***
(2) Descriptive	***2.1***	***Intersubjectively verifiable criteria for each maturity level and level of granularity***
	2.2	***Target group-oriented assessment methodology*** *a) Procedure model* *b) Advice on the assessment of criteria* *c) Advice on the adaptation and configuration of criteria* *d) Expert knowledge from previous application*
(3) Prescriptive	***3.1***	***Improvement measures for each maturity level and level of granularity***
	3.2	***Decision calculus for selecting improvement measures*** *a) Explication of relevant objectives* *b) Explication of relevant factors of influence* *c) Distinction between an external reporting and an internal improvement perspective*
	3.3	***Target group-oriented decision methodology*** *a) Procedure model* *b) Advice on the assessment of variables* *c) Advice on the concretization and adaption of the improvement measures* *d) Advice on the adaptation and configuration of the decision calculus* *e) Expert knowledge from previous application*

Market situation #1 – Cases of no Physical Twin or no data link

- Figure 8 shows two trinity models to constitute a Digital Twin instance system between physical and virtual worlds: one consisting of a Physical Twin, a Digital Twin, and a data interface between them, and the other one composed of geometrical, structural, and behavioral models for the Digital Twin model.

  NOTE 1: The Digital Twin instance refers to the DTI (Digital Twin Instance) concept of Michael Grieves. It has a twin relation between physical and corresponding virtual objects, while the DTP (Digital Twin Prototype) exists solely without its counterpart physical object, as described in "Hierarchical aggregation [7]." The DTP consists of the designs, analyses, and processes to realize a physical product and exists before a physical product exists. The DTI is the Digital Twin of each individual instance of the product once it is manufactured [18].

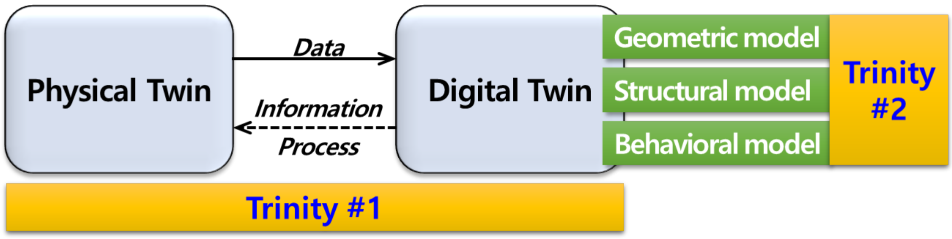

Figure 8 – Two trinity models of Digital Twin system [7]

  Theoretically, any case without one element cannot conform to the Digital Twin concept, nor can it be called a Digital Twin system. But in reality, market situations don't fit with such logical and theoretical understanding. This market situation #1 deals with the conformance to the trinity #1 case, and the following market situation #2 considers the conformance to the trinity #2 case.

- Referring to the trinity #1 case of Figure 8, the Digital Mock-Up (DMU) [7] and the Computer-Aided Engineering (CAE) [7] don't have a Physical Twin and data link as described, but they only have a Digital Twin, i.e., DTP, to build an as-designed Physical Twin.

  NOTE 2: Michael Grieves said, "There is a 'first-born.' The first-born in this model is the Digital Twin. The product idea shape, functionality, and plans for realizing those always precedes the actual realization of the product in physical form [19]." That is, only "Digital Twin" is fundamental.

- As explained above, the DTP exists before a physical product is made, and the DTP case has yet no physical counterpart or data connection.

- Virtual Singapore hasn't built data connections between virtual Singapore objects and corresponding physical objects. It has many virtual models for simulation, and people conceive of Virtual Singapore as a Digital Twin city. CAE (Computer-Aided Engineering) is also the same case.

- Our conclusion from these market situations is that both Physical Twin and data link are optional for the Digital Twin concept adopted in the market so far, but the Digital Twin is a mandatory element.

Market situation #2 – Cases of only a geometrical model or no behavioral model

- Referring to the trinity #2 case of Figure 8, a question raised by the market is whether only a geometrical model can also be treated as a Digital Twin. For example, the Korean government has pursued a development initiative called *"National Digital Twin,"* aiming to establish 3D-based GIS data for buildings, roads, underground spaces, facilities, and so on. It is mainly geometrical data, implying that the structural movement of a bascule or lift bridge, for example, cannot be represented.

  However, many application cases require a combined model of geometrical and structural data to support the correlated nature of geometric shapes and structural dynamics. This allows for simulating the impact of changes in one aspect on the other.

  Furthermore, certain applications may require the integration of system behaviors into the combined model, resulting in a trinity model of the Digital Twin.

  Therefore, there are three types of models: a geometrical model, a geometrical and structural model, and a trinity model that includes behavioral models together. The appropriate model type is determined by the level of detail required for specific purposes and relevant requirements. As such, in Korea, the market also understands the geometrical model replicating a real-world object as a Digital Twin model. Conclusively, either type of theirs can be a Digital Twin with a different level of detail.

- The geometrical model can be formed in 2D or 3D. The digital map is a typical 2D data model. It is a digital representation of a geographic area, such as a city or a region. Digital maps can be customized to include additional information, such as satellite imagery and live traffic updates. They can also have features such as roads, landmarks, buildings, and bodies of water, as well as points of interest such as restaurants, shops, and parks. This allows users to get a more detailed and accurate understanding of an area and make more informed decisions when planning their route.

  Another question raised by the market is whether a 3D-based geometrical model is the only form of a Digital Twin model. The history of 2D digital maps is longer than that of the Digital Twin concept. Our answer is:

  "No. 2D-based geometrical model, e.g., digital map, can also be a Digital Twin model, just in a different level of detail."

  According to Table 2, Atkins/IET's maturity model assigns the 2D map/system to Level 1. It has the same view as our clarification. Consequently, both of them, i.e., 2D/3D, can be a Digital Twin model with a different level of detail.

Market situation #3 – Old but similar-looking ones

- Long-standing technologies such as SCADA (Supervisory Control And Data Acquisition), DCS (Distributed Control System), CAM (Computer-Aided Manufacturing), CAD (Computer-Aided Design), CAE (Computer-Aided Engineering), and GIS (Geographic Information System), were not initially branded as Digital Twin instances before the widespread adoption of the Digital Twin concept in the market.

With the emergence of the Digital Twin concept and the subsequent increase in business opportunities, technology and solution vendors have started offering their products as solutions that enable Digital Twin capabilities. This is because specific functionalities of these technologies can meet particular functional requirements for creating a Digital Twin instance. However, this may only result in a partial resemblance, as explained in the following *"NOTE 1."* This approach cannot be considered wrong, as there are no standardized or universally accepted Digital Twin specifications and use cases.

NOTE 1: SCADA and DCS systems are composed of three main components: the target physical systems, monitoring and control systems, and data interfaces connecting both sides. This configuration resembles a twin system, as described in NOTE 2 below. CAD can represent geometrical and structural models, while GIS can construct geometrical models for physical objects. CAE enables the manipulation of a comprehensive model containing geometrical, structural, and behavioral representations of "as-designed" products. It facilitates testing and simulations of the product's physical properties during the development engineering phase. CAM primarily involves monitoring and controlling machinery to transform raw materials into a finished product with a specified shape based on its CAD model and associated data.

NOTE 2: Consider the following real story. SCADA systems have been employed for several decades to monitor and control industrial facilities. They encompass three primary components: physical facilities and objects constituting the physical system, data processing and management objects forming the cyber system, and the data links connecting them. Operational status information of a facility is displayed on an operation and management screen, sharing similarities with the Digital Twin concept in terms of monitoring and responding to the physical aspect. In this context, an engineering staff member from a facility posed the question, "Why not is it a Digital Twin system?" No one could definitely answer, "No."

ETRI's proposed Digital Twin maturity model

ETRI's maturity model

We have established the following Digital Twin maturity model and assigned market usage cases to Levels 1, 2, and 3 accordingly, based on the above design principles and market situations:

Table 15 – Digital Twin maturity model from the capability perspective

Maturity level	Reference name	Capability requirements	Examples
5	Autonomous	• Autonomous operations by live synchronization and orchestration without any human intervention • Initiative operation supported	N/A
4	Federated	• Federated, synchronized, and interactive operations among Digital Twins, but through human intervention for action • Application/service-specific data exchanges through a federation interface among cross-domains	N/A
3	Modeling and simulation	• Behaviors and dynamics modeled for operation and simulation • What-if simulations provided • Proactive operations supported • Cause analysis possible by reproductive simulation • State synchronization between a twin pair • Data threading throughout a lifecycle flow	CAE, HILS, CPS, Digital Factory, Digital mock-up, Virtual sensor, Virtual Singapore, etc.
2	Monitoring and control	• Persistent, static, and initial data connection • Static process control logics applied without processing models for behaviors and dynamics • Passive or reactive operations supported • Real-time monitoring through a synchronization interface • Partial automatic control, but mainly through human intervention for action	SCADA, DCS, CAM, etc.
1	Mirroring	• Physical objects modeled to have a similar shape, size, structure, and appearance and rendered in 2D or 3D	CAD, BIM, GIS, Navigation map, etc.

NOTE 1: Lower levels are inclusive in their higher levels. For example, Level 5 includes all the lower-level functions, as depicted in Figure 6 (p. 29).

NOTE 2: The reference names of the maturity levels have referred to the result of the collective intelligence of technical experts organized by the Institute of Information & Communications Technology Planning & Evaluation (IITP), Korea [20].

Details of Digital Twin maturity levels

Level 1: Mirroring

(2D or 3D models are rendered geometrically and structurally for a physical object.)

- *Physical object modeled to have a similar shape, size, and appearance and rendered in 2D or 3D:* A physical object is rendered geometrically and structurally as a 2D or 3D representation model. It can be displayed in a cyber world as in the real one. Its model has static data that doesn't support structural behavior simulation.

- Typical technology solutions: 2D/3D design tools and CAD, BIM, and GIS systems are representative solutions of Level 1.

NOTE 1: Level 1 doesn't assume any data connection is required. "Consideration of data integration levels (p. 43)" has an additional description.

NOTE 2: It can accommodate that CAD, BIM, and GIS solution providers have said our solutions support Digital Twin.

NOTE 3: The 2D digital map is also a Digital Twin model, as described in "Market situation #2 – Cases of only a geometrical model or no behavioral model (p. 32)."

Level 2: Monitoring and control

(A process control system monitors and controls a physical object through a fixed processing logic.)

- *Persistent, static, and initial data connection:* Overall operation environments of Level 2 are static. After a process control system, represented as a Level 2 Digital Twin, is initially connected to its target physical system, its processing logic and data connection are persistent and fixed during its life unless they are rebuilt or recommissioned.

- *Static process control logics are applied without models of behaviors and dynamics:* With having no dynamics and behavior models of a physical object, step-by-step processing logics comprised of real-time monitoring and reactive control to the physical object are developed and work during the operational time.

- *Passive or reactive operations supported:* A passive operation can run unidirectionally with no feedback channel. MTConnect is an example communication protocol to support the passive operation of tool machines at industrial factories. A reactive operation can also run through the bidirectional path with forward and backward channels.

  NOTE 1: The psychological behavior of a reactive person can represent a reactive operation. A reactive person – which includes most of us – is the waiter. They wait for things to happen (not necessarily on purpose) and then react to the situation that results. They are always a little behind as it takes time to assess an event and come to a conclusion about how to behave in regard to it [21].

- *Real-time monitoring through a synchronization interface:* Status data from physical entities are delivered to processing logics for monitoring, and reactive controls can be made for operation and management.

  NOTE 2: Here, the term "real-time" needs to be clarified because application requirements may interpret it differently. For example, a remote metering application requires 15 minutes for real-time responses, and the reflection of a thing in a mirror expects an instantaneous response at the speed of light. Thus, the timeliness of real-time depends on applications. "A.7 Consideration of real-time (p. 57)" has additional descriptions.

  NOTE 3: A real-time operation may consist of real-time monitoring and reactive control. The reactive control may be performed either automatically by management logic or manually by human intervention. Automatically-reactive control can enable real-time operation. However, the manually-reactive control doesn't due to human engagement taking more time.

  NOTE 4: Real-time monitoring requires synchronization interface technologies. There are many different interface solutions, such as MTConnect, OPC-UA, OMA DDS, PROFIBUS, Modbus, and RAPIEnet, where the timeliness of real-time may vary according to application requirements.

- *Partial automatic control but mainly through human intervention for action:* Reactive controls against real-time monitoring can be performed automatically when the operations and controls of a physical system are very stable and reliable. A part of the system can take advantage of automatic control. However, since the operations and controls of the whole system haven't been matured to fully automated control, it is performed primarily by human interventions.

  NOTE 5: The human-intervened operation is a type of Human-in-the-Loop or Human-on-the-Loop. A human operator should engage the loop operation process between a physical object and its Digital Twin.

  NOTE 6: Status information by monitoring, control actions, and reactive responses are visualized on display.

- Example application cases: SCADA, DCS, and CAM are representative solutions of Level 2. They have been used and proven reliable for a long time in various industries through a twin-like HMI (Human-Man Interface). Level 2 adopted this market situation, also as described in *"Market situation #3 – Old but similar-looking ones (p. 32)."*

NOTE 7: Every Level 2 use case for those required functions is based on a data interface, and Level 2 can specify the data interface as mandatory. "Consideration of data integration levels (p. 43)" has an additional description.

Level 3: Modeling and simulation
(A represented virtual model can simulate the behavioral operations of its corresponding physical object.)

- *Behaviors and dynamics modeled for operation and simulation:* In addition to geometric and structural representation models for physical objects, their behaviors and dynamics for operation are characterized and represented as virtual models at Level 3. Structural and characteristic behaviors belong to this. Their fidelity in terms of the granularity of characterization depends on modeling purposes.

- *What-if simulations provided:* Virtual behavior models comprising a Digital Twin can simulate certain situations by arbitrary input parameters for its physical object. Structural or behavioral simulation results can help understand how the physical object behaves in its future situation.

- *Proactive operations supported:* What-if simulations can support proactive operations.

  NOTE 1: The psychological behavior of a proactive person can represent the proactive operation. A proactive person – which includes many of us – is the sharp one who anticipates the events that are about to happen and is ready with both a response and plan to deal with the outcome. People who are aware of their surroundings and wish to avoid being surprised by such things as odd job interview questions or negative results from medical tests will plan ahead, be wary, and try to forestall the worst of it by being prepared [21].

- *Cause analysis possible by reproductive simulation:* Virtual behavior models of a Digital Twin can reproductively simulate what happened to its physical object. Reproductive simulation results can help analyze why it happened.

- *State synchronization between a twin pair:* Virtual models of a Digital Twin are synchronized with behaviors of its physical object in terms of their operating states, but interactions for execution between them aren't made all the time concurrently. People can intervene for sure to execute an action on the physical object because autonomous execution by a Digital Twin system may cause significant problems in the real world.

  NOTE 2: Synchronization refers to the act of synchronizing the virtual and physical states, for example, the act of measuring the state of a physical object and realizing that state in its Digital Twin such that the virtual and physical states are "equal," in that all of the virtual parameters are the same value as physical parameters [22]. The synchronization may apply between a twin pair via a "A.3 Synchronization interface (p. 52)."

  NOTE 3: Many data link technologies can support synchronization between a Physical Twin and its Digital Twin. Their examples are MTConnect, OPC-UA, OMA DDS, MQTT, XMPP, AMQP, CoAP, PROFIBUS, Modbus, RAPIEnet, CC-Link, EtherCAT, etc.

- *Data threading throughout a lifecycle flow:* Various behavior models of Digital Twin systems share specific information and interrelate associated information with related cooperation peers throughout a lifecycle via *"A.4 Threading interface (p. 53)."*

  NOTE 4: The threading interface can accommodate the above NOTE 3's interface technologies into its communication framework.

- Example application cases: Computer-Aided Engineering (CAE), Digital Mock-Up (DMU), Hardware-in-the-Loop Simulation (HILS), Cyber-Physical System (CPS), Virtual sensor, and Digital Factory are representative solutions of Level 3. The Virtual Singapore is another development case. CAE and Virtual Singapore have various behavior and dynamics models for operation and can support the simulation of particular situations with different input parameters where no data connection is engaged. Also, Digital Factory, HILS, and CPS have various behavioral and dynamics models for operation and can support relevant simulation cases, but data connections are engaged.

NOTE 5: Level 3 doesn't require a data interface as mandatory but optional, as described in "Market situation #1 – Cases of no Physical Twin or no data link (p. 31). Therefore, synchronization doesn't happen all the time. "Consideration of data integration levels (p. 43)" has an additional description.

Level 4: Federated

(Multiple Digital Twins are federated by each other and perform mutual interactions for their cross-dependent operations.)

- *Federated, synchronized, and interactive operations among Digital Twins, but through human intervention for action:* While the reference usages of Levels 1, 2, and 3 Digital Twin have been presented as singular, the reference usage of Level 4 Digital Twin is shown in the plural as *"Digital Twins."* Level 4 deals with the cases where a Digital Twin affects other Digital Twins, and multiple Digital Twins interact with each other to carry out their collaborative works.

  NOTE 1: It may be said that the federation of multiple Digital Twins is considered as an additional output and input relation from a Digital Twin to other Digital Twins. However, this is not a simple connectivity issue but an integration and convergence issue among different domains, which means that different worlds are coupled closely and interact with each other. Therefore, it is a big step and can cause a challenge to orchestrate their mutual interactions.

- *Application/service-specific data exchanges through a federation interface*: As described in Level 3, people should intervene for sure to execute an action against other Digital Twins and associated physical entities. The lifecycle of an application usage or service instance is not considered. Data exchanges dealing with their common concerns are conducted among all engaged Digital Twins along with their federated relations.

  NOTE 2: The federation interface refers to a data exchange channel over every engaged domain federated for communication. Its technical details will depend on federation topologies such as supervised topology, distributed topology, mixed topology, or other ways. OAGIS (Open Applications Group Integration Specification) is based on a distributed topology. Although OAGIS has been developed to support manufacturing business data exchanges, its technical way may be a reference for developing a distributed topology-based federation interface. "Consideration of data integration levels (p. 43)" has an additional description.

Level 5: Autonomous

(Physical entities and their Digital Twins are synchronized in real-time and interact through autonomous orchestration without manual interventions. Specific autonomous levels can be defined, referring to "Consideration of autonomous levels (p. 44).")

- *Autonomous operations by live synchronization and orchestration without any human intervention:* Level 5 assumes that the mutual relationship between the structure and behavior models of a physical object and corresponding virtual models of its Digital Twin is stable, reliable, and dependable for action to the real world. In this case, physical entities and their Digital Twin models are synchronized in real-time and interact through autonomous and live orchestration without manual interventions. Autonomous operation means no manual interventions are required to execute the physical entities.

  NOTE 1: The time constraints of real-time depend on application requirements, as described in NOTEs 2, 3, and 4 of Level 2. For example, for visual synchronization with people, real-time needs to be up to 10 msec.

  NOTE 2: The live orchestration refers to timely synthetic alignments between physical entities and their participating Digital Twins.

  NOTE 3: We observed strong concerns for autonomous operation at Level 5 because AI-based autonomous decision-making is not yet stable nor reliable, and human intervention cannot be excluded. Nonetheless, it still depends on the application levels of Digital Twin and their modeling and operation boundaries. In reality, there are such cases of autonomous execution in simple systems at Level 2.

  NOTE 4: The degree of autonomy is a development issue, i.e., how autonomously a Digital Twin operation can be conducted. "Consideration of autonomous levels (p. 44)" has clarified the degree of autonomy.

- *Initiative operation supported:* The initiative operation represents autonomous operations.

  NOTE 5: The psychological behavior of an initiative person can represent an initiative operation. An initiative person – which includes most world leaders and creative types – starts the process of change themselves. They don't wait for something to happen. They are the agent of making it happen. That puts them in far greater control of the outcome and also makes for a more exciting life as what they have initiated will undoubtedly be handled in different ways by the reactors and the proactive people in the environment [21].

Consideration of human engagement types

Human engagement for Digital Twin systems can be characterized by three operation models: Human-off-the-Loop, Human-on-the-Loop, and Human-in-the-Loop in terms of non, passive, or active participation.

Non-participation, resulting in Human-off-the-Loop

Human-off-the-Loop refers to a scenario where a Digital Twin system operates independently without human intervention or control. In this context, non-participation implies that a person merely observes the interaction between the Physical Twin and the Digital Twin without intervening in decision-making or execution processes, as shown in Figure 9 and Figure 10. Consequently, Digital Twin systems function autonomously, relying on algorithms, artificial intelligence, or other automated decision-making methods to perform tasks or make decisions.

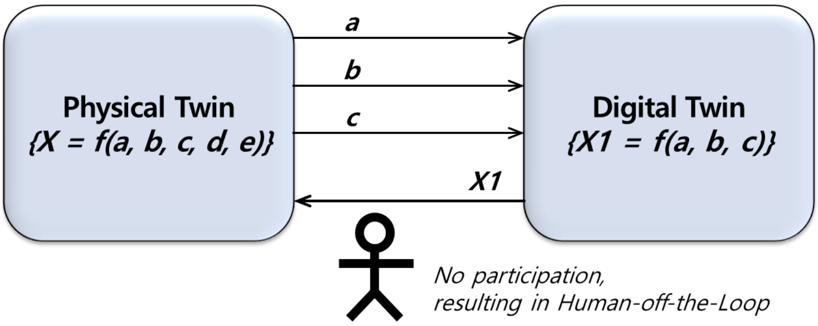

Figure 9 – Human-off-the-Loop while both interworking

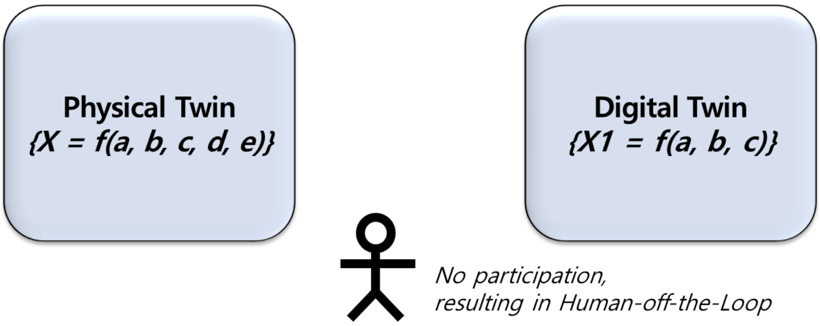

Figure 10 – Human-off-the-Loop without interworking

NOTE: Referring to "Gartner's maturity model (p. 8)," the Level 1 description of FunctionBay reflects the Human-off-the-Loop case of Figure 10. The Virtual Singapore also represents the same case.

The primary goals of Human-off-the-Loop systems are to enhance efficiency, reduce human error, and accelerate processes while ensuring reliability. However, these autonomous interactions can only be effective when the systems demonstrate proven reliability, stability, and safety.

In complex scenarios, such as city-scale systems, unexpected issues can lead to severe operational failures and potential breakdowns. In such instances, establishing interoperation between the twin pair may not be feasible. Nonetheless, pre-loaded offline data can enable the twin pair to simulate interworking once operation assurance has been fully verified. This approach ultimately results in a Human-off-the-Loop model, as shown in Figure 10, even in the face of challenges posed by complex cases.

Passive participation, resulting in Human-on-the-Loop

As shown in Figure 11, Human-on-the-Loop refers to a scenario in which a human user continuously monitors the Digital Twin system and can intervene when necessary.

Passive participation involves observing the operational status, assessing the system's performance and working situation, and deciding whether to execute a specific function within the working system. The user is responsible for evaluating the operating situation and parameter values before deciding whether to execute the operation function *"X1."* The user cannot directly influence the working system as an input parameter. But it can indirectly impact it, for example, by delaying the execution of a particular function.

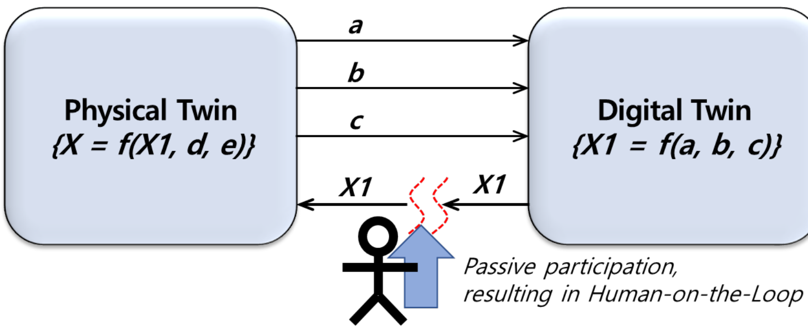

Figure 11 – Human-on-the-Loop by passive participation

The primary goal of Human-on-the-Loop systems is to combine the benefits of automation, such as speed and efficiency, with the advantages of human oversight, such as adaptability and situational response. By incorporating human monitoring, these systems can maintain the advantages of automated operation while ensuring that human users can step in when needed to address unexpected situations.

Active participation, resulting in Human-in-the-Loop

Human-in-the-Loop refers to a scenario in which a human user is actively involved in making decisions for a Digital Twin system. This involvement allows the user to intervene and modify the system's behavior by providing additional input, potentially producing different output results. This active participation allows the human user to engage in the cyclical operation of physical and virtual activities, directly influencing the system's operation process by acting as an additional input parameter, as illustrated in Figure 12.

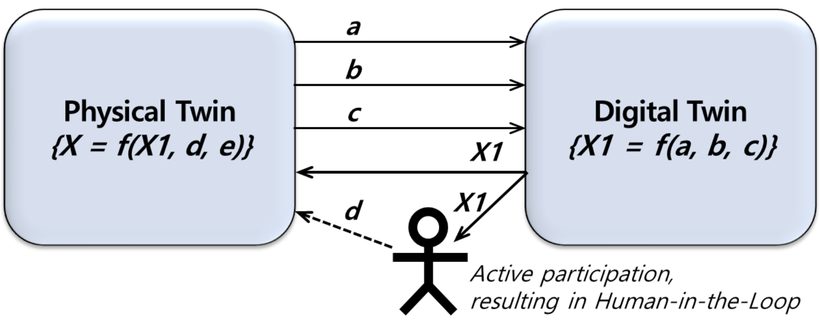

Figure 12 – Human-in-the-Loop by active participation

The primary goal of Human-in-the-Loop systems is to combine the advantages of automation, such as speed and efficiency, with the benefits of human involvement, including understanding, adaptability, and situational response. By incorporating human expertise, these systems can better tackle complex tasks and make more informed decisions, especially when context or nuance is required.

Augmented Reality (AR) can serve as a supporting technology for both Human-in-the-Loop and Human-on-the-Loop systems. By providing an immersive, interactive environment for human user participation, AR enables users to visualize and manipulate digital data in real-time, overlaying it onto the physical world. Integrating digital information with the user's environment enhances the user's understanding of the Digital Twin system and allows for more effective decision-making and control.

The integration of AR with Human-in-the-Loop or Human-on-the-Loop systems can significantly improve performance and user experience in various Digital Twin use cases. For example, in industrial settings, AR can help technicians visualize equipment data and make informed decisions about maintenance or repairs. In urban planning, architects and city planners can use AR to better understand the impact of proposed changes on both physical and digital aspects of the environment, considering their interplay.

Consideration of personality

For example, many manufacturing sites have frequently experienced that different users for the same physical equipment produced different output results. The production performance may vary between skilled and non-skilled workers.

Because of personality traits such as risk-taking behavior or decision-making styles, a Digital Twin system can suffer from the behavioral constraints of a particular user. Digital Twin modeling must ensure that the system's behavior can be consistent with those constraints.

Thus, human behaviors and personal attitudes in Human-on-the-Loop or Human-in-the-Loop systems should be considered when a physical object is modeled for its Digital Twin. Personality consideration can support personalized and more natural interactions between the user and the system.

There is a technical challenge for that. Formulating personality traits into machine-processable forms is very difficult. How to resolve this challenge is a study item to be tackled, where the FBS (Function-Behavior-Structure) framework [23][24] may be extended to the FBPS (Function-Behavior-Personality-Structure) framework, as below.

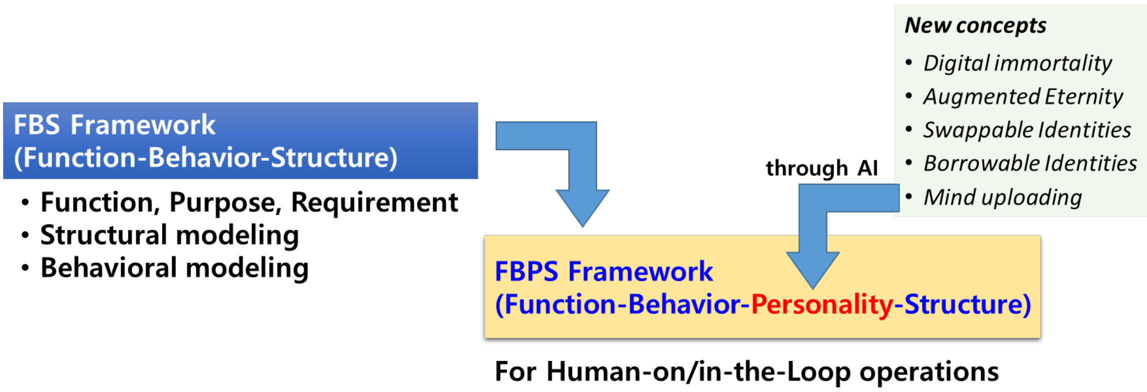

Figure 13 – An extended FBS framework, i.e., FBPS

A prominent solution to formulate human behaviors, personal attitudes, and habits is to use the Artificial Intelligence technologies, summarized as follows, *"With enough data about how you communicate and interact with others, machine-learning algorithms can approximate your unique personality — or at least some part of it [25]."*

Other relevant concepts introduced in *"Digital immortality [7]"* may be related together to how to formulate them. Their techniques can help imbue the personality into system behaviors.

Consideration of human engagement for maturity levels

Following *"Consideration of human engagement types (p. 39),"* this document assumes that only active participation can be possible at Levels 3, 4, and 5, but passive participation can work at Levels 2, 3, and 4, while Level 5 does not allow passive participation. That is, the relations are summarized in Table 16 below.

- Level 2 can work only by passive participation because it operates based on a persistent and static feedback loop without a user's free will;
- Level 3 can work by both active and passive participation;
- Level 4 can work by both active and passive participation; and,
- Level 5 can work only by active participation because the autonomous operation doesn't depend on human intervention, while passive participation is unnecessary.

Table 16 – Availabilities for human participation

Level and Participation types	Off-the-loop	On-the-loop, i.e., passive participation	In-the-loop, i.e., active participation
Level 5	N/A	N/A	**X**
Level 4	N/A	**X**	**X**
Level 3	N/A	**X**	**X**
Level 2	N/A	**X**	N/A
Level 1	**X**	N/A	N/A

NOTE: The combination of the off-the-loop and Level 1 implies offline between the two peer worlds. Such an offline case of Level 1 is described in "Gartner's maturity model (p. 8)." Passive or active participation can be carried out at off-line Digital Twin systems. It doesn't matter in the off-the-loop system because it cannot affect a physical object.

Consideration of data integration levels

"Details of Digital Twin maturity levels (p. 35)" has described data exchange relations for each level as follows:

- Level 1's NOTE 1 reads, *"Level 1 doesn't assume any data connection is required."*
- Level 2's NOTE 7 reads, *"Every Level 2 use case for those required functions is based on a data interface, and Level 2 can specify the data interface as mandatory."*
- Level 3's NOTE 5 reads, *"Level 3 doesn't require a data interface as mandatory but optional, as described in "Market situation #1 – Cases of no Physical Twin or no data link (p. 31)." Therefore, synchronization doesn't happen all the time."*
- Level 4's federated data exchanges are based on data communication among participating Digital Twin models, implying that its data connection is mandatory.

- Level 5 is also based on mutual data exchanges between the physical and virtual worlds, implying that its data association is mandatory.

In summary, Levels 1 and 3 have the optional requirement for data communication between the physical and virtual worlds, but Levels 2, 4, and 5 have the mandatory requirement.

Data communication can occur in four levels as follows, where the other three levels except Level 1 can refer to Figure 4 [10][11]:

- Level 1: No status reflection because of Digital Twin existing solely, i.e., a DTP
  (e.g., CAE, DMU, Virtual sensor, CAD, BIM, GIS, etc.)
- Level 2: Off-line from a physical status to its virtual status and vice versa for manual reflection
  (e.g., Virtual Singapore, Figure 4's digital model, etc.)
- Level 3: One-way from a physical status to its virtual status for automatic reflection
  (e.g., MTConnect-based monitoring and management system, Figure 4's digital shadow, etc.)
- Level 4: Both ways from a physical status to its virtual status and vice versa in the mutual way of automatic reflection
  (e.g., SCADA, DCS, CAM, CPS, Digital Twin, HILS, Digital Factory, Figure 4's digital twin, etc.)

Consideration of autonomous levels

Level 5 deals with autonomous operations in Digital Twin systems. Its concept is meaningful, but its specifics are vague, and development engineers can feel difficulty interpreting the Level 5 concept for their applications.

Referring to *"Consideration of human engagement for maturity levels (p. 43)"* and the Level 5 description of *"Details of Digital Twin maturity levels (p. 35)," "autonomous"* has been exploited in terms of how human users engage Digital Twin systems.

Autonomy can be defined as an *"ability or characteristic of being self-managing and self-adapting within a directional policy or delegated authority without external intervention or control"* and can support minimizing human errors, timely reacting to particular events, and saving consumption of resources such as budget, time, and personnel. It can be more specifically described as follows [26]:

"A Level 5 Digital Twin system is an advanced model that allows for self-directed learning and optimal responses in the real world. It can detect environmental or situational changes and predict situations, then use this information to optimize the real world without human intervention.

This system can operate at each level of Level 1 Mirroring, Level 2 Monitoring, Level 3 Modeling and simulation, and Level 4 Federated through self-management and self-adaptation capabilities. It is designed to minimize or exclude human intervention for optimal responses to uncertain changes.

All actions are undertaken within defined policies and rules, as well as the scope of delegated privileges."

Autonomous systems can learn from their working environment and automatically take appropriate actions for themselves [27].

The Society of Automotive Engineers (SAE) has established six levels of vehicle autonomy to categorize the extent of human involvement [28][29]. These autonomy levels can be referred to for defining the autonomy of Digital Twin systems, since they share a similar development perspective. Specific autonomous levels can help interpret the Level 5 Digital Twin concept for various development activities. A comparative table of both autonomy models is provided in Table 17, as below:

- Level 1 (Partially autonomous): Applied to specific targets, this level of autonomy can operate with some degree of automation, but still requires significant human intervention.
- Level 2 (Conditionally autonomous): Applied to certain conditions, this level of autonomy can operate autonomously under specific circumstances, but still requires human intervention under other conditions.
- Level 3 (Highly autonomous): Intervening in abnormal cases such as failure, this level of autonomy can operate with a high degree of automation, but still requires some human intervention to handle unforeseen events.
- Level 4 (Fully autonomous): With no manual intervention required, this level of autonomy can operate with complete automation under normal and abnormal conditions.

Table 17 – Autonomy maturity models

Level	ETRI's autonomy levels for Level 5 Digital Twin	Comparison to SAE's autonomy levels
	N/A	Level 0: No driving automation
		Level 1: Driver assistance
1	Partially autonomous, applied to particular targets	Level 2: Partial driving automation
2	Conditionally autonomous, applied to certain conditions	Level 3: Conditional driving automation
3	Highly autonomous, intervened in abnormal cases such as failure	Level 4: High driving automation
4	Fully autonomous, no manual intervention engaged	Level 5: Full driving automation

NOTE 1: For example, Supervisory Control and Data Acquisition (SCADA) systems are positioned as Level 2 Digital Twin cases, as described in "Details of Digital Twin maturity levels (p. 35)." However, they typically operate at Level 2 (Conditionally Autonomous) or Level 3 (Highly Autonomous) in terms of Digital Twin autonomy.

At Level 2, SCADA systems can operate autonomously under certain conditions, such as when the system is operating within normal parameters. However, human intervention is still required to handle unforeseen events or abnormal conditions.

At Level 3, SCADA systems have a higher degree of autonomy and can intervene in abnormal cases such as system failure. While human intervention is still required in some cases, the system can operate with a high degree of automation.

It's worth noting that the exact level of autonomy for a SCADA system can vary depending on the specific application and how it's configured. However, as a general rule, SCADA systems tend to fall within the Level 2 to Level 3 range of Digital Twin autonomy.

A Digital Twin system is formed as a three-sided shape of a physical object, virtual object, and data connection between them as described in *"Definition [7]."* The physical object is the reference point and static for Digital Twin modeling and system operations so that it can be excluded from the development of autonomy. But, the Digital Twin model and data communication remain to be development targets to deal with the autonomy of Digital Twin systems.

Moreover, a Digital Twin model is a trinity object of a physical object's geometrical, structural, and behavioral models as described in *"Geometrical, structural, and behavioral modeling [7],"* so they are also development targets.

Consequently, the autonomous levels can be tackled from geometrical, structural, behavioral, and data communication aspects, as illustrated below in Figure 14. *"Behavior model calibration [7]"* will be a development issue to support an autonomous activity of behavioral models.

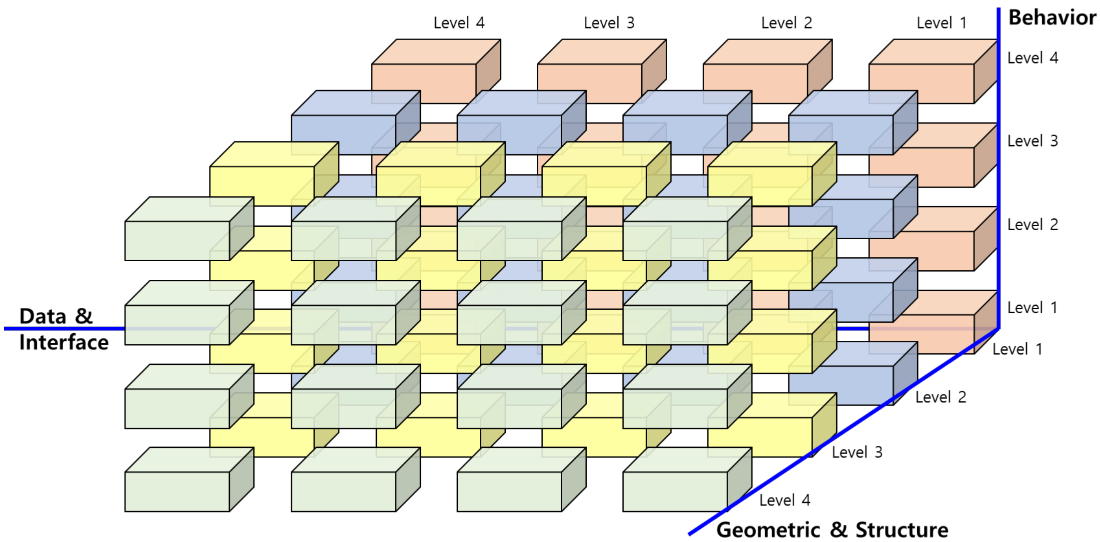

Figure 14 – Application of autonomous levels to development targets

Level 5 Digital Twin systems allow for active participation, as shown in Table 16 (p. 43), which means that a human user can be directly involved in the system's operation. However, it's important to distinguish between active participation and manual intervention.

Manual intervention refers to situations where a human user intervenes to confirm that the system is operating normally within an established set of parameters. This type of intervention is presented as an activity outside the system, where the user is acting as an operator who affects the system from the outside.

In contrast, active participation means that a human user is treated as a system component and participates in the system's operation as such. In this case, the user is an input factor that contributes to the overall functioning of the system, working as a system component inside the system.

ETRI's 3D-type maturity model

As described in *"NOTE 1"* of *"IoT Analytics' maturity model (p. 13),"* we have the same view that the following three dimensions should be the primary perspectives in assessing the maturity of Digital Twin models and their instance systems. However, we simplified a few specific items as described in its *"NOTE 2"* and incorporated ETRI's 1D-type model instead of the *"Most common uses"* dimension:

- ***Hierarchical aggregation levels***: ISO/IEC 30173, *"Digital Twin – Concepts and terminology,"* defines four types of Digital Twin models, as follows:

  - A Component Digital Twin is typically a major element that significantly impacts the performance of the target entity to which it belongs.

  - An Asset Digital Twin can consist of Component Digital Twins. Asset Digital Twins provide visibility at the unit level.

  - A System Digital Twin is a collection of target entities and digital entities performing a system or network-wide function together. A System Digital Twin provides visibility into a set of interdependent target entities.

  - A Process Digital Twin is a Digital Twin that provides a view into a set of activities or operations. The Process Digital Twin can consist of a set of physical entities or System Digital Twins but focuses more on the process itself rather than the physical entities.

  NOTE 1: The "Informational" factor of "IoT Analytics' maturity model (p. 13)" has been omitted due to its highly detailed nature. The "Multi-system" factor hasn't been included, as it can be supported by a process twin that can apply to a supply chain or cooperative partnership group and can also be handled by the federation of ETRI's model.

- ***Functionality and usage levels***: This dimension refers to *"ETRI's maturity model (p. 34)."*

- ***Time-phased process flow***: This dimension refers to the lifecycle phases of *"IoT Analytics' maturity model (p. 13)."* However, *"Optimize"* has been deleted because the *"Maintain"* or *"Operate"* phase can encompass the optimization activity. The term *"End-of-life"* has been used instead of *"Decommission"* because of its popular use in various industries. The *"End-of-life"* includes activities such as decommissioning, recycling, reusing, and disposing of the target object or system.

  NOTE 2: NIST's lifecycle stages for production systems encompass design, build, commission, operation/maintenance, and decommission/recycling stages [30]. It is noted that the operation and maintenance activities have been integrated because they are conducted during the production period. The optimization can be done somewhere during the operation and maintenance activities.

  NOTE 3: The time-phased process flow levels are not fixed but can vary depending on the characteristics of the assessment target, which may include products, production processes, businesses, systems, and also application domains. Consequently, specific level indicators can differ. The key takeaway is that the dimension pertains to any time-phased process flow, and its definition should be adapted to the context of the assessment target.

A resulting 3D-type maturity model can be developed, as shown in Figure 15.

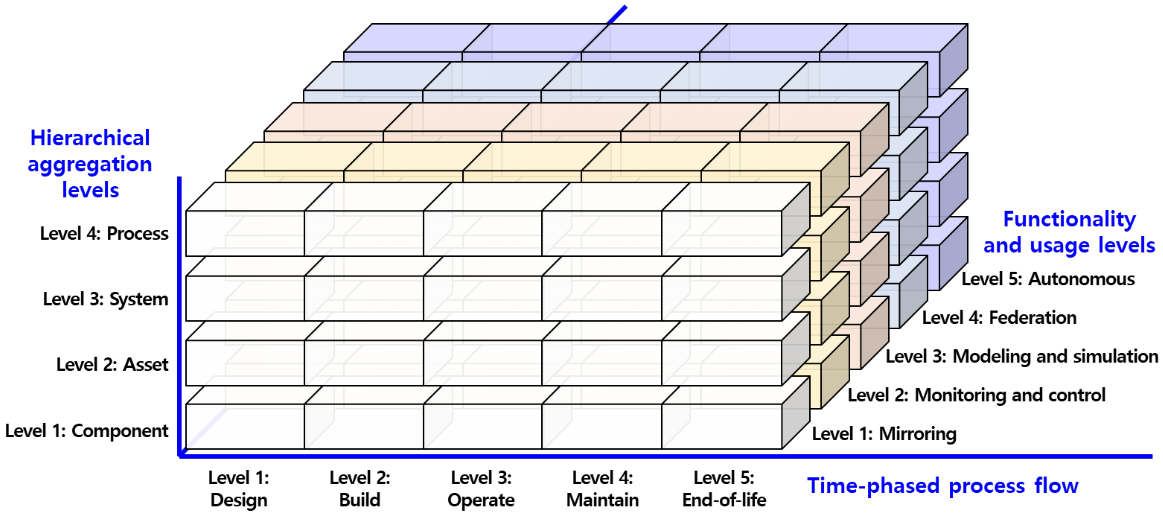

Figure 15 – A 3D-type Digital Twin maturity model

Digital Twin evolution with the maturity model

According to the time phases, Sanjay Ravi introduced the Digital Twin evolution [31], as captured in Figure 16 below.

Figure 16 – Time phases and maturity levels of Digital Twin [31]

Levels 1 and 2 functions belong to the *"Information Mirroring Model"* phase following the figured time phases. Level 3 functions are associated with the *"Digital Simulations, 3D Printing"* phase, as well as the *"Intelligent and Connected IoT Services"* and *"Mixed Reality, Cognitive and AI"* phases.

Because the technical features of the last two phases are somewhat sophisticated technologies that can support a higher quality of processing and operation, Level 3 may take advantage of them for better performance and higher quality. The required functions of Levels 4 and 5 haven't been presented yet in the market. The next stages of the Digital Twin evolution may encompass them.

It should be noted that a lower maturity level doesn't correspond to old and obsolete technological features but to different levels of functional requirements. For example, as a technology solution of Level 2, RS-485 is still in operation for monitoring and controlling in various industries and can be a part of a large-scale Digital Twin system of Level 5.

Short conclusions

A summary of conclusions for various Digital Twin maturity models is provided below:

- Maturity models shall not be used for competitive evaluation and certification.
- They shall be used for self-assessment to find development issues to evolve to the next stages.
- They shall be used consistently.
- They can be used to set the analysis boundary and the same level of consideration issues.
- They can provide technical items to be considered.

Annex A – Consideration of Digital Twin interfaces

A.1 Definition of interface

Michael Grieves drew the original concept model of Digital Twin, as shown in Figure 13 (a). It contains three fundamental elements: a) physical products in the real space, b) virtual products in the virtual space, and c) the connections of data and information that tie the virtual and real products together [32].

Figure 13 (b) shows that the founder updated the concept model to adopt relevant evolutions since birth [19].

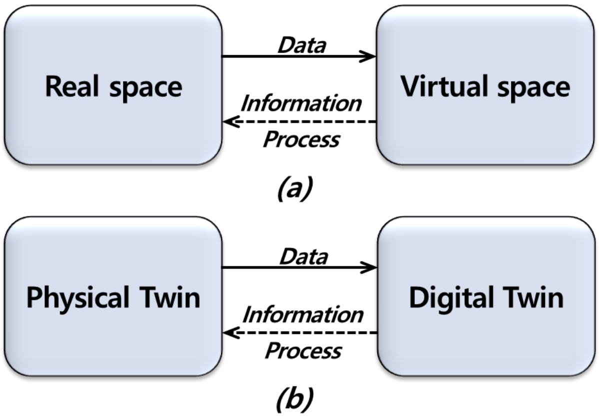

Figure 17 – Concept models of Digital Twin system

NOTE 1: Unfortunately, Figure 13 (b) confused people in understanding the concept and its components. Michael Grieves said, "the term that is commonly used is the 'Digital Twin,' which refers to both the Digital Twin and its sibling, the Physical Twin [19]." That is, the concept name is Digital Twin, but the component name is also Digital Twin. Therefore, merely saying Digital Twin may mislead people's understanding because they cannot recognize which one the Digital Twin indicates, i.e., the Digital Twin component or the whole concept and system. It should be noted to communicate with other people that the Digital Twin may be used as the representative name for the whole concept as well as the Digital Twin component. Even though there is an ambiguity, the discussion context can tell which one is indicated, and this document also follows such usage. This document refers to the Digital Twin system for the case of representing all three components.

It has been observed that data interfaces' significance hasn't been considered much enough, even though Michael Grieves addressed the data interface as one of the three key elements of the Digital Twin, where a data interface refers specifically to the format and structure of the data that is being exchanged between systems or devices. It defines how data is organized, represented, and transmitted between different systems.

Communication is a prerequisite condition for interactions between peer entities. Certain intelligence is hardly possible without communication within a group of entities. Data communication occurs everywhere in the OSI 7 Layer model and does so in cross-layers as well. Communication takes place through a particular interface among communication peers.

NOTE 2: Various existing data interface technologies may support the data interface to realize a Digital Twin system. Otherwise, new interface technologies may be required to fill a gap if needed.

A.2 Interface model

The interface is a general term used to describe the means by which systems or devices connect and exchange information with each other. Various Digital Twin models or systems can be aggregated for intended purposes, for which various data interface technologies are needed to enable communication between them.

The data interface concept of Figure 13 shows data exchanges only between two peers of a twin. But it can extend its communication scope to other Digital Twins for their incorporation with each other.

Data exchanges always take place between associated elements. Application requirements define communication participants and their communication associations, where data exchange associations can be established as follows:

- *Synchronization interface* between twin peers of the physical and virtual worlds;
- *Federation interface* between federated stakeholders for specific application context sharing by an agreement or contract;
- *Threading interface* between business partners and functional interaction peers along a factory-wide or enterprise-wide workflow, business cooperation process flow, such as a product's lifecycle; and
- *Augmentation interface* between a user's interaction device and a Digital Twin system.

NOTE 1: The IT industry has generally referred to "synchronization" as the act of making the states of different peers identical. We should avoid creating new terms for the same meaning to avoid confusion and keep consistent usage. This document has used "synchronization" for the meaning and defined "twinning" as the act of establishing a Digital Twin model from its corresponding physical object.

Figure 18 illustrates those interface cases feasible to support various communication relationships. Details are described in the following sub-clauses. Therefore, Digital Twin shall work with various interface technologies. An interface model entailing them by their relations and supporting communication roles will help people understand the Digital Twin concept, systems, and interworking.

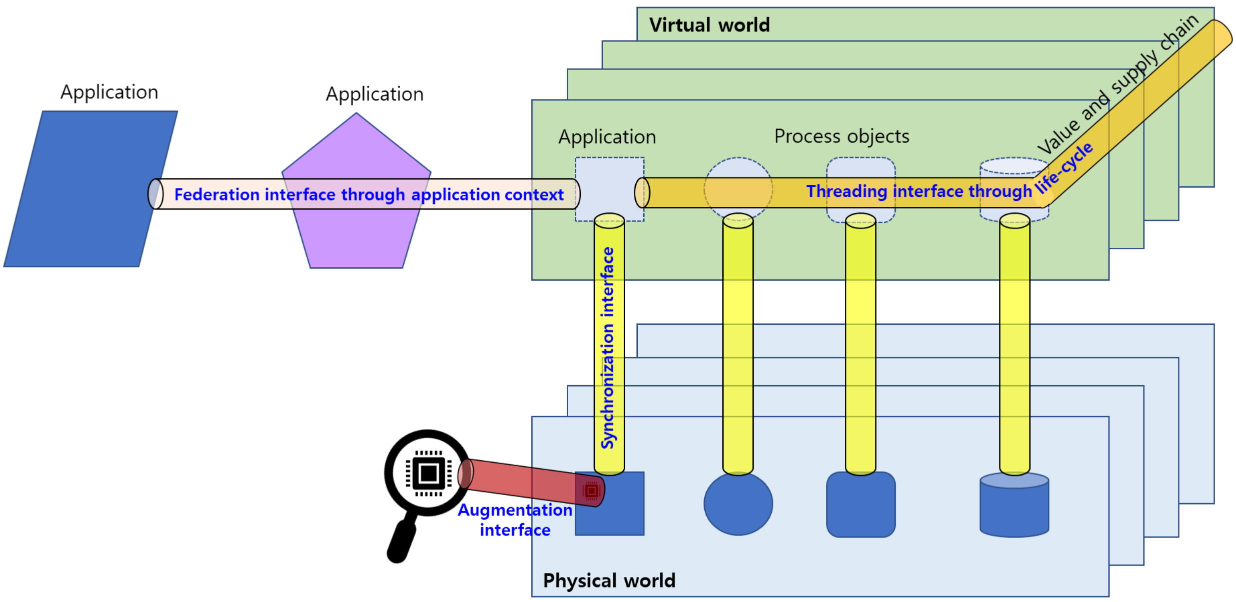

Figure 18 – Interface cases

"Internet" of the Internet of things means focusing on connectivity and communication. Therefore, many IoT experts have illustrated various hierarchical interface models to help understand various IoT protocols and their relations. For example, they identified the following communication roles with many interface protocols available to support the communication roles in the market [33][34]. Thus, the interface is a matter of choice to meet a particular requirement.

- Connectivity infrastructure
- Identification
- Communication and transport
- Discovery
- Application data protocols
- Device management
- Semantic
- Multi-layer frameworks

They can be referenced to draw a Digital Twin interface model. This document hasn't provided an interface model yet but describes a few interface types by communication roles, which can be a seed to draw the interface model.

A.3 Synchronization interface

Synchronization is the act of making the virtual and physical states identical. For example, it is the act of measuring the state of a physical object and realizing that state in the virtual environment such that the virtual and physical states are *"equal"* in that all the virtual parameters are the same value as physical parameters [22].

Although currently under development, there is a technical standard, IEEE 2888, *"Interfacing Cyber And Physical World Working Group,"* consisting of six sub-projects [35],

- IEEE P2888.1, *"Specification of Sensor Interface for Cyber and Physical Worlds"*
- IEEE P2888.2, *"Standard for Actuator Interface for Cyber and Physical Worlds"*
- IEEE P2888.3, *"Standard on Orchestration of Digital Synchronization between Cyber and Physical Worlds"*
- IEEE P2888.4, *"Standard on Architecture for Virtual Reality Disaster Response Training System with Six degrees of Freedom (6 DoF)"*
- IEEE P2888.5, *"Evaluation Methods of Virtual Training Systems"*
- IEEE P2888.6, *"Holographic Visualization for Interfacing Cyber and Physical Worlds"*

IEEE P2888.1 and IEEE P2888.2 may be related to the synchronization interface. IEEE 1451, *"Smart transducer interface for sensors and actuators,"* defines a set of open, common, network-independent communication interfaces for smart transducers (sensors or actuators) to achieve sensor data interoperability between cyber and physical components [36]. IEEE 1451 may also be related to the synchronization interface. Other known and proven interface technologies support state synchronization, such as MTConnect for manufacturing equipment.

NOTE 1: The synchronization interface and the sensor and actuator interfaces may run on different interface layers. Sensor and actuator interfaces have some state information to be synchronized for physical connectivity, but geometric and structural models and behavior models of Digital Twin have their states of being synchronized for continuous interaction with relevant objects of Physical Twin. Therefore, their state information will be different because of different communication purposes.

A.4 Threading interface

The key challenging issue for the threading interface is lifecycle consideration. The threading concept aims to share specific information and interrelate associated information with related cooperation peers throughout a lifecycle, working based on tightly-coupled cooperation.

The synchronization interface is a unit interface for a twin pair between a physical object and its corresponding virtual object, but it may extend to other twin pairs interworking with each other throughout the lifecycle of the physical object. The treading interface refers to an extended interface, and its known and developed case is the Digital Thread. That is, the threading interface is a terminology for the interface concept, but the Digital Thread is its development and technical solution case.

The Digital Thread refers to a communication framework that allows a connected data flow and an integrated view of the asset's data throughout its lifecycle across traditionally siloed functional perspectives. The Digital Thread concept raises the bar for delivering *"the right information to the right place at the right time"* [37]. Deloitte Consulting's experts have captured this introduction into a flow diagram of data through the Digital Thread, as shown in Figure 19.

Even though the Digital Thread has been known as a technical solution to the threading data interface, its technical details haven't been introduced much, looking more like a proprietary solution. But the threading interface is a conceptual technology like Digital Twin, so technology solution vendors can build their product packages for that and name their products Digital Thread solutions.

NOTE 1: The United States Patent and Trademark Office (USPTO) assigned a Serial Number #78571561 to the DIGITAL THREAD trademark which is filed in the category of Advertising, Business & Retail Services. The current status of the DIGITAL THREAD filing is "Abandoned – Office Action Response Not Filed or Filed Late [38]."

The market has relevant interface technologies such as MQTT (Message Queuing Telemetry Transport), XMPP (Extensible Messaging and Presence Protocol), AMQP (Advanced Message Queuing Protocol), OPC-UA (Open Platform Communications Unified Architecture), CoAP (Constrained Application Protocol), and OMA DDS (Data Distribution Service). They haven't been designed to support the threading interface but can be extended or integrated with other relevant interfaces to accommodate the visions and functional requirements of the threading interface of chained Digital Twin systems. IEEE P2888.3 is likely to support the threading interface from an interpretation of its title.

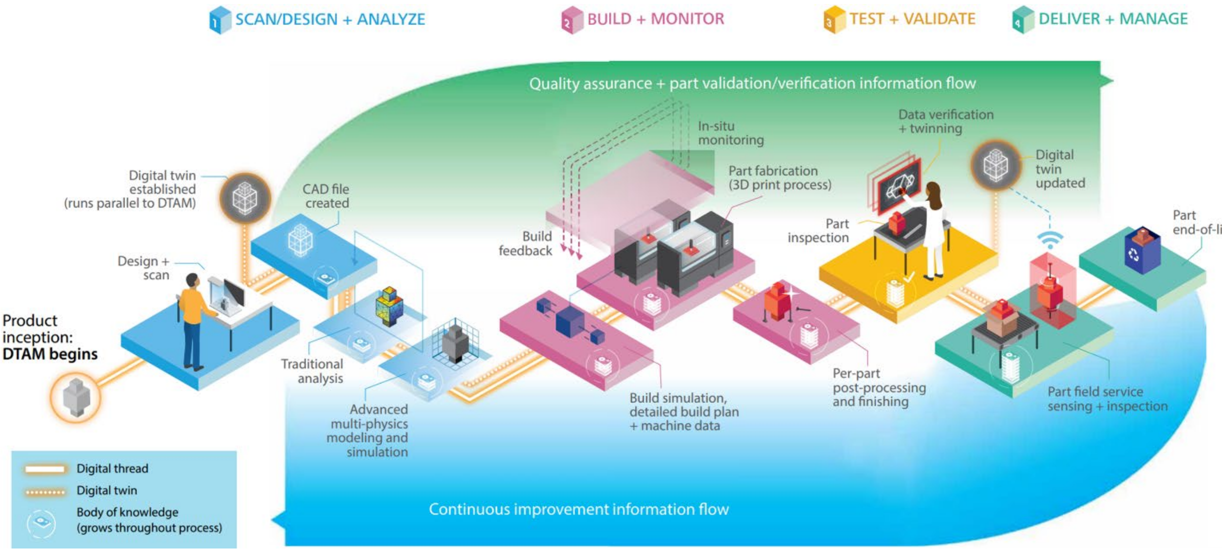

Figure 19 – An illustration of the Digital Thread [39]

IoT platform stakeholders have undertaken a similar study item, i.e., IoT platforms interoperability. Actually, business planners and marketers may view Digital Twin systems to be positioned as a companion to IoT systems. Hence, their communication interfaces of an IoT interface framework may have to be correlated, and IoT platform interoperability can affect the threading interface scheme of Digital Twins.

The threading interface should provide a formal framework for a controlled interplay of authoritative technical and as-built data with the ability to access, integrate, transform, and analyze data from disparate systems throughout the product lifecycle into actionable information. For example, the product lifecycle includes design, procurement, test & evaluation, production, field operation, and sustainment services [40].

It should be noted that the threading interface deals with data exchange protocols and also data models among cooperation peers for specific information sharing for their application purposes. Appropriate data models should be developed and integrated into the threading interface according to business cooperation purposes.

The article of Conrad Leiva provides an interesting comparison of current and future scenarios for a manufacturing case by Digital Twin and Digital Thread implementations as follows [40]:

“The current approach to the handover between departments follows the "throw it over the wall" approach, including the following:

- *Product engineering creates a 3D model and throws it over the wall to Manufacturing Engineering*
- *Manufacturing Engineering creates 2D drawings from 3D models and throws them over the wall to Quality and Suppliers*
- *Quality creates conformance requirements and throws them over the wall to Production*
- *Production throws the product unit over the wall to the customer and into the sustainment cycle without any data on the specific unit beyond the original design*
- *Production archives as-built to records for auditing purposes*

The future scenario, using the digital thread and digital twin, would look something like the following:

- *Product Engineers working together with Manufacturing Engineers create a 3D model linked to visuals for production process instructions*
- *Product characteristics are linked to 3D models and extracted directly out of designs into conformance requirements*
- *Conformance requirements are linked to the manufacturing process and inspection instructions*
- *As-built data is delivered by Production along with the product unit to a customer and is made available for sustainment services to continue evolving the unit's data during operation and maintenance services*
- *Product design changes follow the same data flow and automatically update downstream models, references, and instructions."*

Such lifecycle-perspective scenarios of the manufacturing industry may be different for other industries and their application types because their lifecycle characteristics may differ.

NOTE 2: "Digital Twin data threading [7]" contains more clarified introduction.

A.5 Federation interface

Federation refers to sharing an application context for cooperation across different Digital Twin systems. The application context is defined as a set of interrelated states in which an application-purpose task is conducted. For example, cities, factories, and power plants share the same concern about environmental problems for reducing pollutants. Such common concerns across different domains and their specific tasks for cooperation correspond to application contexts and are resolved based on loosely-coupled cooperation, as in a business process flow, supply chain, and value chain. The application context scheme is governed issue by issue.

The federation interface doesn't consider the lifecycle management for a physical or virtual object but supports application-specific information exchanges to handle common issues across different Digital Twin domains, as shown in Figure 20.

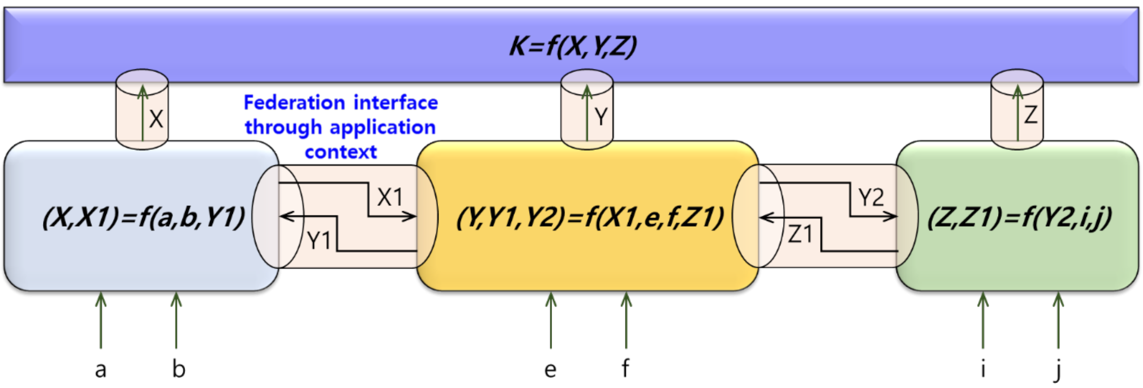

Figure 20 – Mathematical illustration for Digital Twin federation

NOTE 1: a, b, e, f, i, j: input parameters to a particular Digital Twin system;

X, Y, Z, K: output of a Digital Twin system; and
X1, Y1, Y2, Z1: output of a partial Digital Twin system, affecting other Digital Twin systems as input.

NOTE 2: An application context shared by engaged Digital Twin systems can be processed through the federation interface.

Common application contexts can interest different application stakeholders, usually described as use-case scenarios and cooperation work procedures. Data exchange between them is possible only by the data content and formats agreed upon by each other. Data that has not been considered and agreed upon cannot be exchanged. The consideration and agreement activities belong to the development of cooperation use-case scenarios and work procedures. It is characteristic of application-domain federations.

NOTE 3: As both the threading and federation interfaces are conceptual technologies, their functional coverage cannot be fixed, some overlaps can occur, and some development cases can happen to be indistinguishable clearly for threading and federation. "Data threading vs. federation [7]" describes their crossover relation.

A.6 Augmentation interface

The augmentation interface should be considered significant in dealing with human engagements in the Human-in-the-Loop and Human-on-the-Loop operations. The augmentation interface is a data communication interface that facilitates the exchange of interworking data between the Digital Twin system and the Augmented Reality (AR) environment. The interface enables seamless communication and interaction between the physical world, the Digital Twin, and the human user through AR technology, ensuring that the human user receives accurate and up-to-date information from the Digital Twin and can provide input or feedback as needed.

The interface ensures that the Digital Twin and AR environment are synchronized, maintaining a consistent and accurate representation of the physical world in real-time. This allows the user to make informed decisions and take appropriate actions based on the most recent data.

The augmentation interface is responsible for converting the Digital Twin data into a format that can be easily visualized and understood within the AR environment. This includes creating 3D models, overlaying data on the physical world, and displaying relevant information in an intuitive and interactive manner.

The interface allows human users to interact with the Digital Twin system through the AR environment, providing input, making decisions, or controlling various aspects of the system as needed. This can be done through various input methods, such as gestures, voice commands, or touch-based interactions.

By facilitating data exchange, synchronization, visualization, and user interaction, the augmentation interface significantly enhances the overall user experience and improves the effectiveness of these AR-integrated Digital Twin systems.

Also, it may characterize different technology domains whose interface relationships can identify how Digital Twin can be associated with VR, AR, MR, and flight simulation.

A.7 Consideration of real-time

A controversial issue is whether real-time can be a representative characteristic of Digital Twin. Its point of concern is that the real-time instances vary across applications, and their time values cannot be universally defined, so such a concerning issue has been raised. For example, even a 15-minute response in remote metering applications may be considered real-time.

This document argues that real-time is indeed a representative characteristic and should be given significant consideration in the design of Digital Twin instances. The concept of Digital Twin is based on the interoperation between a physical object and its virtual counterpart. Changes in either one should affect the other, reflecting their synchronization. Human users of Digital Twins expect prompt responses from their virtual replicas, with promptness determined by and aligned with application requirements and user expectations.

For example, users may expect their virtual twins reflected in a mirror to respond instantly at the speed of light, indicating that a prompt response must occur at such a speed. Remote electric consumption metering may require data every 15 minutes, suggesting that a 15-minute interval constitutes a prompt response. Any status change within this specified time is deemed insignificant, reflecting the real-time characteristic.

The controversy over real-time stems from the fact that there is no one-size-fits-all definition of real-time, as it can vary depending on the applications. This issue arises when different time values are compared without considering application requirements. However, the crux of real-time consideration lies in providing prompt responses that meet the expectations of human users and working systems, captured by the term *"timeliness."*

Timeliness refers to the extent to which a task, event, or action is executed at the appropriate or expected time. It encompasses the promptness or punctuality with which something occurs or is completed. In essence, timeliness measures how well a task or event adheres to a predetermined schedule or timeline and aligns with the expectations and requirements of stakeholders. As a result, real-time can be understood as a matter of timeliness.

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