University of Stuttgart
Institute for Control Engineering of Machine Tools and Manufacturing Units (ISW)

Digital Twins

And the Asset Administration Shell

Prof. Dr. rer. nat. habil. Andreas Wortmann

Question

Is the Asset Administration Shell a Digital Twin?

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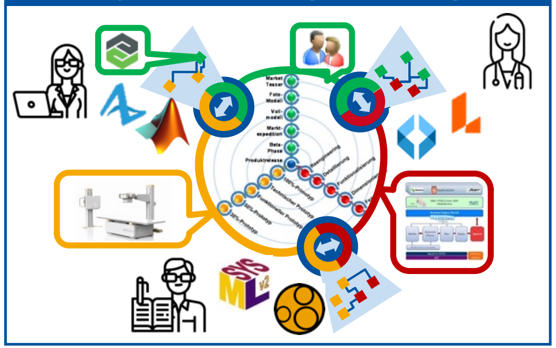
Institute for Control Engineering of Machine Tools and Manufacturing Units (ISW)

- Director of ISW, University of Stuttgart
- Professor for Model-Driven Development in Manufacturing
- European Association for Programming Languages and Systems
- Research interests
  - Model-driven engineering
  - AI for engineering
  - Digital twins
  - Cyber-physical systems
- 160+ publications (h: 38, i10: 93)
- Organized 40+ conferences, founded EDTconf.org

Advanced Software and Systems Engineering

Through better abstraction and automation

Model-Driven Software & Systems Engineering

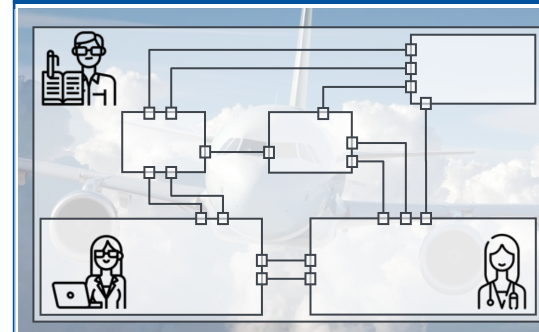


- Component-based language engineering
- Modeling languages
- Model-Based Systems Engineering
- MDE for service robotics

Artificial Intelligence for Engineering

- Sustainable IT/OT through better software
- Automated program and model optimization
- Software engineering and modeling assistance

Methodical Model-Driven Operations



- Digital twins for monitoring, control, optimization
- Integrate explicit models of domain expertise
- Better understanding and more efficient use of CPS

A Simple Truth about Digital Twins

A digital twin represents a system

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A Simple Truth about Digital Twins

Is it?

A digital twin represents a system

Is it always one? Can there be many?

Digitalization entails abstraction: how much can we abstract?

What does it mean to be a twin?

Is this the only purpose?

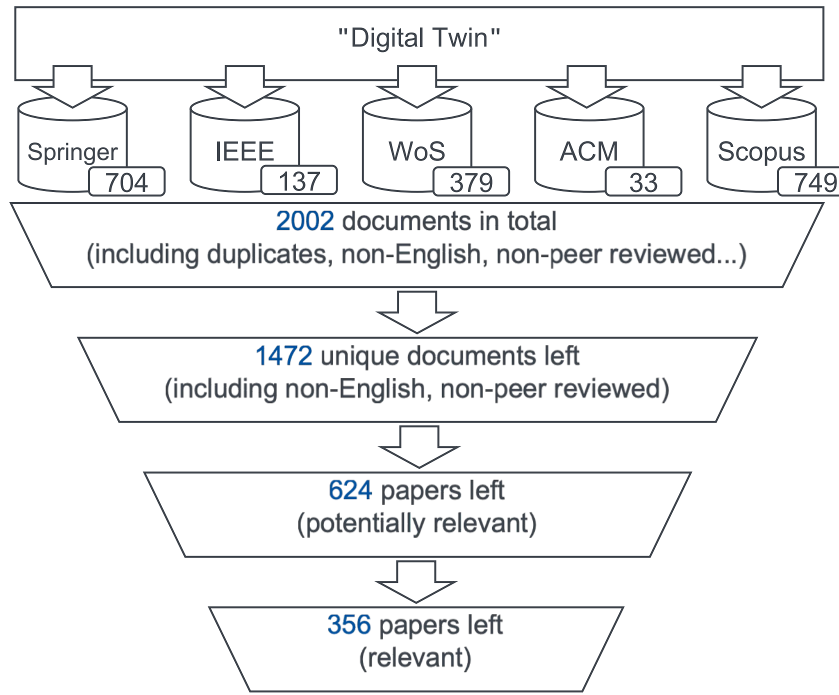
A single one? Many? Systems-of-systems? Does the system need to exist already?

Does it need to be a CPS? Process twins or person twins?

A Cross-Domain Systematic Mapping Study for Digital Twins[1]

Research questions and overview

1. Who uses Digital Twins for which purposes?
2. What are the conceptual properties of Digital Twins?
3. How are Digital Twins engineered?
4. How are Digital Twins deployed?
5. How do Digital Twins operate?
6. How are Digital Twins evaluated?



1. M. Dalibor, N. Jansen, B. Rumpe, D. Schmalzing, L. Wachtmeister, M. Wimmer, A. Wortmann: A Cross-Domain Systematic Mapping Study on Software Engineering for Digital Twins. Journal of Systems and Software, 111361, 2022

How Research Describes Digital Twins

And why this is problematic

Ambiguous Descriptions

Refer to other, undefined, terms

- "digital avatar" [74]
- "replica of a business process" [337]
- "mimic of a real-world asset" [386]
- "digital equivalent to a physical product" [523]
- "digital duplicate" [1389]

Narrow Descriptions

Focus on a specific kind of system or implementation tech.

- "digital model of the real network environment" [379]
- "a virtual representation of a specific product" [388]
- "virtual representation based on AR-technology" [827]

Unfeasible Descriptions

Theoretically nice, practically unfeasible

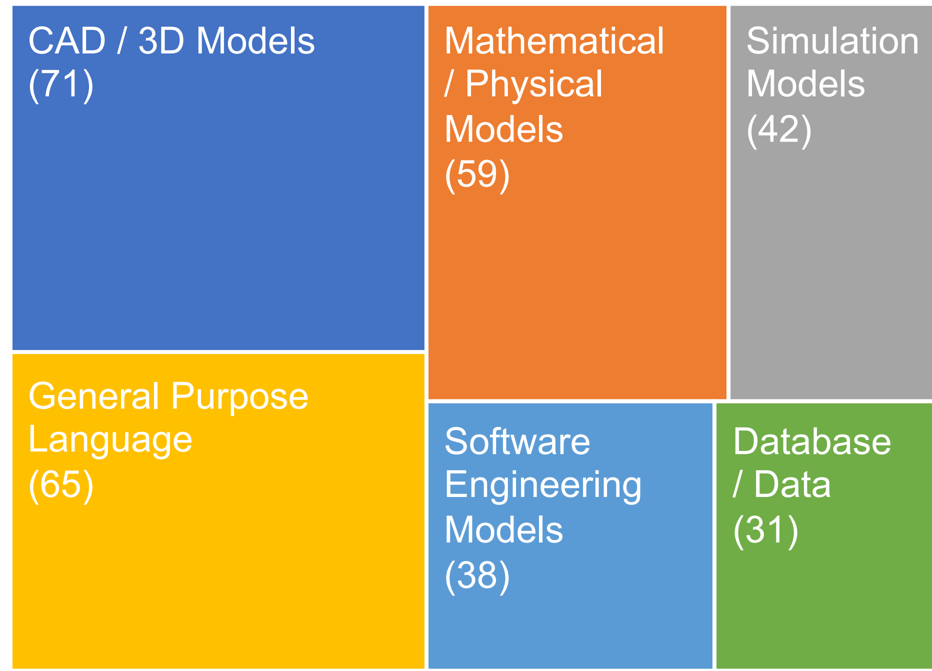
- "integrated virtual model of a real-world system containing all of its physical information" [393]
- "a complete virtual repre-sentation of a physical part or process" [1079]

1. M. Dalibor, N. Jansen, B. Rumpe, D. Schmalzing, L. Wachtmeister, M. Wimmer, A. Wortmann: A Cross-Domain Systematic Mapping Study on Software Engineering for Digital Twins. Journal of Systems and Software, 111361, 2022

Digital Twins are Mostly Build with CAD models and Code

Software engineering models used less prominently

- Most prominent CAD > GPL > Math/Phys > Simulation > SE > …
- CAD often used at design-time and/or for visualization of the twinned system
- GPL used for data transfer, analyses
- Mathematical/physical models for static analysis
- Simulation models for dynamic analysis
- Some digital twins don't use models at all



1. M. Dalibor, N. Jansen, B. Rumpe, D. Schmalzing, L. Wachtmeister, M. Wimmer, A. Wortmann: A Cross-Domain Systematic Mapping Study on Software Engineering for Digital Twins. Journal of Systems and Software, 111361, 2022

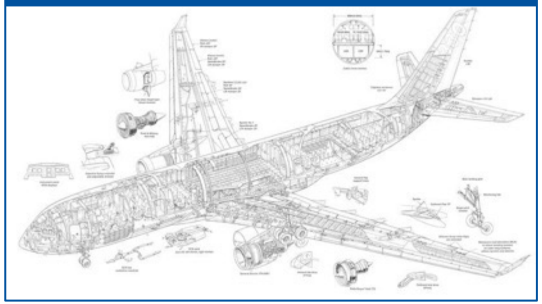
Take-away message

A digital twin is a simulation model of an existing system

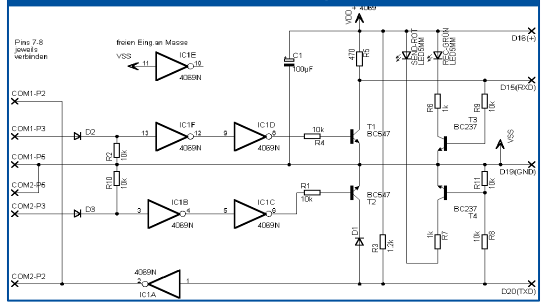
Then all of these Models Must be Digital Twins

As all of these models can be used to simulate an existing system

CAD



Circuit Diagram

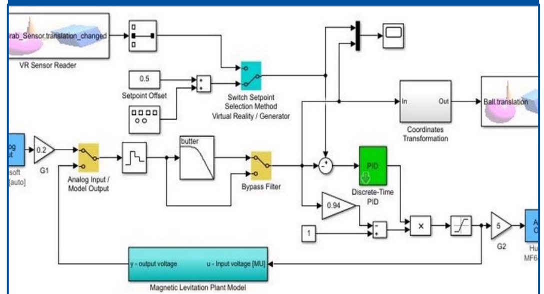


NN

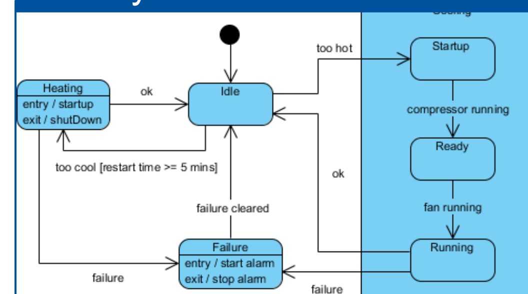
Math

$$s[m] = v\left[\frac{m}{s}\right] * t[s]$$

Simulink



SysML Statemachine



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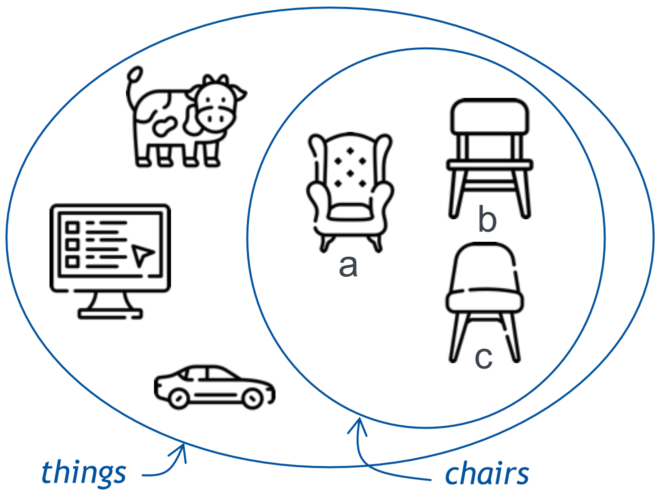
Take-away message

A digital tw[illegible]mulation model of an existi[illegible]m

Without a Proper Definition, Digital Twins are a Piecemeal Technology

Most definitions of digital twins are either ambiguous, narrow, or impossible

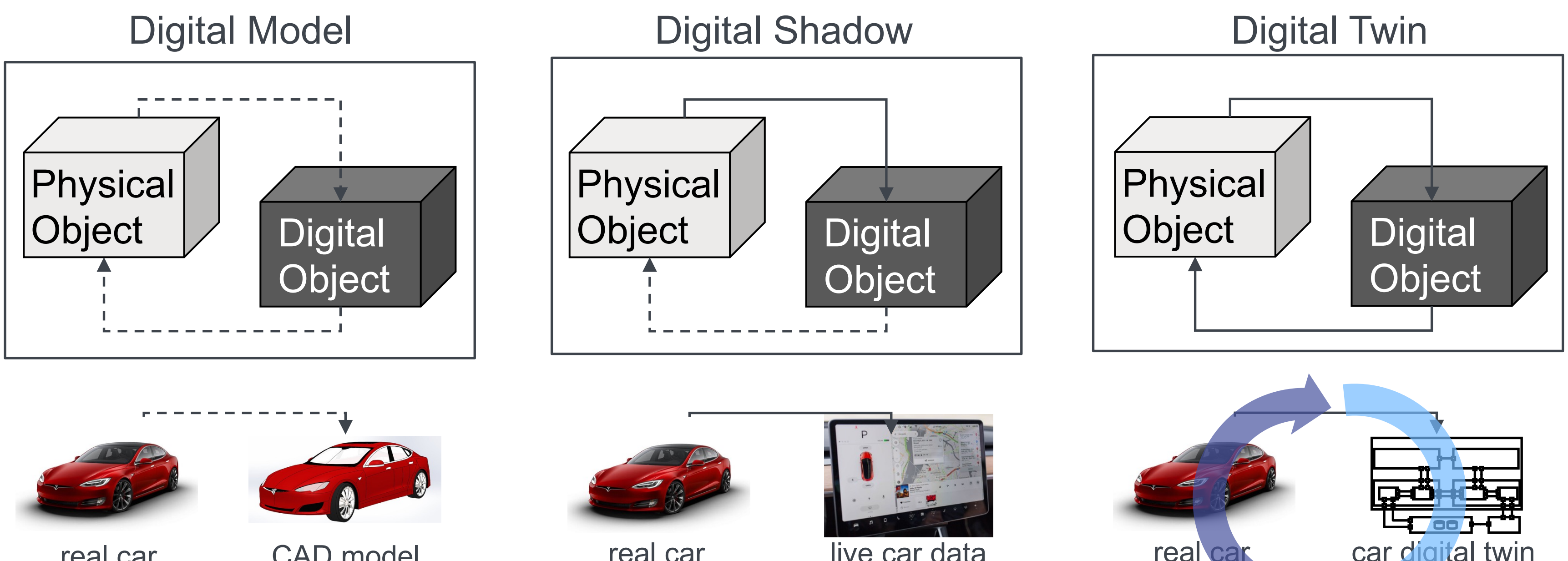
- A definition separates a set into included things and excluded things
- Intensional: Characterize the nature of included things
  - Example: *A chair is a physical object that has legs, a backrest and does not move by itself*
- Extensional: Enumerate included things
  - Chairs := {a,b,c}
- We need a proper intensional definition of digital twins
- To communicate about them, build theories, reuse parts, …



Challenge 1: Find a commonly accepted, intensional, definition of “Digital Twin” that does (a) not rely on undefined terms, (b) is independent on a domain/technology/application, (c) feasible to achieve

A Characterization based on Data Flows[1]

If the data flows between system and twin are of a specific form, then it is a …



Implication 1: the (cyber-physical) physical original must exist (partly)

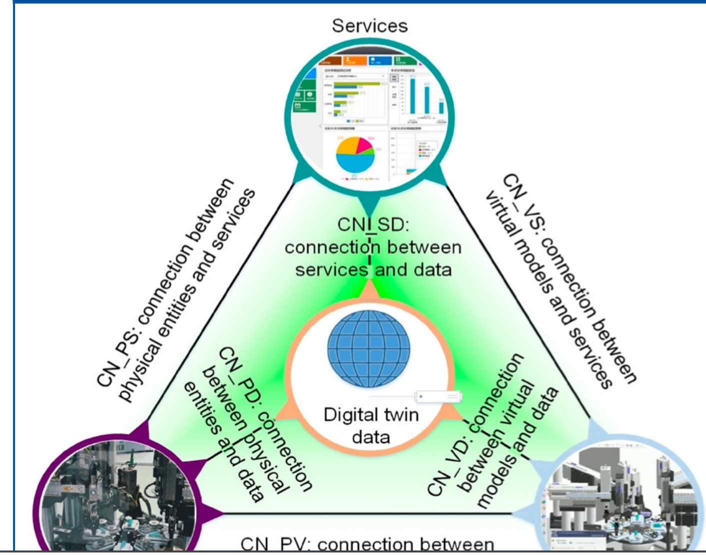
1 Kritzinger, W., Karner, M., Traar, G., Henjes, J., & Sihn, W: Digital Twin in manufacturing: A categorical literature review and classification. IFAC-PapersOnLine, 2018.

A Definition based on Constituents

In the 5D digital twin model, a digital twin comprises…

1. Physical object: Beings, cyber-physical systems, …
2. Digital object: Models, software infrastructures, VR, …
3. Services: Monitoring, optimization, prediction, …
4. Digital data: Sensor readings, manufacturing orders, …
5. Connections: WiFi, ethernet, fieldbus, …

5D Digital Twin Model[1]



⇨ Implication 2: the digital twin uses data, models, and provides (added-value) services

1. Qi et al.: Enabling technologies and tools for digital twin. In: Journal of Manufacturing Systems, Elsevier, 2019

Digital Twin Capabilities Periodic Table (DTC)

A wishlist of potential features of digital twins

1 Data Acquisition & Ingestion	9 Synthetic Data Generation	17 Enterprise System Integration	23 Edge AI & Intelligence	29 Prediction		39 Basic Visualization	45 Dashboards
2 Data Streaming	10 Ontology Management	18 Eng. System Integration	24 Command & Control	30 Machine Learning ML		40 Advanced Visualization	46 Continuous Intelligence
3 Data Transformation	11 Digital Twin (DT) Model Repository	19 OT/IoT System Integration	25 Orchestration	31 Artificial Intelligence AI	35 Prescriptive Recommendations	41 Real-time Monitoring	47 Business Intelligence
4 Data Contextualization	12 DT Instance Repository	20 Digital Twin Integration	26 Alerts & Notifications	32 Federated Learning	36 Business Rules	42 Entity Relationship Visualization	48 BPM & Workflow
5 Batch Processing	13 Temporal Data Store	21 Collab Platform Integration	27 Reporting	33 Simulation	37 Distributed Ledger & Smart Contracts	43 Augmented Reality AR	49 Gaming Engine Visualization
6 Real-time Processing	14 Data Storage & Archive Services	22 API Services	28 Data Analysis & Analytics	34 Mathematical Analytics	38 Composition	44 Virtual Reality VR	50 3D Rendering
7 Data PubSub Push	15 Simulation Model Repository	52 Device Management	54 Event Logging	56 Data Encryption	58 Security	60 Safety	51 Gamification
8 Data Aggregation	16 AI Model Repository	53 System Monitoring	54 Data Governance	57 Device Security	59 Privacy	61 Reliability	62 Resilience

Implication 3: the provides different services according to ist purpose

1. https://www.digitaltwinconsortium.org/initiatives/capabilities-periodic-table/

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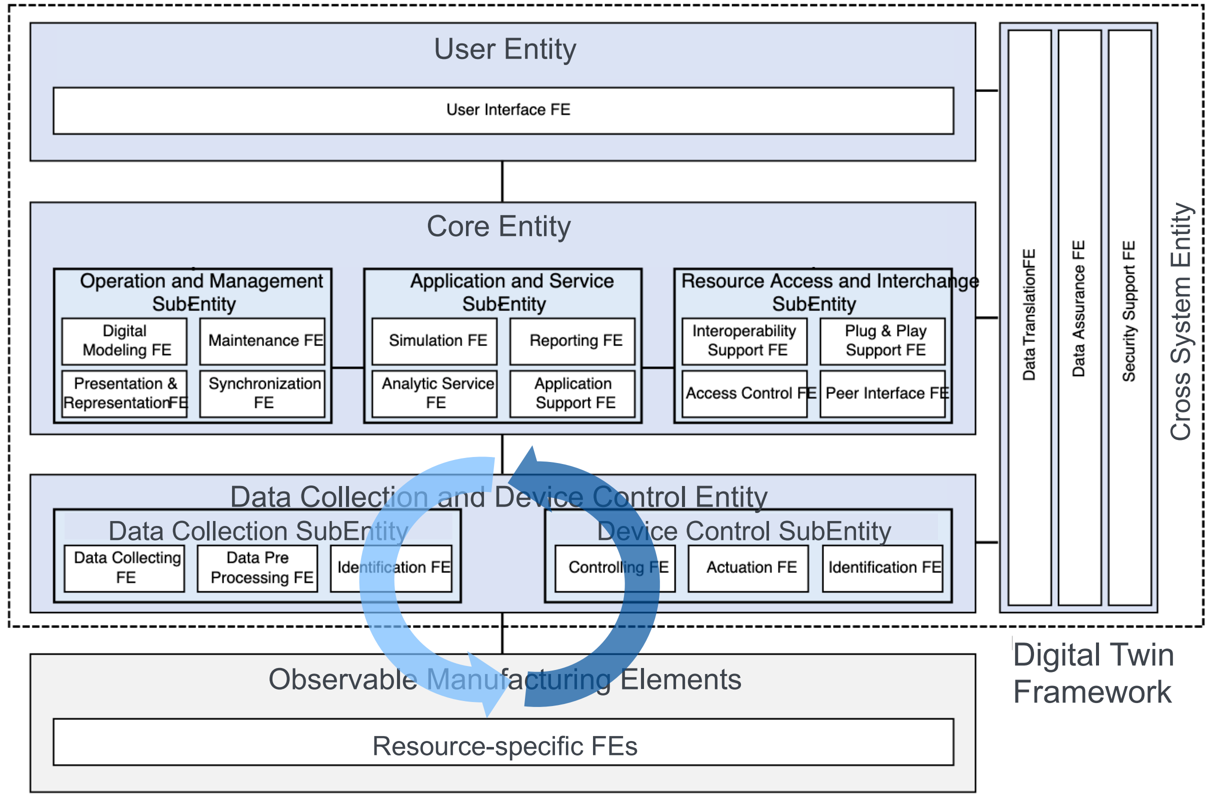
Digital Twin Framework for Manufacturing (ISO 23247)

Build on functional entities (= software modules)

- Published in 2021
- Part 1: Overview and general principles
- Part 2: Reference architecture
- Part 3: Digital representation of manufacturing elements
- Part 4: Information exchange



Source: Automation systems and integration - Digital twin framework for manufacturing - Part 2: Reference architecture

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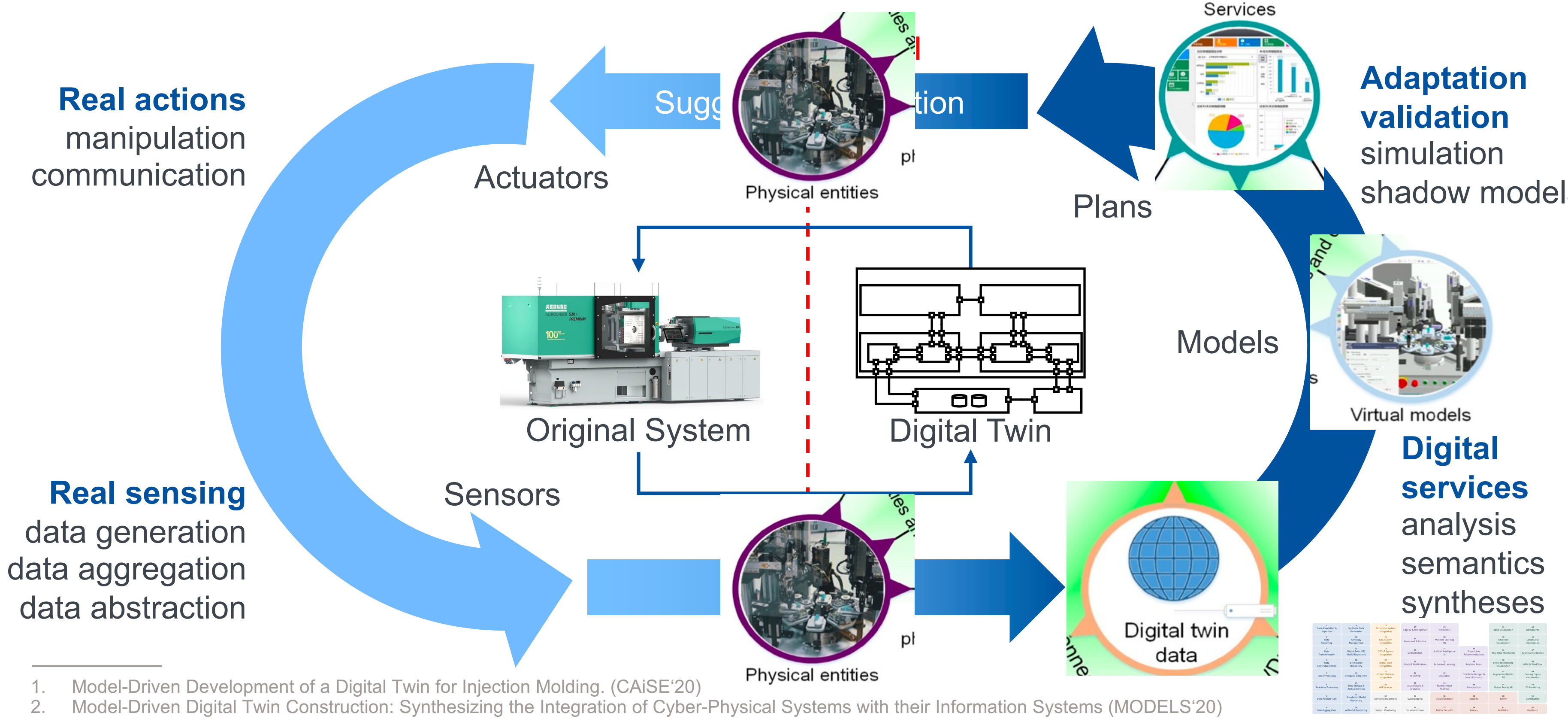
A Pattern for Digital Twins as Adaptive Systems

MBDO

That represent and manipulate their CPS counterpart

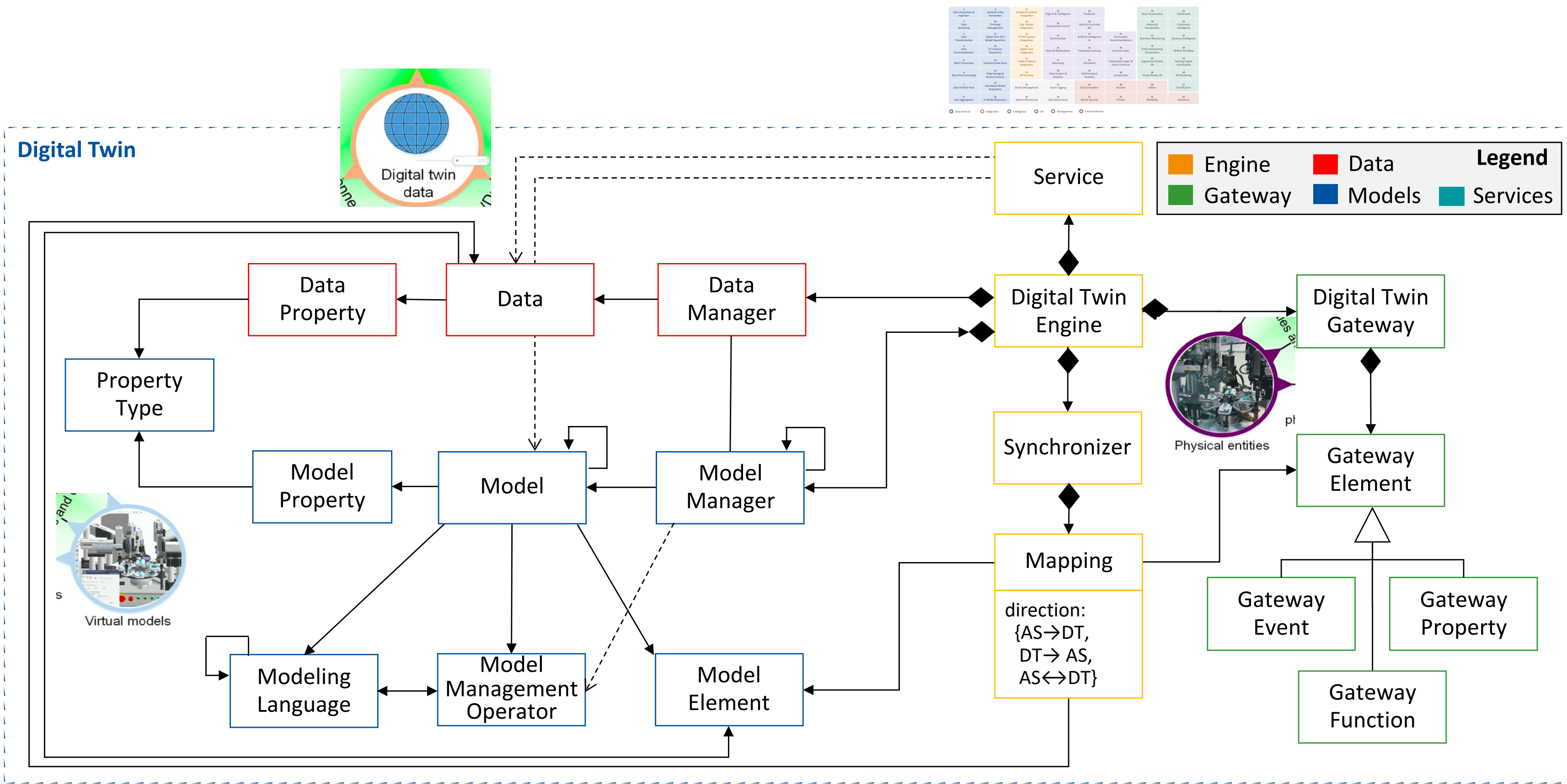


1. Model-Driven Development of a Digital Twin for Injection Molding. (CAiSE‘20)
2. Model-Driven Digital Twin Construction: Synthesizing the Integration of Cyber-Physical Systems with their Information Systems (MODELS‘20)

Take-away

A digital twin is a software system that uses data, models and services to purposefully represent and manipulate the original system during its lifecycle.

A Reference Architecture for Digital Twins



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The AAS aims to Locate all Relevant Information About an Asset Centrally

Submodels are the main content of asset administration shells

Capabilities

- End milling
- Drilling

Maintenance

- Cutting time
- Latest service

Operational Data

- Sensor data
- Energy consumption

Asset Administration Shell

Asset

Technical Data

- Max. spindle speed
- Axis count

Digital Nameplate

- Contact data
- Serial number

3-axis milling machine

Number of our submodels: 99

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Common Requirements on Digital Twins

- Extracted from popular definitions
- ISO standards
- Academic definitions
- Definitions of associations

Req.	The digital twin...	Sources	Context
R01 (Asset Receiving)	can receive data from its twinned counterpart.	All	This capability can have the form of automated data flows from the twinned system to the digital twin [55, 91], dedicated data collection components [49], or data ingestion functionalities [33].
R02 (Asset Sending)	can send data to its twinned counterpart.	All	This capability also is foundational to all investigated digital twin models.
R03 (GUI)	has a user interface.	[33, 49]	The form of the UI is generally underspecified [49] but could range from basic visualizations to virtual reality [33].
R04 (Representing)	can represent its counterpart digitally.	All	Either through data or models. This does not entail requiring a user interface (see R03).
R05 (Synchronizing)	can synchronize (selected) properties with its counterpart.	[49, 55]	This is vital for the definition data-flow-based definition of digital twins [55] and made explicit by requiring a synchronization component according to [49].
R06 (Reporting)	can report information to selected recipients aside from the AAS, *e.g.*, by sending a message to the asset's operator.	[33, 49]	Using unspecified reporting capabilities [33] or a reporting component [49].
R07 (Twin Communication)	can communicate with other digital twins.	[33, 49]	Either through unspecified integration means [33] or a dedicated peer interface [49].
R08 (System Interaction)	can interact with third-party systems *e.g.*, a manufacturing execution system or an ERP system.	[33, 49]	This can have the form of dedicated interoperability support components [49] or of interfaces to external data source [33].
R09 (Added Value Services)	provides services to act on data and models.	[33, 49, 91]	Much of the added value functionality of a digital twin is very specific to the AS or the processes on the AS, i.e., it can hardly be generalized. Instead, [49] and [33] propose that digital twins yield services that realize this added value functionality specifically tailored to their use cases.
R10 (Reasoning)	can reason about data from/about the twinned counterpart as well as about data obtained from other systems (*cf.* R08, R09).	[33, 49]	To enable various kinds of such reasoning, the different frameworks propose specific analytics services [49, 33].

1. Zhang, J., Ellwein, C., Heithoff, M., Michael, J., & Wortmann, A. (2025). Digital twin and the asset administration shell. *Software and Systems Modeling*, 1-23.

What IDTA requires for a Type 1 AAS

According to our review

○Required ◐ Suggested ●Required

Req.	Eval.	Explanation
R01 (Asset Receiving)	○	The serialized files require an interface to write data on them. The Type 1 AAS is used like a file system.
R02 (Asset Sending)	○	The Type 1 AAS collections of related serialized files without any behavior.
R03 (GUI)	○	There is no off-the-shelf GUI for Type 1 AASs.
R04 (Representing)	●	The information on the asset can be stored inside the serialized files with their relations.
R05 (Synchronizing)	○	Synchronization between AAS and asset is not included for Type 1 AASs.
R06 (Reporting)	○	There are templates supporting specifying recipients *e.g.,* other AAS aside from itself, in the Type 1 AAS, but no data exchange mechanism is implemented.
R07 (Twin Communication)	○	The recipient specification mechanism of **R06** (Reporting)could be used as the base for any twin to twin communication. However, there is not off-the-shelf support for such.
R08 (System Interaction)	○	There is no active behavior in Type 1 AAS.
R09 (Added Value Services)	○	The interface for interacting with the AAS is implemented in BaSyx, but the Type 1 AAS does not provide services by default.
R10 (Reasoning)	○	Since neither **R08** nor **R09** is fulfilled the AAS Type 1 cannot actively reason about data from the twinned counterpart.

1. Zhang, J., Ellwein, C., Heithoff, M., Michael, J., & Wortmann, A. (2025). Digital twin and the asset administration shell. *Software and Systems Modeling*, 1-23.

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What IDTA requires for a Type 2 AAS

According to our review

○Required ◑ Suggested ●Required

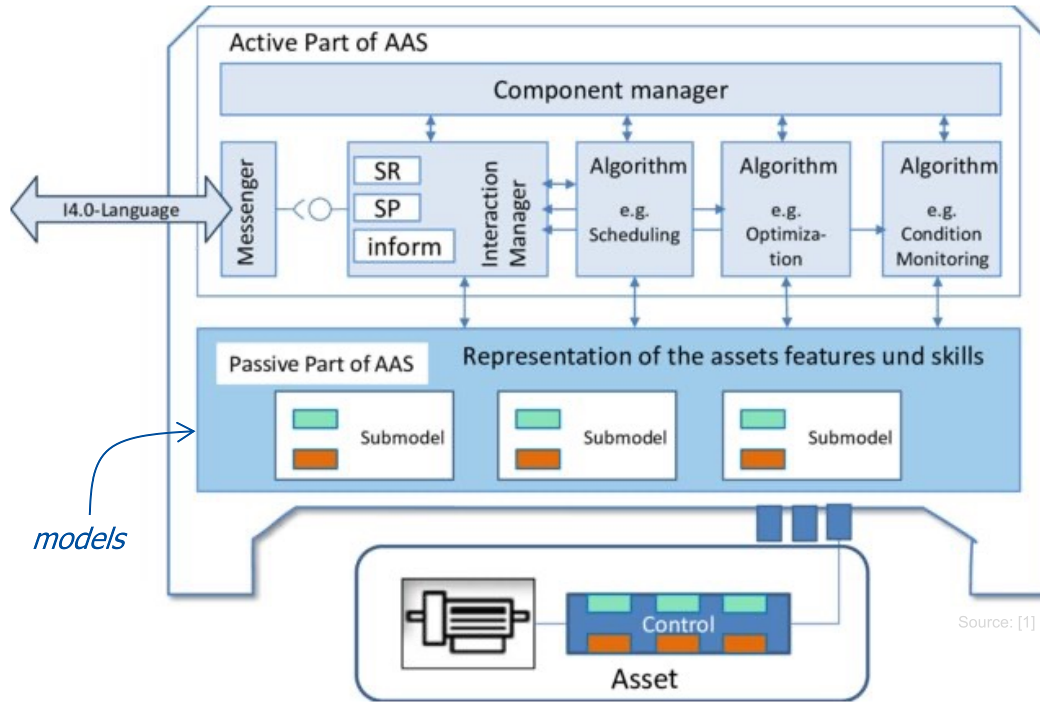
Req.	Eval.	Explanation
R01 (Asset Receiving)	●	The Type 2 AAS is capable of passively receiving data from the Asset or multiple AAS through an API.
R02 (Asset Sending)	○	The Type 2 AAS cannot actively send data to the twinned counterpart.
R03 (GUI)	○	The Type 2 AAS requires an implementation for the API. In relation to the implementation the API may of may not be a full user interface, which is not specified by the IDTA.
R04 (Representing)	●	The Type 2 AAS can represent its counterpart digitally through the submodels and their relations.
R05 (Synchronizing)	◑	The Type 2 AAS as specified by the IDTA comes with a possibility of defining a timer for the update of data within the AAS. The active synchronization relies on implementation.
R06 (Reporting)	◑	The Type 2 AAS is also not capable of actively reporting information to selected recipients, but through references between submodels it may propagate data to further Type 2 AAS.
R07 (Twin Communication)	○	The Type 2 AAS can adjust relations between properties in submodels and refer to further Type 2 AAS submodels. Thus it cannot perform data exchanges with other DTs.
R08 (System Interaction)	○	The Type 2 AAS can indirectly interact with other systems by defining references to further submodels of other AAS. Overall the Type 2 AAS cannot interact with other systems.
R09 (Added Value Services)	◑	The Type 2 AAS provides an API for manipulating submodels. Whether these API are sufficient enough to be a service is dependent on the actual implementation.
R10 (Reasoning)	◑	The Type 2 AAS cannot actively reason about data from the twinned counterpart, but *e.g.,* there can be references defined inside submodels calculating metrics for evaluating the throughput or performance. Further the IDTA defines an option with regex queries to reason on data. This again depends on the actual implementation.

1. Zhang, J., Ellwein, C., Heithoff, M., Michael, J., & Wortmann, A. (2025). Digital twin and the asset administration shell. *Software and Systems Modeling*, 1-23.

A General Architecture of Type 3 Asset Administration Shells[1]

A potential blueprint for digital twins

- Component manager orchestrates AAS behavior
- Service requester/provider interact with environment
- Algorithms perform computations
- Interact with models and asset
- Reference implementation, e.g., with BaSyx
- A lot of JSON…



Source: [1]

1. Belyaev, A., Diedrich, C. (2019). Aktive Verwaltungsschale von Industrie 4.0 Komponenten," in Automationkongress 2019, Baden-Baden.

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What IDTA requires for a Type 3 AAS

According to our review

○ Required ◐ Suggested ● Required

Req.	Eval.	Explanation
R01 (Asset Receiving)	●	The type3 AAS has an active communication with its asset.
R02 (Asset Sending)	●	Via the I4.0 language, the Type 3 AAS can send data to its asset.
R03 (GUI)	◐	With its active behavior, the Type 3 AAS could implement and host a graphical user interface.
R04 (Representing)	●	The type3 AAS can represent its counterpart digitally through the submodels and their relations.
R05 (Synchronizing)	◐	Via the I4.0 language, the Type 3 AAS can send synchronizing commands to its asset.
R06 (Reporting)	◐	The Type 3 AAS comprises active components that could implement sending reporting information via the I4.0 language.
R07 (Twin Communication)	●	The Type 3 AAS comprises active components and defined interfaces, so that it can communicate with other DTs for specific submodel purposes.
R08 (System Interaction)	●	The Type 3 AAS comprises active components that could implement communicating with other systems for specific submodel purposes.
R09 (Added Value Services)	◐	Within its active behavior, the Type 3 AAS is supposed to (autonomously) compute data, *e.g.,* for analysis purposes. But the extent is not defined by the IDTA.
R10 (Reasoning)	◐	Within its active behavior, the Type 3 AAS is supposed to (autonomously) compute data, *e.g.,* for analysis purposes. But the extent is not defined by the IDTA.

1. Zhang, J., Ellwein, C., Heithoff, M., Michael, J., & Wortmann, A. (2025). Digital twin and the asset administration shell. *Software and Systems Modeling*, 1-23.

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There are 3 Kinds of Asset Administration Shells

And they relate to digital twins differently

Type 1 AAS

- Shells are serialized files
- Contain static information
- Data model governed by AAS meta model
- Describe types and instances of assets as-designed
- No automated dataflows from/to asset

→ **Idealized, static, description of an asset**

Digital Model

Type 2 AAS

- Runtime instances: may contain static and dynamic information from real device
- Interact w. other components
- Ex: frontend for device services, live sensor data, …
- Properties, operations, events via generic runtime interface
- Automated dataflows only from real system

→ **Well-informed Dashboard**

Digital Shadow

Type 3 AAS

- Extend type 2 AAS
- Have active behavior
- Can start to communicate & to negotiate on their own
- Well-defined language and message structures (VDI/VDE 2193)
- Automated dataflows from/to real system
- **Software interfacing asset**

Digital Twin

Answers

A type 3 AAS is a digital twin according to Kritzinger, Tao, ISO, …

The others are not

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