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Visualization elements of digital twin — Visualization fidelity

Éléments de visualisation du jumeau numérique — Fidélité de la visualisation

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Foreword

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This document was prepared by Technical Committee ISO/TC 184, *Automation systems and integration*, Subcommittee SC 4, *Industrial data,* in collaboration with Technical Committee ISO/IEC JTC 1 *Information Technology*, Subcommittee SC 24, *Computer graphics, image processing and environmental data representation* and Technical Committee ISO/TC 171, *Document management applications*, Subcommittee SC 2, *Document file formats, EDMS systems and authenticity of information*.

This second edition cancels and replaces the first edition (ISO/TR 24464:2020), which has been technically revised.

The main changes are as follows:

— the title is changed;

— a three-elements architecture is added;

— this document focuses more on fidelity among visualization elements.

Any feedback or questions on this document should be directed to the user's national standards body. A complete listing of these bodies can be found at www.iso.org/members.html.

Introduction

This document analyses the visualization fidelity among the visualization elements of a digital twin system. Since digital twin (DTw) is a new technology, various definitions are being proposed in the sector as a whole, so they collide with each other, and cross-reference is underway at the same time. This document analyses the element technologies and the properties that make up the DTw system, it also attempts to reveal the nature of the DTw, and focuses on visualization elements. This is expected to further solidify the identity of DTw, reduce confusion and consequently help further spread the use of DTw technology.

Visualization elements of digital twin — Visualization fidelity

1 Scope

The content of this document is divided into two parts.

— This document analyses the overall configuration of an industrial digital twin system, and proposes a three-elements architecture, focusing on the twinning interface between the physical twin (PTw) and industrial digital twin (iDTw).

— The characteristics, and the visualization elements and visualization fidelity of iDTw are analysed.

This document:

a) analyses the twinning interface between the PTw and iDTw;

b) proposes a three-elements architecture;

c) analyses the visualization element and its fidelity, which is a key component of the interface among the three-elements architecture;

d) analyses the elements that constitute an iDTw system to understand the unique properties of iDTw;

e) explores the differentiation from cyber physical systems (CPS) or augmented reality (AR), which are similar to existing concepts of iDTw.

This document excludes:

— applications of iDTw;

— implementation of iDTw.

2 Normative references

There are no normative references in this document.

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

ISO and IEC maintain a terminology database for use in standardization at:

— ISO Online browsing platform: available at https://www.iso.org/obp

— IEC Electropedia: available at https://www.electropedia.org/

3.1
accuracy
closeness of agreement between a test result or measurement result and the true value

[SOURCE: ISO 3534-2:2006, 3.3.1, modified — Notes 1 to 3 to entry have been removed.]

3.2
asset
any item, thing or entity that has potential or actual value to an organization

[SOURCE: ISO/TS 15926-11:2023, 3.1.1]

3.3
asset administration shell
standardized digital representation of an *asset* (3.2)

[SOURCE: IEC 63278-1:2023, 3.1.2]

3.4
digital model
dataset to represent the *shape* (3.12) and any other desired characteristics for target synthetic model

[SOURCE: ISO 22926:2023, 3.1, modified — Term "digital anatomical bone model", Notes 1 to 2 to entry and the example have been removed.]

3.5
federation
community of domains

[SOURCE: ISO 12967-1:2020, 3.4.2]

3.6
fidelity
degree to which a model or simulation reproduces the state and behaviour of a real-world object or the perception of a real-world object, feature, condition, or chosen standard in a measurable or perceivable manner

[SOURCE: ISO 16781:2021, 3.1.4]

3.7
industrial digital twin
digital representation of a physical entity

Note 1 to entry: It represents the bit world rather than the atom world.

3.8
industrial digital twin system
compound model composed of a *physical twin* (3.10), an *industrial digital twin* (3.7), and a *twinning interface* (3.15) which is used for state *synchronization* (3.13) between two twins

3.9
level of detail
alternate representations of an object at varying fidelities based on specific criteria

[SOURCE: ISO/IEC 18023-1:2006, 3.1.8]

3.10
physical twin
object which exists in the real world

3.11
real time
guarantee response within specified time constraints

Note 1 to entry: Often referred to as “deadlines”.

3.12
shape
form of an object or its external boundary, outline, or external surface, as opposed to other properties such as colour, texture, or material type

3.13
synchronization
joining up or handshaking of multiple processes at a certain point, to reach an agreement or commit to a certain sequence of action

3.14
twinning
pairing or union of two similar or identical objects

3.15
twinning interface
mediator which allows mutual augmentation between *iDTw* (3.7) and *PTw* (3.10)

3.16
visualization
rendering of an object, situation or set of information as a chart or image

[SOURCE: ISO/IEC TS 5147:2023, 3.1.15, modified — Note 1 to entry was removed.]

4 Abbreviated terms

AAS	asset administration shell
AI	artificial intelligence
AR	augmented reality
AWI	approved work item
CAD	computer aided design
CAE	computer aided engineering
CG	computer graphics
CPS	cyber physical system
DTw	digital twin
fps	frames per second
FPSO	floating production storage offloading
HiFi	high fidelity
HW	hardware
iDTw	industrial digital twin
IoT	internet of things
JWG	joint working group
LoD	level of detail
LRC	local RTI component
MAR	mixed and augmented reality
MEMS	micro electromechanical systems

MR	mixed reality
NP	new proposal
O&M	operation and maintenance
P&ID	piping and instrumentation diagram
PLM	product life cycle management
PPI	pixels per inch
PTw	physical twin
RAMI4.0	reference architecture model industry 4.0
RPM	revolution per minute
RTI	run-time infrastructure
SMRM	smart manufacturing reference model
SMRL	STEP module and resource library
STEP	standard for the exchange of product model data
SW	software
TTR	technology trend report
VR	virtual reality
WiFi	wireless fidelity
XR	extended reality

5 Needs of DTw visualization

5.1 Atom world and a bit world

The concept of the digital twin (DTw) can be elucidated through the paradigms of the atom world and the bit world. The atom, being the fundamental unit of matter, serves as the foundation for the real world. This realm, governed by traditional economic principles, is often referred to as the physical world, characterized by the tangible presence of materials. Within the atom world, the economy is predominantly influenced by three factors: land, capital and labour.

Contrastingly, the bit world represents the online domain, where the economic paradigm shifts significantly from that of the atom world. In this digital space, data are stored as bits which do not require physical space, and the processing speeds surpass those encountered in the atom world.

5.2 Visualization of big and small things

As man-made products, including ocean platforms, satellites, factories, power plants, and urban infrastructures, grow in size and complexity, the challenge of managing these entities escalates. Consequently, there is an expanding demand for the utilization of DTws to manage these large and complex products. Similarly, in the realm of micro-materials, such as DNA and micro-electro-mechanical systems (MEMS), digital models replicating real-world objects are increasingly employed for planning, designing, producing, operating, monitoring, and maintaining these materials. Nonetheless, digital models, whether for macro or micro-scale applications, are often simplified or idealized versions of their physical counterparts, leading to inherent limitations.

The absence of visualization technologies raises questions about the practical value of a constructed DTw. This paradox underscores the critical importance of visualization capabilities. Visualization technologies, including video, are becoming increasingly vital in accurately simulating real-world scenarios with DTws.

5.3 Visualization of big data

With advancements in the internet of things (IoT) and sensor network technologies, an increasing volume of operational data are being digitized and stored through the internet and sensor devices, thus contributing to the formation of substantial big data assets. Figure 1 illustrates the process in which operational data, gathered via edge computing devices like smartphones, is archived and leveraged as big data within cloud computing infrastructures.

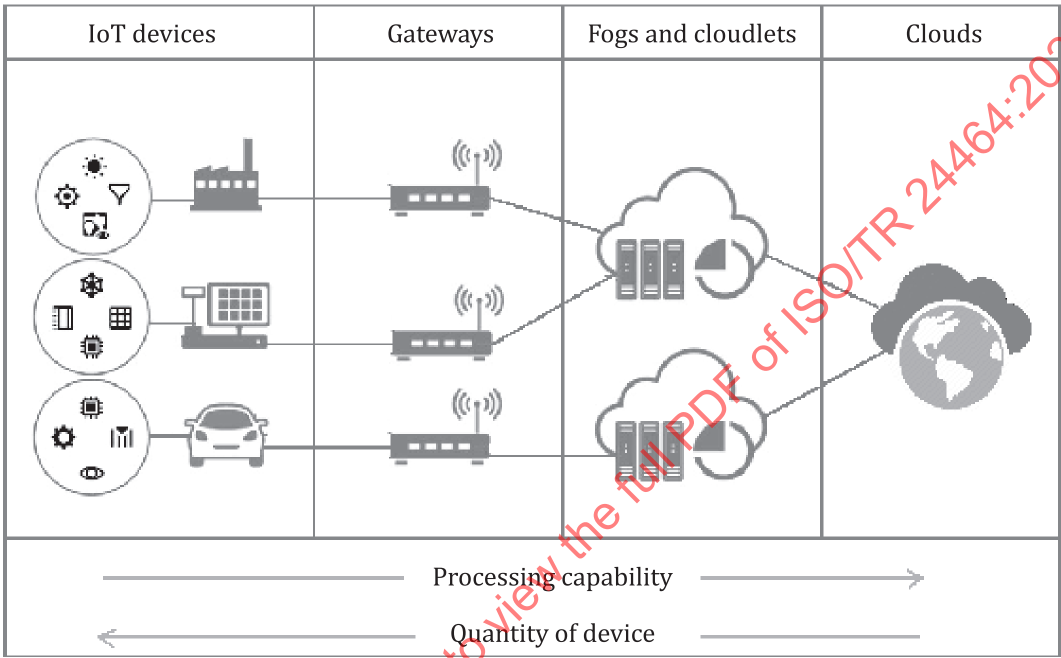


Figure 1 — IoT produces big data[29]

The sheer volume of this big data surpasses human analytical capabilities, heralding new horizons as artificial intelligence (AI) is deployed for its analysis. With big data integrated into digital assets and constructed as DTws, the fidelity in mirroring real-world scenarios surpasses that of traditional digital models.

The utilization of computer graphics (CG) for the visualization of big data has been established for quite some time, notably in applications such as climate modelling with supercomputers, biological cell or chemical modelling, and the interpretation of simulation outcomes via digital product models, including automobiles. These scientific visualization techniques pivot on CG rather than mere numerical calculations (Figure 2). The simulation outcomes, represented as numbers and compiled into big data, gain interpretative clarity through the application of AI and/or visualization techniques.

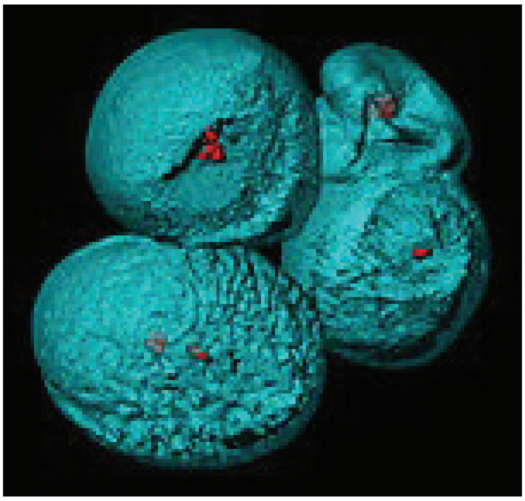


Figure 2 — Scientific visualization [39]

5.4 Visualization fidelity of the twinning interface

As depicted in Figure C.5 and Figure 3, the industrial digital twin (iDTw) system is composed of three core elements: the physical twin (PTw), the iDTw, and the twinning interface (see also Clause 6). This document primarily addresses the twinning interface that facilitates interaction between the PTw and iDTw, focusing on the standardization of visualization fidelity that is either shared or integrated between the PTw and the iDTw.

6 Three-elements architecture of the iDTw system visualization

6.1 General

As the interest in DTw grows, the introduction of varied definitions and architectures for DTws has led to confusion. To address this issue, formal concept analysis, as introduced in D.1, serves as a useful tool. It is important that the definition of an entity-of-interest is grounded in its properties.

In numerous references, the term "digital twin" is often equated with a digital replica. However, this document adopts the three-elements architecture based on the definition provided by Michael Grieves, who is credited with the concept of the DTw. The selection of terminologies are further explained in Annex B.

The iDTw system is characterized by a three-elements model, as illustrated in Figure 3, encompassing the PTw and the iDTw, both of which are integrated via the twinning interface. This model is collectively referred to as the "iDTw system". Annex E outlines a series of use cases that are applicable to the three-elements model.

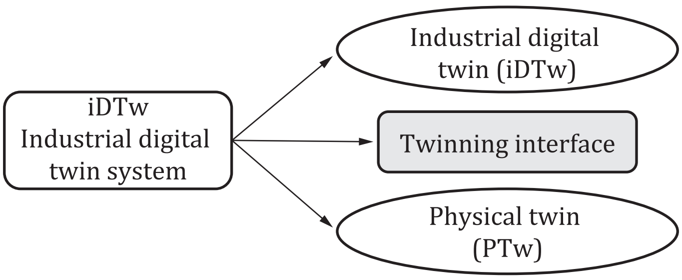


Figure 3 — Three-elements architecture of the iDTw system

6.2 Component technologies of DTw visualization

Drawing from the model proposed by Dr. Michael Grieves and the associated three-element architecture, the technologies integral to DTw visualization are delineated in Figure 4. Given the complex nature of DTws, capturing all component technologies within this document proves challenging. Thus, the focus is narrowed to the visualization aspects, which are systematically categorized. The various definitions of DTw are grouped and presented in Table A.1.

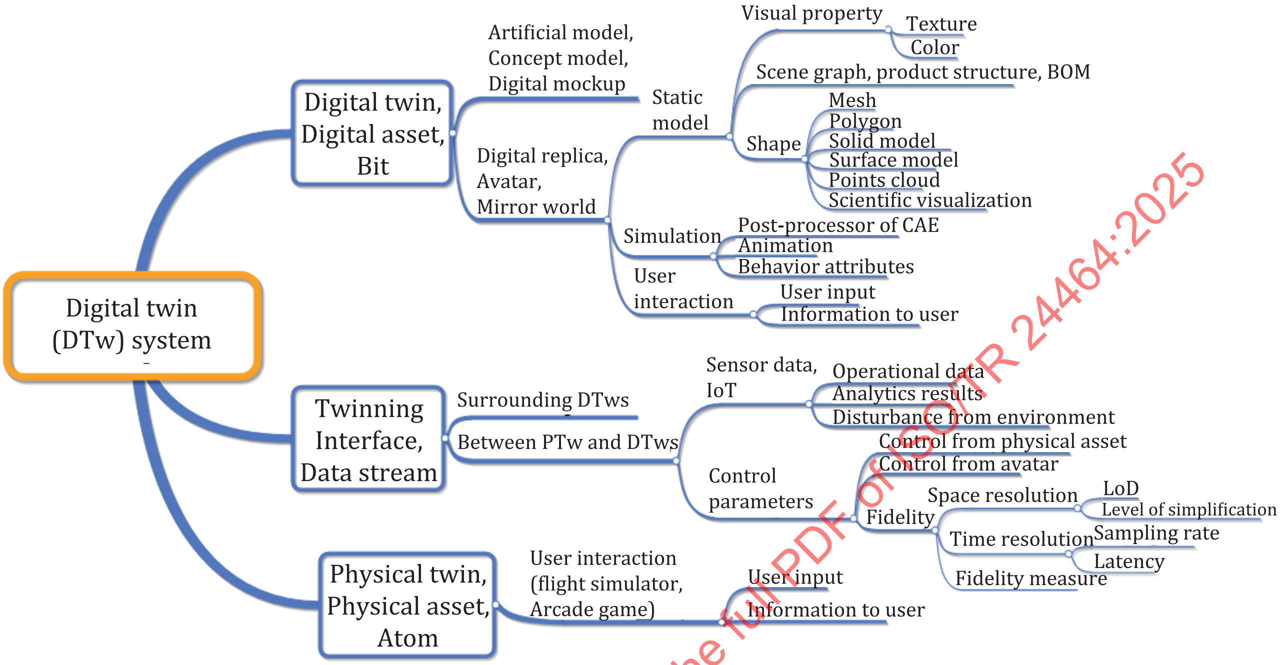


Figure 4 — Component technologies of DTw visualization

A substantial portion of the over 600 SMRL (STEP module and resource library) data models or product models (schemas) can be identified as components integral to DTws. The SMRL serves as the foundation for the STEP standard (ISO 10303 series), which encompasses not just design models but also those pertinent to production or manufacturing, including models dedicated to visualization purposes. For instance, the visual presentation aspect is specifically addressed in ISO 10303-46:2022, C.7.

6.3 Comparison with existing architecture

To explain the characteristics of the three-elements architecture, a comparative analysis with pre-existing architectures is conducted. Figure 5 illustrates the architecture outlined in the ISO 23247 series juxtaposed with the three-elements architecture detailed in this document. Within the scope of the ISO 23247 series, DTw applications, DTw, and certain aspects of the communication layer with physical devices are designated as "DTw for manufacturing". Whereas the present document classifies observable elements under PTw, and the communication layer is aligned with the twinning interface. It is noteworthy that "applications of DTw" are excluded from the iDTw system architecture as defined in this document.

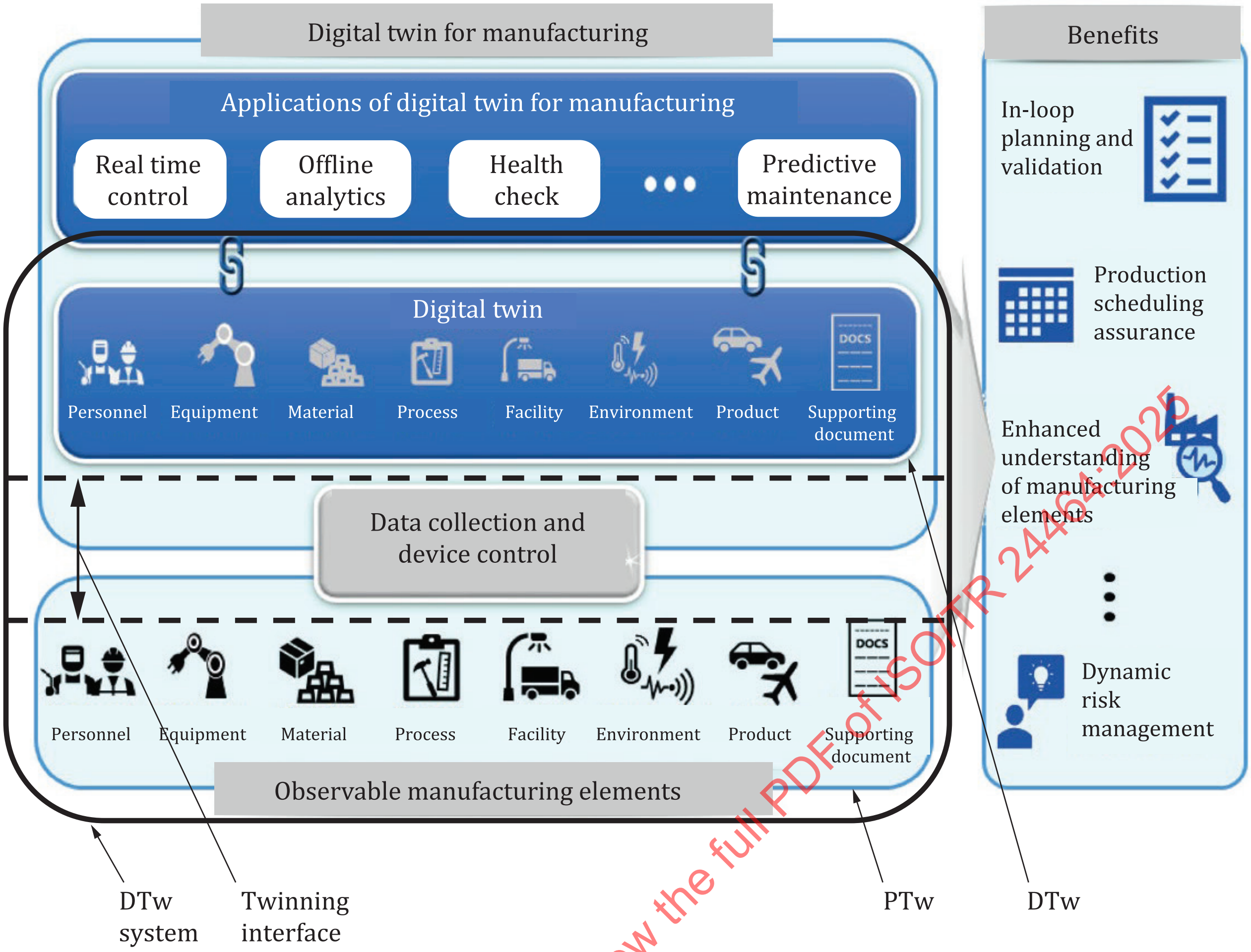


Figure 5 — Comparison with the ISO 23247 series

Figure 6 presents the reference architecture of the DTw as cited in Reference [16]. The components enclosed within the red box are indicative of the "iDTw system" as conceptualized within the three-elements architecture of this document. The real-world entity (RWE), which encompasses both a physical model and conceptual models or software (SW), aligns with the PTw as defined in this document. The real-digital gateway (RDG) is equivalent to the twinning interface outlined herein.

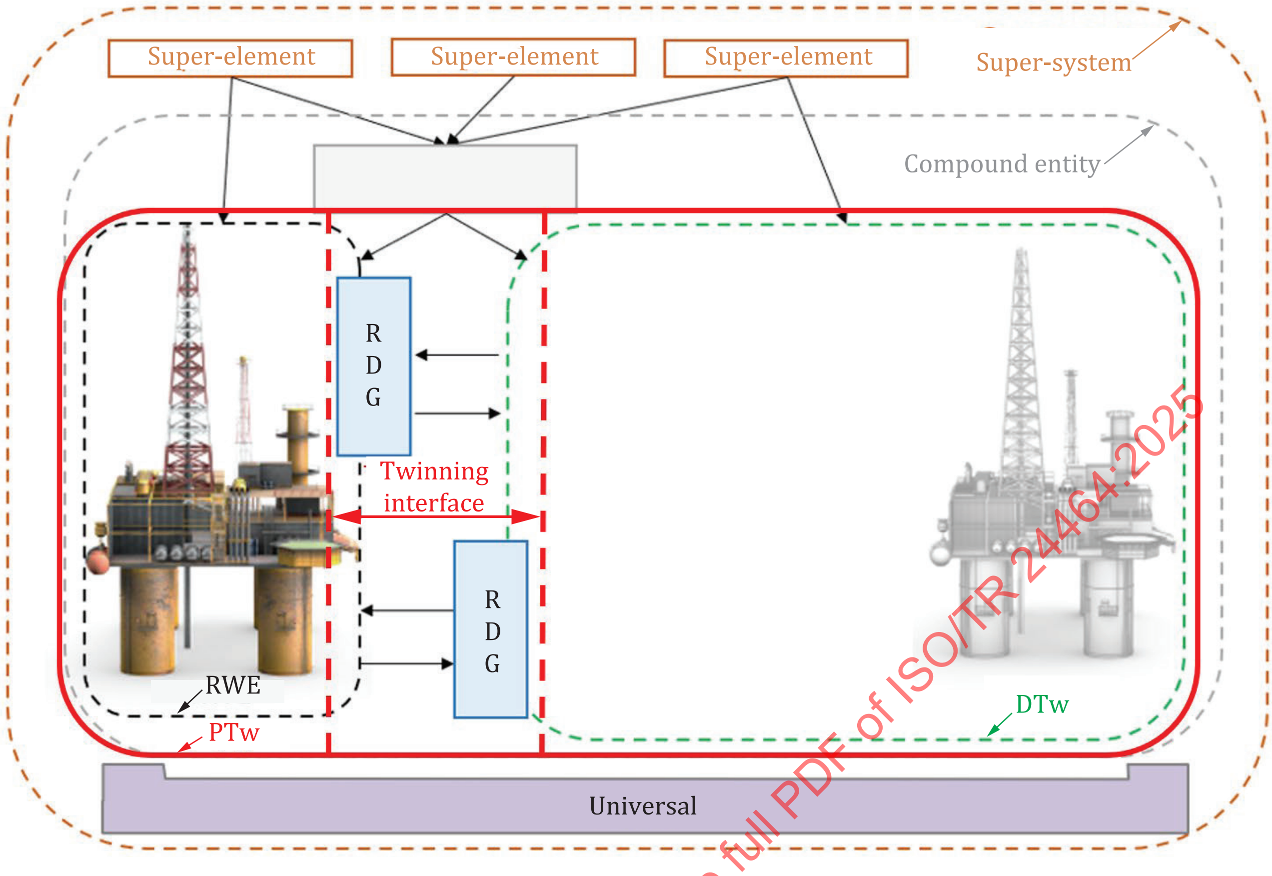


Figure 6 — Comparison with digital twin reference architecture [16]

Figure 7 illustrates the DTw ecosystem, which is further elaborated in Figure C.1[13]. An overlaid black box within this ecosystem delineates the scope of the iDTw system as defined in this document. Beyond the boundaries of the black box, the broader DTw system encompasses both a library and API components. The model encapsulated by the black box shares similarities with the iDTw system of this document, albeit with minor differences in terminology. The integration of modelling and data within this context is synonymous with the twinning interface of this document.

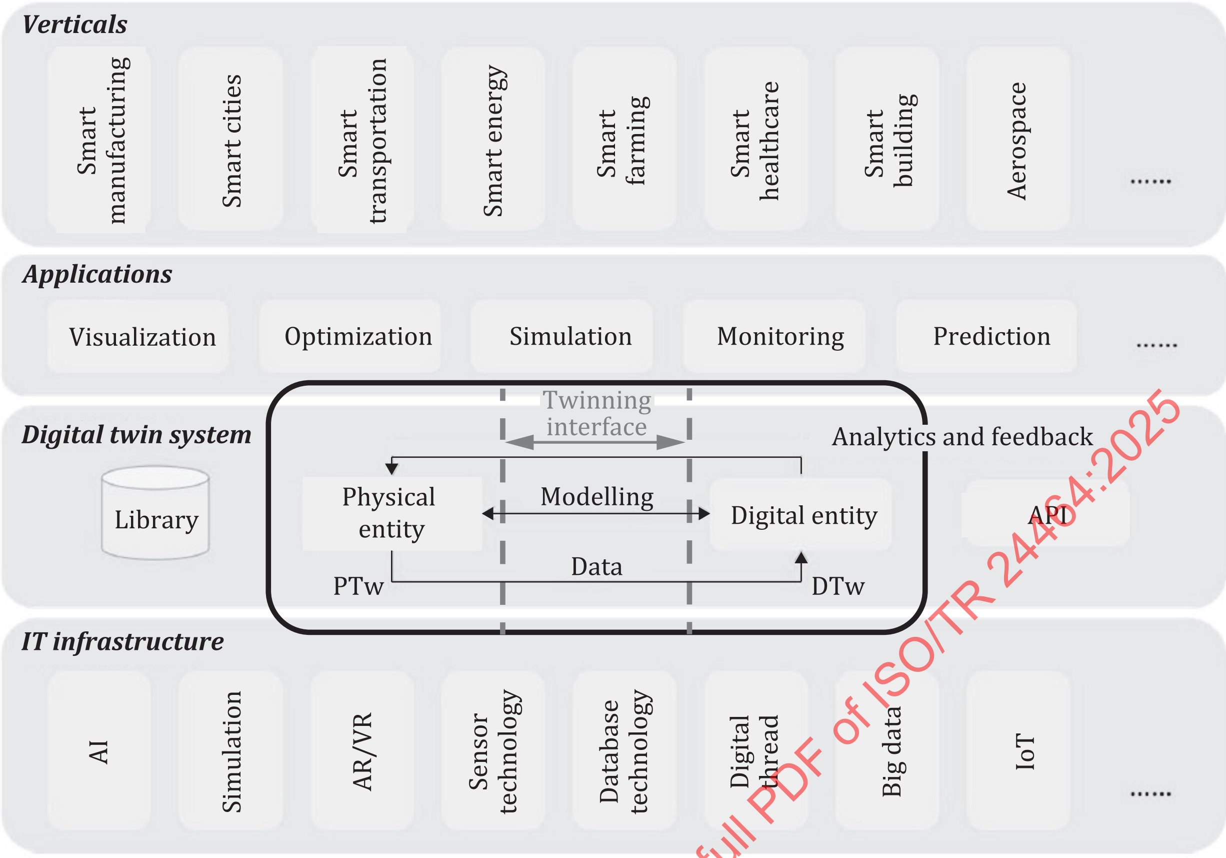


Figure 7 — Comparison with digital twin ecosystem architecture[13]

7 Characteristics of the iDTw system

7.1 Mutual augmentation through twinning cycles

7.1.1 General

If the DTw is perceived as similar to concepts such as CPS or augmented reality (AR), it might be criticized for lacking originality, potentially reducing DTw to just another industry buzzword. Identifying the unique features of DTw is crucial.

Previously, physical assets (PTw) and digital assets (iDTw) were developed and used separately, without significant integration or interaction between them. However, with the advent of high-speed internet technologies like 5G, the IoT, and digital sensor networks, there is now a closer interface between the twins.

It is anticipated that the twins, which were used independently, will develop into a relationship that complements each other, enhancing their overall effectiveness. The interface between the PTw and iDTw, which is near-real time and high-resolution, will be crucial. The ability to analyse big data exchanged between the twins, becomes important.

As illustrated in Figure 8 and Figure C.3, iDTw and PTw can support each other and improve the level of fidelity. The iDTw system increases the fidelity level of digital models by utilizing big data from the operation of physical products. The technology of monitoring and controlling physical products with computer simulation models has been in use for several decades. With digital models enhanced by operational big data, more accurate simulations and predictions are possible, enabling optimal control.

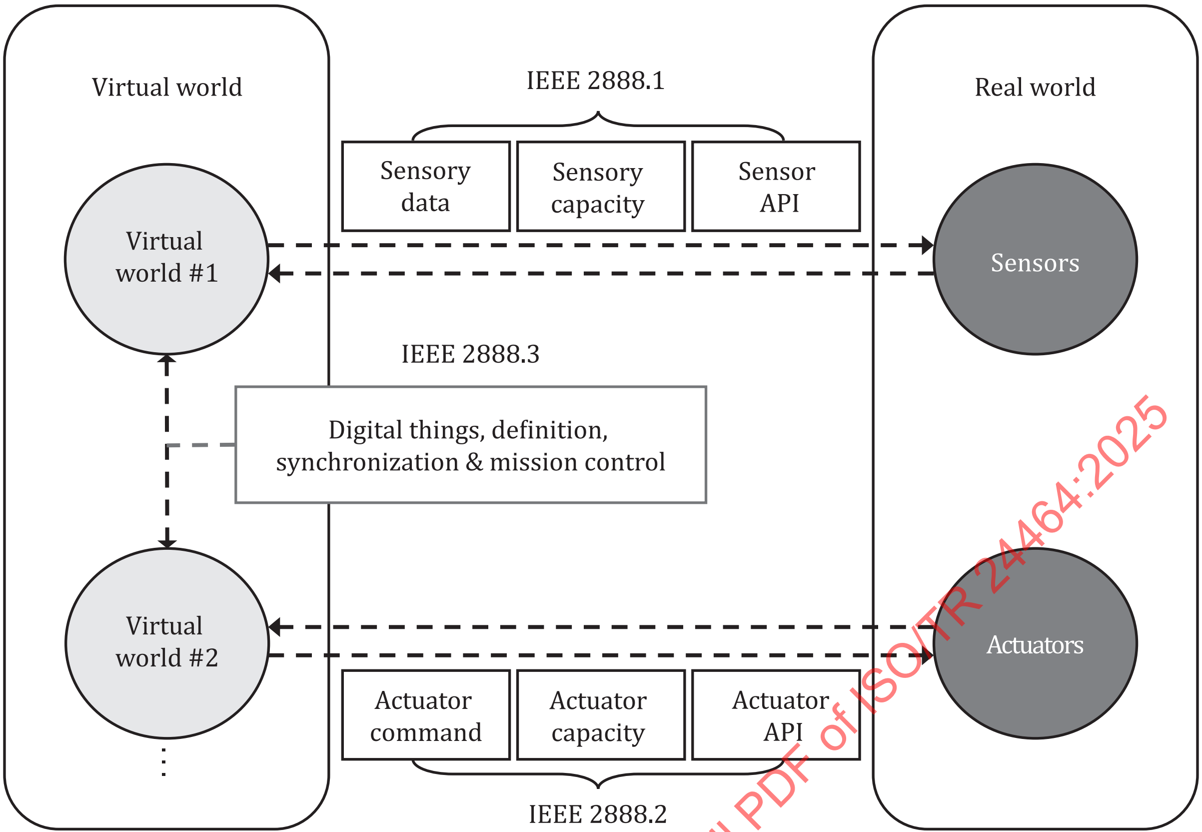


Figure 8 — Mutual twinning (IEEE 2888)

7.1.2 Augmentation from PTw to iDTw

Operational big data, gathered through digital sensors, is utilized to enhance the corresponding iDTw, facilitating improvements in the operational processes of physical products.

The initial design model, conceptualized prior to the realization of the physical model, often represents an idealized form, challenging to account for real-world environmental disturbances. While statistical techniques, employing historical data, can partially accommodate external disturbances, acquiring statistically significant environmental disturbance data in real time proves to be a complex task.

Enhancing the design model (iDTw) with operational big data, derived from real-world operations (PTw), is feasible. The practice of refining the (computer aided design) CAD model with point-cloud data from laser scans, as indicated in Table 1, is becoming an increasingly common practice among owner-operators of engineering plants.

Motion texture, a term utilized within the context of graphics rendering, aligns with the concepts of texture maps or depth maps. It specifically denotes data derived from motion capture processes. Motion texture serves to address the limitations inherent in traditional motion dynamics-based animation, contributing to an enhanced realism in the movements of digital characters of animation films.

Similarly, deficiencies in CAD models can be addressed through the integration of laser scanning models or point clouds. The amalgamation of data from the iDTw, such as the motion of polygons or kinematics, with big data from the PTw, including point clouds or motion textures, facilitates an elevation in the fidelity level of the iDTw.

7.1.3 Augmentation from iDTw to PTw

The integration of digital models (iDTw) with physical assets (PTw) encompasses both short-term and long-term augmentation strategies.

Short-term augmentation focuses on optimizing the operational parameters of the PTw by fine-tuning the control parameters for the asset's operation. This approach aligns with techniques already employed in automatic control systems.

Long-term augmentation, on the other hand, aims to enhance or upgrade the finished product by revising the design itself, thereby altering the design version. Such improvements can be achieved through simulations using digital models or by analysing operational big data. Occasionally, this process is undertaken internally by manufacturers over a medium-term period, involving quality inspections, while more extended periods of enhancement are driven by market feedback on the product.

The method of improving physical products through such augmentations is a well-established practice. With the increasing fidelity of iDTws, augmented by operational big data, enhancements to physical products can be executed with greater precision and comprehensiveness. This advancement also facilitates quicker response times, allowing for immediate adaptation to market feedback or changes in the product's operational conditions.

7.2 Life cycle of iDTw system

7.2.1 General

Throughout the product life cycle, the visualization elements and the necessary data exchange between the two components of an iDTw system, the iDTw and the PTw, evolve. The product life cycle encompasses stages such as planning, design, manufacturing, operation and maintenance (O&M), and disposal, with visualization elements adapting accordingly.

At the inception of the product life cycle, a PTw does not exist; only an iDTw or a conceptual model is present. Initially, the conceptual product envisioned by the designer is represented through hand sketches or as digital assets (iDTw) within a computer system. These digital assets can undergo validation or simulation within a virtual manufacturing environment. Subsequently, products materialize as physical assets (PTw) via physical manufacturing processes. From this juncture, both twins coexist, enabling the control of the PTw through actuators by leveraging real-time operational data from sensors and control parameters.

Figure 9 delineates the life cycle of the DTw, illustrating the transition of virtual products to real products via the production processes, a concept encapsulated within traditional product life cycle management (PLM) systems.

Throughout the operation phase of a real product, operational data are collected, verified and then utilized as the foundation for continuous performance enhancements. This life cycle model incorporates the three-elements architecture of an iDTw system, wherein the conceptual model or digital asset (iDTw) materializes into a physical asset (PTw). Moreover, performance indicator data are reciprocated through the twinning interface, facilitated by the IoT sensor network.

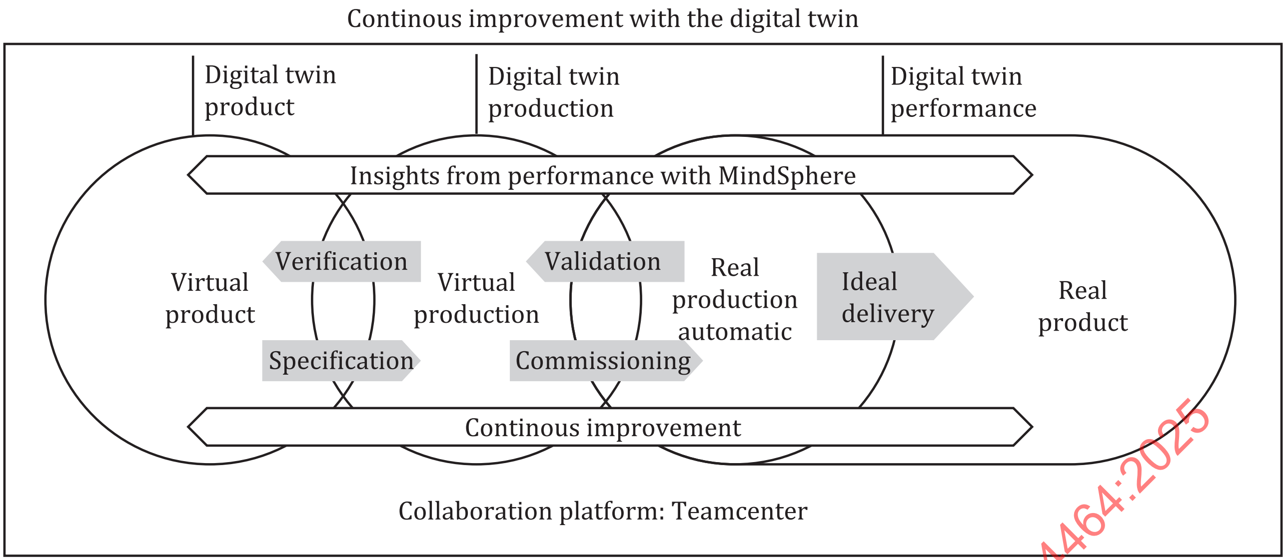


Figure 9 — Life cycle model of DTw

7.2.2 Separation between artificial model and digital replica

Within the life cycle of an iDTw system, a distinction is made between artificial (or conceptual) models and mirror models. Artificial models, which exist solely in the virtual domain, are differentiated from digital replicas of real objects that have physical world counterparts. The concept of mirror models[40] has led to discussions regarding its equivalence to the DTw concept. Mirror models serve as a distinguishing factor between virtual reality (VR) and AR; VR is composed entirely of artificial models, whereas AR integrates the mirror model of the PTw with the artificial model. Notable examples of mirror models include Google Earth, Microsoft's Virtual Earth, and automotive navigation systems.

A century ago, conceptual designs were initially conceived in the designer's mind and subsequently depicted on paper drawings. These drawings facilitated the transition of product concepts into physical products through production processes. With the advent of computers in the 1950s, the creation of digital models commenced. Today, various digital models and digital assets (iDTw) are employed, utilizing CAD software to transcend traditional paper drawings and achieve significant advancements.

The evolution of the Internet has revolutionized the utilization of operational data by transforming sensor data from analogue to digital format. Although analogue sensor data can indicate operational status, accumulating performance data in analogue form presents challenges. Currently, operational big data are collected via IoT and archived, interfacing with AI for diverse applications. Figure 10 encapsulates the process of concept realization. Technologies such as the iDTw system, AR and CPS facilitate feedback from physical assets (PTw) to digital assets (iDTw), enabling various enhancements through the analysis of operational big data.

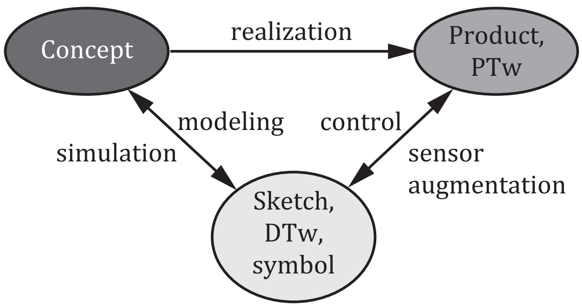


Figure 10 — Concept realization with iDTw system

7.2.3 Spatial fidelity enhancement along the life cycle

Figure 11 illustrates the development timeline of a product, referred to as the "valve", initiating from an artificial or conceptual model, progressing towards increased tangibility, and culminating in the realization as a physical product. Subsequently, a mirror model is derived from the physical product. This timeline allows for observation of the evolution in spatial resolution and spatial fidelity throughout the process, facilitating a distinction between the iDTw and the PTw (see also Table 1). Upon completion of the actual product (PTw) and the commencement of its operation, IoT sensors start generating operational big data.

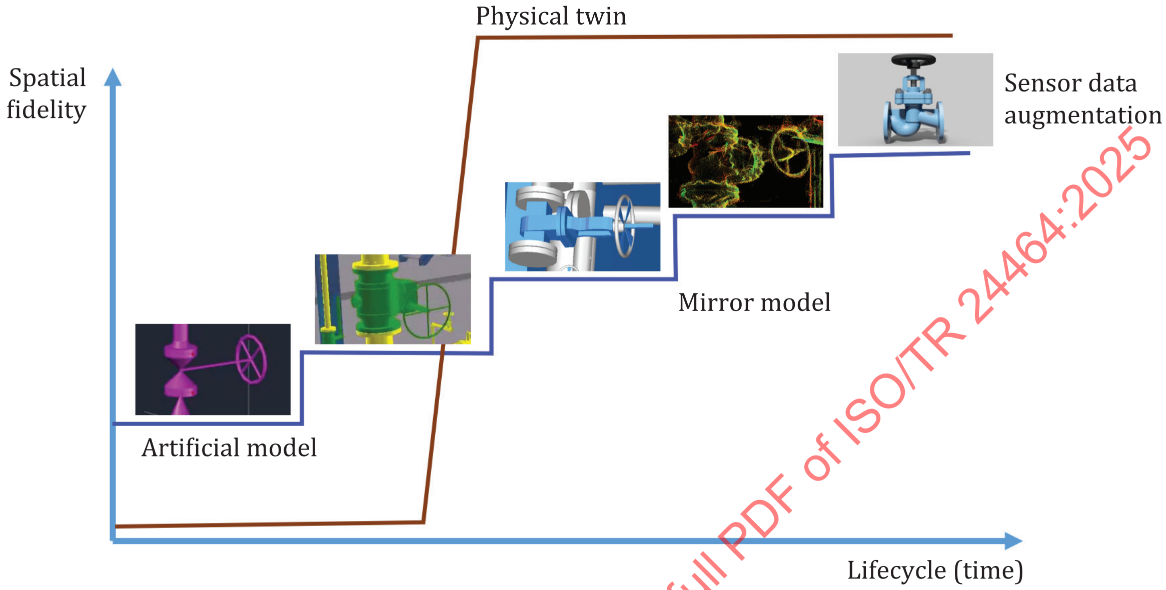


Figure 11 — Spatial fidelity along the life cycle of iDTw

7.3 Inclusion between iDTw and PTw

Within the context of smart cities' iDTw, an observed phenomenon is the challenge arising from the computer system hardware (HW) utilized for the iDTw system often being physically located within the PTw of the smart city itself. This scenario leads to a situation where the iDTw appears to be a component of the PTw, complicating the distinction between these entities, especially when considered on a global scale, such as an Earth-scale iDTw.

This document maintains a delineation between iDTw and PTw, even in instances where iDTw is situated inside PTw. The two entities, iDTw and PTw, are collectively defined under the umbrella of the iDTw system, which encompasses the twinning interface facilitating interaction between them. This approach mirrors the conceptual separation of the human mental world from the physical body. Figure 12 provides a visual representation of how the human mind operates.

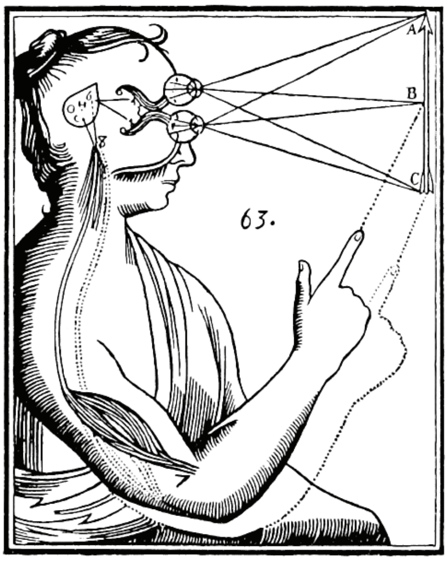


Figure 12 — Mind-body problem[41]

The semiotic triangle, a conceptual framework used to elucidate the relationship and operational principles between the human mind and body, is applied to analyse the inclusion relationship between the iDTw and the PTw. In Figure 13, the semiotic triangle's vertices represent a scenario where iDTw is positioned as an alternative representation of an object, given that iDTw constitutes a digital data compilation of the physical object. This arrangement suggests a bifurcation of the object into two distinct forms: a digital object (iDTw) and a physical object (PTw).

Incorporating a construct termed "symbol" into Figure 10 evolves the diagram into a semiotic triangle that encompasses iDTw. Within this framework, the concept is perceived as an entity residing in the human mind, positioning iDTw as an alternate depiction of PTw (the object) and categorizing it alongside the symbol. This perspective underscores iDTw's role as a digital manifestation of the physical object, aligning it conceptually with symbols in the realm of semiotics.

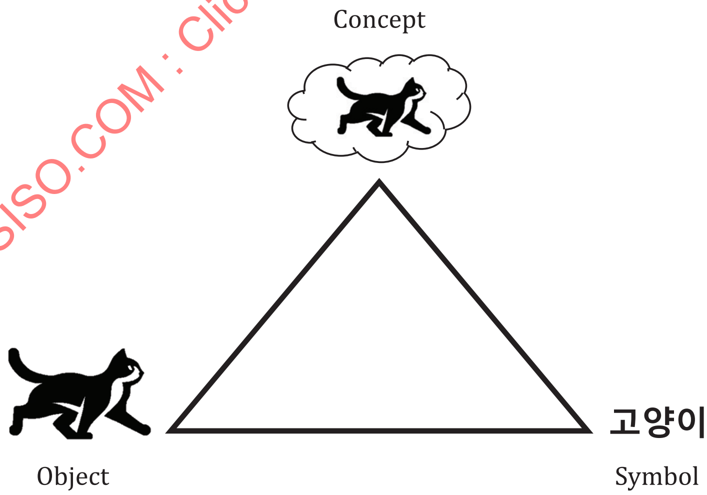


Figure 13 — Semiotic triangle

8 Visualization fidelity of iDTw

8.1 General

Visualization of a product's operational status is an established discipline within CG, commonly referred to as scientific visualization. To leverage the advancements in the CG domain, incorporating CG technologies as a visualization component within the iDTw system is advised.

Animation within this context extensively utilizes motion textures derived from data captured through motion sensors. Beyond traditional polygon mesh animation, there is a need for further technological advancements to adapt animation techniques to point cloud models. As an illustration, the concept of a 3D video could be introduced. Analogous to a 2D video, which sequences images of two-dimensional pixels along a time axis, a 3D video would sequence groups of point clouds, composed of three-dimensional voxels, in a temporal continuum. Similar to holographic technology, a 3D video could present varying images based on the observer's viewpoint.

Visualization fidelity serves as a metric to assess the equivalence between the iDTw and the PTw, taking into account both spatial and temporal dimensions.

8.2 Level of detail (LoD) of plant equipment models

Visualization models are essential in the processes of 3D printing and 3D laser scanning. Originating from traditional CAD models, 3D printing utilizes mesh models akin to those found in design or computer simulation models. The intricate micro-structures encountered in additive manufacturing demand an enhanced LoD for accurate depiction.

With the adoption of 3D laser scanning becoming more widespread, the introduction of point cloud models has become prevalent. These models offer an alternative or complementary approach to the conventional mesh models, highlighting the importance of examining the discrepancies or variations in detail levels between the two methodologies. As illustrated in Table 1, various LoD can be discerned, reflecting the fidelity level of the DTw [28].

Table 1 — Classification of plant equipment models based on LoD[28]

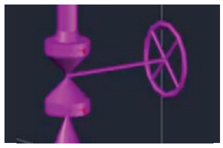
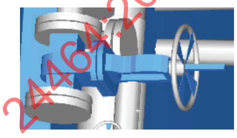
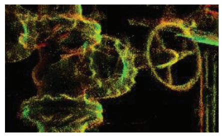
No	Type	Description	Example (Valve)
1	Symbol-level model (basic design stage, send to manufacturer)	Simple model (3-dimensionalized symbol from P&ID) Model in default libraries (known as catalogue model) provided by a PlantCAD system.	
2	Production model (production design stage of plant)	Model that a plant manufacturer re-models based on vendor-package (collection of 2D drawings, simplified symbol model) of equipment. The product model which is suitable for plant manufacturer.	
3	Handover model (reconstructed model from scanned data)	Model that a plant owner or operating company requests. Has different LOD depending on the requests.	
4	Scanned model (during or after construction)	A points cloud model from 3D scanning during or after manufacturing or construction of the plant It shows additional material such as insulation material surrounding the equipment.	
5	Detailed model from manufacturing (vendor)	Detail model of vendor for producing the equipment Contains all (geometric/non-geometric) information about the product, e.g. internal geometric information as well as detailed surface information. Due to security issues, only vendors have the model.	

Table 1 showcases a valve utilized within an ocean engineering plant, illustrating that, despite being the same valve, various computer model versions and levels of detail are employed at different stages of the product life cycle, including design and production phases in shipyards.

The Level 1 model presented in Table 1, while a 3D model, possesses a LoD akin to a two-dimensional symbol. In the plant industry, piping and instrumentation diagram (P&ID) drawings serve as foundational and critical representations, depicting equipment and their interconnecting pipes through symbols and lines, analogous to circuit diagrams in the electronics industry. Occasionally referred to as 3D P&ID, the digital valve models are typically sourced from default libraries (catalogue models) provided by commercial PlantCAD systems. Due to the simplistic 3D shape at Level 1, supplementary information such as attributes, annotations, or local conventions are appended as digital data.

Level 2 delineates the equipment's size and location by modelling the physical apparatus rather than employing 3D symbols, critical for assembling ocean plants like FPSOs or ships where three-dimensional size and location are paramount. Nevertheless, the Level 2 model simplifies the physical equipment's outline, avoiding detailed internal shape modelling to prevent the entire plant CAD model, potentially comprising 1 million pieces of equipment, from becoming unmanageably large. To circumvent this challenge, an "envelope" technique, which omits internal parts or features, is frequently utilized.

The Level 3 model represents the detail of the CAD model that is transferred to the owner-operator upon completion of the engineering plant. Historically, paper drawings were handed over to the owner-operator. However, with a growing trend towards automation of engineering plant operations, an increasing number of owner-operators are requesting more digital information, including detailed computer models that can serve as DTws. It is a customary practice in shipyards to initiate with a production CAD model as depicted in Level 2, subsequently refining and enhancing the Level 3 model by referencing the point cloud data acquired in Level 4, which is then provided to the owner-operator.

Level 4 encompasses a point cloud model derived from laser scanning the completed engineering plant. In large-scale constructions, such as engineering plants or high-rise buildings, minor discrepancies between the design drawings and the final product are occasionally discovered. The adoption of scanned point cloud data for quality inspections to identify these differences is gaining popularity.

The precision level required varies significantly across different product domains. For instance, dental bolts or construction bolts are manufactured from distinct materials and necessitate varying degrees of precision. Accordingly, iDTws with differing precision levels can be developed and utilized based on specific use cases.

The characteristics of the point cloud model vary depending on the timing of the scan, particularly during the construction stages of a building, where the appearance changes significantly with the progress of interior works. In many cases within engineering plants, steel pipes are covered with insulation material, raising the question of whether to include the insulation material's appearance in the scan. The insulation could obscure the mechanical devices, hindering the observation of their actual function.

Level 5 represents a CAD model provided by the manufacturer of individual pieces of equipment, which includes detailed modelling of both the external and internal configurations. As the equipment (e.g. a valve) constitutes the final product for the equipment manufacturer, detailed modelling of the equipment's components is essential for the manufacturing process.

Conversely, engineering plant manufacturers purchasing and installing the equipment (such as valves) focus primarily on the equipment's exterior for installation purposes and the connection points to adjacent pipelines, as reflected in the production CAD model (Level 2) of the engineering plant. However, for owner-operators tasked with the long-term O&M of engineering plants, a different level (Level 3) of the DTw is necessitated.

The depiction of the valve across the five distinct levels outlined in Table 1 demonstrates the varied modelling approaches throughout the design and construction life cycle of the equipment. The detail levels at each life cycle stage are not consistent, highlighting the diverse requirements and perspectives of different stakeholders involved.

8.3 Fidelity measure

8.3.1 General

Within the twinning interface that connects the digital asset (iDTw) with the physical asset (PTw), an in-depth analysis is conducted on the visualization elements that are either shared or integrated between the two. Discussions encompass visualization fidelity and metrics of fidelity to assess the congruence between the digital and physical manifestations of the asset.

Figure 14 illustrates the disparities between the design model (iDTw) and the actual manufactured product (PTw)[40]. The figure's left side displays a photograph of the completed product, the centre presents a CAD model of the designed product, and the right side showcases a point cloud derived from laser scanning, utilized to verify the product's accuracy.

In theory, the production of the product aligns with the design model and the specifications detailed in the design drawings. However, due to the intricate nature of complex engineering plants, the CAD modelling process often results in a simplification of the model's details. Moreover, minor discrepancies or errors may arise in the final product during the manufacturing phase. Identifying these minor differences between the design model and the manufactured product has become a common practice, achieved by laser scanning the completed product for quality inspection and comparing the outcomes with the generated point cloud model.

Beyond the discrepancies between the design and manufactured models, deviations may also emerge during the operation phases. On-site engineers at large facilities might implement modifications or add supplemental components without updating the master data, necessitating another rationale for scanning the physical product. This process allows for a comparison with the digital asset and, if required, an update to the digital asset to ensure accuracy and consistency.

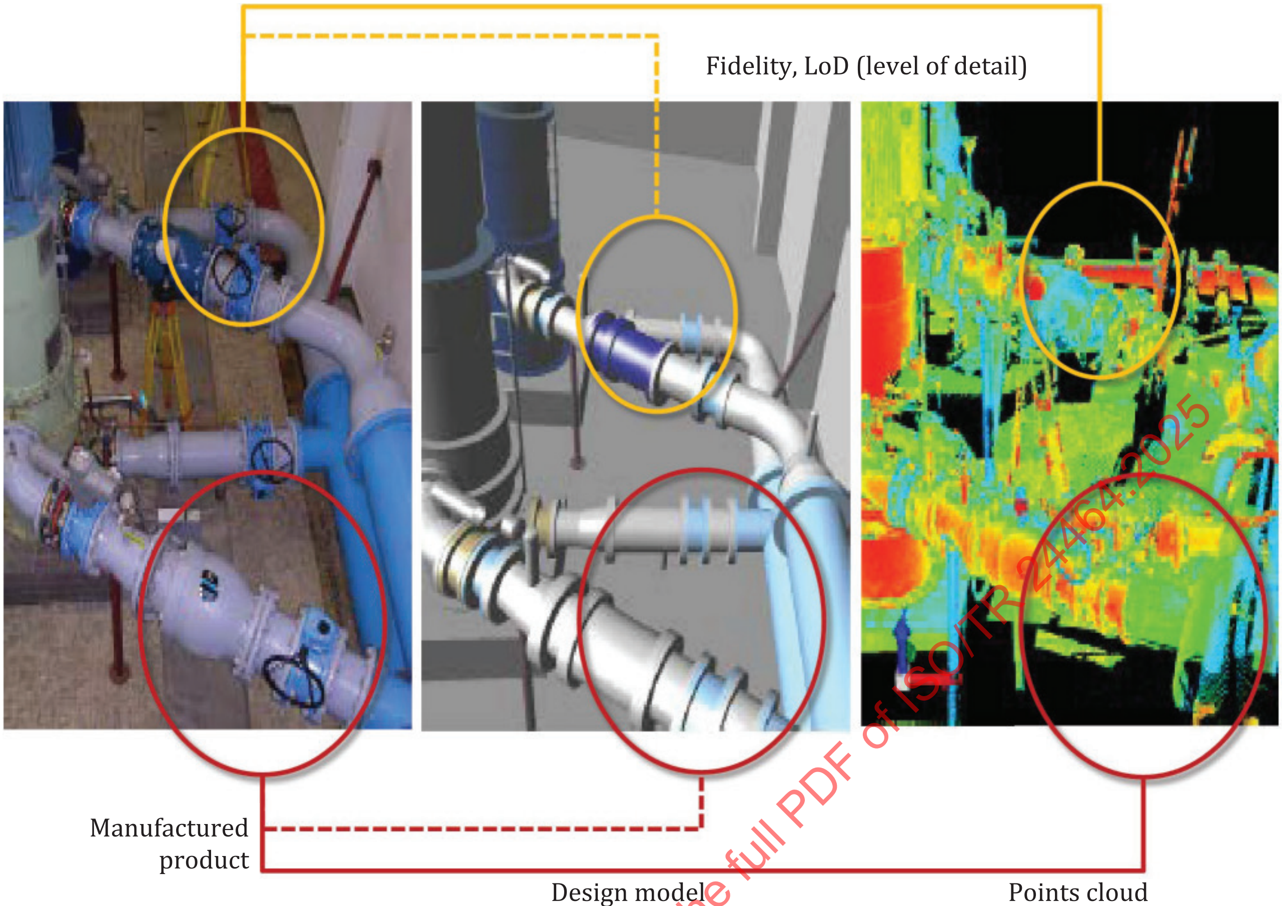


Figure 14 — Laser-scanned point cloud for verifying design model against manufactured product[35]

Digital assets, including iDTws or CAD models, as depicted in Figure 15, present a clear and aesthetically pleasing appearance but are, in essence, simplified representations of their physical counterparts (PTw)[36]. In the case of large-scale products such as automobiles or ships, it becomes challenging for digital assets (iDTw) to fully substitute physical assets (PTw), especially when detailed accuracy down to the nanoscale or molecular scale is imperative. Typically, physical assets (PTw) are considerably abstracted and modelled into the digital assets only to the extent necessary for the purposes of computer simulations.

Figure 15 — Fidelity comparison of physical asset, point cloud, CAD model

The concept of "fidelity" is adapted from terms such as HiFi (high fidelity) and WiFi (wireless fidelity), emphasizing the accuracy or exactness of reproduction. Fidelity encompasses various components that collectively define its characteristics. A fidelity measure serves as a tool to assess how closely digital assets (iDTw) mirror their physical counterparts (PTw). Within this document, two primary measures of fidelity are introduced: spatial resolution and temporal resolution. These measures are indicative of spatial fidelity and temporal fidelity, respectively, aligning with space resolution and time resolution.

8.3.2 Space measure: Spatial resolution

PPI (pixels per inch) or DPI (dots per inch) are metrics utilized to quantify the resolution in raster graphic devices such as displays or printers. While vector graphics held prominence in the early stages of CG development, contemporary graphics equipment predominantly employs raster graphics. The display resolution plays a critical role in determining the spatial resolution compatibility of digital assets (iDTw) with their physical counterparts (PTw). Figure 16 illustrates the range of display resolutions prevalent in the television and beam projector market.

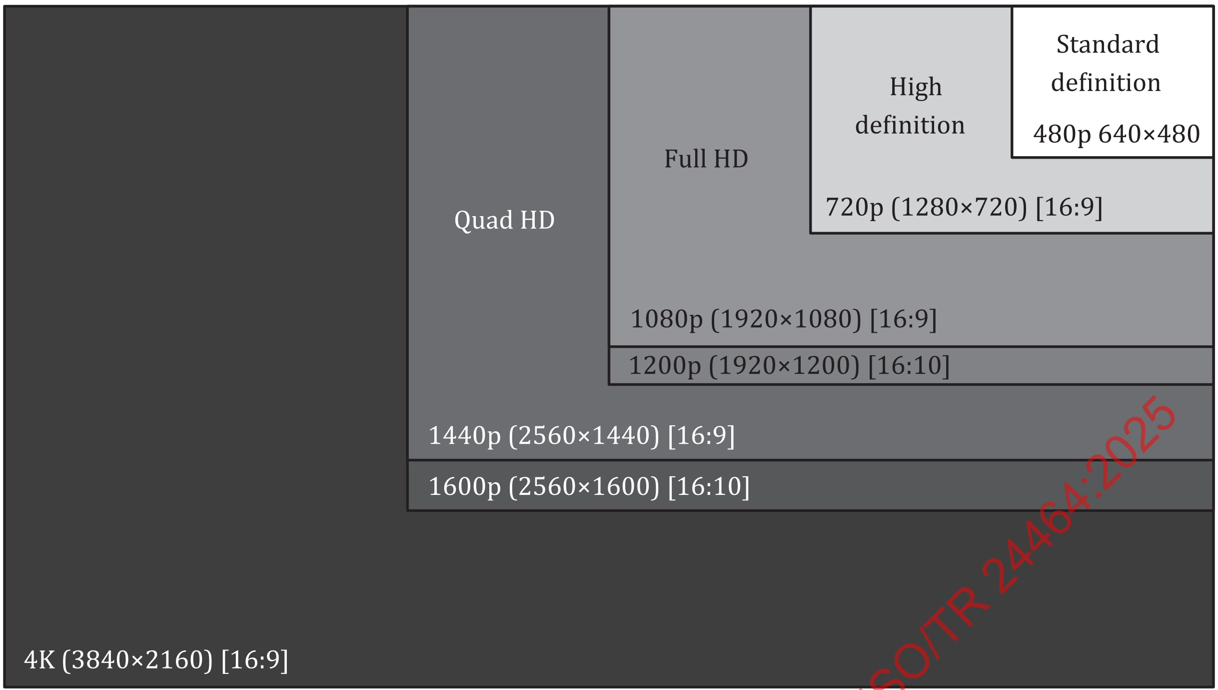


Figure 16 — Video file resolution

In the realm of digital model visualization, the quantity of meshes and the dimensions of each mesh are crucial factors. Similarly, the density of point clouds plays a vital role in accurately depicting the intricate details of the corresponding physical asset (PTw). When reduced to two dimensions, the 3D mesh analogously aligns with a 2D polygon, while the point cloud (voxel) is comparable to a pixel. The scale and count of these elements are significant parameters that define the resolution of the visualized space, impacting the overall fidelity of the digital representation.

8.3.3 Time measure: Latency and sampling rate

In the context of network delay, latency, as depicted in Figure 17, is characterized by the duration required for a request to travel from the sender to the receiver, coupled with the time taken by the receiver to process said request. An instance of this is the round-trip time between a web browser and a server.

— Latency is defined as the measure influencing the speed at which content is moved through a conduit from the client to the server.

— Bandwidth specifies the conduit's capacity, with its dimension dictating the volume of data that can be concurrently transmitted; a more constricted capacity results in lesser data flow, and the broader it is, the greater the data that can be moved.

— Throughput represents the volume of data successfully transferred within a specified time frame.

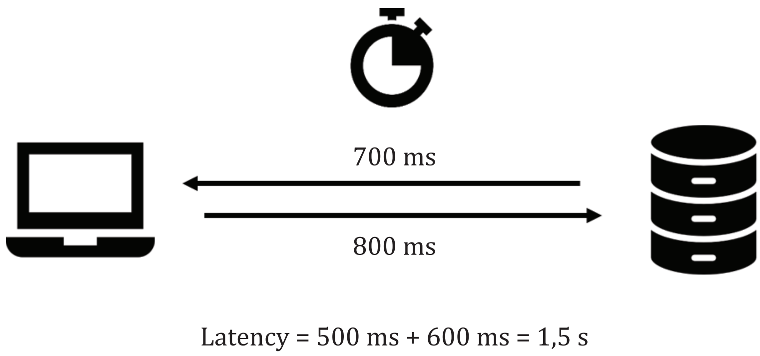


Figure 17 — What is latency?

Prior to the deployment of unmanned vehicles on highways or local roads in smaller communities, considerations regarding policy and safety require time resolution. Presently, technical challenges represent the most significant barrier to the implementation of autonomous vehicles.

Network latency emerges as a critical technical issue for preventing collisions. Although it is premature to determine if a rapid 5G wireless network will provide a comprehensive solution, 5G technology offers promising capabilities, including a significant increase in simultaneous connections (billions), reduced latency (1 ms for 5G versus 50 ms for existing 4G), and enhanced throughput (10 Gbps).

For aircraft, ships or ocean engineering facilities operating at considerable distances from populated areas, the necessity to transmit substantial volumes of data in real time is paramount. Consequently, both the speed and throughput of the data network serve as crucial metrics.

Data sampling rate serves as a critical parameter influencing visualization fidelity, analogous to how sound quality on a music CD fluctuates with changes in sampling rate, as depicted in Figure 18. The production of a 3D video, which integrates a point cloud sequence over time, is impacted by the sampling rate, directly affecting video quality. Given that the human eye typically perceives no discrepancy at a frame rate of 24 fps (frames per second), a similar fidelity measure—namely, the scale of sampling rate—is essential for achieving comparable time resolution in 3D videos.

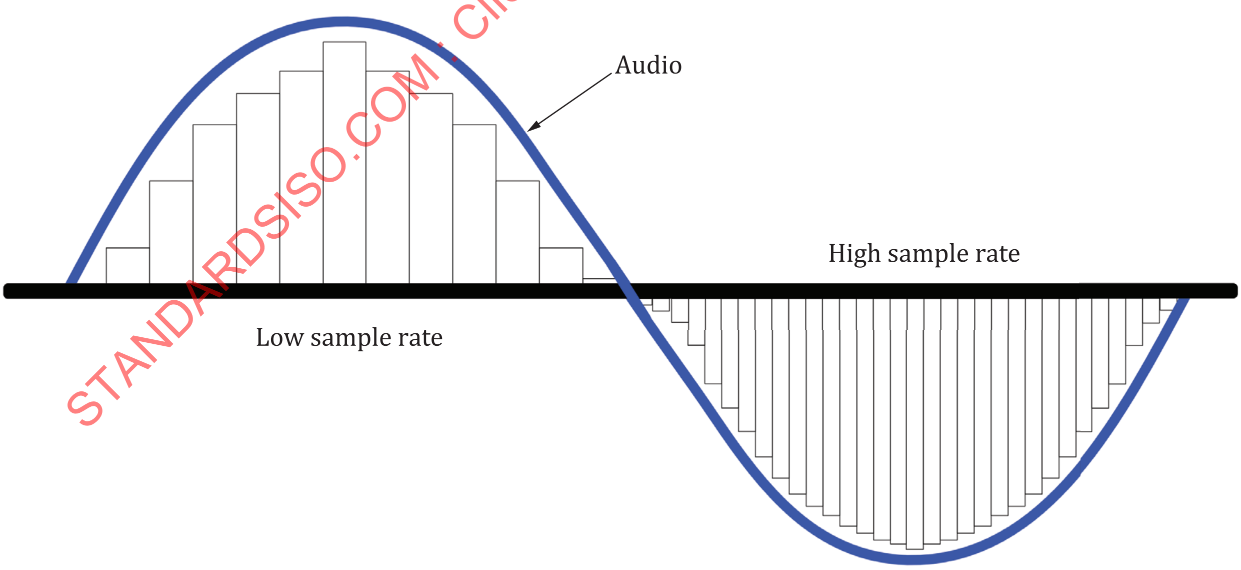


Figure 18 — Sampling rate

Annex A
(informative)

Collection of DTw definitions

Definitions of DTw have been aggregated from various sources. Table A.1 features a compilation where the definition provided by the Digital Twin Consortium[37] is integrated with the collection from Reference [25] representing a consolidation of definitions sourced from previously issued standard documents.

Table A.1 — Existing DTw definitions [25], [37]

Source	Output result
ISO/IEC 30173:2023 (JTC1/SC41/WG6)	digital representation of a particular entity or process with data connections that (1) enable convergence between the physical and digital states at an appropriate rate of synchronization, (2) has the capabilities of connection, integration, analysis, simulation, visualization, optimization and (3) provides an integrated view throughout the life cycle of the entity or the process
IEV 831-01-21[18] (IEC SyC-SC)	formal, explicit, computer-readable and computer-executable representation of an object or system
ISO/TR 24464:2020	compound model composed of a physical asset, an avatar and an interface
ISO/TS 18101-1: 2019	digital asset on which services can be performed that provide value to an organization
ISO 23247-1,	<manufacturing> fit for purpose digital representation of an observable manufacturing element with a means to enable convergence between the element and its digital representation at an appropriate rate of synchronization
Reference [24], B.8, definition 5	digital replica of physical assets (physical twin), processes and systems that can be used for various purposes
Reference [24], B.8, definition 6	fit for purpose digital representation of some realized thing(s) or process(es) with a means to enable convergence between the realized instance and digital instance at an appropriate rate of synchronization
Reference [24], B.8, "relevance".	Digital twin is a concept that will enhance the development and realization of smart manufacturing since, being based on measurements that create an evolving profile of the object or process in the digital world, it provides important insights on system performance, leading to actions in the physical world such as a change in product design or manufacturing process
Digital twin consortium[37]	A digital twin is a virtual representation of real-world entities and processes, synchronized at a specified frequency and fidelity.

The definitions of DTw presented in Table A.2 are replicated from the table in Reference [27].

Table A.2 — DTw definitions[27]

Key points	Definitions	Ref.
Integrated system	Integrated multi-physics, multiscale, and probabilistic simulation composed of physical product, virtual product, data, services and connections between them. An ultra-realistic integrated multi-physics, multiscale, probabilistic simulation of a system. A big collection of digital artefacts that has a structure, all elements are connected and there exists meta-information as well as semantics. Comprehensive physical and functional description of a component, product or system together with all available operational data. A systematic approach consisting of sensing, storage, synchronization, synthesis and service.	[16], [57], [58] [22] [53] [55] [60]
Clone, counterpart	Computerized clones of physical assets. The virtual and computerized counterpart of a physical system. Functional system formed by the cooperation of physical production lines with a digital copy.	[15] [46] [33]
Ties, links	Connections of data and information that ties the virtual and the real product together. New mechanisms to manage IoT devices and IoT systems-of systems. Technology that links the real and the digital worlds.	[19] [11] [65]
Description, construct, information	Comprehensive physical and functional description of a component, product or system. A digital information construct about a physical system. The notion where the data of each stage of a product life cycle is transformed into information.	[45] [24] [62]
Simulation, test, prediction	A safe environment in which you can test the impact of potential change on the performance of a system. Reengineering computational model of structural life prediction and management. A simulation based on expert knowledge and real data collected from the existing system. Virtual models for physical objects to simulate their behaviours.	[51] [20] [54] [56]
Virtual, mirror, replica	A virtual representation of the system. Digital mirror of the physical world. Digital model that dynamically reflects the status of an artefact. Detailed virtual model of ourselves. Virtual representation of a real product. A digital copy of a physical system. Virtual model of a physical asset. A replication of real physical production system. Cyber copy of a physical system. A dynamic digital representation of a physical system. A virtual model of physical object.	[27] [61] [63] [64] [47] [66] [67] [59] [48] [52] [34]

Annex B
(informative)

Selection of terms

B.1 Abbreviation for digital twin - DTw

The rationale for selecting key terminologies is elucidated.

The abbreviation DT frequently denotes digital twins in scholarly references. However, DT is more commonly utilized to signify digital transformation, a term with broader application than digital twin, leading to potential ambiguity.

In ISO/TR 24464:2020, "digital twin" is abbreviated to DTw. This abbreviation was introduced by Dr. John Dong, a professional affiliated with Boeing.

Furthermore, this abbreviation is recognized in ISO/IEC 30173.

B.2 iDTw system and twin siblings

In various references, a DTw typically signifies merely the digital representation of an entity. Nonetheless, within this document, the iDTw, its physical counterpart (PTw), and their interconnecting interface are collectively termed as the iDTw system, embodying a three-elements architecture (refer to Clause 6 for additional details).

Similar to how in human twin relationships, the older sibling is referred to as the elder twin sibling, denoting the pair with additional descriptors for clarity.

While the term DTw may at times denote solely the digital representation or alternatively be utilized to refer to the "iDTw system", addressing the term's polysemy through standardization is feasible. The formula, iDTw system = iDTw + PTw + Twinning interface, elucidates the distinction between iDTw and the iDTw system.

Figure B.1 reconstructs Table 2 from Reference [25], highlighting terms like twinning, synchronization, mirroring, convergence and relation, indicative of interactions between two entities. Consequently, this document defines the iDTw system as comprising both iDTw and PTw, with a twinning interface distinctly facilitating their interaction (also see Clause 6).

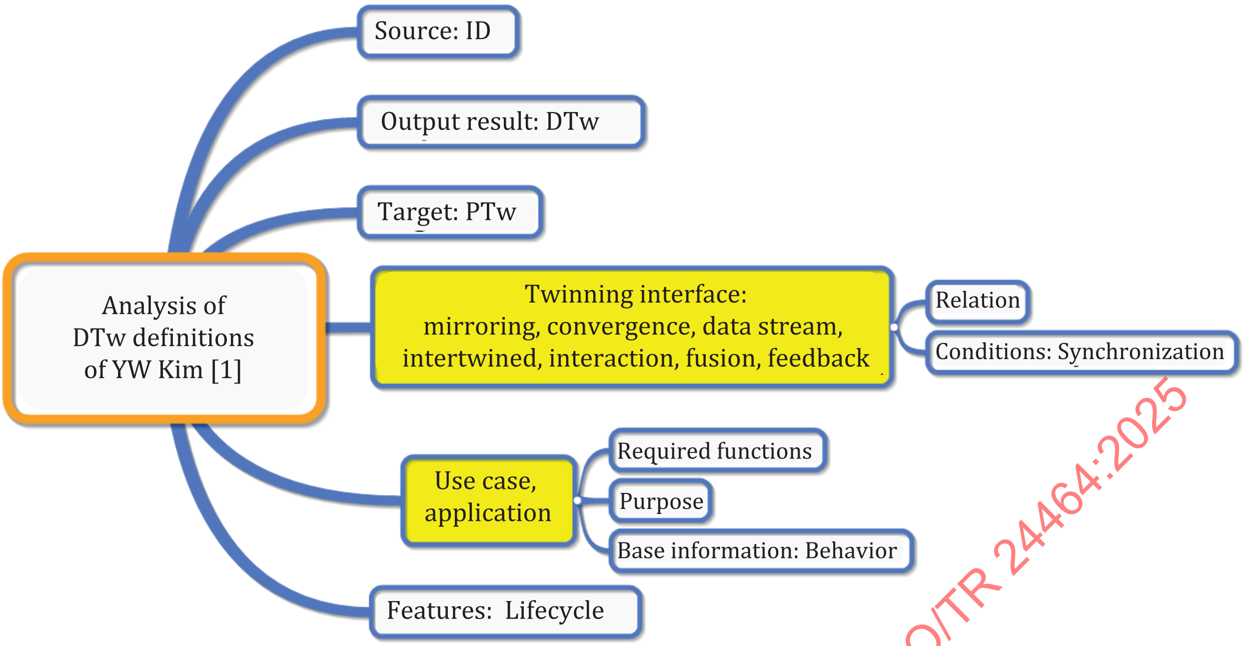


Figure B.1 — Keyword grouping of DTw definitions[25]

B.3 Three interfaces: twinning interface, human interface and federation interface

Interfaces between the iDTw and the PTw are delineated into three categories[27].

a) Twinning interface:

This interface facilitates the data flow between iDTw and PTw.

b) Human user interface:

Two variations exist for the interface with human users: one where the user interacts with PTw and another where the interaction is with iDTw. For instance, in a smart home scenario, the physical structure is PTw, whereas the smartphone represents iDTw. A user can activate a device directly within the home (PTw) or remotely via a smartphone application (iDTw). Thus, the human user acts as an element of the iDTw system's external environment.

c) Federation interface:

Interactions among diverse DTws' mirror those among components or entities within a tangible physical environment. In the context of a DTw federation, it is pertinent to consider the corresponding PTw federation of DTw constituents, necessitating the definition of a more intricate federation framework. Figure B.2 illustrates a case of the DTw Federation[38].

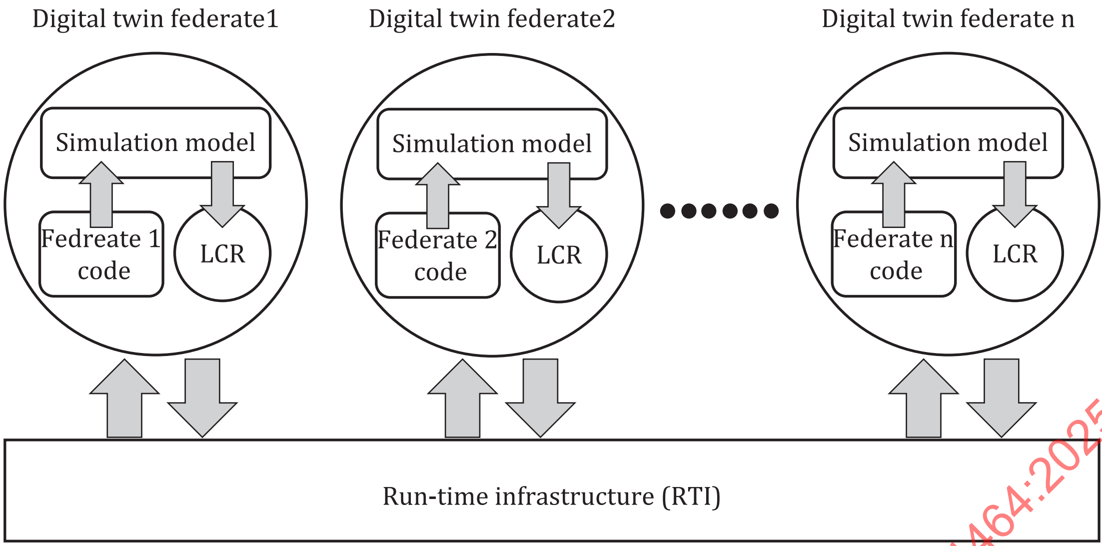


Figure B.2 — Digital twin federation based on high-level architecture (HLA)

Annex C
(informative)

Analysis of international standards related to DTw visualization

C.1 DTw

C.1.1 Reference architecture[16]

Figure C.1 is featured in ISO/IEC 30173, delineating the DTw ecosystem and its applications. This figure is structured into four distinct layers: the topmost layer catalogues the industrial sectors employing DTw, followed by the second layer which outlines general-purpose systems underpinned by DTw. The third layer encapsulates the DTw itself, aligning with this document's iDTw system and its three-elements architecture. The final, fourth layer compiles the IT technologies essential for DTw implementation. Notably, "simulation" is highlighted within both the second and fourth layers.

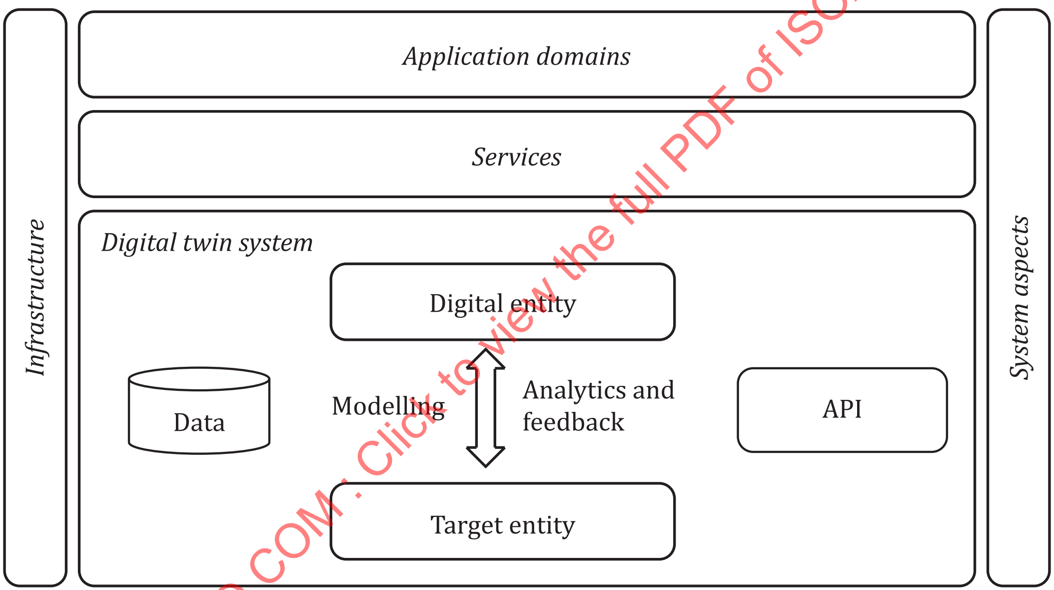


Figure C.1 — DTw ecosystem[13]

C.1.2 Concepts and terminology – ISO/IEC 30173

Figure C.2 encapsulates the terms and definitions featured in ISO/IEC 30173. On the left side of Figure C.2, the iDTw system is concisely outlined, aligning the terminology with the three-elements architecture described in this document.

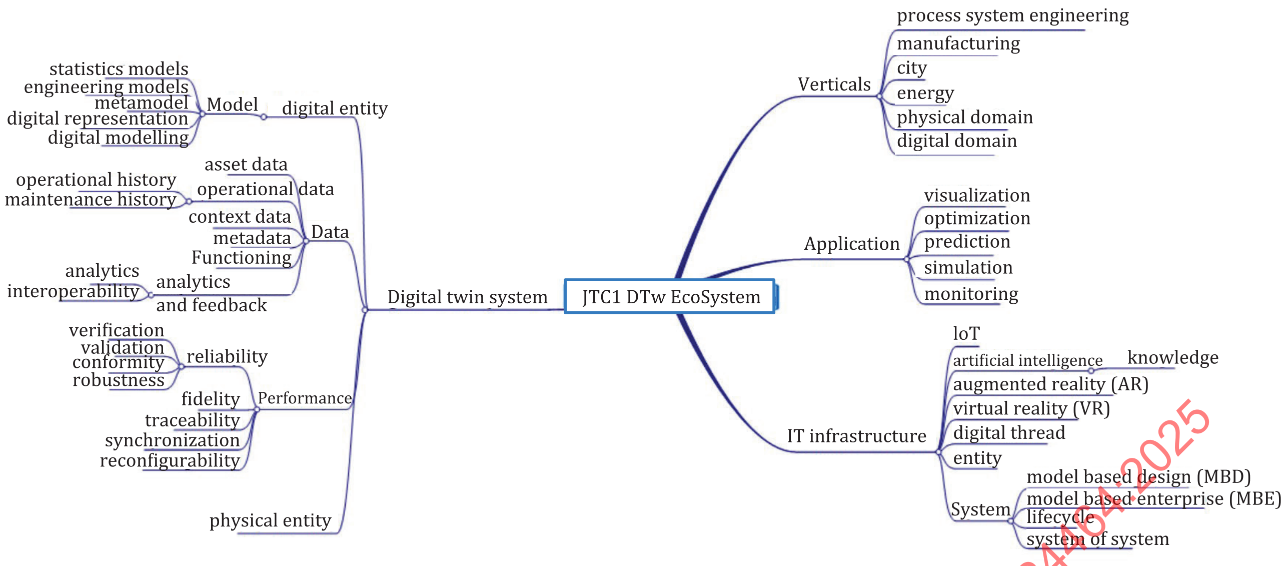


Figure C.2 — Terminology of DTw ecosystem[13]

C.1.3 Use cases – ISO/IEC TR 30172

For the aggregation of diverse DTw use cases, a standardized format is employed to compile these instances.

Use cases of the three-elements architecture of iDTw system are listed in Annex E.

C.2 Two journal papers of literature review

C.2.1 A Survey on DTw: Definitions, characteristics, applications, and design implications

The content of this journal paper[27] aligns closely with the assertions and explanations presented in this document. Specifically, the article discusses the data flow interface between PTw and iDTw, as well as the data flow interface between iDTw and its surrounding environment, corresponding to B.3. An excerpt from the journal paper is provided below.

The paper identifies three primary communication processes that can be established:

1) Between the physical and the virtual twin.

2) Between the digital twin (DT) and other DTs within the surrounding environment.

3) Between the DT and domain experts who interact with and manage the DT via user-friendly and accessible interfaces.

This document distinguishes the user interface between humans and the iDTw by dividing it into two sub-categories: one between PTw and humans, and the other between iDTw and humans. The interfaces involving adjacent iDTws are depicted in Figure 4.

C.2.2 Characterizing the DTw: A systematic literature review

This literature survey paper[30] compiles and scrutinizes approximately 100 publications pertinent to DTw. Terminologies are examined and categorized utilizing the CORPUS tool. Figure C.3 segregates the physical and virtual entities into two distinct pairs, enabling the differentiation of their interactions based on directionality. Notably, the concept of interaction is elucidated through the use of the term "twinning", with IT technologies employed at various stages presented within light green boxes.

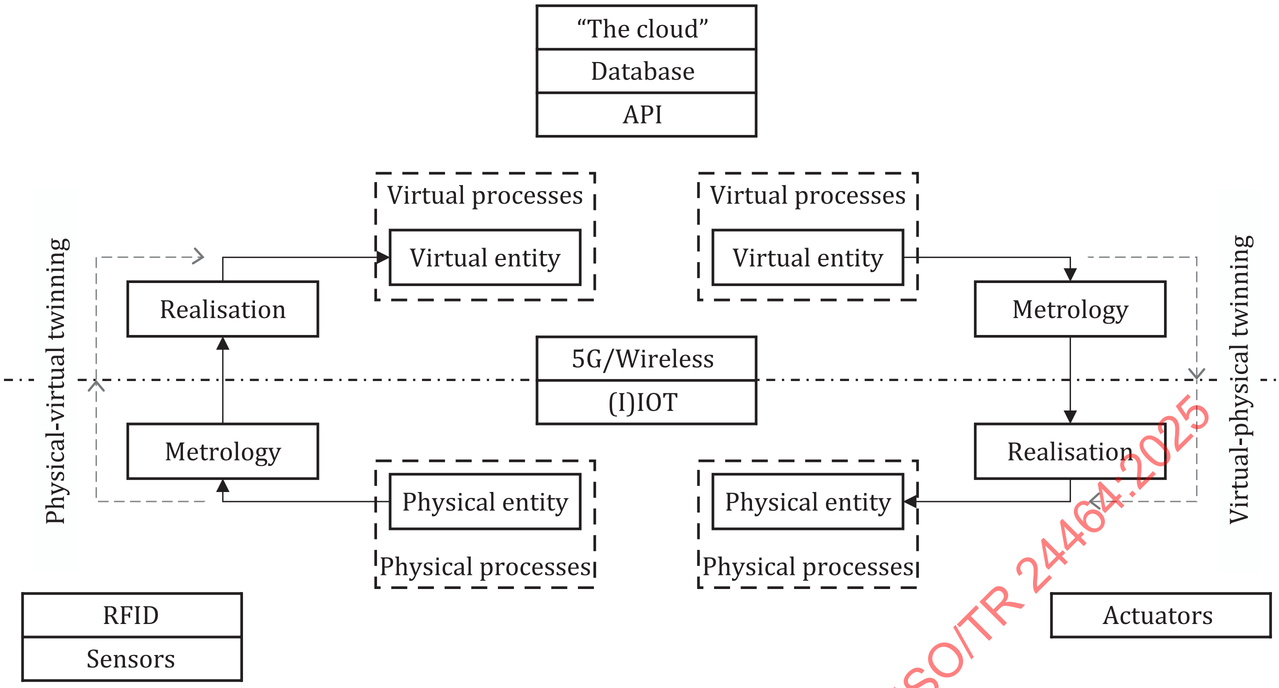


Figure C.3 — Technology mapped to the twinning cycle

Figure C.4 illustrates the outcomes of categorizing and consolidating keywords identified in the literature review,[30] aligning with the three-elements architecture outlined in this document. As depicted in Figure C.4, the keywords related to the interface aspect are further subdivided into two groups based on the directions of twinning.

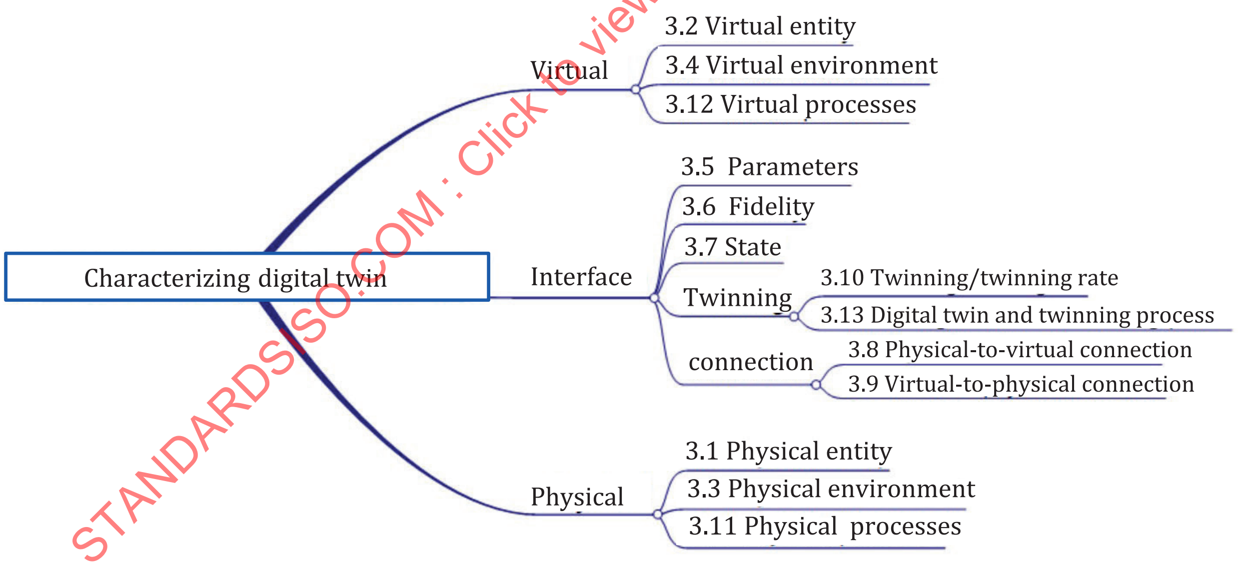


Figure C.4 — Grouping of DTw keywords of Reference [30]

C.3 Data architecture of the DTw [23]

The DTw data architecture[23] outlines two chosen definitions and provides five additional definitions for the DTw. While the original definition by Michael Grieves is highlighted at the report's outset, it is not among the two definitions selected. Conversely, this document embraces Michael Grieves' three-elements model. Furthermore, the report addresses the concepts of resolution, latency, and fidelity as detailed in Clause 8.

The term "digital twin" was originally introduced by NASA's John Vickers in 2002 and subsequently adopted by Michael Grieves in 2003. While Grieves' concept is rooted in the realm of PLM, NASA's engagement with DTw technology is driven by the operational needs of spacecraft, employing DTws for the maintenance and repair of systems in outer space.

Figure C.5 depicts the conceptual model of the DTw, comprising three primary components: a) physical entities within the tangible realm, b) digital counterparts within virtual environments, and c) the data and information bridging the virtual and tangible entities[31].

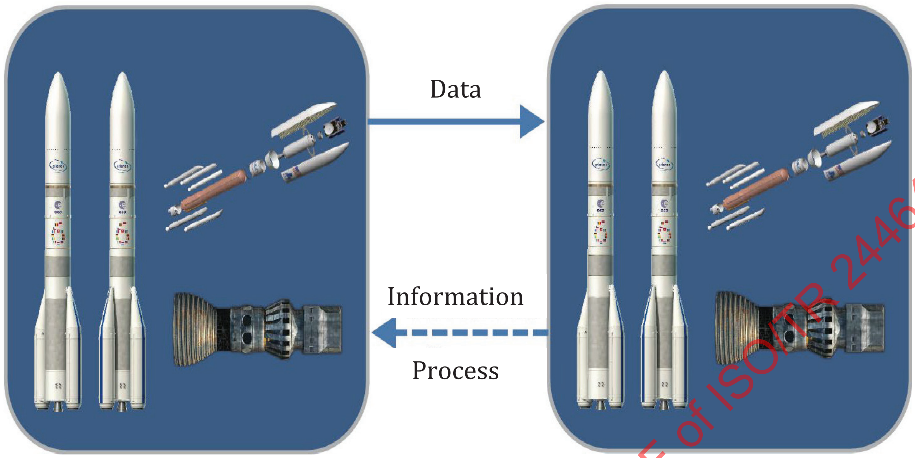


Figure C.5 — Information mirroring model[31]

Figure C.5 illustrates that the DTw comprises three components. The exchange of data between the twin entities is facilitated by a critical data interface. Notably, the near real-time exchange of large volumes of data are a defining feature of DTws. The utilization of big data, produced by the PTw's operations, to enhance digital assets (digital replicas) leads to improved operational efficiency and precision.

C.4 Technology trend report[14]

The Technical Trend Report (TTR) for digital twin[14] delineates seven definitions of the digital twin, encompassing the tripartite components model suggested by Michael Grieves. The definitions presented originate from Wikipedia, Deloitte, Japan's JST, GE, SAP, IBM, and Siemens, predominantly describing DTw as a digital replica of physical assets (PTw).

Figure C.6, featured in Reference [14], mirrors the three-element iDTw architecture outlined in this document. The foundational two layers in Figure C.6 represent the physical and cyber (digital) layers, between which real-time information is reciprocally exchanged. The top layer is depicted as an aggregation of application systems, employing the DTw system within an application stratum.

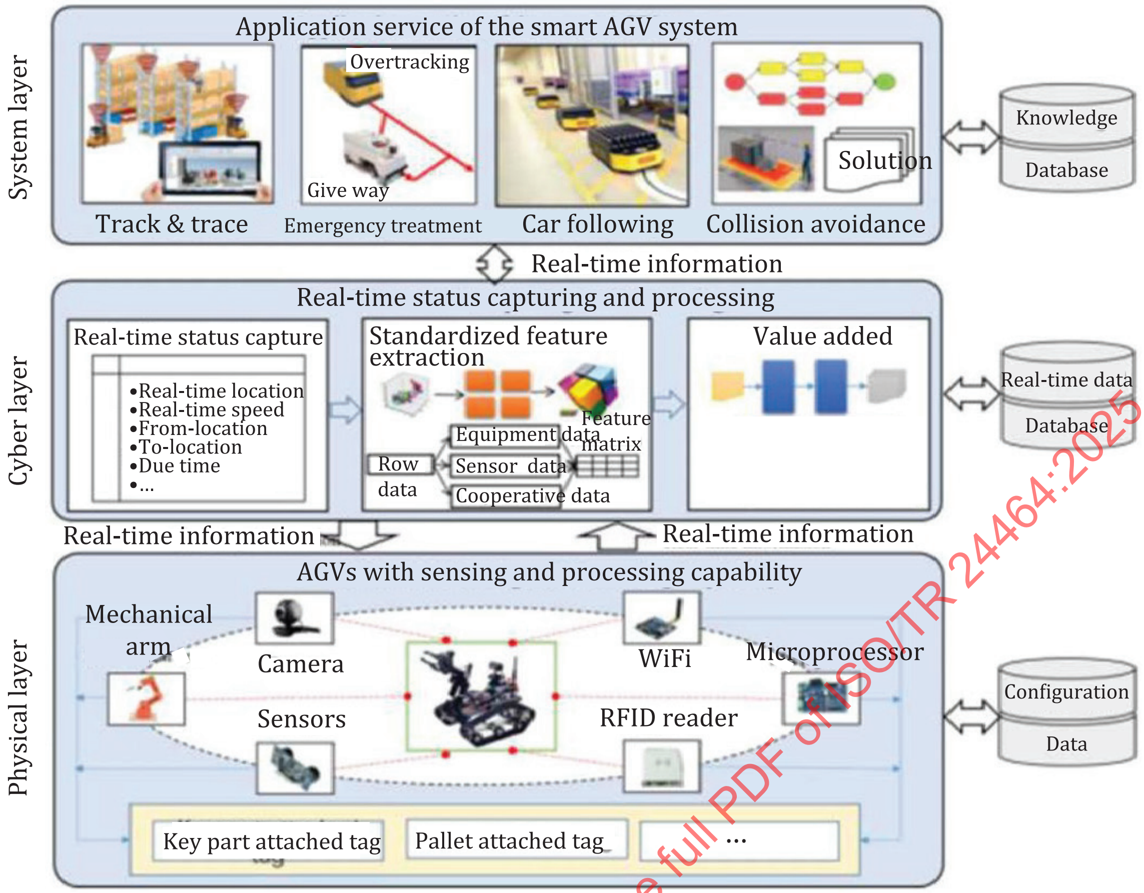


Figure C.6 — Instance of data management system[14]

C.5 ISO 23247 series - Digital twin framework for manufacturing[11]

Figure C.7, referenced from ISO 23247-1, depicts the process where physical facilities at the bottom layer are transformed into their digital counterparts, as illustrated in the middle layer. The uppermost layer represents a utilization layer, akin to the arrangement seen in Figure C.6, wherein this layer's foundation is the DTw positioned in the middle layer.

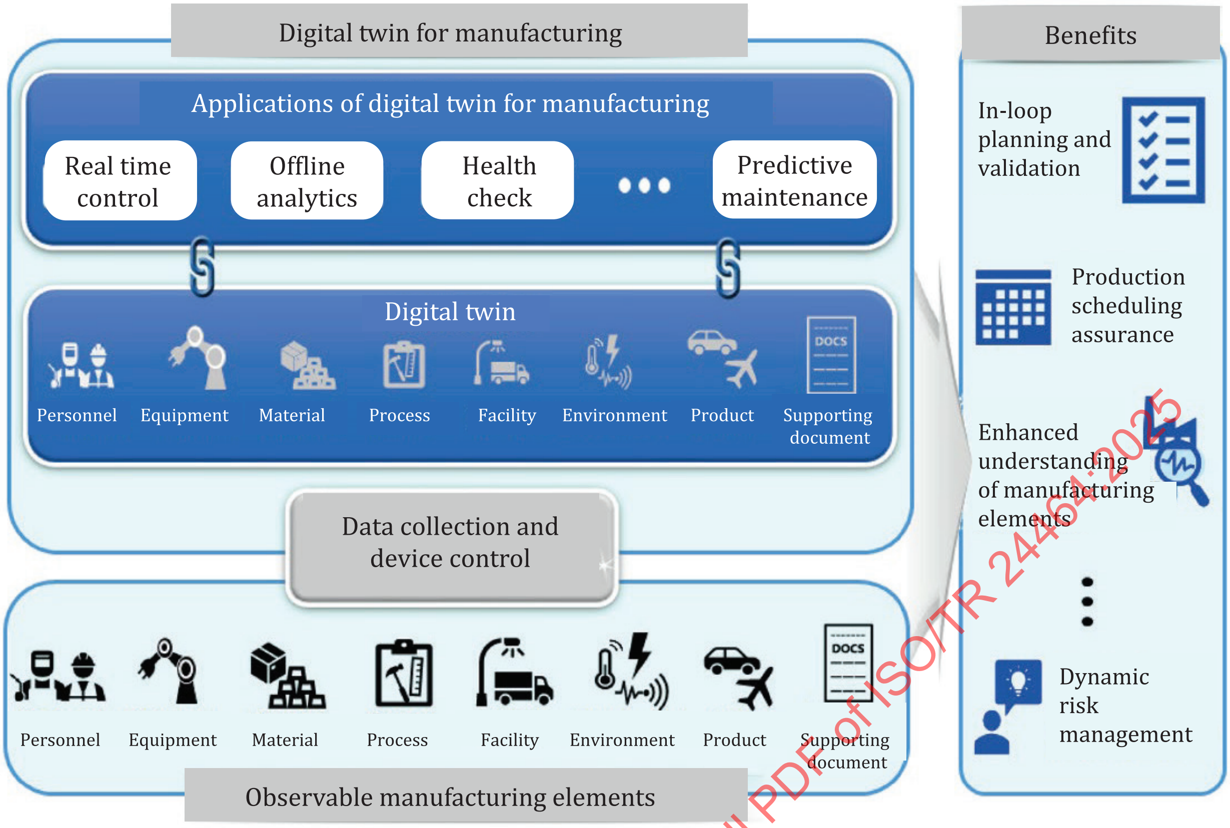


Figure C.7 — Concept of DTw for manufacturing[11]

The DTw for manufacturing, as outlined in ISO 23247-1, follows the digital transformation process from PTw to DTw and appears to concentrate primarily on the application of DTw within the manufacturing sector. Conversely, this document endeavours to deconstruct the iDTw itself, aiming to grasp the distinctive features of iDTw by examining its components, with a specific emphasis on the interface connecting iDTw and PTw.

C.6 Characterization of DTw[32]

The report[32] encompasses a diverse range of topics associated with DTw, extending into areas of literature and philosophy, such as endeavours to broaden the DTw concept to include Zhuangzi's butterfly dream.

Table C.1 delineates the DTw maturity model as presented in the report, bearing resemblance to the maturity model for smart cities. Level 1 is defined as the stage where digital modelling of DTw is finalized; Level 2 covers the monitoring and control mechanisms between DTw and PTw; Level 3 details the behaviours and simulations associated with DTw; Level 4 elucidates on the federation where DTws interact amongst themselves; and Level 5 portrays the autonomous phase of DTw.

Table C.1 — Maturity model of DTw[32]

Maturity level	Name	Functional requirements of elaboration
5	Live digital twins	Autonomous operations by live synchronization and orchestration
4	Interactive digital twins	Federation and interactive operation of DTws Federated and synchronized operations but human intervention for action
3	Active digital twin	Behaviours and dynamics for operation represented as virtual models What-if simulation provided Cause analysis by reproductive simulation Synchronized operations but human intervention for action
2	Static digital twin	Connection and communication mandatory Real-time monitoring Partial automatic control but mainly manual control Status and control displayed
1	Dimensional digital twin	Physical entity modelled dimensionally and visualized in 2D or 3D Connection and communication not mandatory

This document's iDTw system primarily emphasizes the first and second levels of the maturity model depicted in Table C.1, with aspects of level three also being marginally incorporated.

C.7 Visual presentation (ISO 10303-46)

In accordance with ISO 10303-46, presentation data are amalgamated with product data for interchange across diverse industrial systems. This presentation data encompasses elements such as presentation style, occlusion, invisibility, markers, fonts, fill styles, shading, rendering and colour[12].

C.8 Organizations for DTw

Interest in smart manufacturing and smart city initiatives is on the rise, recognized as a core aspect of the Fourth Industrial Revolution. In this context, new terminologies such as DTw, RAMI4.0, AAS, and CPS are being introduced[28].

The JWG21, responsible for developing the Smart Manufacturing Reference Model (SMRM), consists of members from IEC Technical Committee 65 (Industrial-Process Measurement, Control, and Automation) and ISO Technical Committee 184 (Automation systems and integration). The Task Team TF8, established in summer 2019 within JWG21, focuses on DTw and Asset Administration Shell (AAS).

Advisory Group 2 (AG2) of ISO TC 184 is addressing the DTw topic (see also C.3). Additionally, in November 2020, the ISO/IEC Joint Technical Committee 1/Subcommittee 41 launched Working Group 6 on DTw, leading to the update of the title of JTC 1/SC 41 to include DTw in addition to IoT (see also C.1)

Annex D
(informative)

Comparison with CPS and AR

D.1 General

Examination of the principal components of the iDTw system reveals parallels with the elements found in CPS or AR. Through the analysis of CPS or AR components, the similarities and distinctions relative to the iDTw system can be discerned. Formal concept analysis serves as a technique for evaluating similarities through element comparison.

D.2 Formal concept analysis

Formal concept analysis (FCA) constitutes a systematic approach for generating a hierarchy of concepts or a formal ontology based on a set of objects and their attributes. This methodology is underpinned by the mathematical constructs of lattices and ordered sets.

A foundational data type in this framework is a data table depicting a heterogeneous relationship between objects and attributes, documenting pairs in the format "object g possesses attribute m". Such a structure is termed a formal context. Within this framework, a formal concept is articulated as a pair (A, B), with A representing a collection of objects (referred to as the extent) and B embodying a collection of attributes (termed the intent), where:

— A, or the extent, comprises all objects that collectively possess the attributes denoted by B, and conversely,

— B, or the intent, includes all attributes common to the objects in A.

The goal of FCA (formal concept analysis) is to enhance the conceptual clarity by elaborating on the observable and fundamental properties of the encompassed objects.

D.3 Cyber physical system (CPS)

The concept of CPS was inaugurated in 2006 by Helen Gill at the National Science Foundation to describe systems integrating computational, networking, and physical processes. Subsequent to its introduction, CPS research has flourished within both the academic and industrial sectors. Figure D.1 delineates the CPS's standard layout, reflecting a structure akin to the DTw system, encapsulating three elements: a PTw, an iDTw, and a twinning interface.

The CPS is structured around three pivotal elements: the physical world, the cyber world, and their communication, marked by the integration of mechanical devices and their digital counterparts. Unlike the IoT, which predominantly concentrates on the physical domain, CPS features a cyber model designed to emulate the functionalities of physical assets.

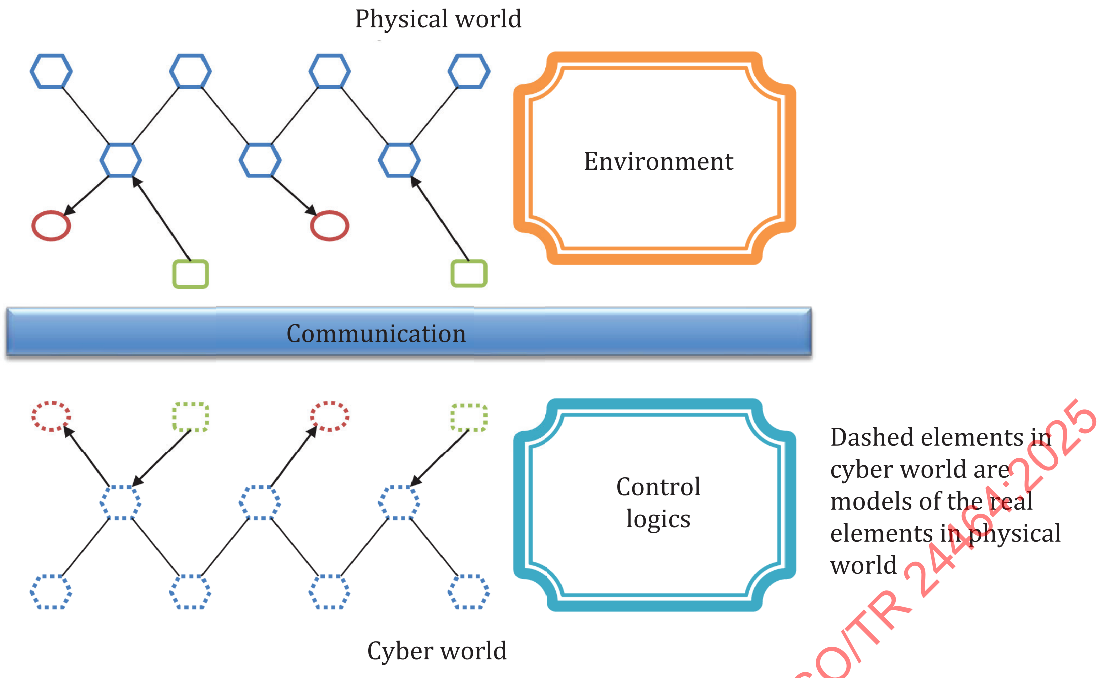


Figure D.1 — A typical CPS[36]

Figure D.2 presents a use case of CPS within the manufacturing sector. CPS is defined by a digital thread that forges a linkage between the cyber world and physical world. This integration is exemplified through cyber twins and physical assets, which collectively represent various manufacturing equipment, interconnected by the IoT.

A CPS is conceptualized as a system composed of cyber twins and physical assets reflecting the real world, alongside a digital thread that serves as the interface uniting them. The assembly of physical machinery constituting a smart factory and the digital assets (iDTw) mirroring these physical components embody an iDTw system. Consequently, both CPS and the iDTw system share analogous components.

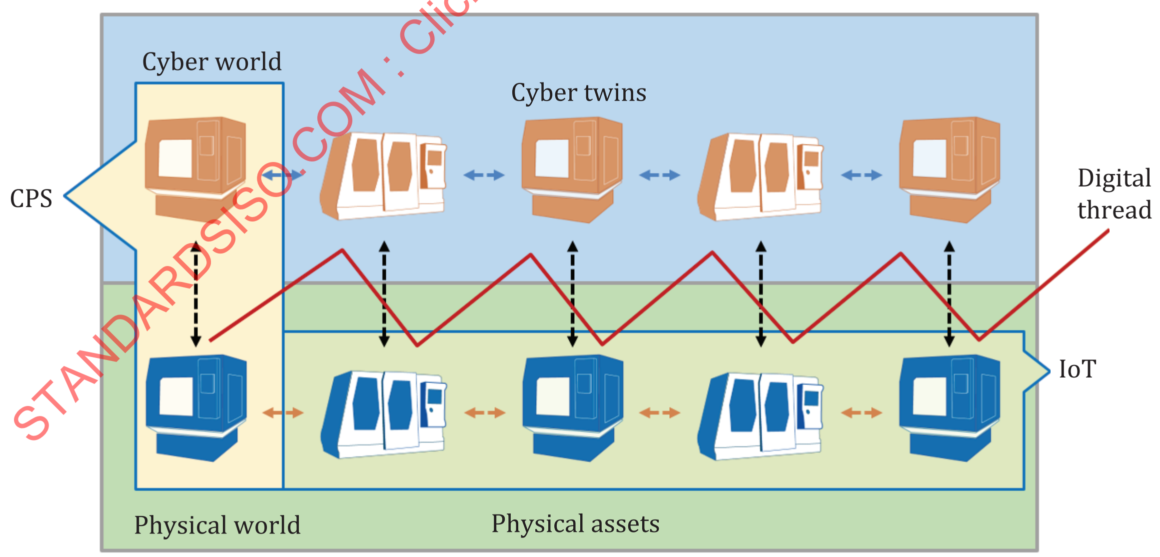


Figure D.2 — Cyber-physical manufacturing system

The AAS, launched under Germany's Industry 4.0 initiative, serves as an interface or pathway for digital transformation, facilitating the linkage between physical reality and the digital realm. AAS is also considered an embodiment of the DTw concept within smart manufacturing. Defined narrowly as a digital replica, AAS embodies the transition of a PTw to an iDTw.

CPS can be understood through both narrow and broad definitions. According to IWA 39:2022, 3.1, the extensive interpretation of CPS is a system incorporating digital, analogue, cyber, physical and human components that interact seamlessly, designed to operate via unified physics and logic. Conversely, the concise definition from ISO 23704-1:2022, 3.1.8 describes CPS as physical and engineered systems managed, coordinated, controlled, and harmonized by a computational and communicative core.

Figure D.3 depicts the tripartite architecture foundational to a CPS, comprising the cyber world and physical world linked by a digital thread. This configuration mirrors the three-element architecture of the iDTw system described in this document.

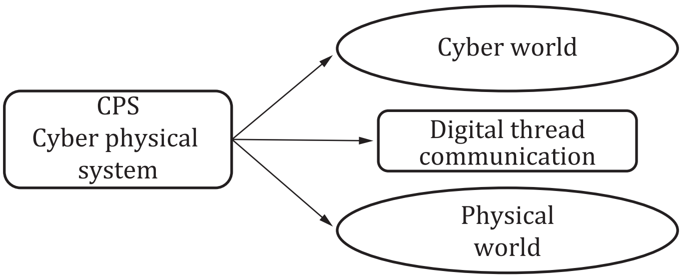


Figure D.3 — Three-elements architecture of CPS

D.4 Mixed and augmented reality (MAR) (ISO/IEC 23488)

In DTw visualization, methodologies from VR and AR are applicable, incorporating elements such as shape, colour, texture and movement animations of the DTw as part of the visualization characteristics.

Furthermore, the visualization can extend to sensor data depicting the operational condition of the PTw, paralleling the visualization techniques of post-processing in numerical simulations.

Mixed reality (MR) and AR, technologies popularized through Pokémon games, have evolved within CG since the 1980s. Despite VR being foundational to MR and AR, these technologies share numerous parallels with CPS and the iDTw system, especially in the integration of real-world data with virtual imagery.

Figure D.4 illustrates the mixed augmented reality (MAR) framework according to ISO/IEC 23488, aiming to standardize MAR. Figure D.4 delineates MAR's dual aspects: a real (R) root and a virtual (V) root, enabling players, through devices like Google Glass, to navigate between the real and virtual realms seamlessly.

Within the AR model framework, the real and virtual roots are interconnected by various nodes. While AR places a greater emphasis on human user interfaces, its structure resonates with the iDTw system or CPS, featuring a PTw, an iDTw, and an interfacing layer, constituting a three elements system.