The Digital Twin Computing Reference Model

Version 2.0

31st March 2021

NTT Digital Twin Computing Research Center

Table of Contents

1. Introduction

1-1. Digital Twin Computing vision

According to the Digital Twin Computing (DTC) white paper, DTC is a vison that entails the use of high precision digital representations of humans and objects called “digital twins” to create diverse worlds in cyberspace that will exceed the limitations of the real world [1]. The DTC includes three features: interoperability among various types of digital twins, simulation capability in cyberspace, and the DTC operations to exchange, fuse, and replicate digital twin data (Figure 1). A more elaborate description of these operations as well as sample use cases can be found in the DTC whitepaper [1].

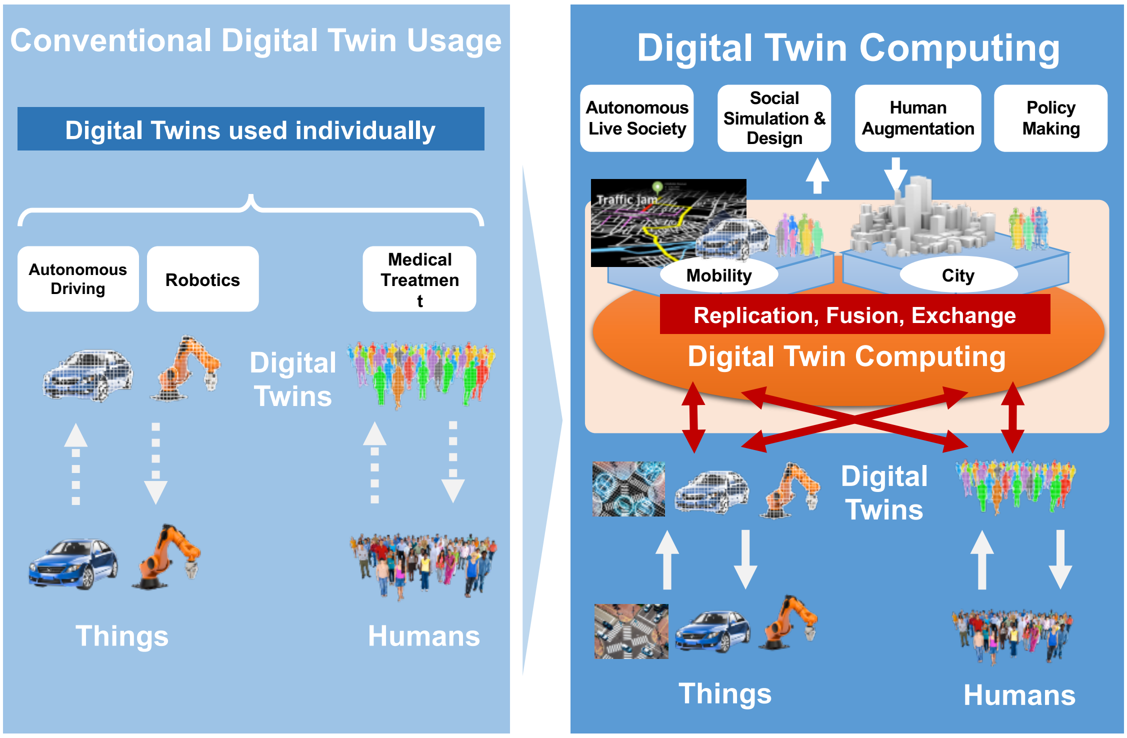


Figure 1 Digital Twin Computing vision

Our vision leverages the existing digital twin concept, which was first introduced in 2003 for product lifecycle management [2]. Since then, digital twins have been widely studied, from NASA’s re-definition of digital twins for aerospace use-case in 2012 [3] to Grieves’ white paper for virtual factory replication in 2014 [2]. Grieves provided insight to use a digital twin in a manufacturing process and proposed the Digital Twin Prototype for product design and the Digital Twin Instance for reflecting the actual product state to the corresponding digital twin [4]. Benjamin proposed two reference models to evolve the product life-cycle: “Representation” specifying scalability, interoperability, and fidelity, and “Abstraction” specifying expansibility [5]. Sadik expanded the scope of digital twins to cover multimedia and focused on data transmission between the physical and virtual worlds [6]. Jacoby summarizes technologies realizing a digital twin such as Asset Administration Shell, Digital Twin Definition Language, and Next Generation Service Interface-Linked Data in context with internet of things [7]. Recently, digital twins have been studied in manufacturing, aviation, and healthcare [8][9].

1-2. Necessity of a common DTC reference model

Although a single definition of a digital twin has not been formally set so far, the definition should be clarified to realize the DTC vision. Common characteristics of a digital twin according to the previous works can be summarized into two aspects: (a) a digital twin digitally represents a real-world entity or system, and (b) a digital twin enables data to be seamlessly transmitted between the physical and virtual worlds.

Future services that leverage digital twins will most likely utilize data from digital twins produced by different vendors. This is also the case with the DTC vision. To enable computation such as described in section **1-1. Digital Twin Computing vision**, we need to enable interaction and data compatibility between digital twins of different vendors. To achieve this, a common DTC reference model may help service providers to enable necessary processing.

When we try to integrate these digital twin principles in our DTC vision, we found that the previous studies were missing one important aspect of digital twins: “interaction” between digital twins. Since many types of digital twins are combined to create a virtual society in the DTC vision, this requires various interactions among digital twins comprising the virtual society. Therefore, we newly define a digital twin as the DTC reference model that covers requirements to realize the DTC vision (Figure 2).

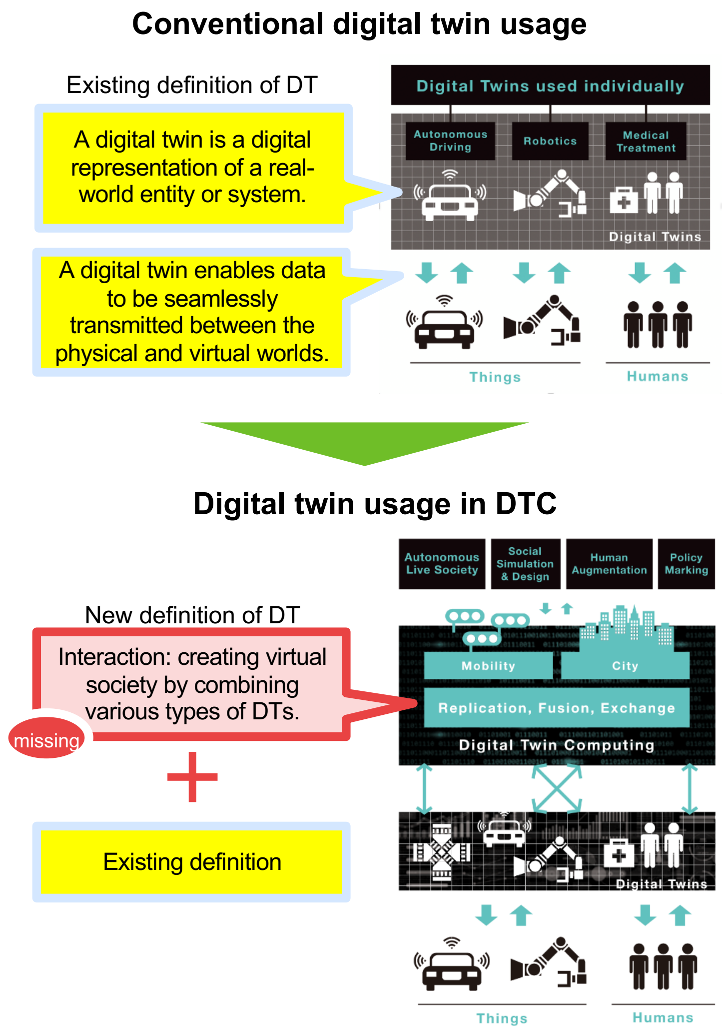


Figure 2 Missing definition of digital twin in the DTC

In addition to the definition of a digital twin, this document provides a structure, functions, and requirements of a digital twin in the DTC vision to clarify technical aspects of a digital twin to be commonly referred to by developers, servicers, and standardization organizations. As this is an architectural assumption of the DTC vision, we welcome constructive comments and discussions about our proposal.

1-3. Relationship with the DTC's four-layered architecture

In the DTC white paper, the four-layered architecture was depicted (Figure 3). As we will propose the digital twin's structure, model, and interaction in the following sections on the basis of the four-layered architecture, a simple explanation of this architecture is provided here for your reference.

The first layer is the Cyber/Physical Interaction Layer. This layer provides functions to collect data required to generate digital twins through sensing of real-world humans and objects, and functions to provide feedback to the real world of the results of trials and controls in a virtual society. These functions are realized by various types of devices and algorithms such as a camera, light detection and ranging (LiDAR), head mounted display for virtual reality (VR)/augmented reality (AR), and machine learning program.

The second layer is the Digital Twin Layer. This layer stores collected data and models that can be used to create a digital twin and provides functions to search for, update, and delete a digital twin on the basis of its data and characteristics, which are up-to-date information based on the actual status of the corresponding object in the real world. A digital twin stored in the Digital Twin Layer may need to adhere to a set of templates that represent a model of a digital twin such as a digital twin model of an object, a computer, or a human.

The third layer is the Digital World Presentation Layer. Digital twins stored in the Digital Twin Layer will be combined and allowed to interact to build a virtual society in this layer. A virtual society can be created for specific purposes such as a traffic environment, an urban space, and an office to simulate interactions among digital twins in a desired time frame, location, and environment. Also in this layer, a derivative digital twin will be created that has attributes such as shape, material, and behavior model that are modified from the originals through operations (replication, fusion, and exchange).

The final layer is the application layer. This layer enables applications to be implemented and executed using the Digital World Presentation Layer. We expect various types of applications to be running in this layer.

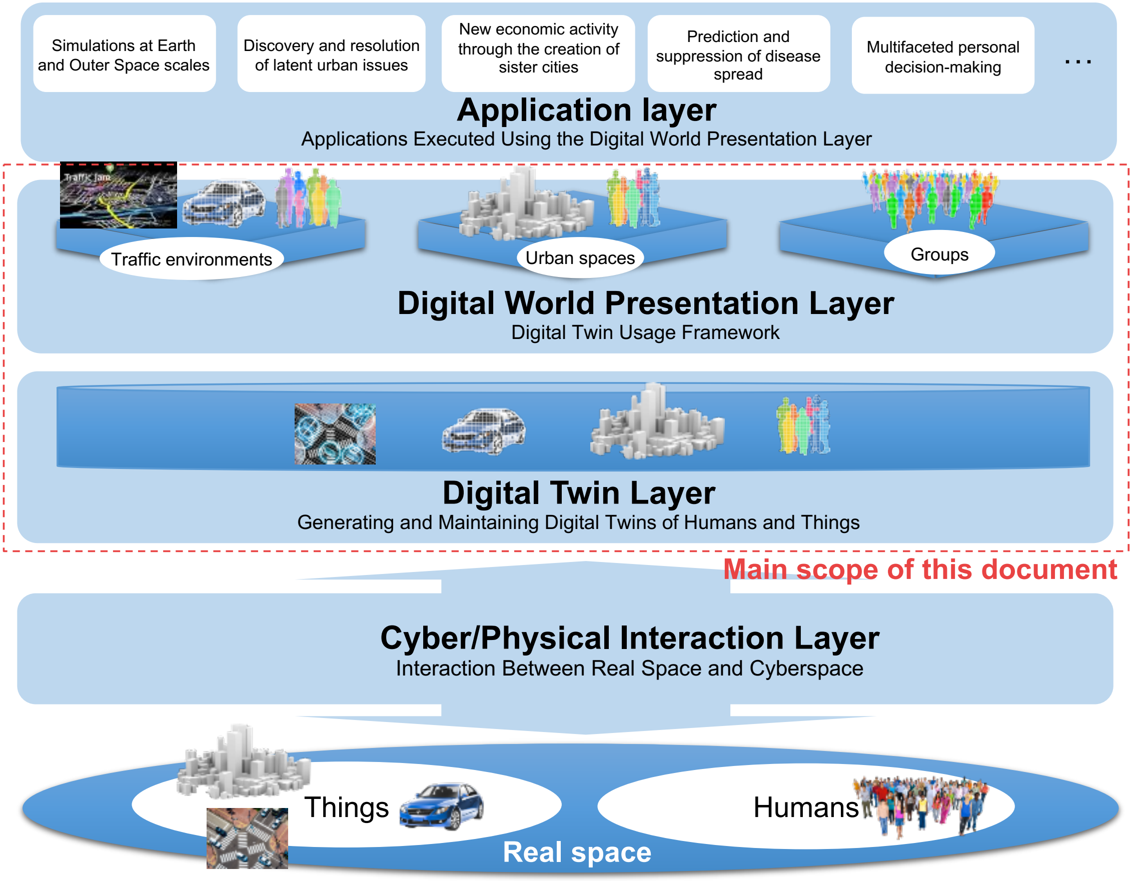


Figure 3 DTC's four-layered architecture

The Digital Twin Layer and the Digital World Presentation Layer are the main scope of this document. We will propose a basic structure, necessary functions, and relevant requirements in the following sections.

[Digital Twin Layer]

- 2-2. Hypothetical general digital twin model
- 2-3. Digital twin primitive and complex
- 2-4. Data structure of digital twin
- 3-1. Reference model of a digital twin
- 4-1. Hypothetical model of human digital twin
- 4-3. Requirements for a human digital twin (Preliminary draft)

[Digital World Presentation Layer]

- 3-2. Digitalization of Physical World
- 3-3. Definition of Interaction with digital twins
- 5. Digital Twin Operations

2. Digital twin's conceptual structure

2-1. Industry landscape of conventional digital twins

Until now, many types of digital twins have been implemented especially in manufacturing, construction, and healthcare. General Electric is one of the most important companies implementing a comprehensive vision and technology from a digital twin perspective. Their white paper shows how they are applying the digital twin concept—leveraging engineering, scientific knowledge amassed over decades, and machine learning—to build digital models of a wide range of equipment assets and manufacturing processes [10]. Their GE Predix platform has been applied to various use-cases such as a designing and operating a gas-powered turbine, monitoring the status of a wind farm, and maintaining an aircraft's jet engine [11]. They are also offering the Digital Twin Framework to enable digital twins to be created that represent an individual asset, an integrated system of assets, or a fleet of assets [12].

Siemens applies the concept of digital twins to various industries including logistics, healthcare, and construction. They diverted the idea of digital twins grown in product development to their logistic network to use an intelligent simulation and consulting model that runs through possible scenarios for the supply chain from start to finish, illustrating all resulting consequences on the basis of real corporate data [13]. They also created a digital twin of a hospital facility to identify ways to enhance and streamline processes, improve patient experience, lower operating costs, and increase higher value of care [14]. In other cases, they utilize the Building Information Modeling to create a digital twin to realize infrastructures that ensure people's safety; provide real-time information, guidance and productivity; and to not only manage greenhouse gas emissions but also generate sustainable energy [15].

Microsoft joined this market with unique approach. They also started their entry to the digital twin market from manufacturing and factory automation, but combined their digital twin offering with their existing line of services including Microsoft Azure and Microsoft Hololens [16]. These two services are strong differentiators as the former is one of the leading cloud services commonly used worldwide, and the latter is a cutting-edge augmented reality (AR) device to visualize digital twins overlaid on to the real world. Gradually, their application focus has expanded to smart building and space management by using the newly introduced Azure Digital Twins [17]. To grow their technology in an open community, they also made public the specifications of the Digital Twin Definition Language (DTDL) so that it can become a common language to define various digital twins and their relationships [18].

As shown in this section, although various attempts to utilize a digital twin have been made in manufacturing, construction, and healthcare, there is no single definition of a digital twin so far.

2-2. Hypothetical general digital twin model

According to the previous works and studies in **1-1. Digital Twin Computing vision** and **2-1. Industry landscape of conventional digital twin**, a unified model of a digital twin has not yet been established. However, through summarizing the aforementioned works and assuming the necessary entities of a human digital twin, we suppose the following hypothetical structure of general digital twins (Figure 4).

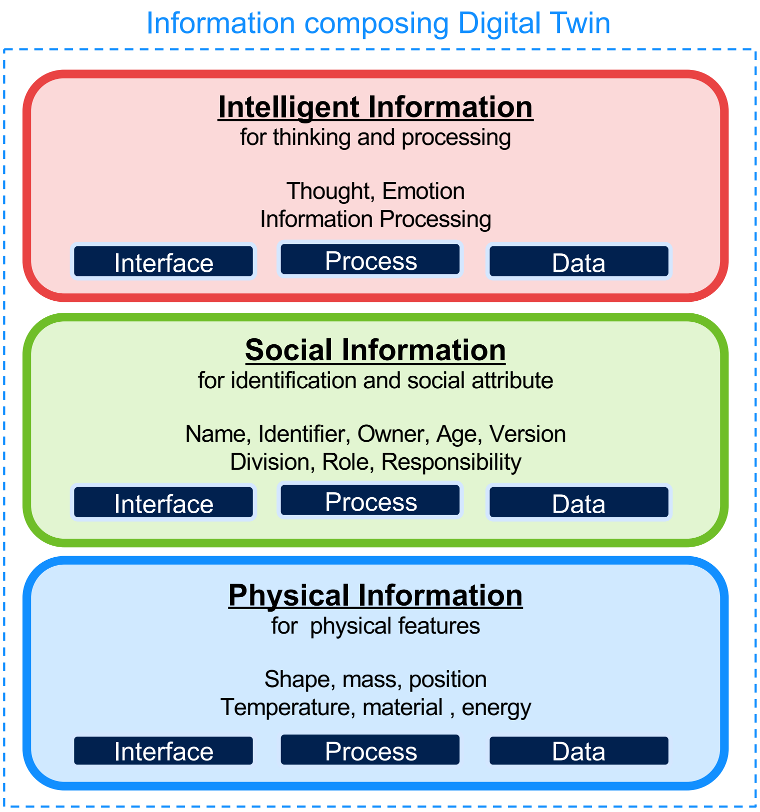


Figure 4 Necessary information composing a digital twin

We assume a digital twin contains three types of information: intelligent, social, and physical. Intelligent information contains intellectual abilities such as thinking and processing to handle information. Social information shows identification and social attributes such as a name, an identifier, and a role in an organization. Physical information represents physical features such as shape, mass, position, and material. In our current consideration, a digital twin basically has all three types of information. However, a digital twin of an inorganic object may have only social and physical information. Difference of composition of necessary information between an inorganic object and a human is still under discussion.

These three types of information are consisted of three entities; Data, Process, and Interface. "Data" contains parameters and attributes of physical, social, and intelligent information. "Process" defines behavior of the digital twin such as thoughts and a behavior model including autonomous decisions, especially in the case of a robot, creature, and human. "Interface" is an interface between a digital twin and other entities including other digital twins and users. For example, Process can obtain necessary Data through Interface of other digital twin to calculate a behavior. We assume "Data," "Process," and "Interface" are the fundamental entities constituting a conceptual structure of a digital twin.

Figure 5 shows examples of interactions between digital twins. Between digital twins such as a chair and a desk, there is only the physical implication to handle physical interaction that is purely calculated under physical laws. On the other hand, between digital twins such as a human and a computer, both the physical implication and intelligent interaction are applied. While the physical implication is calculated under physical laws on the basis of the digital twin's physical information, the intelligent interaction is conducted through the intelligent information contained in digital twins. A specific response or reaction should be generated by the intelligent information defined in a digital twin.

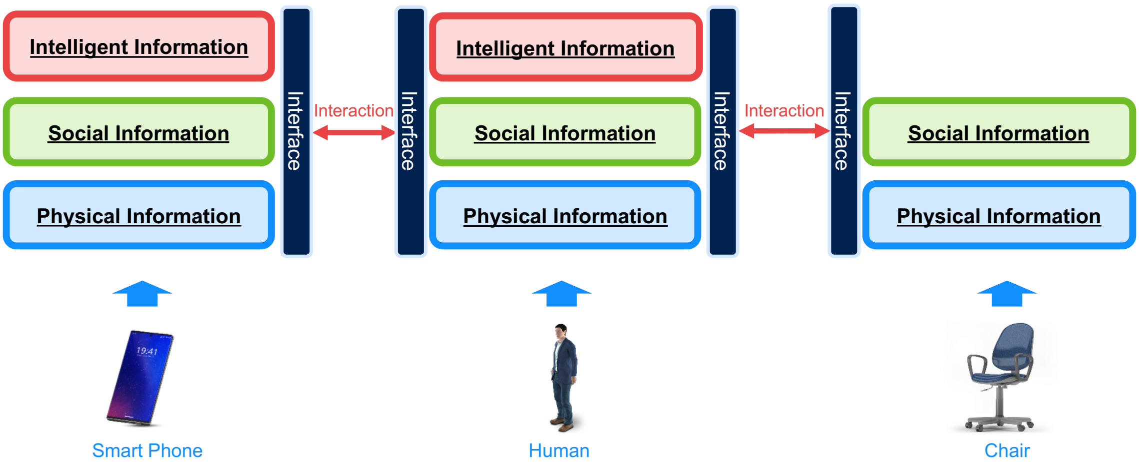


Figure 5 Examples of interaction between digital twins

2-3. Digital twin primitive and complex

A digital twin consists of a digital twin model including physical, social, and intelligent information as shown in **2-2. Hypothetical general digital twin**. This is a basis to create a digital twin especially for a target with a simple structure. However, there are more complicated machines, buildings, and humans in the real world that combine many components. To represent these targets composed of various sub-elements, we introduce a concept of two types of digital twin structure: Primitive and Complex (Figure 6).

Primitive is a basic element of a digital twin that does not have sub-elements. A Primitive has a single digital twin model including physical, social, and intelligent information to represent its physical features, functions, and thoughts.

On the other hand, Complex is a set of Primitives and other Complexes as sub-elements. A Complex has multiple digital twins to represent features of an intricate target such as a machine, building, and human body.

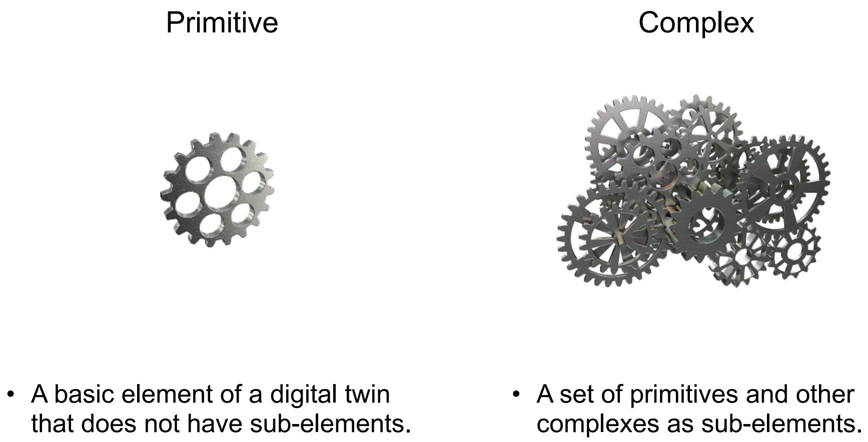


Figure 6 Digital twin's Primitive and Complex

What is the suitable unit of the Primitive? There is no simple answer to this question as the suitable unit is different from purposes to create a virtual society. However, a guiding principle could be defined to decide a unit of the Primitive.

The basic guideline is that a suitable unit of the Primitive should be a granularity to observe interactions between digital twins. For example, if you want to observe an individual's behavior in a city, an individual person or vehicle the person drives should be a unit of the Primitive to observe interactions between the person and his/her surroundings. If you want to observe activities of urban infrastructure such as traffic and power, these infrastructure systems should be a unit of the Primitive to observe interactions among the systems. Figure 7 shows examples including different targets of observation and the corresponding suitable unit of the Primitive.

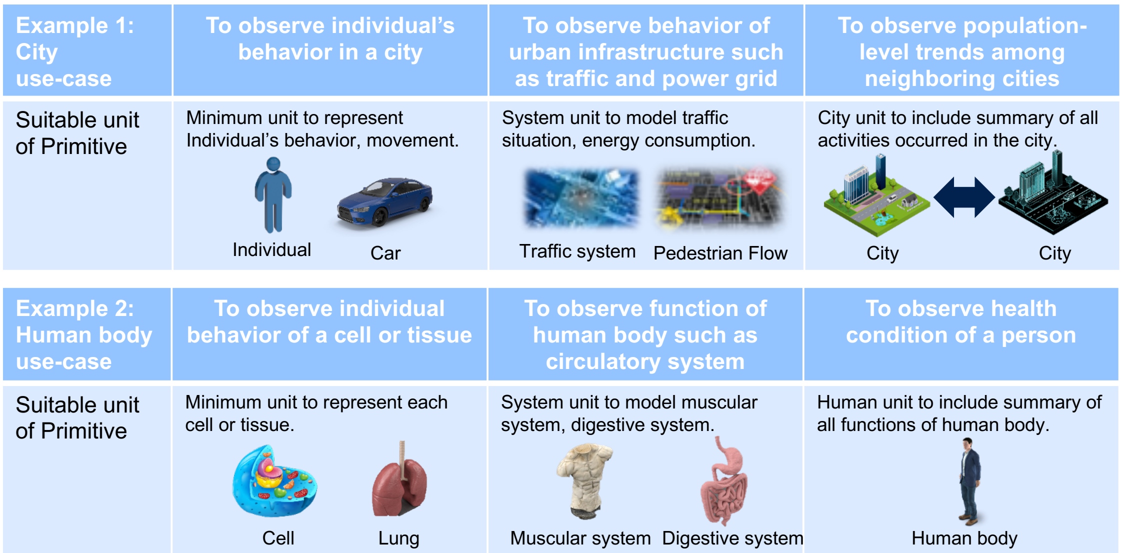


Figure 7 Examples of suitable unit of Primitive

2-4. Data structure of digital twin

Various types of data structure have been used to create a digital twin or similar data so far. One example is the Digital Twin Definition Language (DTDL) mentioned in **2-1. Industry landscape of conventional digital twin**. In the DTDL described by the JSON format, a digital twin is represented as a set of nodes and graphs that contains parameters and the corresponding values, attributes, and interfaces [18]. Automation ML is another example to digitally represent a factory topology with deployed machines. Their function and appearance are also represented as nodes and graphs including 3D geometry and kinematics [19]. To represent 3D geometry, glTF (GL Transmission Format) is a reference to understand how to format necessary data such as mesh, material, and animation. In this format, 3D geometry and its attributes including materials, texture, and animation are described as structured nodes and graphs that are hierarchically combined to show the Complex of 3D objects [20].

In accordance with the existing technologies mentioned above, we assume that the data structure of a digital twin can consist of nodes and graphs to contain various types of data such as object shape, location, position, physical features, a behavior model, and a thought process. Figure 8 shows simple examples of a Primitive and a Complex for a digital twin. In the case of the Primitive, the data structure includes a dataset of a digital twin's Primitive. On the other hand, the Complex contains a dataset combining several Primitives and other Complexes as hierarchical sub-elements to represent an intricate digital twin. These datasets contain at least one of the three types of information: intelligent, social, and physical.

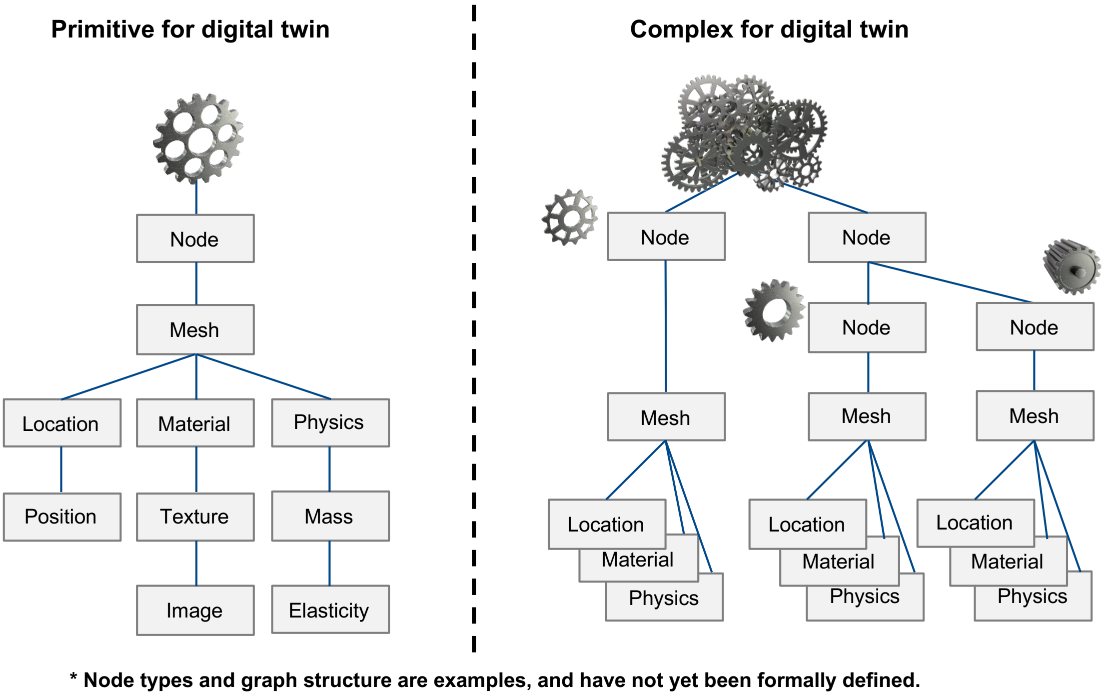
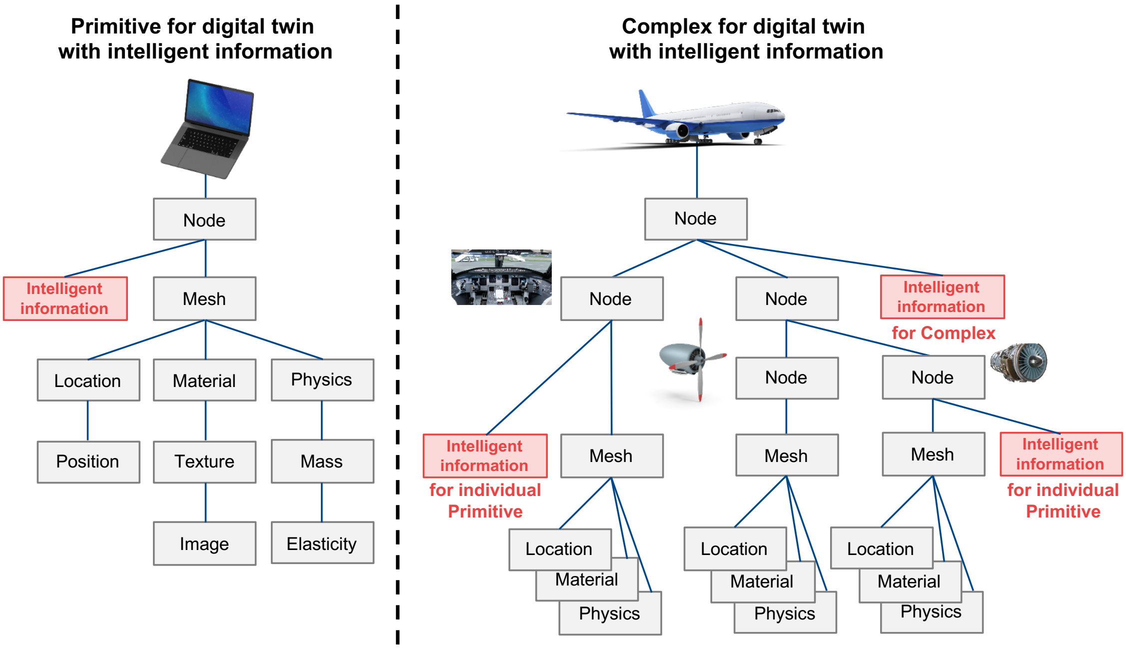


Figure 8 Data structure of Primitive and Complex for digital twin

Figure 9 shows another example of a Primitive and a Complex for a digital twin with intelligent information. In this case, the data structure contains intelligent information in addition to physical and social information. Although the best position and representation of intelligent information are under consideration, we assume the Complex needs to have an integrated intelligent information as a representative interface to the outside world. The way in which the intelligent information in Complex and Primitive will work collaboratively is under consideration.



* Node types and graph structure are examples, and have not yet been formally defined.

Figure 9 Data structure for digital twin with intelligent information

2-5. Elements of virtual society

In this section, we have hypothetically proposed the digital twin's conceptual structure. However, to digitally compose a virtual society, additional entities are needed other than the digital twins discussed above.

One additional entity is the digital information of an abstract idea to be used by a digital twin, especially a human digital twin. This information includes a concept (e.g., nation, religion, law, and money), an event (e.g., incident, festival, and vacation), fiction (e.g., story and movie), and so on. They originally exist as digital data since they are essentially information without a physical body. Another additional entity is a principle universally applied to a virtual society. A typical example of this entity is a law of nature (e.g., gravity). The principle is applied to a virtual society as a universal principle of digitally composed space and time.

Figure 10 shows three categories of digital entities including digital twins, digital information, and a principle that are essential entities to compose a virtual society. The digital twin includes various types of digital twins from a simple physical object such as a stone and a cup to an intelligent creature such as human, although appropriate positions of a creature and a robot are still under consideration. A virtual society is digitally created by combining these digital twins with the digital information and the principle.

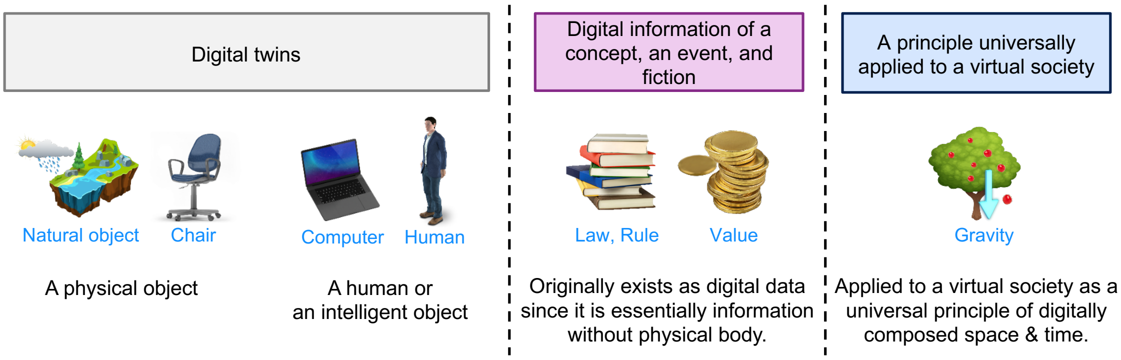


Figure 10 Categories of digital entities

Figure 11 shows elements of a virtual society that consists of the aforementioned three digital entities and a framework of the virtual society including space and time. Although the way we will use these elements is still under consideration, a virtual society should be created by combining these elements appropriately.

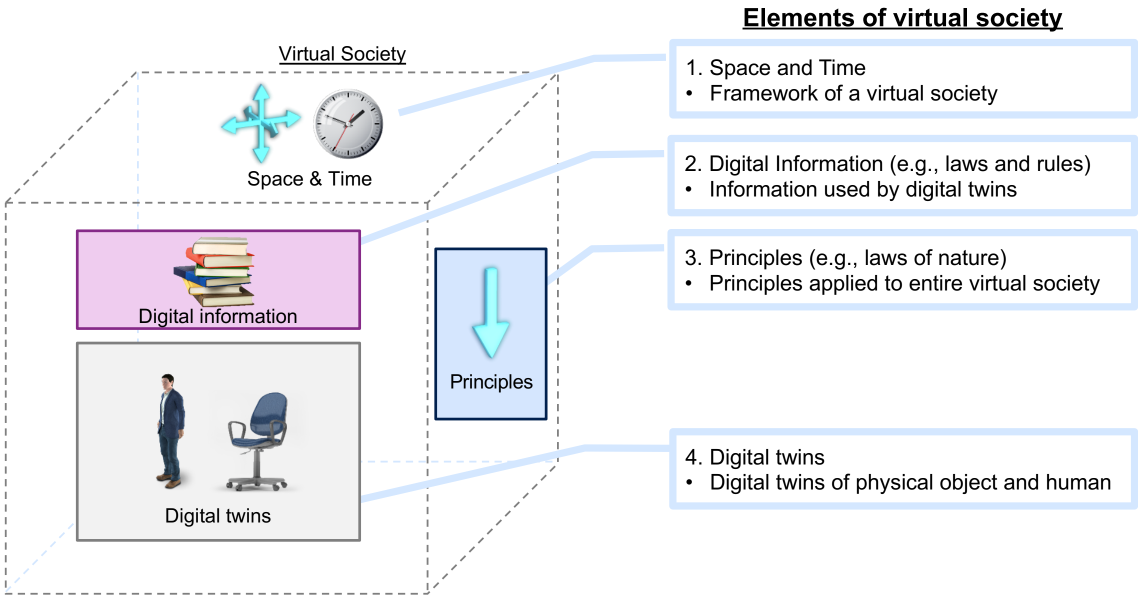


Figure 11 Elements of virtual society

From the next sections, we will show details of each element in the context of the DTC vision.

Section 3: a digital twin for a physical object in a framework of a virtual society including space & time and a principle

Section 4: a digital twin for a human

3. Digital Twin for Physical Object

3-1. Reference model of a digital twin

In this section, we propose definition and structure for a digital twin of a physical object representing a digital twin without intelligence. First, information of a physical object that should be digitalized should be clarified. Data from a digital twin of a physical object may include basic physical information such as position and shape, and these types of data may experience changes over time (Table 1). These types of information form a digital twin and provide necessary information to rule interactions between digital twins. We call this set of information "physical object information."

Table 1 Examples of basic physical object information

Physical Object Info.	Explanation	Changes over time	Remarks
Position	Coordinate in space and its changes	Movement	Incl. 6DoF
Shape	3-dimensional shape	Transformation	Incl. division and combination
		Oscillation	Incl. sound
Color	Reflection of light	Change of color	
Temperature	Surface temperature	Change of quality	
Hardness	Surface hardness		Incl. elasticity
Material	Quality of material		

A digital twin is composed of a set of physical object information. To realize a virtual world envisioned by the DTC, a digital twin needs to adhere to three conditions: a digital twin shall (1) be a digital representation of a physical object, (2) have a connection to the physical twin, and (3) be able to interact with other digital twins. Conditions (1) and (2) are inherited from the existing studies (see **1-2. Necessity of a common DTC reference model**), while condition (3) is newly introduced to realize the DTC vision where various types of digital twins are combined and interact.

(1) A digital twin shall be a digital representation of a physical object

This condition means extracting physical object information from an individual object and reconstructing a virtual replica of the individual object digitally by combining the information (Figure 12).

An object represented as a digital twin should be treated as an individual entity to calculate possible interactions on the basis of information it retains.

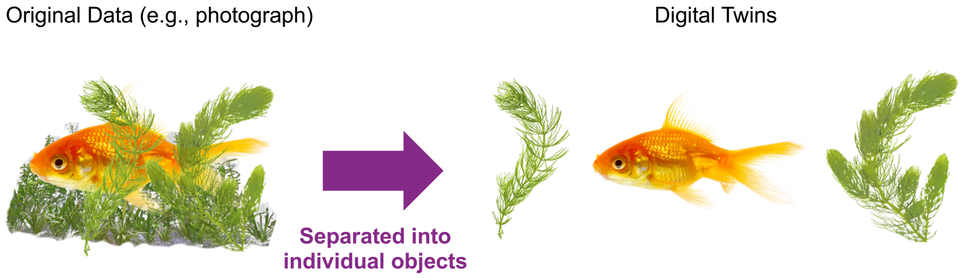


Figure 12 Digital representation per a physical object

(2) A digital twin shall have a connection to the corresponding physical object

This condition means a connection between a physical object and the corresponding digital twin through data transmission including updating a digital twin with status of a physical object and feedback to a physical object from a result of digital twin behavior (Figure 13).

As a digital twin is a replica of a physical object, physical and digital entities need to be synchronized to know, configure, and predict the physical object's status through the digital twin.

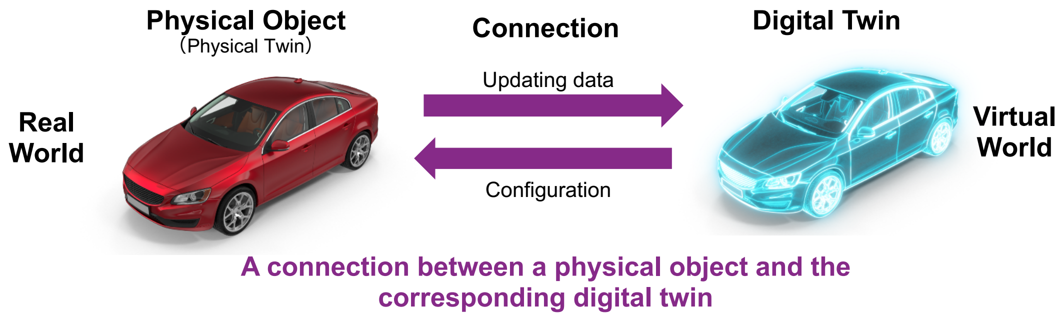


Figure 13 Connection between a physical object and a digital twin

(3) A digital twin shall be able to interact with other digital twins

This condition means an interaction between digital twins such as physical contact or thermal conduction needs to be calculated on the basis of the position, shape, and other characteristics of digital twins comprising a virtual society (Figure 14).

In the virtual society envisioned by the DTC vision, various types of digital twins can be combined. This leads to calculation of tens of thousands of interactions between digital twins to simulate realistic behavior of entities creating the virtual society. This is an important concept introduced to use a digital twin in the DTC vision.

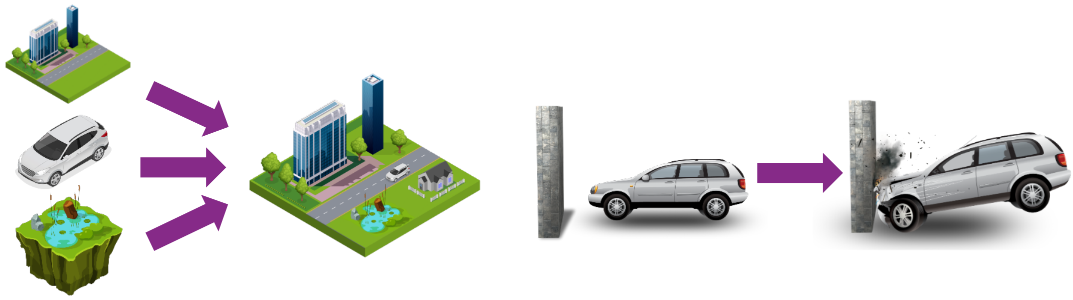


Figure 14 Examples of digital twin interactions

3-2. Digitalization of Physical World

In the previous section, the definition of digital twin in the DTC vision is discussed. The next step is how we can digitalize our real world to a virtual society with defined digital twins. Our real world is composed of various types of objects and notion such as space and time. Therefore, models and rules to transform the real world into digital twins are definitely needed.

3-2-1. Related works and studies

Although several works and studies have been conducted for creating a model to digitalize the real world, there is no universal model that can be applied to various use-cases to create a virtual society from our observation.

In 2015, Dassault Systemes started working to develop Virtual Singapore, a realistic and integrated three-dimensional (3D) model with semantics and attributes in the virtual space [21]. They constructed Virtual Singapore with three phases: Virtualize (3D modeling of land, buildings, and others), Visualize (integration of additional data and making them VR/AR), and Venturise (open architecture for modeling and simulation) [22]. Their approach is the first to create a static city digital twin as a foundation of a virtual world and then add other necessary information on top of the foundation. However, by using this approach, it is difficult to observe the changes to moving objects over time and the impact of dynamic environment properties such as light, temperature, and tide. These dynamic objects and environment can be only seen as simulation results.

There is also a study that focuses on the development of a reference model for risk control and prevention in manufacturing [23]. The reference model proposed in their paper is made up of four main layers (Process industry physical space, Communication system, Digital Twin and User space), while the implementation steps of the reference model have been divided into five phases (Development of the risk assessment plan, Development of the communication and control system, Development of Digital Twin tools, Tools integration in a Digital Twin perspective and models, and Platform validation). As their approach focuses on a manufacturing process and its anomaly prediction, it should be difficult to extend to cover other general use-cases and a scalable target like a virtual city. Therefore, we define the DTC model to transform the real world into digital twins.

3-2-2. DTC digitalization model for physical world

The DTC vision requires digitalization of all entities forming the real world to realize a virtual society where many digital twins are combined flexibly to mirror phenomena that exist in the real world. Thus, we propose a model to categorize entities in the real world into (A) space and time, (B) environmental properties, (C) liquid and gas, and (D) solid objects. All entities are digitalized individually and then categorized before they are re-constructed to create a virtual world. The DTC digitalization model is shown in Figure 15.

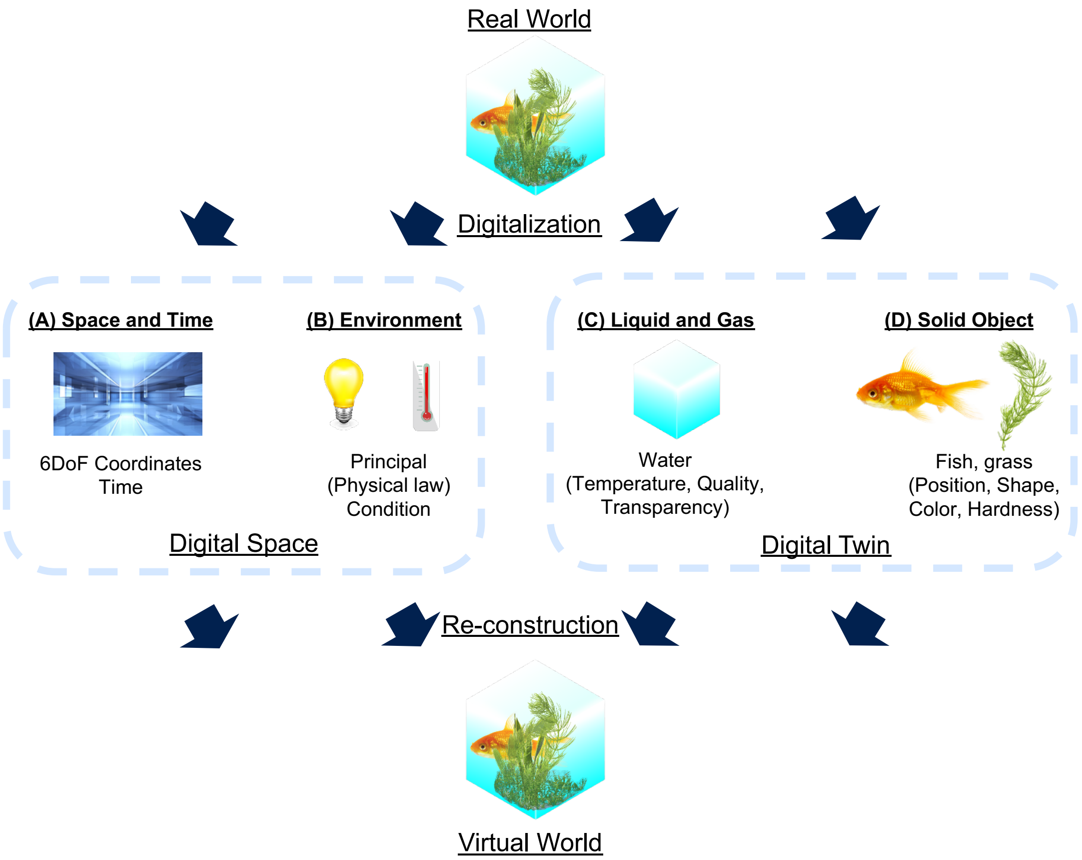


Figure 15 DTC digitalization model

These four categories are further grouped and split into two bigger categories: Digital Space and Digital Twin. The Digital Twin is a digital representation of liquid, gas, and an object as defined in **3-1. Reference model of a digital twin**. On the other hand, the Digital Space is a newly introduced concept that is used for an entity that cannot be represented as a single digital twin entity due to it having an intangible notion but is a necessary foundation of a virtual society. Table 2 summarizes the four types of entities digitalized to create a virtual society. Combining the Digital Space and the Digital Twin enables a realistic virtual society to be created on the basis of the real world.

Table 2 Four types of entities forming the real world

Categories	Entities	Explanation	Remarks
Digital Space	(A) Space and Time	Coordinates to indicate position in space and time.	There may be private, local, universal spaces & times.
	(B) Environmental properties	Principle and condition applied to associated space.	e.g. gravity, solar energy, weather system
Digital Twin	(C) Liquid and Gas	Digital twin of liquid and gas material.	
	(D) Solid object	Digital twin of a solid object incl. rigid and soft material.	

Figure 16 shows samples of application of the DTC digitalization model with different targets and scales. From a single living entity to a complex city, this model fully digitalizes necessary entities to the Digital Space and the Digital Twins to be re-constructed as a virtual society that reflects the original real world. Although we need appropriate digitalization technologies for each entity, the DTC digitalization model is theoretically considered as a valid approach to transform the real world into a mirrored virtual society.

Figure 16 DTC digitalization model applied to different scales

3-3. Definition of Interaction with digital twins

As stated in **1-2. Necessity of a common DTC reference model**, various types of digital twins interact in a virtual society created by the DTC digitalization model. The “interaction” among digital twins means relationships and reactions between digital twins. The relationship between a user and a digital twin is distinguished as “experience and operation” (Figure 17).

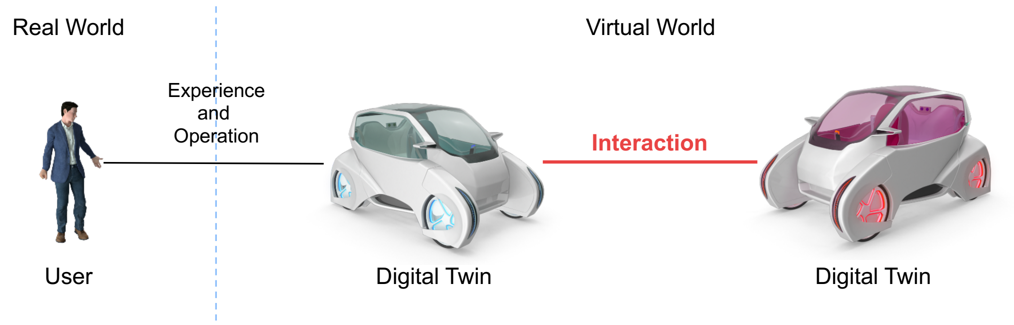


Figure 17 Interaction between digital twins

As “interaction” contains various notions from physical contact to communication among people, the definition of interaction in terms of digitalization of a physical object should be clarified. Our world has several classes of interactions from a physical level to a social level, and they look like a layered structure as shown in Figure 18. In the context of a digitalized physical object in the DTC vision, the interaction stands for the physical interaction between more than one physical object without knowing the semantics/meaning of the interaction. This includes physical interactions such as physical contact, chemical reaction, heat conduction, and light propagation (Table 3).

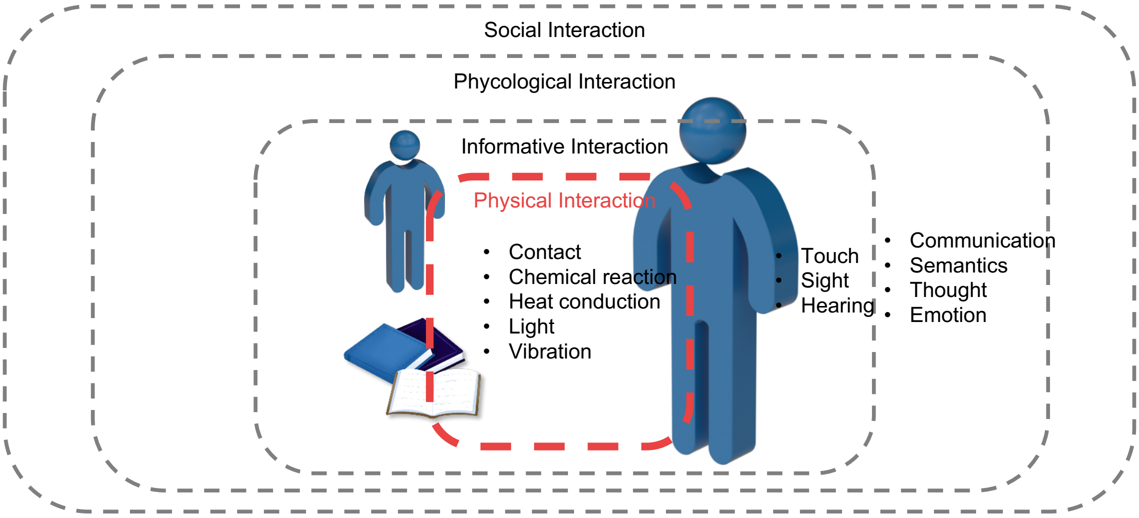


Figure 18 Classes of interactions with layered structure

Table 3 Examples of physical interactions

Type	Explanation	Similar interactions
Contact	Digital twin contacts other digital twins	Collision, Friction
Mixture	Liquid or gas digital twins are mixed	
Chemical Reaction	Chemical reaction among digital twins	
Heat Conduction	Heat conduction between digital twins	Convection, Radiation
Gravity	Gravity applied to digital twins	

3-3-1. Related works

Several game engines can now provide a unified platform to handle interactions between digital objects, especially contacts such as collision and friction. Although specific physical interactions and reactions have been widely studied in natural science, we focus on the unified platform to digitally manage various interactions of digital object. In this context, Unity [24] and Unreal Engine [25] are two major technologies in this field.

Both game engines have a similar concept to create a digital object and to manage interactions. The basic structure of their concept is that a digital object such as a ball, a vehicle, and a human is represented as an object instance with attached attributes including material, a physical character, and a collider. The material contains information of physical properties such as friction and bounciness, while the physical character shows a rigid, flexible, or fluid body with its mass and air resistance. The collider is used to detect contact with other digital objects on the basis of the configured condition such as box shape, sphere shape, and mesh shape. Moreover, laws of nature such as gravity are contained in a parameter of a digital space where a digital object is deployed. A digital object's position and time in the digital space are managed in the platform.

Then the platform runs the digital space with deployed digital objects and calculates their position to detect a collision. Once a collision is detected, the platform calculates the reaction on the basis of physical laws by using a physical simulation engine and generates an appropriate response.

3-3-2. Calculation of interaction in the DTC digitalization model

In a virtual society created by the DTC vision, the physical interaction between digital twins is calculated by collecting information contained in the Digital Space and the Digital Twin defined as the DTC digitalization model (see **3-2-2. DTC digitalization model for physical world**). To accurately know the relationship and reaction affected by an interaction, the exact position and time are collected from (A) Space and Time entity to precisely synchronize digital twins, and relevant environmental conditions such as gravity and weather are also obtained from (B) Environment entity. Then, the calculation of interactions detects when and where the interaction happens and determines what reaction will happen next on the basis of physical object information included in (C) Liquid and Gas entity and (D) Solid Object entity (Figure 19).

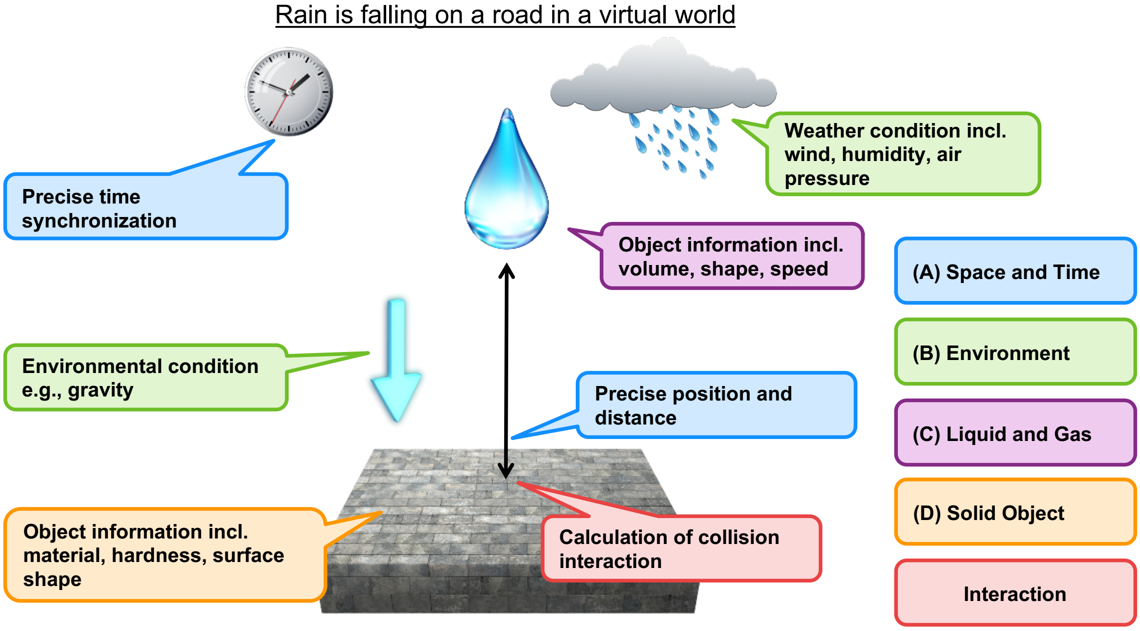


Figure 19 Calculation of interaction in the DTC digitalization model

This framework of interaction calculation provides a generalized way to detect an interaction and to conclude a reaction. We realize the virtual society envisioned by the DTC vision including various types of digital twins through the universal definition of a digital twin (see **3-1. Reference model of a digital twin**), the DTC digitalization model (see **3-2. Digitalization of Physical World**), and the general framework of interaction calculation.

4. Digital Twin for Human

A digital twin of a person, hereafter referred to as a human digital twin, plays a quite important role in the DTC vision, which aims to provide a wide scope of value through interaction with other digital twins in a virtual society. In this section, we propose a definition and structure for a human digital twin to provide a reference model.

Human digital twins will be used not only for monitoring the corresponding individuals' current states but also for predicting their future states, substituting their activities, and conducting simulations of various future societies. Therefore, a human digital twin should not just be a collection of information, such as photographs, biological signals, and action logs, but also have processes to perform human-like behaviors.

Human behaviors are affected by various mental/internal factors such as thoughts, memories, and emotions, but we currently have no rational model that can describe all of the corresponding structures and mechanisms. Therefore, to build a human digital twin, it is necessary to design such mental/internal elements according to reasonable assumptions. We believe that the existence of such mental/internal elements, which can be assumed as the consciousness of a digital twin in a sense, is a unique and important characteristic of human digital twins in DTC.

We assume that the physical aspects of human digital twins, such as their appearance and superficial movements, will conform to the definition and structure of digital twins of physical objects as described in **3. Digital Twin for Physical Object**. Therefore, when considering only these superficial/physical aspects — e.g., monitoring a human's posture or heart rate or simulating a new hairstyle or golf swing — it is unnecessary to follow the definition for a human digital twin described in this section; rather, it is sufficient to follow the definition for a physical object. On the other hand, if mental/internal factors such as thoughts, memories, intentions, and emotions are important even for a non-human entity, we recommend referring to this section.

4-1. Hypothetical model of human digital twin

As described in the hypothetical structure of digital twins in **2-2. Hypothetical general digital twin model**, a human digital twin consists of three kinds of information: physical, intelligent, and social; moreover, each kind of information consists of three types of entities: "Data", "Process" and "Interface". For a human digital twin, the Data includes not only the instantaneous state of the corresponding individual but also the structure and characteristics that model that individual. The Process entails the mechanisms and algorithms to drive the human digital twin. Thus, the Process generates autonomous reactions on the basis of Data in response to real- or virtual-world stimuli obtained through the Interface. Basically, a reaction involves updating a human digital twin's Data, and interaction is achieved by observing such updated information from other entities.

In this subsection, we describe the typical elements for each kind of information. Note that the elements presented here are just examples and do not cover all potential elements. Furthermore, we do not require that human digital twins include all of these elements.

4-1-1. Physical information for human digital twin

We define the physical information as observable or measurable. Hence, observed external or superficial information such as appearance can be considered part of the physical information. The physical information may also include internal but measurable data, such as data about muscles, and blood vessels, and biometric information such as the body temperature, heart rate, genome, and epigenome. Note that the types of physical information for a human digital twin are basically the same as those for a physical object, as described in **3-1. Reference model of a digital twin** although the representation format or granularity of the information could be different.

To simulate human behaviors and visualize a human digital twin in a virtual society, physical information may also be described in terms of rational structures and mechanisms; that is, the Data of physical information could be expressed as a set of structural models and their parameters. For example, the shape of a human digital twin can be expressed as a set consisting of a 3-dimensional reference-postured model with skeleton information and joint angles [26, 27]. The Facial Action Coding System (FACS) is another example, in which human facial expressions can be represented as combinations of fundamental facial movements called action units [28].

We also assume that the Process for physical information can be descriptive and explainable by using mathematical models based on common principles such as the laws of physics. For example, a human walking action can be described by using a kinematic parameterization [29].

4-1-2. Intelligent information for a human digital twin

We propose to define internal psychological information, such as affects, emotions, memories, thoughts, and intentions, as the intelligent information for a human digital twin. This kind of information is processed in the human brain and cannot be acquired directly by using sensors or other means.

The Data of intelligent information consists of the psychological or mental status of the corresponding person in the real world. We assume that the Data is expressed by using representational models that can be directly understood by humans, rather than by physical signals or quantities of chemical substances, which would need to be interpreted or translated by experts. Note, however, that such physical signals and chemical quantities can still be considered as physical information for a human digital twin.

The Process of intelligent information corresponds to the internal mechanisms of human psychological and mental behaviors, and it thus determines the psychological and mental status of a digital twin in a simulation. Note that the Process of the intelligent information generates reactions not only for intelligent information but also for physical information.

Various representations and mechanisms have been proposed for intelligent information not only in computer science but also in other fields including psychology and neuroscience. To the best of our knowledge, there is no complete, unified definition. For example, roughly speaking, emotions have at least two different representations — the discrete categorical model and the continuous dimensional model— and no one can judge which is better. As for the internal mechanisms, many studies have modeled the human decision making process in the context of agent-based (social) simulation [30]. The most historical model is a simple production-rule system, but a neurologically inspired model has been studied as a more persuasive model.

We assume that a wide variety of representations and models might be used and could coexist in the DTC platform. We do not require that one human digital twin must have all kinds of representations and models, but we should define a common Interface to allow interaction between human digital twins based on different models, in order to achieve interoperability of digital twins constructed for different purposes.

4-1-3. Social information for a human digital twin

The social information for a human digital twin is defined as various kinds of information that accumulate in human relationships. It includes, for example, a person’s name, gender, occupation, values, common knowledge, rights, and culture. In contrast to intelligent information, social information is meaningful only when considering interactions with others. Social information may be referred to by the Process for intelligent information and may affect its output.

We assume that at least two types of social information should be considered. One is information that can be shared with others at a certain moment. This type of information includes the common knowledge, values, and historical views that are shared by an ethnic group, nation, or similar kind of group. The other is information originating from spatiotemporal continuity. This type of information represents the characteristics within a group that result from shared history. For example, it may include parent-child relationships, the support of a fan for a sport team, and other attachments.

4-2. Digitalization of Human

This section discusses how to build a human digital twin as described in the previous section. Humans are quite complex and most aspects of them have not been elucidated, but we will describe the methodology that we currently envision to digitalize real-world individuals.

4-2-1. Related works and studies

There have been many works and studies on building digital models of humans in various research fields to date. Modeling of human physical information has been conducted in the field of computer graphics since the 1960s; a pilot model was presented as the first digital animation model of a human in 1964 [31]. While more precise human digital representations are still being explored, various technologies have also been developed to scan real humans in the computer vision community. By using multiple cameras and lights, precise surface geometry (i.e., shape, and reflectance information) can be obtained, resulting in a photo-realistic 3D model that looks exactly like the scanned person [32]. Note that a 3D model built by scanning in this way is generally a fixed, static model, but by applying the computer graphics technologies called rigging and skinning, it is possible to generate a parameterized variable model to which different postures and facial expressions can be applied.

Technologies for direct acquisition of such parameters for generating postures and facial expressions from humans in the real world are also being actively researched and developed among recent AI-related technologies. Human pose estimation is one of the most basic research topics; for example, MIT's OpenPose is one of the most popular technologies showing the potential for digitalization of human motion in the wild through deep-learning technology [33].

As for intelligent information, as mentioned in the previous section, there is no universal representation; however emotion is a typical kind of intelligent information, and many technologies have been developed for human emotion estimation. Some of these technologies estimate human emotion from information such as facial expressions and voices that can be observed by the five human senses [34], while other technologies use biological signals such as brain activities and heart rates [35]. Although these technologies can achieve quite high performance in terms of accuracy for labels based on third-person judgement, it is still difficult to judge whether they actually estimate a person's subjective emotions. Moreover, the existing technologies only estimate around 4-8 kinds of emotions, called basic emotions, and it is still difficult to estimate the more complex emotions that human have.

Mental/internal processes have also been studied in many research areas, including philosophy, psychology, neuroscience, and computer science. The research is ongoing, and we cannot yet define a universal, rational model even for a part of the intelligence process. For example, the human decision-making process is considered one of the most basic human processes and is thus being actively studied, especially in the area of agent-based modeling. As reviewed in [30], a wide variety of models have been proposed for different purposes. One of the most traditional models is production-rule systems [36]. A production-rule system models the human decision making process with a set of simple behavioral "if-then" rules. Although humans are not as simple as that, this kind of modeling might be useful for analyzing simple tasks performed by humans and implementing them in a machine or robot. In contrast, cognitive models were proposed to achieve more realistic social simulation based on knowledge in cognitive science. PECS is one of the simplest cognitive models [37] and has a component-oriented architecture. It includes physics, emotion, cognition, and social status components in its internal layer in order to model physical, emotional, cognitive and social influences. It seems possible to model a minimum level of human-like mental/internal processes, but the rational modeling methods for each component have not been clarified.

Lastly, psychologically and neurologically inspired models are among the most complex models, but they seem to have a relatively rational structure because the structural properties of the human brain are considered in their design. Most models in this category are designed to implement human cognitive functions and learning mechanisms. Although their main purposes include understanding specific human behaviors and the brain system, their architectures are designed to be simple, and other aspects such as emotions and social elements are rarely considered. For example, ACT-R, which is one of the most famous models in this category, was developed to model human behavior in psychological experiments, and the core scheme is based on a production system [38]. SOAR has a relatively complex memory module and leaning architecture, but it has no affect-related module [39], even though emotion is one of humans' fundamental functions. This might be because there was no rational structure or mechanism in the fields of neuroscience and cognitive science.

4-2-2. DTC digitalization process for human

To obtain a human digital twin, it is necessary to digitalize each person individually. As defined in **4-1-1. Physical information for human digital twin**, the physical information for a human digital twin is observable or measurable; it is thus possible to digitalize such real-world information by using sensor devices and other methods that are appropriate for the target information. Because the physical information of humans in the real world changes constantly, though it might be sometimes quite subtle, digitalization (i.e., sampling) should be performed at the necessary intervals for a DTC application.

In contrast, the intelligent information for a human digital twin is not directly observable or measurable; thus, the Data for intelligent information is estimated from the measured physical information. We refer to this estimation process as psychological decoding. To perform psychological decoding, it is necessary to define a representation model for the target intelligent information in advance. For example, we should define whether to use a discrete categorical model or a continuous dimensional model as a representational model for emotions, as well as the kinds of emotional categories or dimensions that will be used. Any method can be adopted for psychological decoding as long as it fulfills the performance requirements of the target DTC application. Deep-learning-based technology can provide highly accurate decoding results. However, such methods are constructed using a huge amount of data from different people and thus might need to be tuned with individual information.

The digitalization of the Process is one of the most important and difficult issues in creating human digital twins. Basically, we assume that human digital twins are modeled on collected "Data" for physical and intelligent information. However, human digital twins will be used not only to reproduce the past activities but also to predict future status and simulate unknown situations; therefore, it might not be appropriate to just model the Process as one that reproduces the inputs and outputs of collected data, as in the recent AI approach. Instead, we think it is necessary to model the Process so as to explain the collected data while defining a reasonable internal structure or mechanism, rather than relying on a black box. As for the definition a reasonable internal structure/mechanism, we think that reference to knowledge in physiology and psychology is one of the best approaches for creating human digital twins.

We assume that one of the typical applications for human digital twins in the DTC vision will be to perform various tasks on behalf of the corresponding real individual [40]. For such applications, it is important that the human digital twin should be recognizable as the corresponding individual not only by himself/herself but also by the people involved in a task. We define this capability via requirements for identity and personality in human digital twins, and we consider it essential to fulfill both requirements. We also expect that it will be quite difficult to achieve such “individualities” only from objective information obtained by sensing. Therefore, some applications might require subjective training or modification of a human digital twin by the corresponding individual.

Human digital twins will live in a virtual society even though they are connected to humans in the real world. Therefore, unlike conventional agent models that are completely separated from the real world, a human digital twin should have a mechanism to reflect real-world information at appropriate times. The Data could be reflected by being overwritten with real-world information. On the other hand, because the Process cannot be directly obtained, we should implement some update strategies. For example, the Process could be tuned at a predetermined time according to the Data stored after a previous update. Another example is a kind of online update method in which the Process would be updated according to errors between predicted Data using the current Process and observed Data, similarly to predictive coding in the human brain. This would provide a kind of mechanism that a human digital twin could grow according to the experiences of the corresponding individual in the real world. There remains an open issue of how to define and implement a growth mechanism of corresponding real human according to the experiences of the human digital twin in the virtual society.

4-3. Requirements for a human digital twin (Preliminary draft)

As described in our DTC white paper, we aim to use human digital twins to extend human capabilities in the real world, compensate for decision-making, and make simulation-based predictions. We think, therefore, that a human digital twin in the DTC vision should fulfill the following requirements. Note that the content in this section is under discussion and might be updated by considering the nature of humans from both the humanities and engineering perspectives.

4-3-1. Connection to corresponding human in real world

This condition is the same as that for a physical object: a digital twin of a person shall have a connection to the corresponding human. However, unlike for physical objects, there may be ethical issues in changing or controlling the physical and psychological status of a human in the real world by manipulating the corresponding digital twin. This requirement means, therefore, that at least the data of a digital twin shall be updated on the basis of the status of the corresponding human in the real world.

4-3-2. Identity

A human digital twin shall be recognized by the corresponding human as a digital version of himself/herself. This requirement implies that a digital twin of a person shall not be created without that person's approval.

4-3-3. Personality

A human digital twin shall be recognized as the digital version of the corresponding human by most of the human's acquaintances. This requirement is a condition for achieving valid simulation of various interactions in a virtual society.

4-3-4. Autonomy

The autonomy of a digital twin is defined as the ability for it to decide its own behavior in response to inputs/stimuli. A human digital twin shall react validly to any inputs/stimuli. Accordingly, a human digital twin shall be not terminated even in unexpected situations.

4-3-5. Ego

A digital twin shall not execute (fire/start) any processes without approval by the corresponding human.

4-3-6. Uniqueness

There shall be only one digital twin for an individual in the Digital Twin layer. This means that a human digital twin and the corresponding real human will have a one-to-one relationship.

4-3-7. Discriminability

A human digital twin and the corresponding real human shall be distinguishable in not only their appearances, but also their behaviors and consequences.

5. Digital Twin Operations

In this section, we will discuss the third layer of the DTC architecture: the Digital World Presentation Layer. The Digital World Presentation Layer provides the most important functionalities of the DTC vision: the Digital Twin Operations to generate new types of a digital twin and assembling a virtual society to execute a digital environment created virtually. We will look at these functionalities in the following sub-sections.

5-1. Related studies

According to a literature review relating to the digital twin technologies [41], there are 19 research themes identified as characteristics of a digital twin. However, interaction and integration between digital twins has not been investigated. Therefore, we need to discuss the necessary virtual environment, which is called a "virtual society" in this document, for associated digital twins to interact in this section.

For a virtual environment where digital twins interact, Shangguan et al. proposed an interesting approach to create hierarchical virtual environments to integrate various levels of digital twins such as a component, a sub-system, and scenarios for different scales of digital twins to interact [42]. This hierarchical framework is one example of constructing a virtual society for various types of digital twins to interact. We will discuss this topic in **5-2. An overview of the Digital World Presentation Layer**.

In a survey of technologies enabling digital twins [43], Fuller et al. identified several technological areas requiring further investigation such as data models, artificial intelligence, and standardization. They also indicated data fusion as one promising area of research. Although data fusion itself has been researched across various areas of science, few studies have applied data fusion to digital twins [44, 45]. Data fusion is considered as an important research area for the DTC vision to create a more precise form of a digital twin by consolidating various types of data including sensor data, design data, and attribute data. Moreover, expanding the concept of data fusion provides new ways to generate digital twins, for example, combining several digital twins to create a complex of objects and mixing digital twin models to generate new digital things or digital humans. We will introduce this new concept called the "Digital Twin Operation" in **5-4. The concept of Digital Twin Operations**.

5-2. An overview of the Digital World Presentation Layer

The Digital World Presentation Layer provides an environment to execute a virtual society or a group of virtual societies. Although virtual societies will be discussed in detail in the following sub-sections, a virtual society is conceptualized as a digital world created for specific purposes such as a traffic environment, an urban space, or an office to simulate interactions among digital twins in a desired time frame, location, and environment as discussed in **1-3. Relationship with the DTC's four-layered architecture**. As the virtual society is a core unit to handle digital twins in the Digital World Presentation Layer, an architecture of a set of virtual societies managed in the layer is discussed in this section to show how they are used and associated.

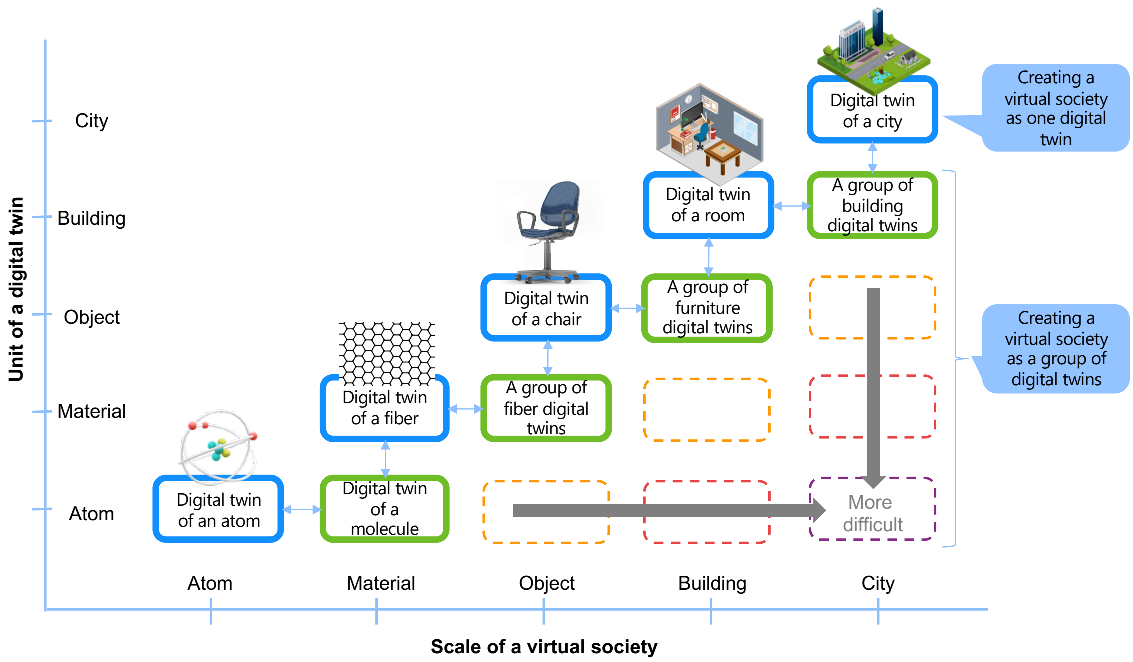


Figure 20 Unit and scale of virtual societies in DTC vision

Figure 20 shows the relationship between virtual societies in different scales. As shown in the figure, a virtual society is able to be created as one digital twin or a set of digital twins in a framework including space and time. For example, a virtual society representing a room can consist of an integrated room digital twin or a set of digital twins of a floor, a wall, and furniture located in the room. In other words, the former consists of a primitive of a room digital twin, while the latter consists of a complex of a floor digital twin, a wall digital twin, and furniture digital twins. This theory is expandable to a smaller level such as a complex of materials or even atoms.

The differences of these virtual societies are caused by the unit sizes of digital twins. Since a digital twin can be represented as a complex of various unit sizes (e.g., a chair digital twin with fibers and plastics, and a chair digital twin with molecules), a virtual society can be transformed into one consisting of different unit sizes of digital twins. When a virtual society is transformed into a smaller unit size of digital twins, it will provide a more microscopic view of the virtual society and may generate slightly different behavior of the virtual society due to very detailed calculation of digital twins requiring more computation power. If a virtual society is transformed into a larger unit size, the opposite effects will happen. This stair form of a relationship between virtual societies with different unit sizes and scale is a fundamental structure of a set of virtual societies in the Digital World Presentation Layer.

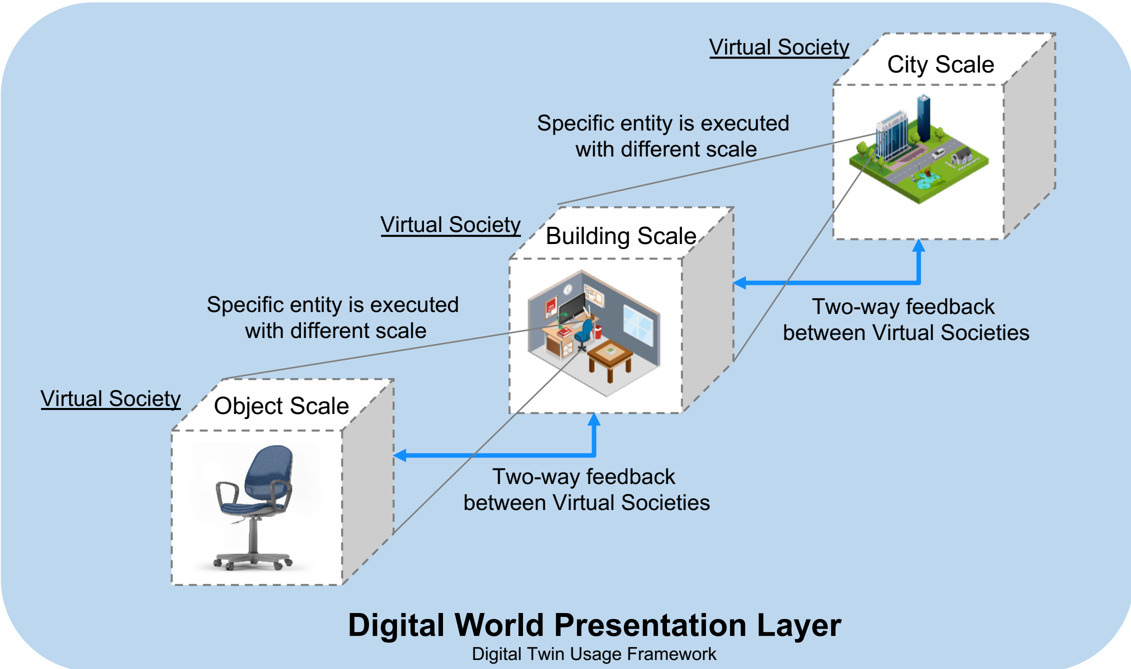


Figure 21 Relationship between virtual societies in different scales

When a virtual society is created in the Digital World Presentation Layer, the virtual society can consist of a set of virtual societies with different unit sizes. Figure 21 shows the relationship between different associated virtual societies to calculate detailed behavior of a specific part of the virtual society. For example, suppose we try to monitor the state of a chair in a room in a building in a city. First, an entire city is created as a city-scale virtual society. Then, a room in a building in this case is created as a building-scale virtual society to zoom into a specific entity in the city. Finally, the chair in a room is created as an object-scale virtual society with an object unit size to monitor the specific state of a target. There are three virtual societies in this example, and they are associated as a set of virtual societies to represent the chair in the room in the building in the city. Two-way feedback between virtual societies is conducted as necessary to propagate one digital twin's behavior and status to another one. This set of associated virtual societies is a functional component to be used to execute a virtually created digital world in the Digital World Presentation Layer.

5-3. The composition of a virtual society

What a virtual society is should be reviewed here to clearly define it. A static structure of a virtual society consists of four entities, specifically digital twins, digital information, a principle, and a framework of the virtual society including space and time in Figure 11 in **2-5. Elements of virtual society**. In addition, dynamic behavior is also mentioned in **3-1. Reference model of a digital twin** as various types of digital twins can be combined in a virtual society to operate tens of thousands of interactions between digital twins to simulate realistic behavior of entities. Figure 19 in **3-3-2. Calculation of interaction in the DTC digitalization model** shows an example for what kind of calculation happens in a virtual society.

In addition to these characteristics, we introduce the concept of inactive and active states of a virtual society. The inactive state means that a static structure of a virtual society is assembled with necessary entities including digital twins, digital information, a principle, and a framework of space and time, but with no time transition. Therefore, there are no interactions between digital twins or changes over time. On the other hand, the active state means that a virtual society changes in accordance with time transition including interactions between digital twins and time series changes. The state of a virtual society can be converted between inactive and active. A virtual society can change from one state to the other at arbitrary times. Figure 22 shows the states of a virtual society and their characteristics.

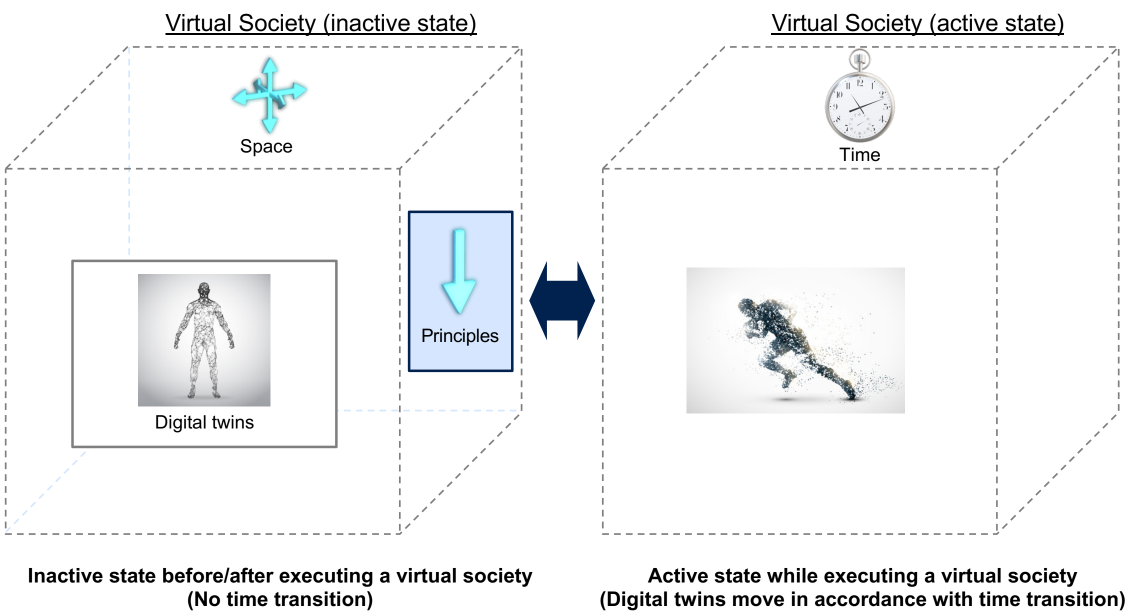


Figure 22 Inactive and active states of a virtual society

In the inactive state, a static structure of a virtual society can be modified, such as replacing a digital twin associated with the virtual society, changing a coordinate of its space, and adding principles applied to the virtual society as shown in Figure 23. In other words, a virtual society is assembled with various elements such as digital twins, digital information, and principles during the inactive state.

On the other hand, in the active state, the rate of time progress can be changed to both forward and backward, and digital twins interact in accordance with the applied principles and properties of the digital twins by using techniques such as simulation and artificial intelligence. Although a virtual society can be a single digital twin in a framework of space and time, only internal transition of the digital twin can occur as digital twins do not interact in this case.

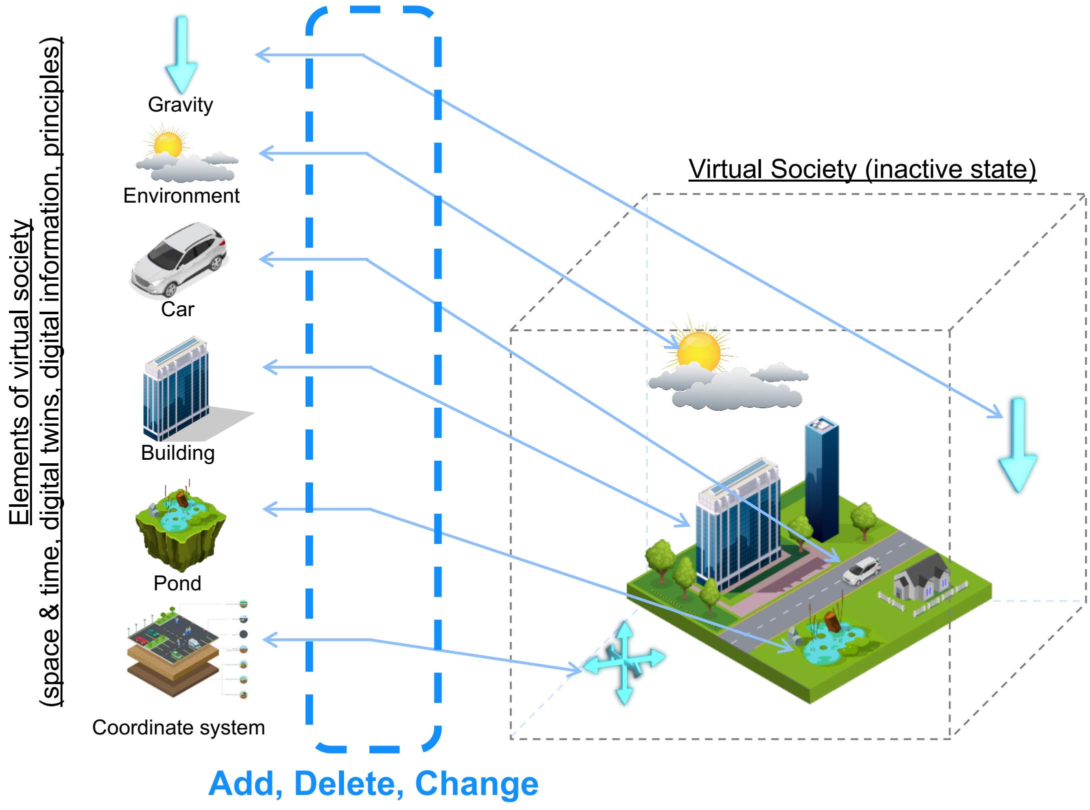


Figure 23 Modification of elements in a virtual society in inactive state

5-4. The concept of Digital Twin Operations

To create a virtual society composed of the aforementioned elements in the previous sub-section, the Digital Twin Operations are introduced to generate a new digital twin to be used as a material for an element of a virtual society and to assemble the virtual society in the inactive state with the generated materials. The Digital Twin Operation is a computation to combine multiple digital twins to create new things and worlds that do not yet exist to experience a future or fictional society with super high reality. In this sense, the newly created digital thing is no longer called a "digital twin" as there is no corresponding physical object with a connection. We call this new digital thing created through the Digital Twin Operation a "derivative digital twin" in this document.

Several types of the Digital Twin Operations are expected to be used to generate derivative digital twins and assemble a virtual society. Figure 24 shows examples of the Digital Twin Operations typically used to create new derivative digital twins through computations such as exchanging a part of digital twins, fusing different digital twins, and replicating original digital twins. Also, assembling a virtual society with digital twins and derivative digital twins is considered as one type of Digital Twin Operation.

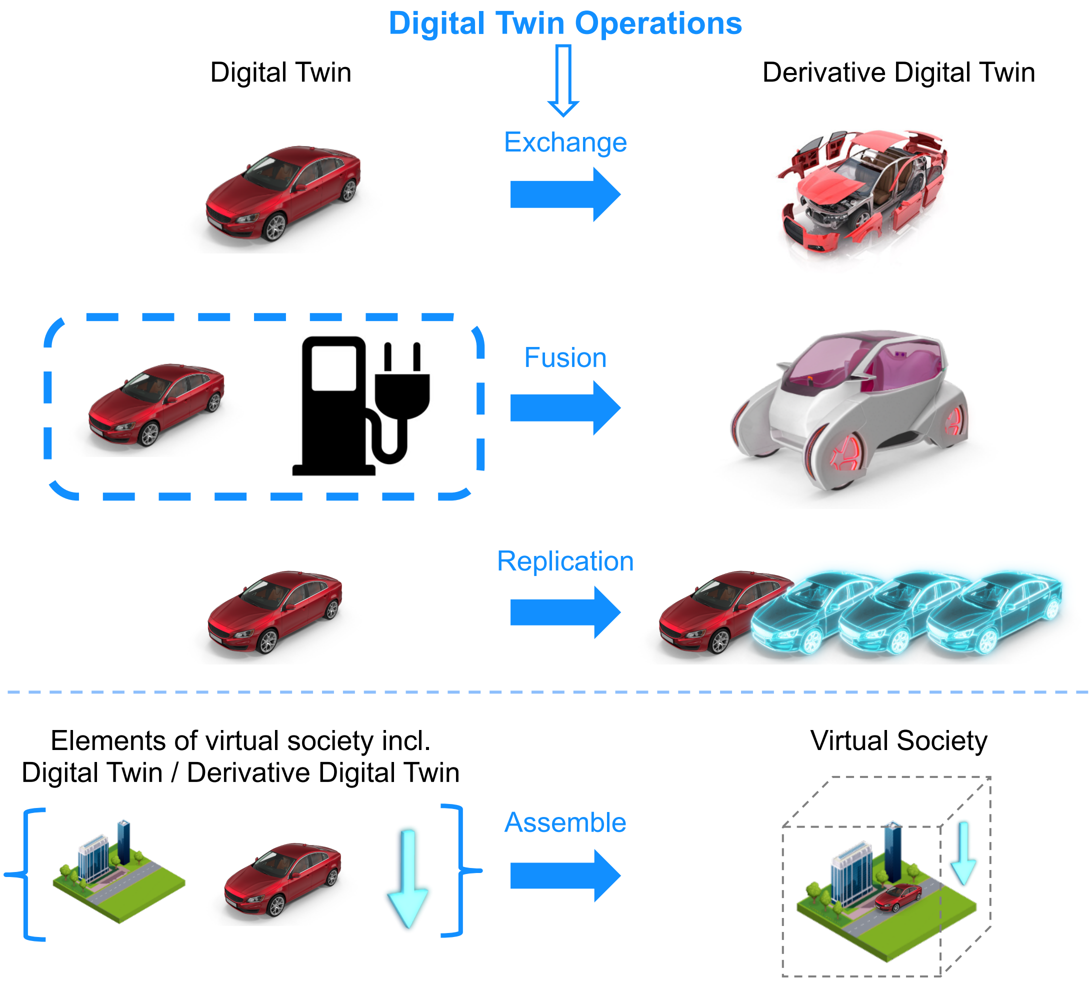


Figure 24 Examples of Digital Twin Operations

Through the Digital Twin Operations, usages in Table 4 will typically be considered. These usages produce new value of digital twin technology: a future or fictional society can be monitored, validated, tested, and experienced by digitally combining digital twins to create a realistic virtual society. This is the key concept of the DTC vision.

Table 4 Usages of Digital Twin Operations

Usage	Explanation	Advantage
Multiplication	Replicating a digital twin to generate multiple digital twins to be used in a virtual society.	Enables a virtual society to contain more people and objects than the real world.
Enhancement	Creating an ideal digital twin that has outstanding skills, knowledge, or features.	Enables a virtual society to produce an ideal world with enhanced people and objects.
Combination	Combining digital twins to produce complex machines or systems.	Enables a virtual society to produce the macroscopic behavior of digital twins.
Generalization	Creating a generalized digital twin without individuality or personality.	Enables a virtual society to simulate behavior of people and objects with anonymity.
Fictionalization	Creating a fictional digital twin with futuristic or imaginary features.	Enables a virtual society to simulate a fictional world with imaginary people and objects.
Invention	Generating novel ideas or concepts through new combinations of digital twins.	Enables a virtual society to generate new ideas and invent things.

5-5. Types of Digital Twin Operations

In this sub-section, details of each Digital Twin Operation will be described. Note that some operations are still under consideration and need more detailed definitions for actual computation of digital twins.

Table 5 shows types of Digital Twin Operations currently identified as useful for creating a virtual society. These operations modify or combine the existing digital twins and generate a new digital twin, a derivative digital twin, or a virtual society. Details of each operation will be discussed in the following sub-sections.

Table 5 Types of Digital Twin Operations

Type	Explanation
Replication	Replicating an entire digital twin to produce a replica.
Exchange	Exchanging a part of one digital twin for a part of another to create a derivative digital twin.
Fusion	Fusing digital twins to generate a complex digital twin.
Resolve	Resolving a complex digital twin into pieces of digital twins.
Extract	Extracting a part of a digital twin to create a derivative digital twin having a specific aspect of the original one.
Assemble	Assembling a virtual society by associating a digital twin, a digital information, a principle, and a framework of space & time.
Disassemble	Disassembling a virtual society into elements including a digital twin, digital information, a principle, and a framework of space & time.

5-5-1. Replication

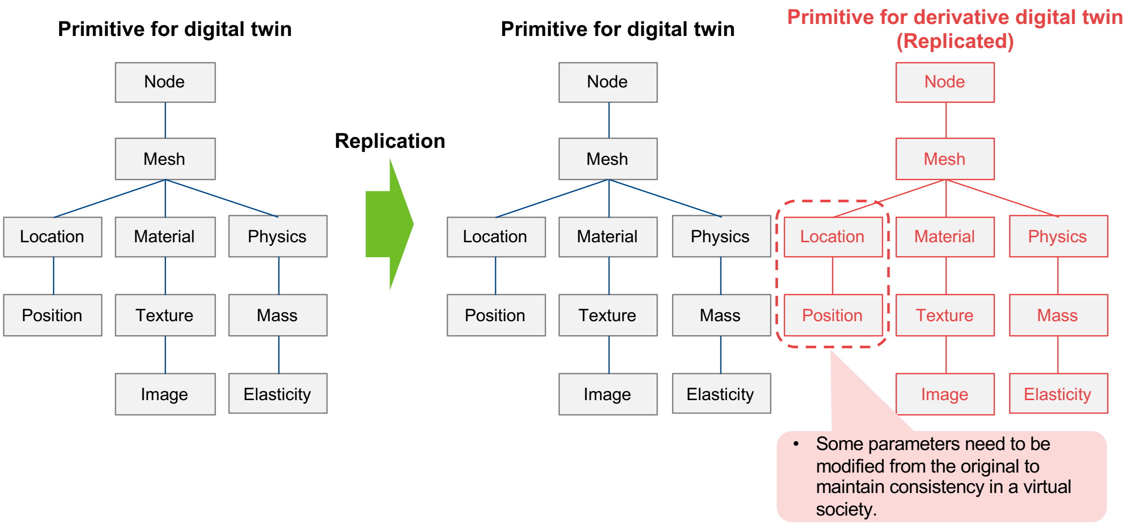


Figure 25 Example of Replication

Replication is used to create replicas of the original digital twin as shown in Figure 25. A new derivative digital twin of the original digital twin is created by replicating the entire model and data of the original one and is ready to be used as an element of a virtual society. Although the replicated digital twin is mostly identical to the original one, some parameters in the replicated digital twin (e.g., identifier, location, and ownership) need to be modified from the original one to maintain consistency in a virtual society. The method to modify a replicated digital twin is under consideration.

5-5-2. Exchange

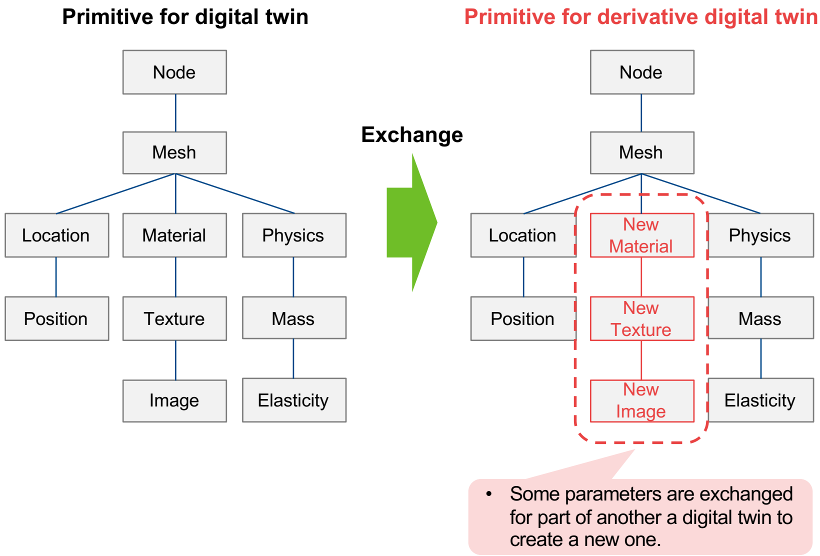


Figure 26 Example of Exchange

Exchange is used to change a part of a digital twin. Some parameters of the original digital twin are exchanged with other values to create a new derivative digital twin. Figure 26 shows an example of Exchange in which parameters of Material, Texture, and Image nodes are exchanged with new values to create a new derivative digital twin that has slightly different features from the original one. A mechanism to maintain consistency of a derivative digital twin (e.g., location, physical property, and identification) after Exchange needs to be considered.

5-5-3. Fusion

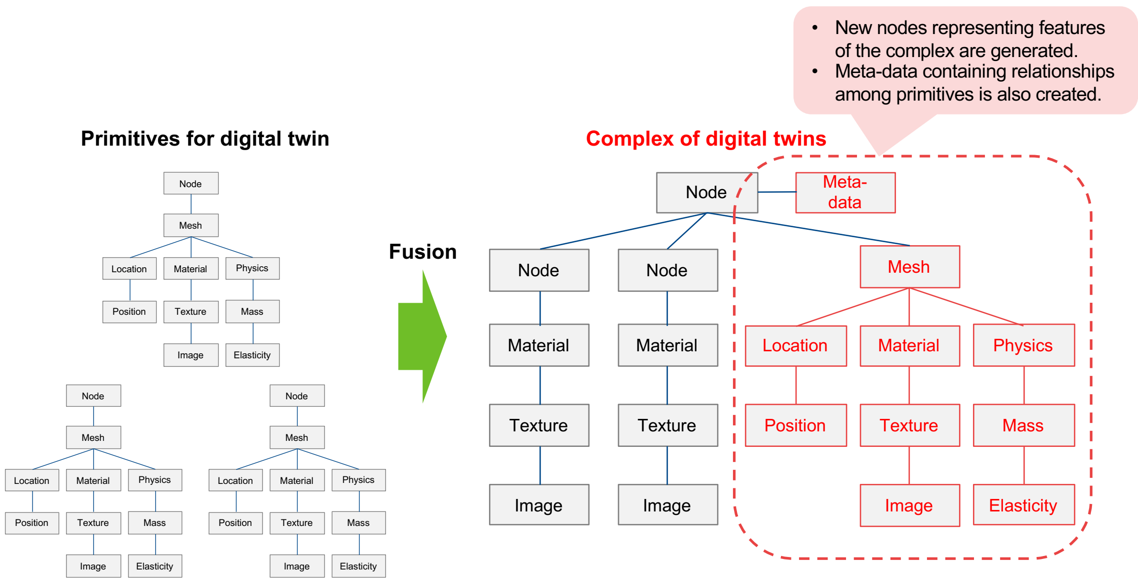


Figure 27 Example of Fusion

Fusion is used to combine several Primitives of digital twins to generate a Complex of derivative digital twins. As shown in Figure 27, Primitives are associated with an appropriate position and relationship in a Complex to form a functional digital twin. Also, new nodes representing features of the Complex are generated to provide a function produced by the Complex. For example, the Fusion of a jet engine and a wing generates a Complex of an airplane that produces a new function (flying), and new nodes representing the new function and relevant parameters are created through Fusion. In addition, meta-data containing relationships among associated Primitives is also generated to keep information of positions and relationships of each Primitive. The method to generate new nodes and meta-data requires further consideration.

5-5-4. Resolve

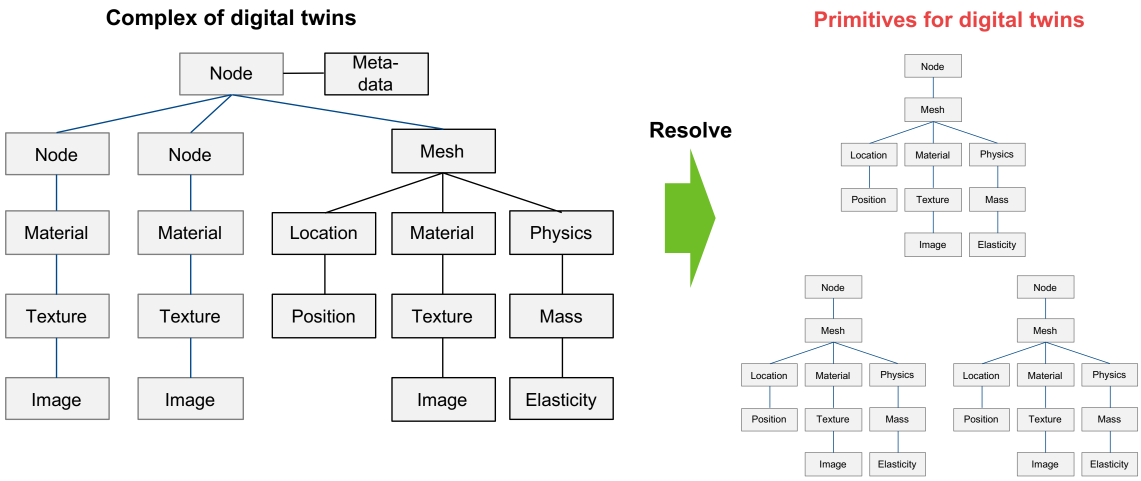


Figure 28 Example of Resolve

Resolve goes in the opposite direction to Fusion: it resolves a Complex into Primitives of digital twins (Figure 28). Basically, Primitives are generated by resolving a Complex along the original breaks between Primitives recorded in meta-data of the Complex. There are still many considerations, for example, if the Resolve creates Primitives that are different from the original one, or if the Resolve breaks a Complex partially.

5-5-5. Extract

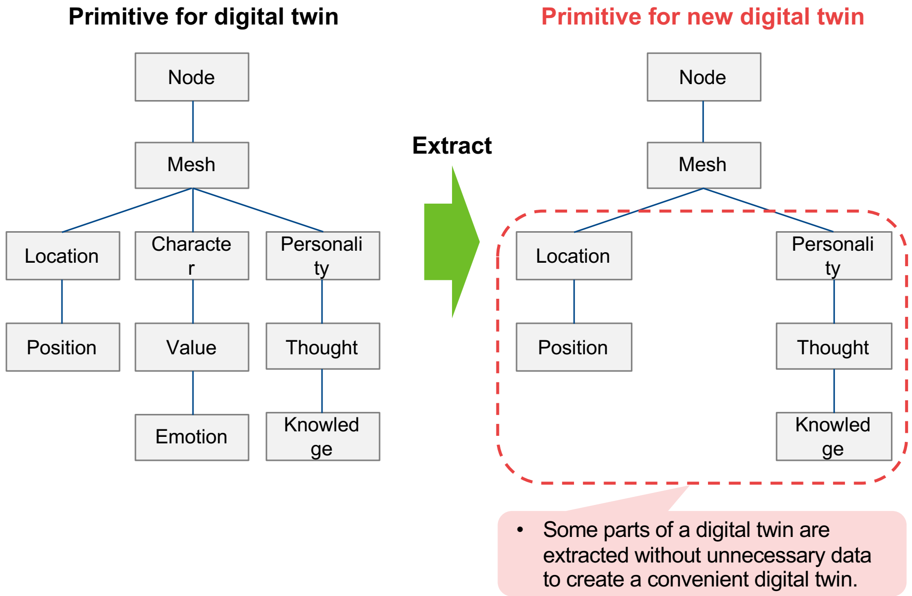


Figure 29 Example of Extract

Extract is used to create an abstract of a digital twin. Through Extract, some parts of a digital twin are extracted without unnecessary data to create a derivative digital twin that is convenient for specific use (Figure 29). For example, a human digital twin with only knowledge and skills of a certain job without personality and emotion could be convenient for automating office work. The method to extract a part of the original digital twin without a contradiction requires further consideration.

5-5-6. Assemble

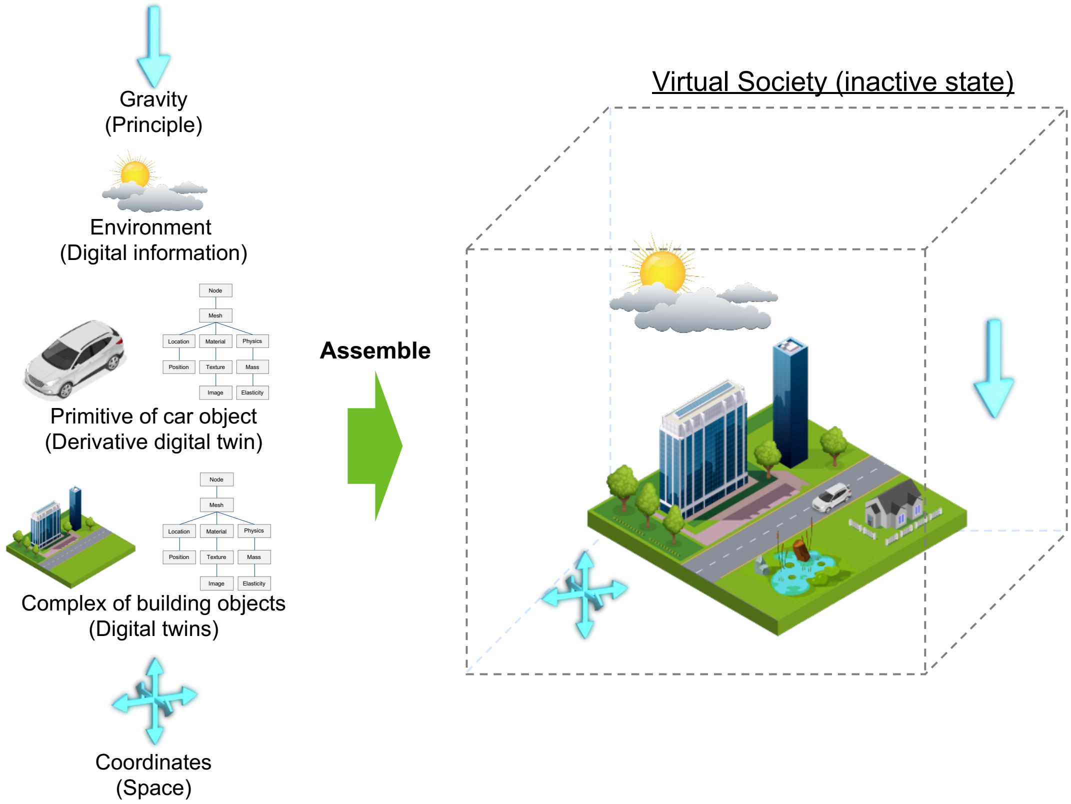


Figure 30 Example of Assemble

Assemble is used to assemble a virtual society in an inactive state with necessary elements including (derivative) digital twins, digital information, space information, and principles. As shown in Figure 30, necessary (derivative) digital twins are combined at appropriate positions in the space of a virtual society, and necessary principles and digital information are applied to them. As the assembled virtual society is still in an inactive state, the assembled elements (e.g., (derivative) digital twins, digital information, and principles) will start to interact when the virtual society is changed to an active state. The details of Assemble are under consideration, and this operation may combine several procedures to form a virtual society.

5-5-7. Disassemble

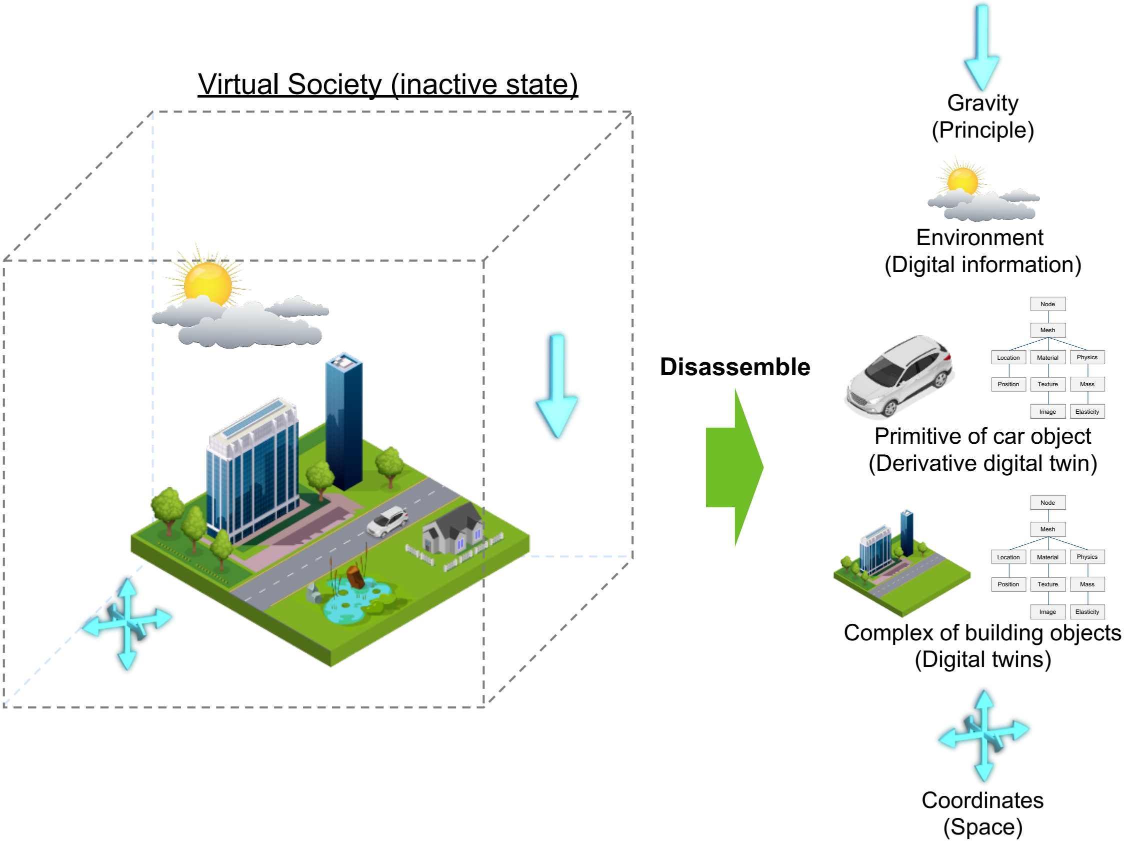


Figure 31 Example of Disassemble

Disassemble goes in the opposite direction to Assemble: it disassembles a virtual society into corresponding elements including (derivative) digital twins, digital information, space information, and principles. This operation can be valid when a target virtual society is in an inactive state. This operation requires further consideration such as how to treat digital twins combined or mixed (e.g., liquid and gas) during the active state of a virtual society.

5-6. Theoretical practice for creation and execution of a virtual society

In this sub-section, we will validate the efficiency of the Digital Twin Operation through theoretical practices in which various types of virtual societies are created and executed.

5-6-1. Enhancement of self-digital twin by adding communication skills

Scenario:

Creating a digital twin of myself by adding language skills that I do not actually have. By using the created digital twin, I can make a sales presentation in the chosen language that is the best for my customer.

Creation:

1. Generating a human digital twin that shares my appearance and necessary knowledge.
2. Adding language skills by using Exchange to add necessary information to speak the languages into the digital twin.
3. Combining the digital twin with other necessary resources such as communication interfaces to customers in a virtual society in the inactive state through Assemble.

Execution:

1. The assembled virtual society moves to the active state, and its time starts elapsing.
2. When I make a presentation to my customers in a different language, I delegate the task to the digital twin in the virtual society, and the digital twin makes the presentation in the appropriate language for my customers.
3. The digital twin's behavior and a response to the customer's question are controlled by artificial intelligence contained in the digital twin to show a similar appearance to me. This natural communication between customers and a digital twin of myself not only helps customers to understand the product features but also increases their trust in me.

5-6-2. Combination of human digital twins to create a representation

Scenario:

Generating a complex of digital twins for a division of a company to discuss a corporate strategy that satisfies all opinions and views from different divisions. A complex of digital twins is generated by combining opinions and views of individuals in a division to create a representative digital twin of the division.

Creation:

1. Generating human digital twins of individuals for each division. The digital twins include opinions and views on a corporate strategy.
2. Creating a representative complex of the digital twins for each division to consolidate opinions and views of constituent members of the division by using Fusion operation.
3. Combining the created complexes of all divisions into a virtual society in an inactive state with other necessary resources such as communication interfaces among the complexes and information regarding corporate performance.

Execution:

1. The assembled virtual society moves to the active state, and its time starts elapsing.
2. The representative complexes of all divisions start a discussion regarding a corporate strategy by using artificial intelligence included in each complex to conduct a discussion on the basis of the consolidated opinions and views of each division.
3. The representative complexes produce a unified corporate strategy reflecting different opinions from all divisions of the company even if not all employees can join the discussion due to time or location constraints.

5-6-3. Generalization of human digital twins to remove personal information

Scenario:

Generating multiple human digital twins for a shop clerk. The digital twins are generated from a specialist to contain necessary skills and knowledge of the task but do not need to have a private memory or strong emotions.

Creation:

1. Generating a human digital twin containing necessary skills and knowledge from a specialist.
2. Eliminating unnecessary memory and emotion by using Extract to extract necessary parts of the human digital twin.
3. Increasing the number of the digital twins by using Replication to meet the volume of demand for the task.
4. Combining the digital twins with other necessary resources such as a database relating to the task and communication tools for customers in a virtual society in the inactive state through Assemble.

Execution:

1. The assembled virtual society moves to the active state, and its time starts elapsing.
2. When a customer comes to the shop, each digital twin serves the customer by using artificial intelligence it contains internally to manage its behavior and responds with answers in accordance with its knowledge.
3. As unnecessary memory and emotion have been eliminated, the privacy and characteristics of the clerk who is the original of the digital twins do not affect services provided by the digital twins and are not violated.

5-6-4. Fictionalization of digital twins to generate a future city

Scenario:

Simulating a future city where flying cars convey people in the city to predict a change in people's movement. A digital twin of a flying car, which does not yet exist in the real world, is generated through a mixture of an existing vehicle and a helicopter to include necessary features such as a capacity, speed, and comfort.

Creation:

1. Generating a digital twin of an existing vehicle and a digital twin of a helicopter.
2. Producing a digital twin of a flying car by using Exchange to mix features of an existing vehicle and a helicopter to create a digital twin that does not yet exist.
3. Increasing the number of digital twins by using Replication to meet the scale of a future prediction.
4. Combining the digital twins with other necessary resources such as a geometry database of a target city, people's movement data, and other digital twins of city transportation (e.g., conventional vehicles, trains, bicycles) in a virtual society in an inactive state through Assemble.

Execution:

1. The assembled virtual society moves to the active state, and its time starts elapsing.
2. The digital twins of people in the virtual society start moving in accordance with a simulation algorithm of people's movement in a city.
3. The influence on people flow caused by newly installed flying cars can be monitored in the virtual society that is a future city model fictionally created through the Digital Twin Operation.

5-7. Issues relating to Digital Twin Operations

The following issues relating to the Digital Twin Operations require further consideration.

5-7-1. (Derivative) digital twin with no connection to a physical twin

In this section, we introduce a derivative digital twin to represent a newly created digital twin that has never existed in the physical world. However, due to this definition, there is no corresponding physical twin to the derivative digital twin or connection between them. Moreover, a complex of a digital twin generated through Fusion can have no firm connection to the corresponding physical twin even if each component in the complex has an individual connection to its physical twin. Taking into account the definition of a digital twin described in **3-1. Reference model of a digital twin**, this could be a contradiction between the definition and a product of the Digital Twin Operation. Further consideration and definition are required.

5-7-2. A virtual society without a corresponding real society

As mentioned in **5-2. An overview of the Digital World Presentation Layer**, a virtual society is conceptualized as "a digital world created for specific purposes such as a traffic environment, an urban space, or an office to simulate interactions among digital twins in a desired time frame, location, and environment". This means a virtual society does not need to be a mirror of an existing real-world society and is created as a fictional world to simulate behavior of things and humans. In this case, there is no real society corresponding to the fictional virtual society or connection between them, although some digital twins used in the fictional virtual society might have a corresponding physical twin with a connection. This is also an inconsistency in the virtual society concept and requires further consideration.

5-7-3. Difference between Digital Twin Operation and simulations

Basic demarcation between the two terms is that the Digital Twin Operation is used to statically assemble a virtual society, while simulation techniques are used to execute dynamic behavior of the virtual society. However, a phenomenon resembling the Digital Twin Operations such as Replication and Fusion could occur during the simulation of a virtual society as a result of interactions among multiple digital twins. We need to consider defining how we distinguish them or whether they are fundamentally the same phenomenon.

6. Open Issues

Table 6 shows the remaining open issues that will be addressed in future works.

Table 6 List of open issues

No.	Issues	Explanation
1	Definition of data model for digital twin interaction	Defining common data model enabling various types of interactions between digital twins.
2	Definition of Digital Space	Defining Digital Space including space and time as a framework of a virtual society.
3	Classification of digital information element	Breaking down the digital information to classify entities to create a virtual society.
4	Classification of achievement levels of a virtual society	Setting level that reflects achievement levels of a virtual society (e.g., static level, dynamic level).
5	DTC's platform interface	Defining platform interface of the DTC exposed to other applications and systems.
6	Reference model of human digital twin	Defining a concrete reference structure for human digital twins (e.g., the kinds of data and processes to equip), including interactions.
7	Definition of digital twin for group of humans	Consider how we can define a digital twin for a group of humans as a Complex human digital twin.

References

[1] Digital Twin Computing White Paper ver.2.0.0, https://www.ntt.co.jp/svlab/e/DTC/whitepaper.html, Oct 31st, 2019,

[2] M. Grieves, “Digital twin: Manufacturing excellence through virtual factory replication,” White paper, 2014. [Online]. Available: http://www. apriso.com/library/Whitepaper_Dr_Grieves_DigitalTwin_Manufacturing Excellence.php

[3] E. Glaessgen and D. Stargel, “The digital twin paradigm for future NASA and U.S. Air Force vehicles,” in Proc. 53rd AIAA/ASME/ASCE/AHS/ASC Struct. Struct. Dyn. Mater. Conf., 2012. [Online]. Available: https://arc.aiaa.org/doi/pdf/10.2514/6.2012-1818.

[4] Grieves, M. and J. Vickers, “Digital Twin: Mitigating Unpredictable, Undesirable Emergent Behavior in Complex Systems”, in Trans-Disciplinary Perspectives on System Complexity, Springer: Switzerland. p. 85-114., 2016

[5] Benjamin, S., “Shaping the digital twin for design and production engineering”, CIRP Annals Vol. 66, Issue 1, Pages 141-144, 2017

[6] Saddik, A. El, et al., "Digital Twins: The Convergence of Multimedia Technologies". IEEE MultiMedia. 25 (2): 87–92., April, 2018

[7] Michael Jacoby and Thomas Usländer, “Digital Twin and Internet of Things—Current Standards Landscape”, Applied Sciences, vol. 10, 18th Sep. 2020.

[8] Fei Tao et al., “Digital Twin in Industry: State-of-the-Art”, IEEE Transactions on Industrial Informatics, Vol. 15, No. 4, April 2019

[9] Barbara Rita Barricelli et al., “A Survey on Digital Twin: Definitions, Characteristics, Applications, and Design Implications”, IEEE Access volume7, 2019

[10] General Electric, “The Digital Twin Compressing time-to-value for digital industrial companies”, February, 2018

[11] General Electric, “PREDIX: The Platform for the Industrial Internet”, https://ecosystems4innovating.files.wordpress.com/2016/11/predix-the-platform-for-the-industrial-internet-whitepaper.pdf, 2016

[12] General Electric, “Project: Digital Twin Framework”, https://www.ge.com/research/project/digital-twin-framework

[13] Siemens Digital Logistics, “The Digital Twin A new Dimension in Logistics”, 2020

[14] Siemens Healthcare, “White Paper: The value of digital twin technology”, 2019

[15] Siemens Switzerland, “Digital twin – Driving business value throughout the building life cycle”, 2018

[16] Microsoft, “The promise of a digital twin strategy”, https://info.microsoft.com/rs/157-GQE-382/images/Microsoft%27s%20Digital%20Twin%20%27How-To%27%20Whitepaper.pdf, 2017

[17] Microsoft, “Exploiting Disruptive Technologies: DIGITAL TWINS”, https://midwestacc.com/wp-content/uploads/2019/11/PJJohnson-Technical-Microsoft-Azure-Digital-Twins.pdf, November, 2019

[18] Microsoft Azure, “Digital Twins Definition Language (DTDL)”, https://github.com/Azure/opendigitaltwins-dtdl/blob/master/DTDL/v2/dtdlv2.md

[19] Automation ML, https://www.automationml.org/o.red.c/home.html

[20] glTF (GL Transmission Format), https://www.khronos.org/gltf/

[21] Dassault Systemes, “Pioneering Virtual Singapore Project to Solve Emerging and Complex Challenges Faced by Singapore”, https://www.3ds.com/press-releases/single/dassault-systemes-and-national-research-foundation-collaborate-to-develop-the-virtual-singapore-pla/, 16 June, 2015

[22] Dassault Systemes, “Smart cities in the age of experience”, https://www.slideshare.net/LuciaGarcia71/alexandre-parilusyan, 23 Mar, 2017

[23] Maurizio Bevilacqua et al., “Digital Twin Reference Model Development to Prevent Operators’ Risk in Process Plants”, Sustainability, Vol. 12, Issue 3, 4th February, 2020

[24] Unity User Manual, https://docs.unity3d.com/2020.2/Documentation/Manual/index.html

[25] Unreal Engine 4 Documentation, https://docs.unrealengine.com/en-US/index.html

[26] Matthew Loper, Naureen Mahmood, Javier Romero, Gerard Pons-Moll, and Michael J. Black. 2015. SMPL: a skinned multi-person linear model. ACM Trans. Graph. 34, 6, Article 248 (November 2015), 16 pages. DOI:https://doi.org/10.1145/2816795.2818013

[27] Osman, Ahmed & Bolkart, Timo & Black, Michael. (2020). STAR: Sparse Trained Articulated Human Body Regressor. 10.1007/978-3-030-58539-6_36.

[28] Ekman P, Friesen W (1978). Facial Action Coding System: A Technique for the Measurement of Facial Movement. Palo Alto: Consulting Psychologists Press.

[29] Shih-Kai Chung and J. K. Hahn, "Animation of human walking in virtual environments," Proceedings Computer Animation 1999, Geneva, Switzerland, 1999, pp. 4-15, doi: 10.1109/CA.1999.781194.

[30] Balke, Tina and Gilbert, Nigel (2014) 'How Do Agents Make Decisions? A Survey' Journal of Artificial Societies and Social Simulation 17 (4) 13 <http://jasss.soc.surrey.ac.uk/17/4/13.html>. doi: 10.18564/jasss.2687

[31] Herbert W. Franke. ″Computer Graphics - Computer Art″. Paidon Press, London, Phaidon Publishers, New York, 1971, p. 103

[32] Debevec, Paul; Tim Hawkins; Chris Tchou; Haarm-Pieter Duiker; Westley Sarokin; Mark Sagar (2000). "Acquiring the reflectance field of a human face". Proceedings of the 27th annual conference on Computer graphics and interactive techniques - SIGGRAPH '00. ACM. pp. 145–156.

[33] Z. Cao, G. Hidalgo, T. Simon, S. -E. Wei and Y. Sheikh, "OpenPose: Realtime Multi-Person 2D Pose Estimation Using Part Affinity Fields," in IEEE Transactions on Pattern Analysis and Machine Intelligence, vol. 43, no. 1, pp. 172-186, 1 Jan. 2021, doi: 10.1109/TPAMI.2019.2929257.

[34] Benitez-Quiroz, C. F., Srinivasan, R., Feng, Q., Wang, Y., & Martinez, A. M. (2017). EmotioNet Challenge: Recognition of facial expressions of emotion in the wild. arXiv preprint arXiv:1703.01210 (see also Challenges and Promises of Inferring Emotion from Images and Video Workshop on CVPR2020, https://cbcsl.ece.ohio-state.edu/enc-2020/index.html)

[35] L. Santamaria-Granados, M. Munoz-Organero, G. Ramirez-González, E. Abdulhay and N. Arunkumar, "Using Deep Convolutional Neural Network for Emotion Detection on a Physiological Signals Dataset (AMIGOS)," in IEEE Access, vol. 7, pp. 57-67, 2019, doi: 10.1109/ACCESS.2018.2883213.

[36] NILSSON, N. J. (1977). A production system for automatic deduction. Technical Note 148, Stanford University, Stanford, CA, USA.

[37] URBAN, C. & SCHMIDT, B. (2001). Pecs - agent-based modeling of human behavior. AAAI technical report, University of Passau, Chair for Operations Research and System Theory.

[38] BYRNE, M. D. & ANDERSON, J. R. (1998). Perception and action. In: The Atomic Components of Thought (ANDERSON, J. R. & LEBIERES, C., eds.), chap. 6. Lawrence Erlbaum Associates, Inc., Publishers, pp. 167-200.

[39] LAIRD, J. E., NEWELL, A. & ROSENBLOOM, P. S. (1987). Soar: an architecture for general intelligence. Artificial Intelligence 33(3), 1-64.

[40] NTT Press Release: “NTT announces new R&D projects of Digital Twin Computing”, https://www.ntt.co.jp/news2020/2011e/201113c.html

[41] David Jones et al., “Characterising the Digital Twin: A systematic literature review”, CIRP Journal of Manufacturing Science and Technology, 9th March, 2020

[42] D. Shangguan, L. Chen, and J. Ding, ‘‘A hierarchical digital twin model framework for dynamic cyber-physical system design,’’ in Proc. 5th Int. Conf. Mechatronics Robot. Eng. ICMRE, 2019, pp. 123–129.

[43] Aidan Fuller et al., “Digital Twin: Enabling Technologies, Challenges and Open Research”, IEEE Access volume 8, 28th May, 2020

[44] Y. Cai, B. Starly, P. Cohen, and Y.-S. Lee, ‘‘Sensor data and information fusion to construct digital-twins virtual machine tools for cyber-physical manufacturing,’’ Procedia Manuf., vol. 10, pp. 1031–1042, Jan. 2017.

[45] Z. Liu, N. Meyendorf, and N. Mrad, ‘‘The role of data fusion in predictive maintenance

using digital twin,'' in Proc. Annu. Rev. Prog. Quant. Nonde- struct. Eval., Provo, UT, USA, 2018, Art. no. 020023.

Contact Information
NTT Digital Twin Computing Research Center
dtc-office-ml@hco.ntt.co.jp

