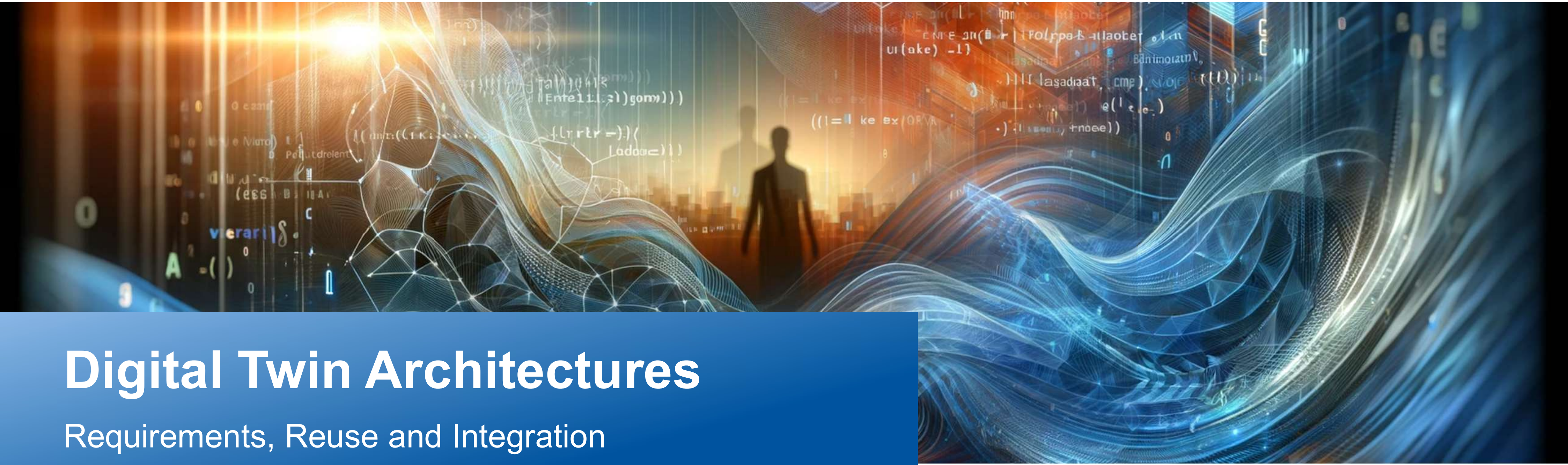


Digital Twin Architectures

Requirements, Reuse and Integration

Dr. Judith Michael
Software Engineering
RWTH Aachen

http://www.se-rwth.de

09.1.2025, University of Antwerp

SE Software Engineering | RWTH AACHEN UNIVERSITY

About me

- *Universität Klagenfurt, Austria*
  PhD in 2014 | Cognitive Modeling for Ambient Assistance

- *RWTH Aachen University, Germany* since 2018
  Team Leader | 9 PhD candidates | lead in several projects
  - Cluster of Excellence „Internet of Production“
    Deputy coordinator work stream „Conceptual foundations of digital shadows“
  - Center for Systems Engineering
  - MaCoCo | InviDas | MontiGem | MBDO

  Habilitation in 2024 on *“Model-Driven Engineering of Digital Twins with Informative and Assistive Services”*

- *Lakeside Science & Technology Park GmbH, Austria*
  Supervisory board | 38.000 m^2 | 70 companies | 1400 employees

- *German Informatics Society*
  Junior Fellow 2015 | Spokesperson QFAM, executive commitee (Präsidium)

RWTH Aachen University | Software Engineering


Established 1870

- 47,078 students (WS 22/23)
  - 4,763 Informatics (939 in 1st sem.)
- 9.715 staff, 557 professors
  - 32 prof. in Informatics
- 9 faculties, 260 institutes
- 3 Clusters of Excellence
- 1,192 Mio € annual budget
  - incl. 488 Mio € third-party funds

INTERNET OF PRODUCTION | RWTH AACHEN UNIVERSITY

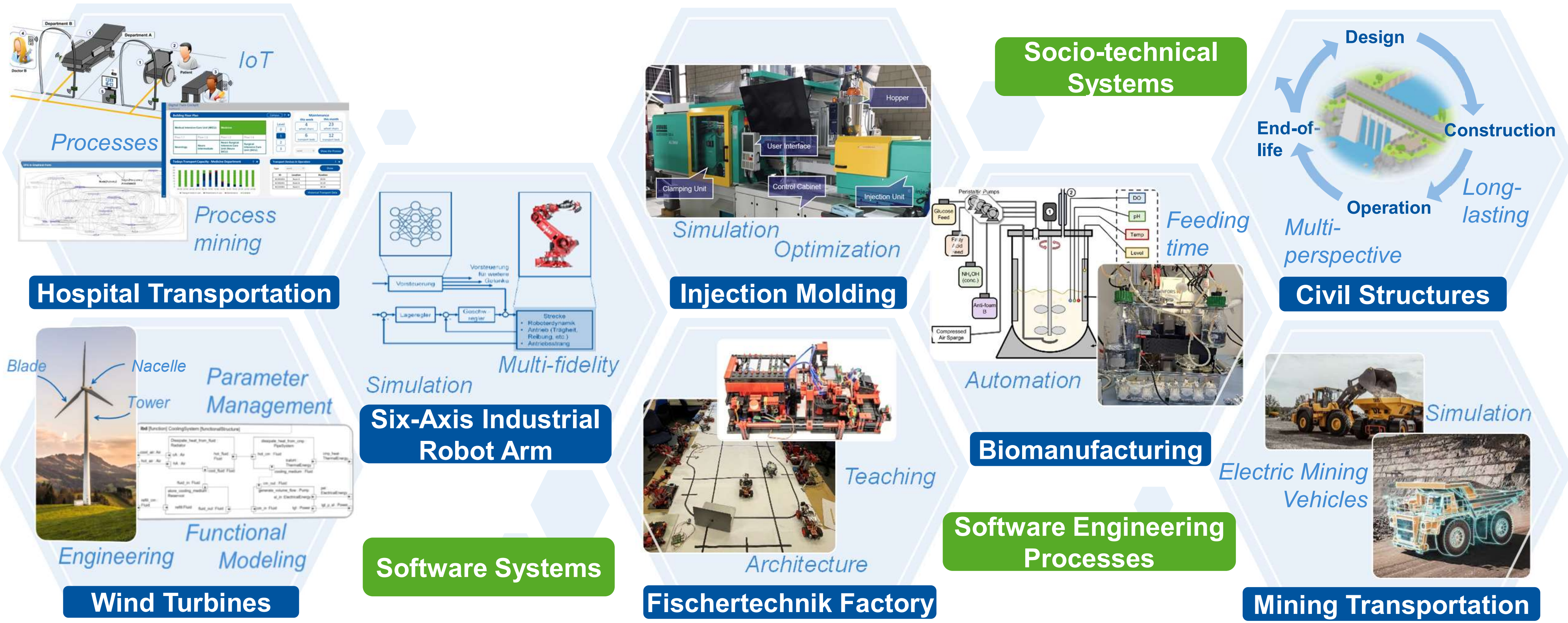
Bernhard Rumpe

- Software Engineering Chair
- Editor-in-Chief SoSyM Journal, MODELS conference series,…
- Co-Founder Center for Systems Engineering

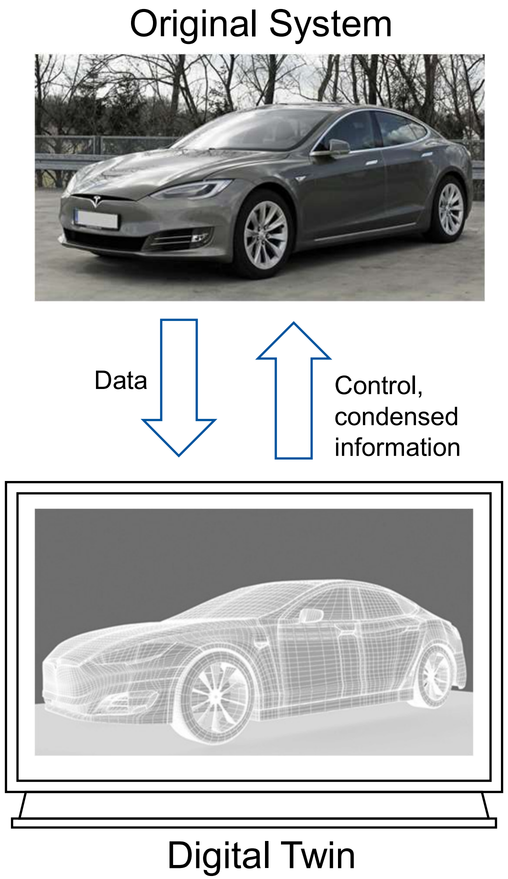
Team

- app. 30 PhD candidates
- 2 Post Docs
- 2 Controlling/Office
- 2 Senior Software Engineers
- 6 trainees

Some Digital Twin Use Cases



Digital Twins as *complex, long-lasting, software-intensive systems*



contextual data and their aggregation and abstraction

A Digital Twin of an original system is a software that consists of

- a set of models of the system and
- a set of digital shadows,
  - both of which are purposefully updated on a regular basis, and
- provides a set of services to use both purposefully with respect to the original system.

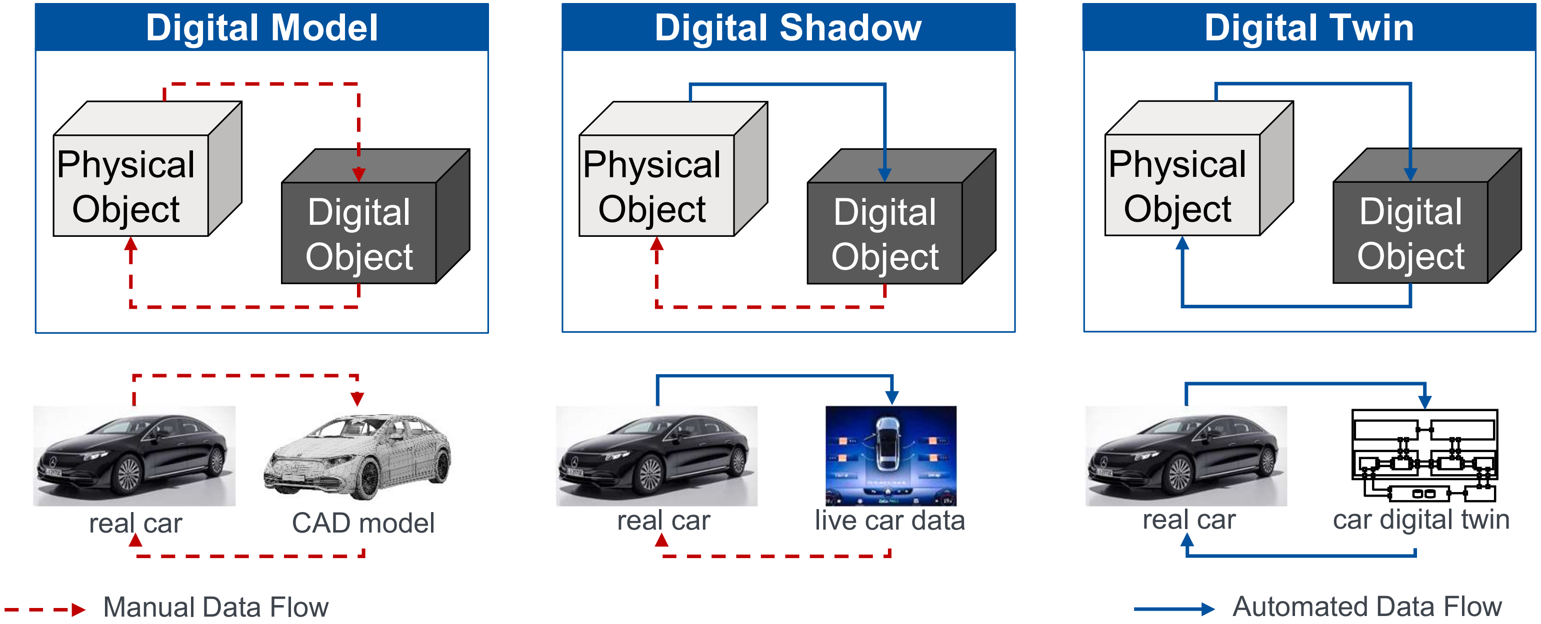
- The digital twin interacts with the original system by
  - providing useful information about the system's context and
  - sending it control commands.

A Characterization based on Data Flows

When to use which term?

- *Properties* of the *data flows*
- Manual vs. automated

- Missing, e.g.,
  - Properties of the digital object
  - Purpose
  - Data aggregation
  - How to realize automation (services?)



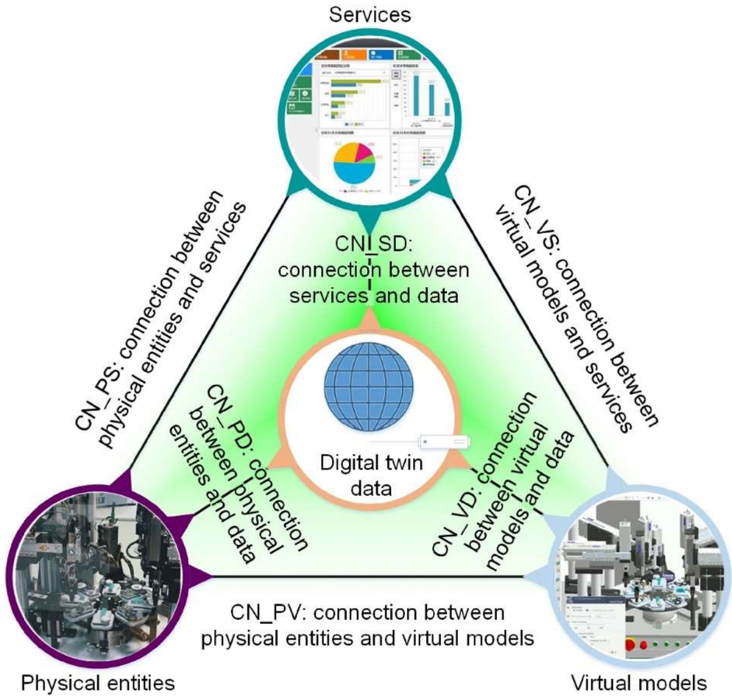
W. Kritzinger, M. Karner, G. Traar, J. Henjes, W. Sihn: *Digital Twin in manufacturing: A categorical literature review and classification*. IFAC-PapersOnLine, 2018.

5D Digital Twin Model

- A definition based on *constituents*

- A digital twin comprises of
  - Physical object, e.g., beings, CPS,…
  - Digital object, e.g., models, software infrastructure,…
  - Services, e.g., monitoring, optimization, prediction,…
  - Digital data, e.g., sensor data, manufacturing orders,…
  - Connections, e.g., WiFi, ethernet, fieldbus,…

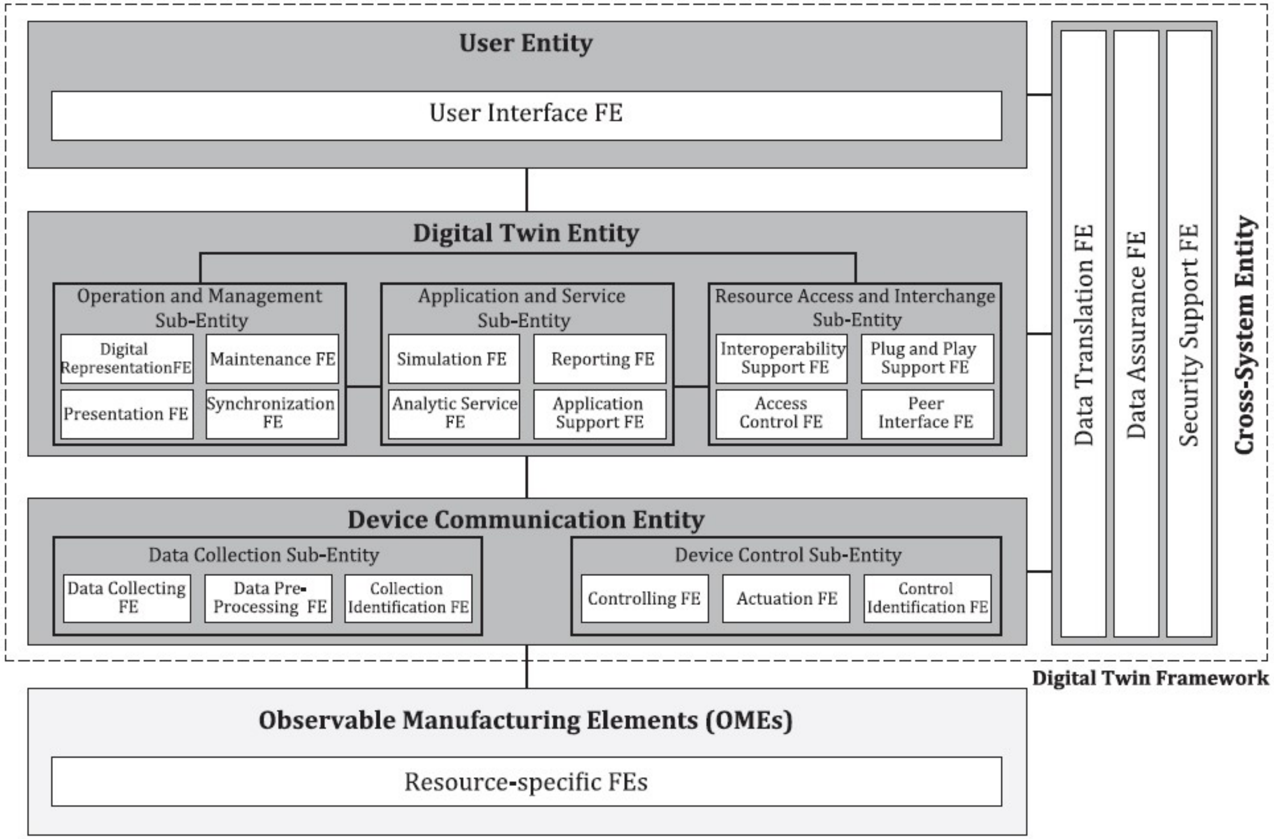
- Missing, e.g.,
  - Border where the digital twin is
  - Details about connections
  - Data aggregation
  - Active vs. passive components
  - Purpose



F. Tao, M. Zhang, Y. Liu, A.Y.C. Nee: Digital twin driven prognostics and health management for complex equipment. In: CIRP Ann-Manuf Technol, 67 (1), 2018.
Q. Qi, F. Tao, T. Hu, N. Anwer, A. Liu, Y. Wei, L. Wang, A.Y.C. Nee: Enabling technologies and tools for digital twin, In: Journal of Manufacturing Systems, 58 (B), Elsevier, 2022.

Digital Twin Framework for Manufacturing (ISO 23247)

- ISO Standard
  - Published in 2021
  - Focus on manufacturing
- Structure
  - Part 1: Overview and general principles
  - Part 2: *Reference architecture*
  - Part 3: Digital representation of manufacturing elements
  - Part 4: Information exchange

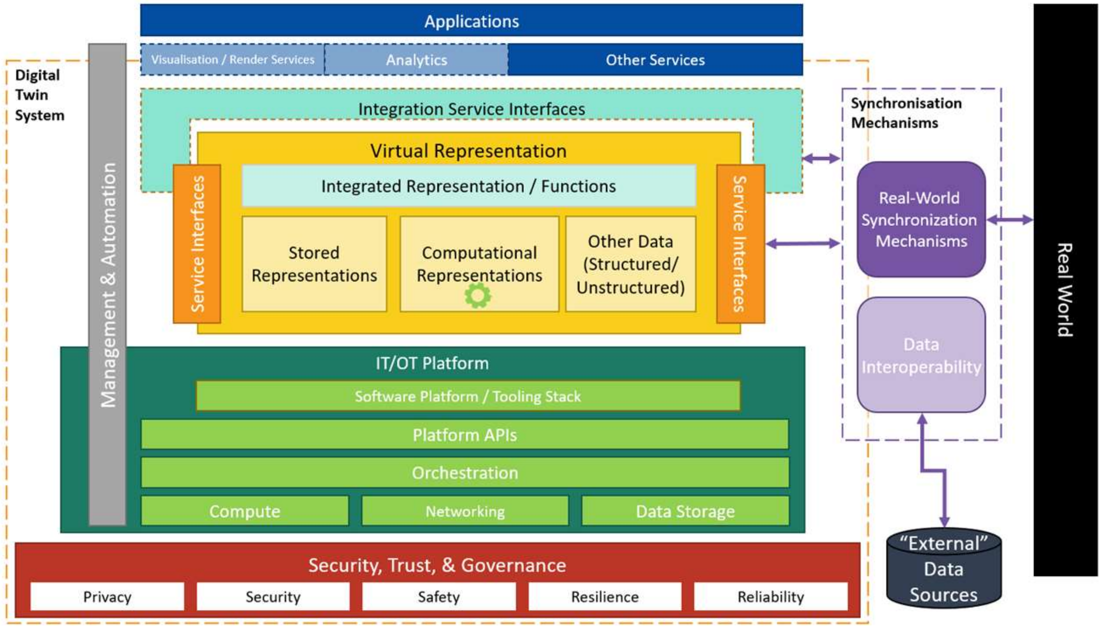


Source: https://www.iso.org/standard/78743.html
E. Ferko, A. Bucaioni, P. Pelliccione, M. Behnam: Standardisation in Digital Twin Architectures in Manufacturing, 20th International Conference on Software Architecture (ICSA), IEEE, https://doi.org/10.1109/ICSA56044.2023.00015

Digital Twin Consortium | Platform Stack Architectural Framework

- Digital Twin Consortium (DTC)
  - Founded in 2020 by Anys, Microsoft, Dell, Lendlease
  - Members, e.g., Google, Dassault Systems, Mitsubishi Electric, Carrier, TÜV Süd

- Platform Stack *Architectural Framework*
  - Virtual Representation
  - Synchronization with the real world & external data sources
  - Applications and services
  - IT/OT Platform
  - Security and Trustworthiness



Source: https://www.digitaltwinconsortium.org/platform-stack-architectural-fram-formework-an-introductory-guide-form/
https://www.digitaltwinconsortium.org/glossary/glossary/

Digital Twin Consortium | Digital twin ecosystem capabilities

DS.AI Data Acquisition & Ingestion	**DS.SG** Synthetic Data Generation	**IR.ET** Enterprise System Integration	**IC.SR** Search	**IC.PR** Prediction		**UX.BV** Basic Visualization	**UX.DB** Dashboards
DS.ST Data Streaming	**DS.ON** Ontology Management	**IR.EG** Eng. System Integration	**IC.CC** Command & Control	**IC.AI** Artificial Intelligence		**UX.AV** Advanced Visualization	**UX.CI** Continuous Intelligence
DS.TR Data Transformation	**DS.RP** Digital Twin (DT) Model Repository	**IR.IO** OT/IoT System Integration	**IC.OS** Orchestration	**IC.PS** Prescriptive Recommendations		**UX.RM** Real-time Monitoring	**UX.BI** Business Intelligenc e
DS.CX Data Contextualization	**DS.IR** DT Instance Repository	**IR.DT** Digital Twin Integration	**IC.AL** Alerts & Notifications	**IC.FL** Federated Learning	**IC.BR** Business Rules	**UX.ER** Entity Relationship Visualization	**UX.BP** BPM & Workflow
DS.BP Batch Processing	**DS.DS** Domain Specific Data Management	**IR.CL** Collab Platform Integration	**IC.RP** Reporting	**IC.SM** Simulation	**IC.DL** Distributed Ledger & Smart Contracts	**UX.XR** Extended Reality (AV/VR/MR)	**UX.GE** Gaming Engine Visualization
DS.RT Real-time Processing	**DS.SA** Data Storage & Archive Services	**IR.AS** API Services	**IC.AA** Data Analysis & Analytics	**IC.MA** Mathematical Analytics	**IC.CS** Composition	**UX.GM** Gamification	**UX.3R** 3D Rendering
DS.AS Asynchronous Integration	**DS.SR** Simulation Model Repository	**MG.DM** Device Management	**MG.EL** Event Logging	**TW.EC** Data Encryption	**TW.SC** Security	**TW.SF** Safety	**TW.RP** Responsibility
DS.AG Data Aggregation	**DS.AR** AI Model Repository	**MG.SM** System Monitoring	**MG.DG** Data Governance	**TW.DS** Device Security	**TW.PR** Privacy	**TW.RL** Reliability	**TW.RS** Resilience

○ Data Services ○ Integration ○ Intelligence ○ UX ○ Management ○ Trustworthiness

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

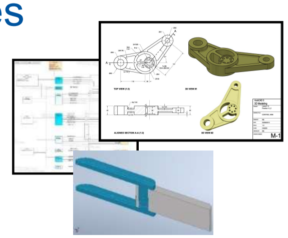
Research Aim

HOW TO IMPROVE THE ***DEVELOPMENT***
OF COMPLEX, SOFTWARE-INTENSIVE ***DIGITAL TWINS***
WITH A VARIETY OF FUNCTIONS AND SERVICES

Overview Digital Twin Research (selected topics)

Architectures

- Connect DT with *Cyber-Physical Systems* and *IoT*
- Self-Adaptive Digital Twin Architectures
- Process Prediction with Digital Twins
- Asset Administration Shell (AAS)



DT Engineering Processes

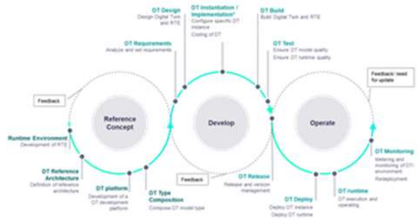
- Digital Twin Maturity Model
- Creating DTs from Engineering Models
- DevOps Digital Twin *Engineering Process*

MDE of Digital Twins & Models at Runtime

- Generating Digital Twin Cockpits & Generate *Process-Aware* DT Cockpits from Event Logs
- Low-Code Platforms for Model-Driven Digital Twins

Composition

- Methods and Variants
- Integration Challenges for DTs

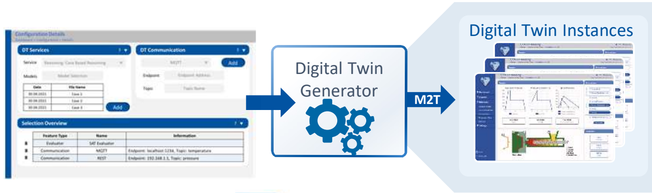


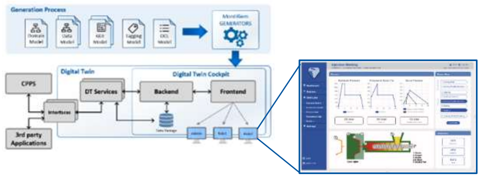
Sustainability

- Digital Twins for Sustainability and Sustainable Digital Twin Engineering

Data in DTs

- Digital Shadows





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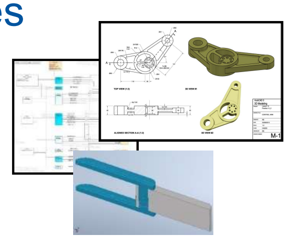

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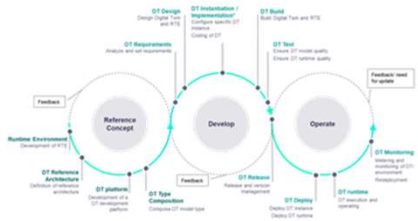

Sustainability

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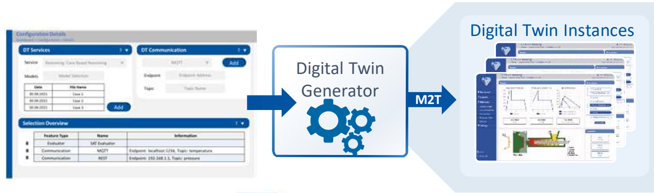
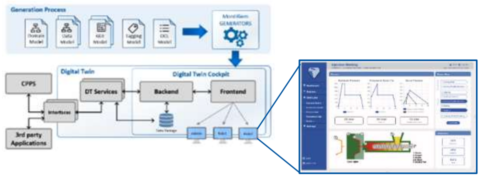
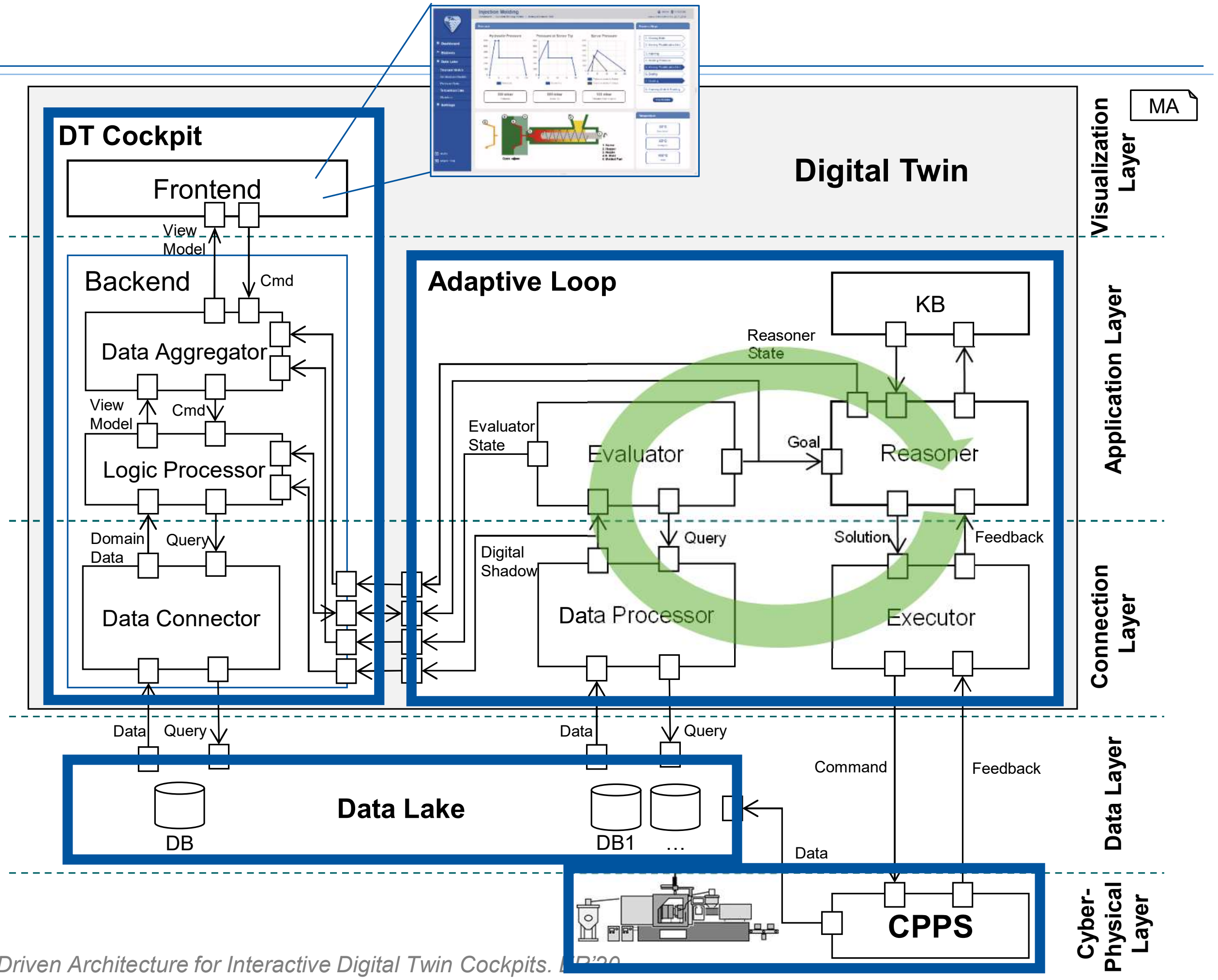




Digital Twin Architecture | An exemplar

- Digital twin services
  - Monitoring and controlling the cyber-physical production system
  - Live supervising production process
  - Self-adaptation

- Digital twin cockpit
  - Aggregating information
  - Visualizing the cyber-physical production system's state and digital twin's state
  - Enabling user interaction with the digital twin

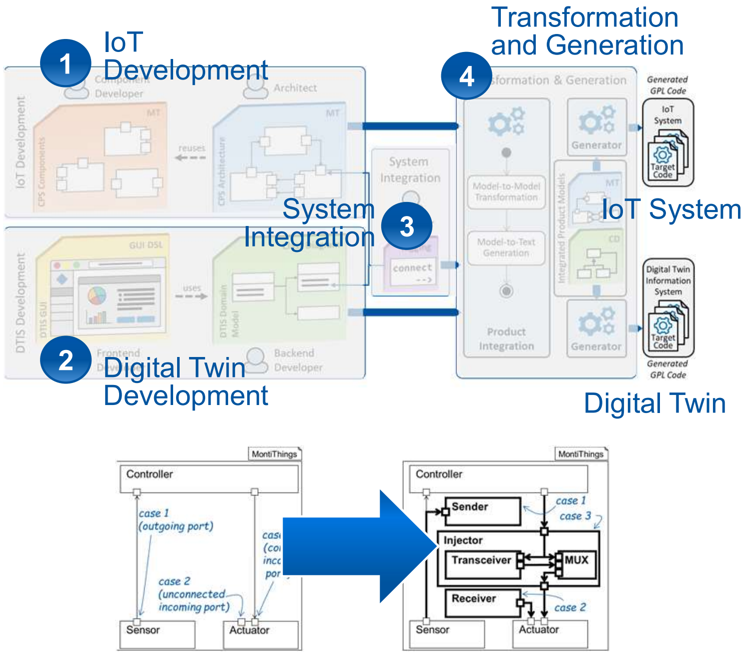


[DMR+20] M. Dalibor, J. Michael, B. Rumpe, S. Varga, A. Wortmann: Towards a Model-Driven Architecture for Interactive Digital Twin Cockpits. ER'20

Model-Driven Engineering of Digital Twins

CPS-DT Integration

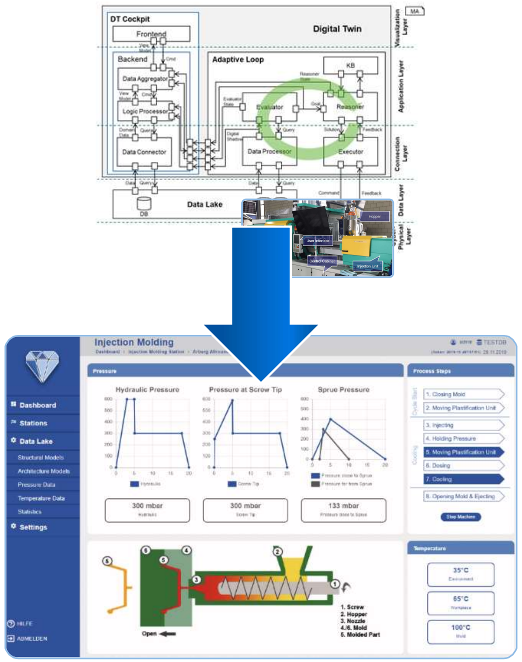
Architectural Integration and Generation



[KMR+20] J. C. Kirchhof, J. Michael, B. Rumpe, S. Varga, A. Wortmann: *Model-driven Digital Twin Construction: Synthesizing the Integration of CPS with Their Information Systems*. MODELS'20

Generating Digital Twin Cockpits

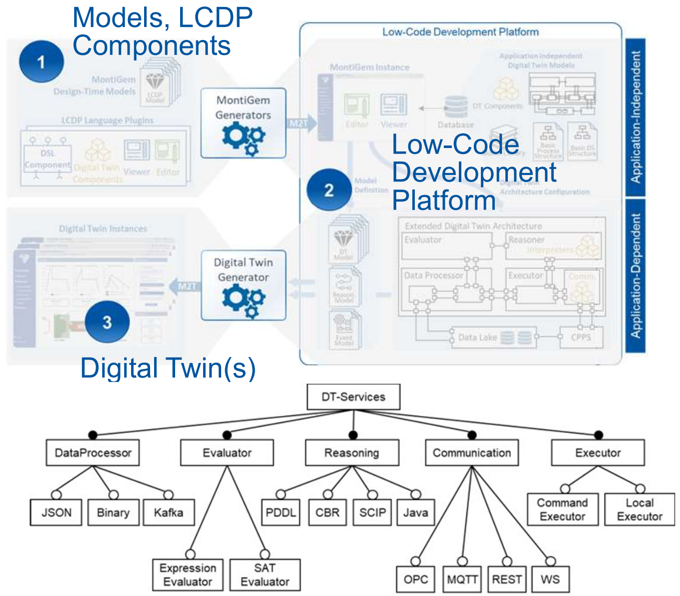
Dashboards for Visualization and Interaction



[DMR+20] M. Dalibor, J. Michael, B. Rumpe, S. Varga, A. Wortmann: *Towards a Model-Driven Architecture for Interactive Digital Twin Cockpits*. ER'20

Low-Code Development Platforms for Digital Twins

2-step Generation and Configuration



[DHM+22] M. Dalibor, M. Heithoff, J. Michael, L. Netz, J. Pfeiffer, B. Rumpe, S. Varga, A. Wortmann: *Generating Customized Low-Code Development Platforms for Digital Twins.* In: Journal of Computer Languages (COLA) 70, Elsevier, 2022.

Digital Twin Architecture Requirements based on Common Definitions and Standards

Requirement	The digital twin. . .	Context
R01 (Asset Receiving)	can receive data from its twinned counterpart.	This capability can have the form of automated data flows from the twinned system to the digital twin, dedicated data collection components, or data ingestion functionalities.
R02 (Asset Sending)	can send data to its twinned counterpart.	This capability also is foundational to all investigated digital twin models.
R03 (GUI)	has a user interface.	The form of the UI is generally underspecified but could range from basic visualizations to virtual reality.
R04 (Representing)	can represent its counterpart digitally.	Through data, models. This does not entail requiring a user interface (see R03).
R05 (Synchronizing)	can synchronize (selected) properties with its counterpart.	This is vital for the data-flow-based definition of DTs and made explicit by requiring a synchronization component.
R06 (Reporting)	can report information to selected recipients aside from the AAS, e.g., send a message to the asset operator.	Using unspecified reporting capabilities or a reporting component.

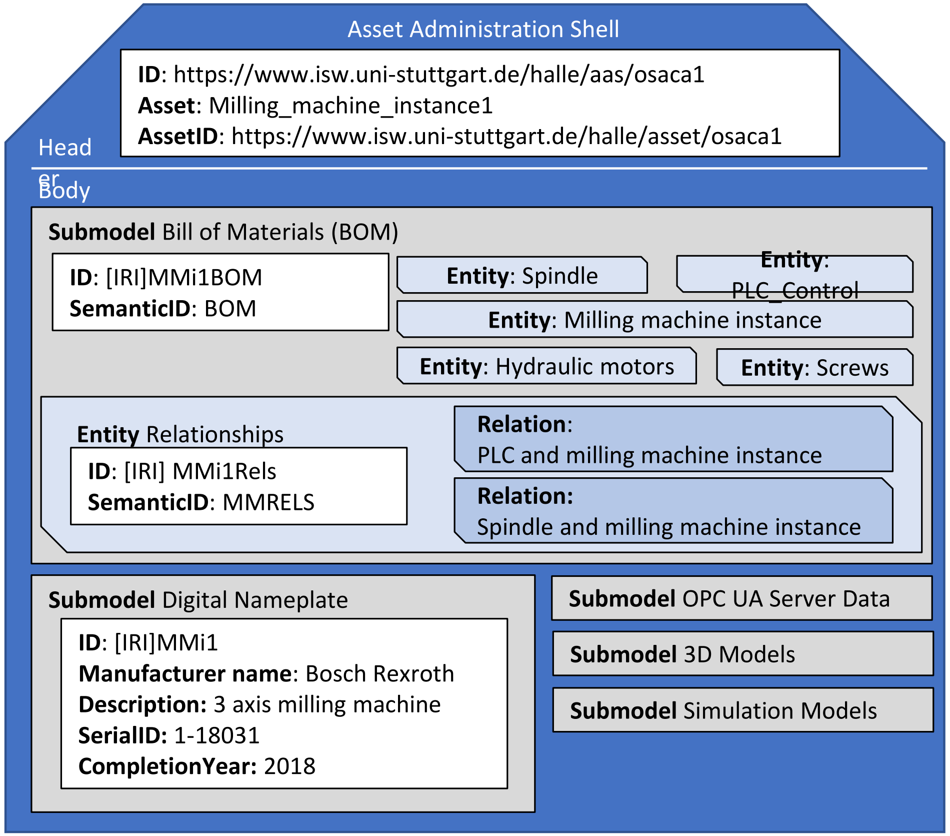
J, Zhang, C. Ellenwein, M. Heithoff, J. Michael, A. Wortmann: Digital Twin and the Asset Administration Shell: An Analysis of 3 AASs Types and their Feasibility for Digital Twin Engineering. SoSyM. 2025.

Digital Twin Architecture Requirements based on Common Definitions and Standards

Requirement	**The digital twin. . .**	**Context**
R07 (Twin Communication)	can communicate with other digital twins.	Either through unspecified integration means or a dedicated peer interface.
R08 (System Interaction)	can interact with third-party systems e.g., MES or ERP.	This can have the form of dedicated interoperability support components or of interfaces to external data source.
R09 (Added Value Services)	provides services to act on data and models.	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, architectures 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).	To enable various kinds of such reasoning, the different frameworks propose specific analytics services.

J, Zhang, C. Ellenwein, M. Heithoff, J. Michael, A. Wortmann: Digital Twin and the Asset Administration Shell: An Analysis of 3 AASs Types and their Feasibility for Digital Twin Engineering. SoSyM. 2025.

3-axis milling machine (OSAKA)



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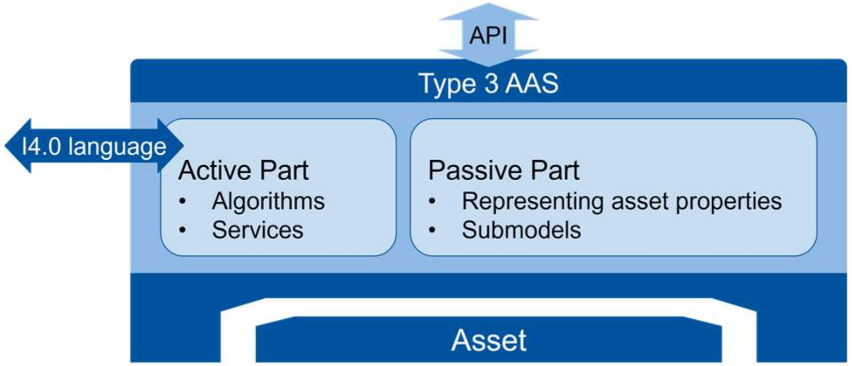
Asset Administration Shell Types (fast forward to type 3)



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.

○ The requirement is not required by IDTA.
◐ The requirement is suggested by IDTA.
● The requirement is defined by IDTA.

Current Work → MDE and the AAS

J, Zhang, C. Ellenwein, M. Heithoff, J. Michael, A. Wortmann: Digital Twin and the Asset Administration Shell: An Analysis of 3 AASs Types and their Feasibility for Digital Twin Engineering. SoSyM. 2025.

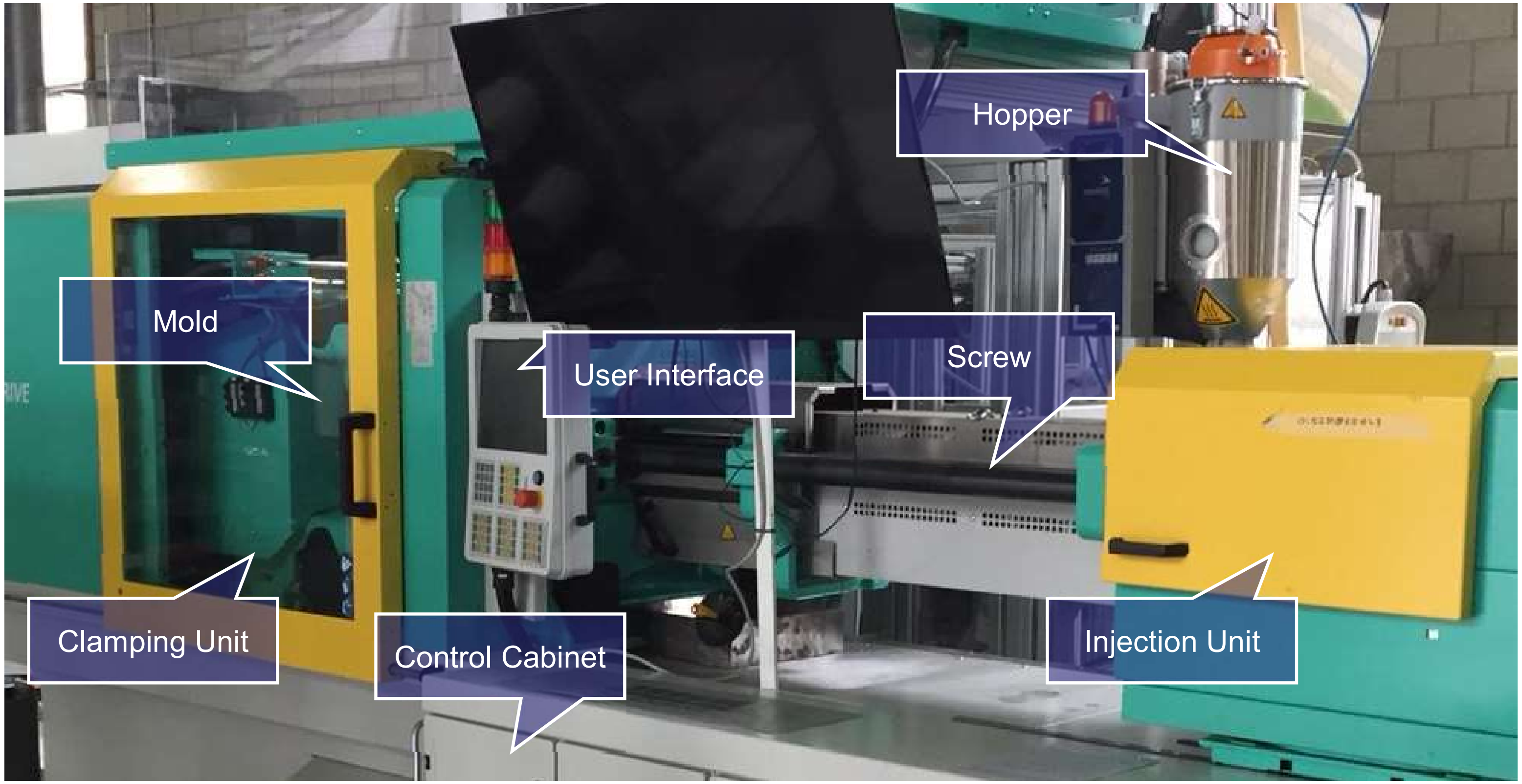
Complex Systems Example | Injection Molding Machine

Challenges

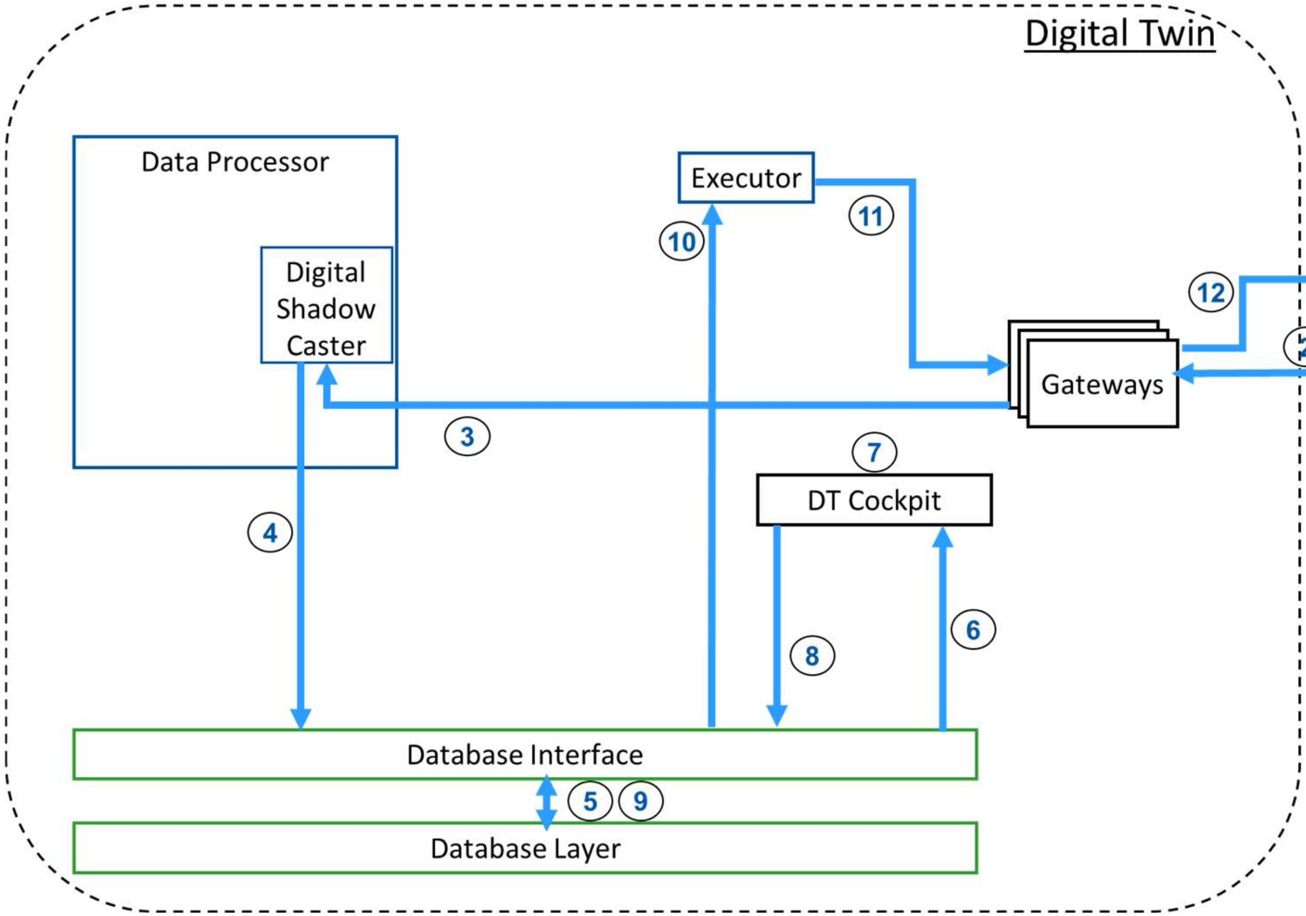
- Highly relevant *context*
- *Large amount* of data
- *Heterogeneous* data
- *Long life span*
- *Real-time* updates
- *Changing* reality

Opportunities

- *Reuse* system models of CPS
- *Data-driven model creation*



UC1: Monitoring and Providing Information to Human Operators



Use Case

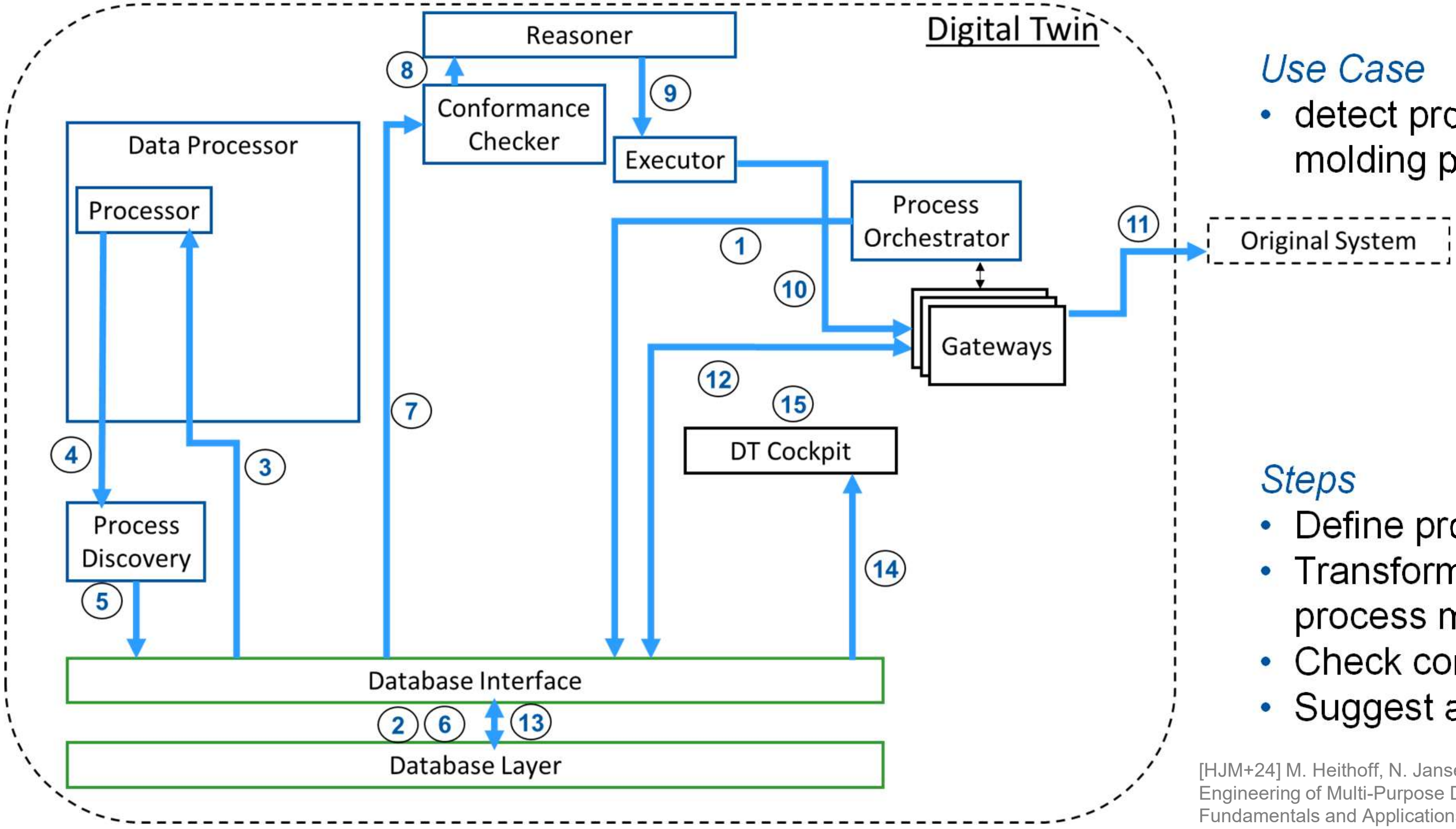
- measure process parameters temperature, and pressure
- indicate quality of the workpiece
- provide information to operator
- experienced operator adapts the configuration

Steps

- Monitoring and data processing
- Visualization
- Adapt configuration

[HJM+24] M. Heithoff, N. Jansen, J. Michael, F. Rademacher, B. Rumpe: Model-Based Engineering of Multi-Purpose Digital Twins in Manufacturing. In: Digital Twin: Fundamentals and Applications. 2024.

UC5: Process Analysis



Use Case

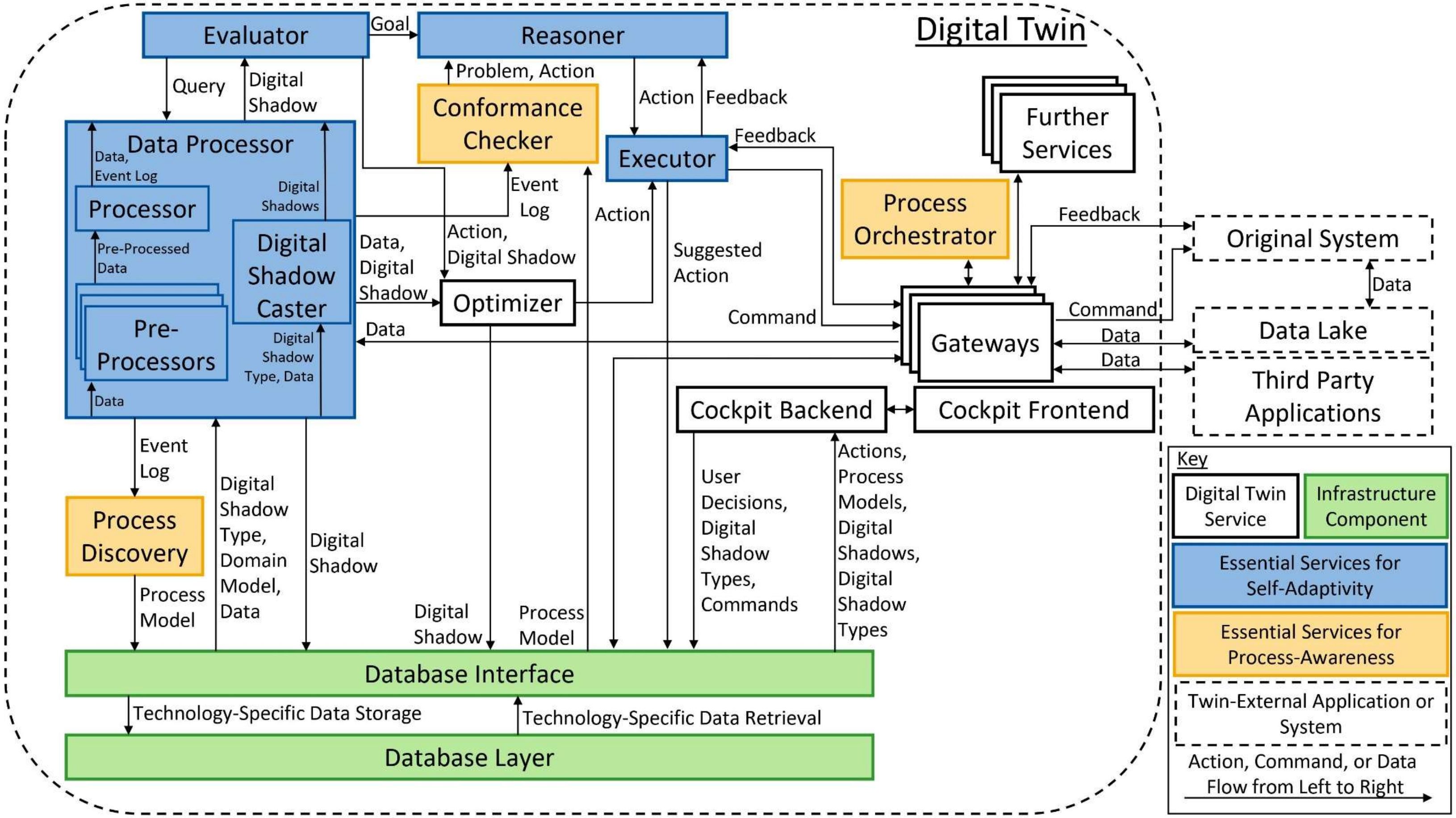
- detect problems during the injection molding process
  - describe measurable steps in a process model
  - discover & check actual process during operation
  - operators act on deviations

Steps

- Define process model to-be
- Transform measured data into process model as-is
- Check conformance with plans
- Suggest actions (execution, inform)

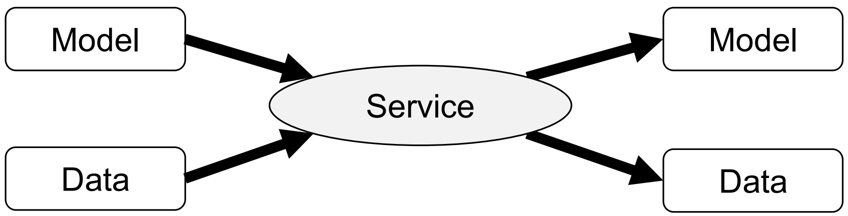
[HJM+24] M. Heithoff, N. Jansen, J. Michael, F. Rademacher, B. Rumpe: Model-Based Engineering of Multi-Purpose Digital Twins in Manufacturing. In: Digital Twin: Fundamentals and Applications. 2024.

Some (Important) Digital Twin Services

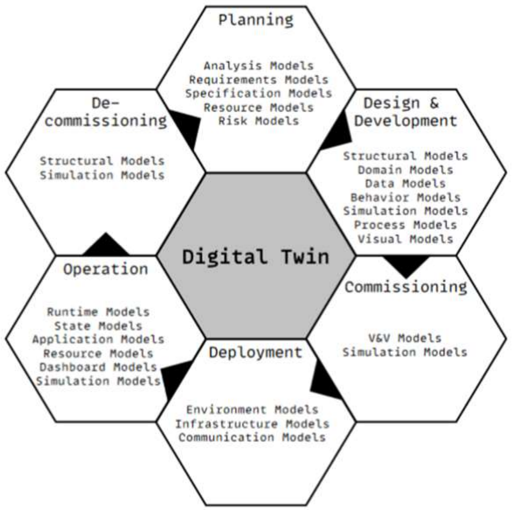


- Model-Driven Software Engineering
  - Component & Connector Architectures
  - Generate parts of the DT
- *Purpose-driven engineering* of DTs needs *different services* in *different life-cycle phases*
  - Evolving DTs

Characterizing Services in Digital Twin Architectures

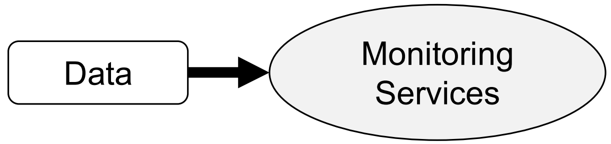


- Types of services
  - input/output (which data, which models)
  - inner behavior
  - cluster main characteristics



- Reuse of services
  - what specification is needed?

- Connectivity via APIs
  - commonalities
  - generation of APIs



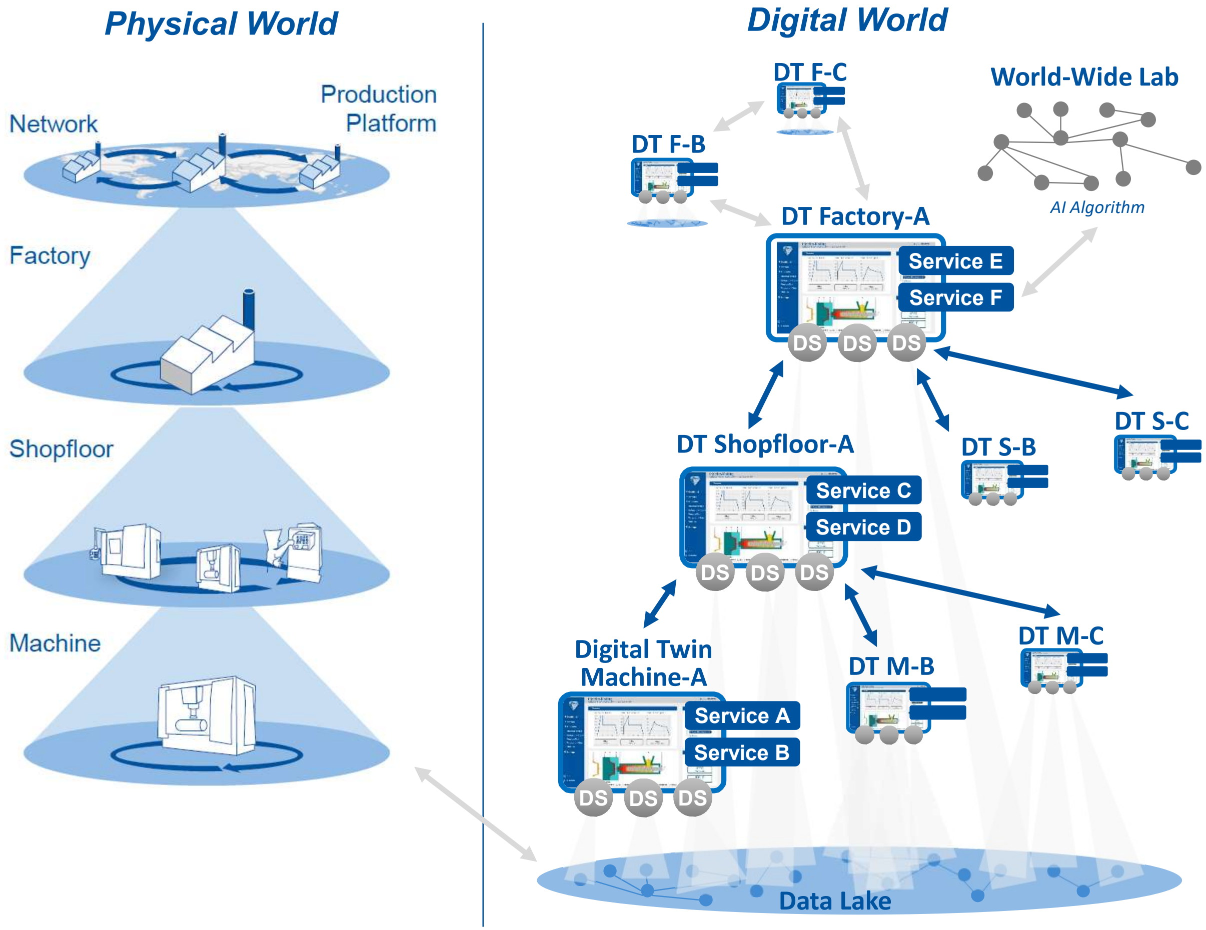
Current Work

MBDO project
https://mbdo.github.io/

Integration, Composition and Complexity Handling of Digital Twins

SE Software Engineering | RWTH AACHEN UNIVERSITY

Digital Twin Systems-of-Systems in the Production Domain



- Current digital twins
  - developed for various levels of the real world
  - developed and used by different organizational units
  - serve different purposes, e.g,
    - analysis, control, behavior prediction,…
  - used at different times relative to the represented system, e.g.,
    - before it exists: explore design space
    - during runtime: optimize behavior
  - …
- Identified 15 challenges (up to now)

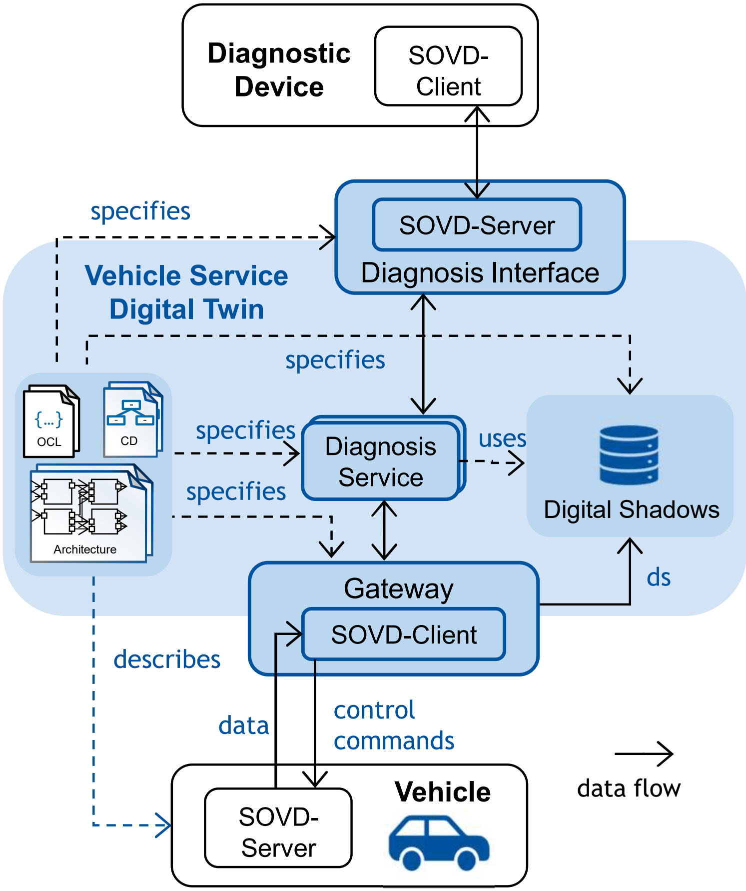
Integration Challenges | Overview

Horizontal integration of DT parts	Protection of intellectual property	Hierarchical functional abstraction
Vertical composition of DTs	Privacy aspects of data	Composition of interfaces DT2DT and DT2CPS
Composition of DTs for different perspectives	Rights and roles in the integrated DT	Interoperability of models and simulation environments
Connection of independently developed systems to a system-of-system	Composition of heterogeneous DT implementations	Integration of graphical user interfaces
Different lifecycle representations of the original system	Conflicting constraints and requirements	Heterogeneous technology-stack and different distribution patterns of DTs

[MPRW22] M J. Michael, J. Pfeiffer, B. Rumpe, A. Wortmann: Integration Challenges for Digital Twin Systems-of-Systems. SeSoS 2022.

AUTOtech.agil: Model-Driven Digital Twin for Vehicle Diagnostics

- Model-driven generation of the DT
  - services, Software Oriented Vehicle Diagnosis (SOVD)-compliant interfaces, data containers for digital shadows
  - architecture models for vehicle service structure and behavior
    - used to simulate expected behavior according to specification
    - comparison of real vs expected behavior
  - CDs + OCL to model
    - function classes for input/output data and function relations (storage of Digital Shadows)
    - classes of software errors for generation of predefined error-class specific diagnosis queries
- Pre-processing data in the vehicle services
  - aggregating raw data for regular transmission
  - detailed raw data on-demand



[HKM+23] M. Heithoff, M. Konersmann, J. Michael, B. Rumpe, F. Steinfurth: *Challenges of Integrating Model-Based Digital Twins for Vehicle Diagnosis*. In: ModDiT Workshop at MODELS 2023

AUTOtech.agil: Hierachical Digital Twin Control Flow

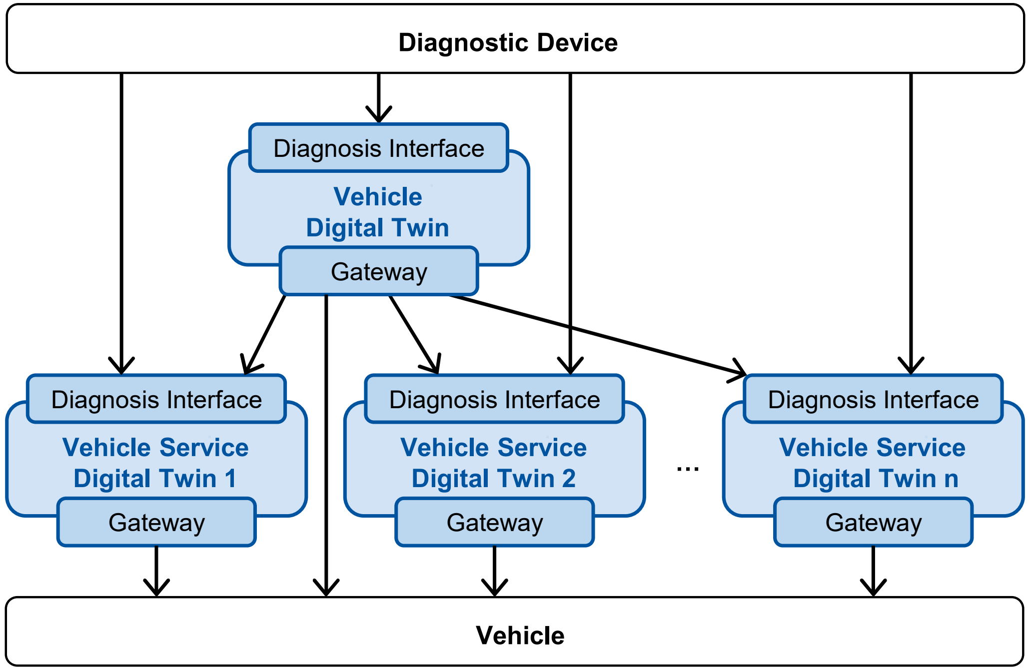
- Receive data from vehicle through gateway
- Send control commands to original system

- Service data saved in respective vehicle service DTs

- Vehicle DT controls vehicle service DTs
  - contains orchestrator DT service to enable diagnosis of service orchestration
  - contains function DT service for each vehicle function involving multiple vehicle services

- SOVD-compliant interfaces enable DT operator to connect via diagnostic device

- Send diagnosis queries to both the vehicle DT and single service DTs



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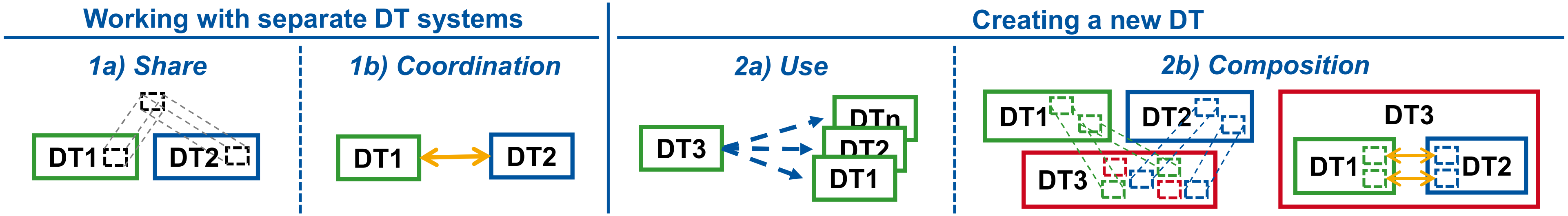
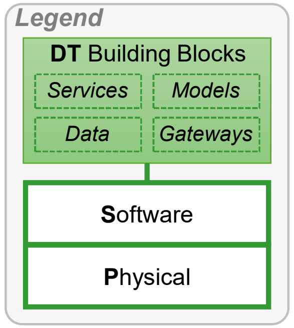
Kinds of Integration





- More complex
  - when splitting it up in concrete building blocks &
  - within different types of one building block

Current Work

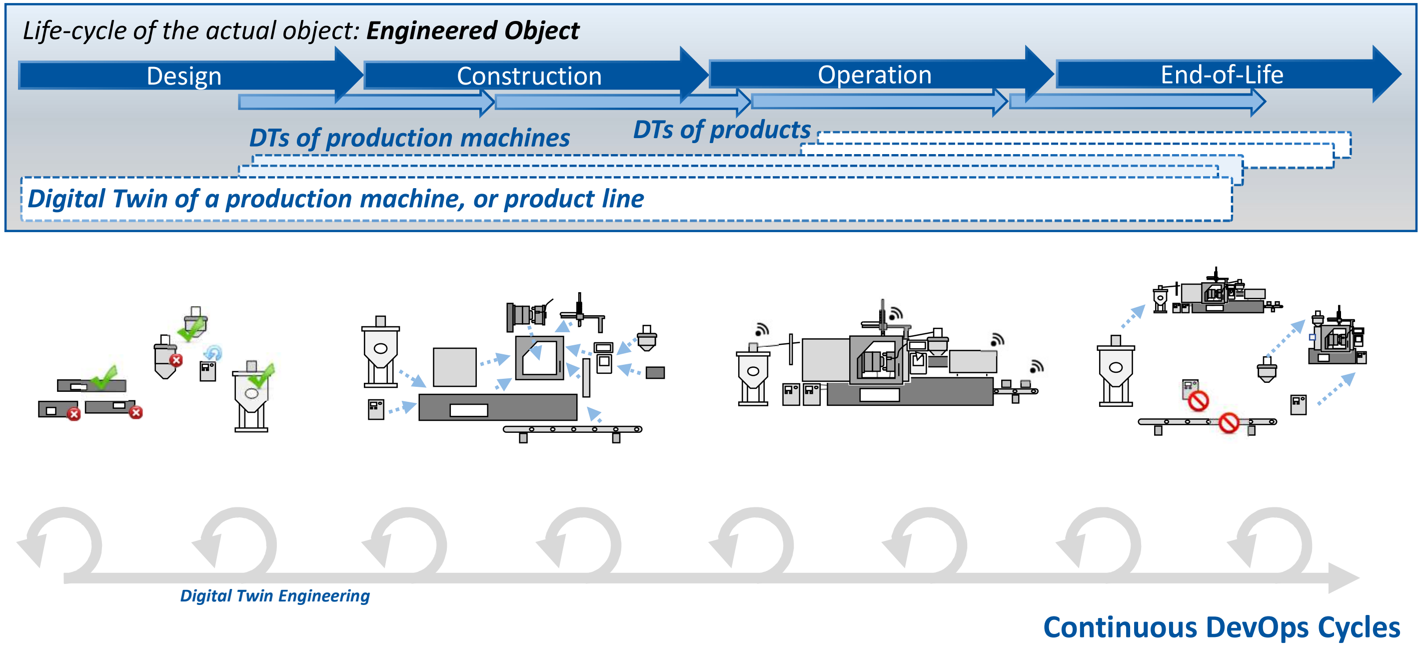
Ongoing discussions, e.g., with B. Combemale, J. Kienzle, G. Mussbacher

Evolving Digital Twins and CPS

- *Purpose-driven engineering* of DTs
  - need *different services* in *different life-cycle phases*
  - want to *answer different questions*

- *CPS* is adapted
  - *manufacturer* adapts the system
  - *autonomous self-adaptation*
  - *user* wishes to adapt the system behavior
  - *external regulations* make adaption necessary

- *Challenges*
  - *Services* of a Digital Twin are intensively *connected to the CPS*
  - *Development cycles/methods* for CPS and IT *differ* radically



Research on Digital Twin Engineering Embedded in International Networks

ANR/DFG
Model-Based DevOps for Digital Twins Project

Digital Twins for socio-technical systems

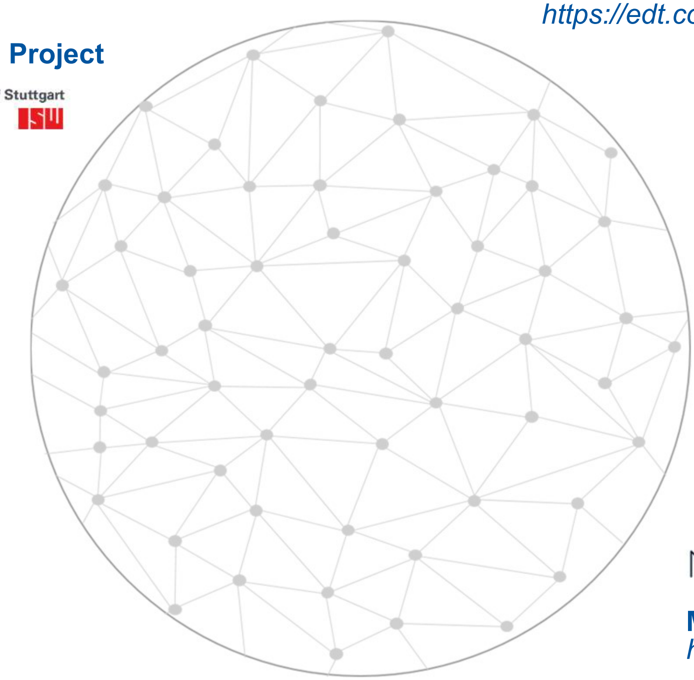
Digital Twins for vehicle diagnosis

RWTH Profile Area ProdE
ManuTech-X

International Dataspaces

Digital Product Passport

International Digital Twin Association
Asset Administration Shell



EDT.community
https://edt.community/

EDT seminar series

EDTconf
http://www.edtconf.org

MDEnet
https://mde-network.com/

International Working-Seminars
Dagstuhl, Bellairs, Cargèse, Winter Modeling Meeting, NII Shanon

International Conference on Engineering Digital Twins (EDTconf) *established 2024*

1st Edition
23.-24. September 2024
JKU Linz, Austria

Nicolaus Hanowski
European Space Agency
ESA Digital Twin Earth

Katia Gatti
Siemens Digital Industries Software
Digital Twins: First Strides Into the Industrial Metaverse

Contributions:
24 full, short, exemplar and tool demonstration paper

Digital Twin Roadshow
Showing-off amazing digital twin solutions

SoSyM Journal Special Section
for extended EDTconf 2024 papers

Next Edition: October 2025
Ann Arbor, Michigan, USA

Co-located with
IEEE/ACM conference MODELS 2025

General and PC Co-Chairs 2025
Romina Eramo, Manuel Wimmer, Steffen Zschaler

General and PC Co-Chair 2024
Chair of the Steering Committee
Judith Michael

www.edtconf.org

SUMMARY…

what should you take with you

- *Engineering methods* to create DTs are still under research
- Model-based approaches support complexity reduction, reuse, evolvement,…
- There is a lot to do…

together?

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