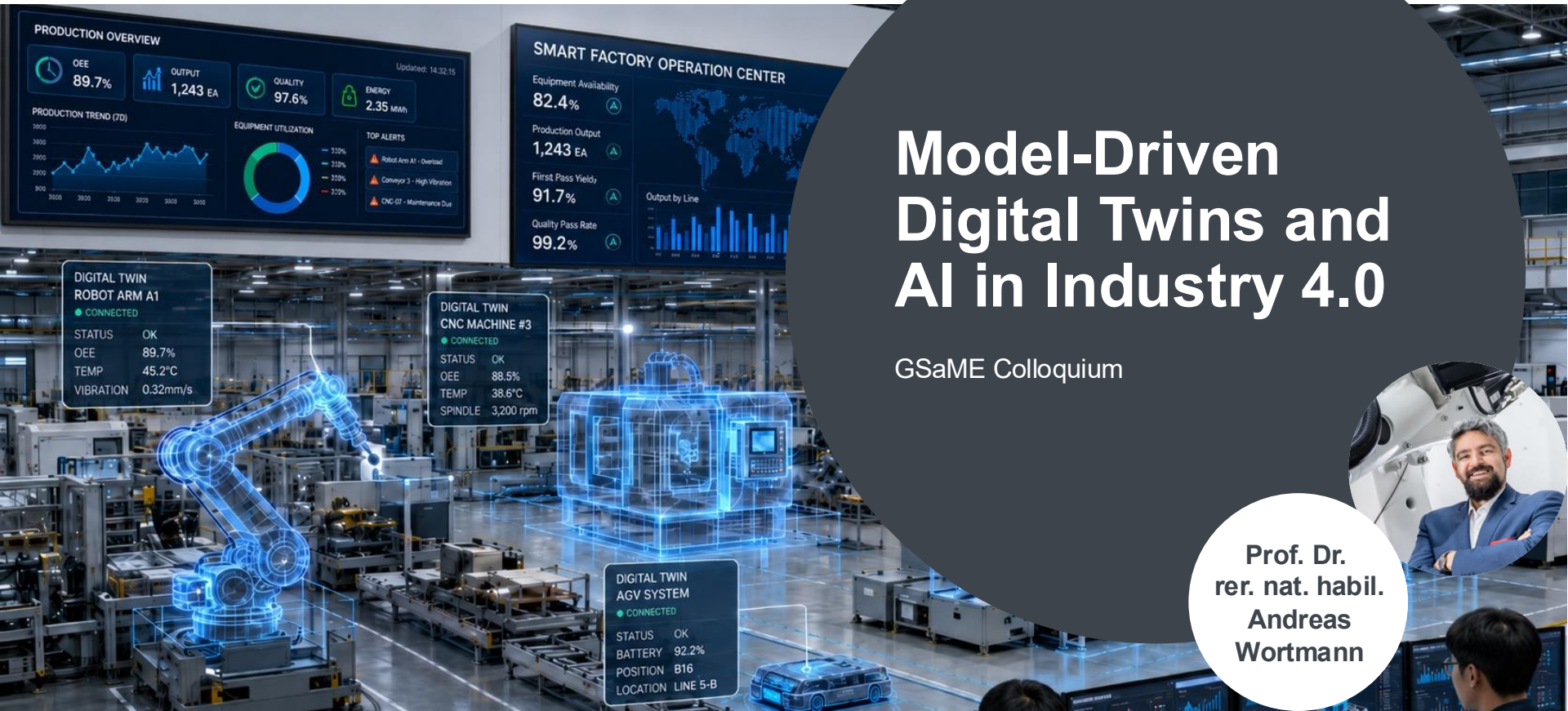
University of Stuttgart
Institute for Control Engineering of Machine Tools and Manufacturing Units (ISW)

Model-Driven Digital Twins and AI in Industry 4.0

GSaME Colloquium



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

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

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

- Director of ISW, University of Stuttgart
- Director of AI Software Engineering Academy at Stuttgart University
- Board of European Association for Programming Languages & Systems
- Spokesperson for AI-Powered Robotics of Robotics Institute Germany
- Founder of ACM/IEEE Engineering Digital Twins conference
- Research interests
  - Model-driven engineering
  - Cyber-physical systems (CPSs)
  - AI for engineering
  - Digital twins



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Head of Institute:

Alexander Verl
Oliver Riedel
Andreas Wortmann
Armin Lechler






Extended Head of Institute:

Carsten Ellwein
Florian Frick
Michael Seyfarth





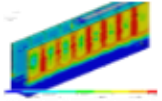
Research fields

- Software- and Engineering Methods
- Industrial Control Engineering
- Real-Time Communication and Control Hardware
- Drive Systems and Motion Control
- Mechatronic Systems and Processes
- Virtual Methods for Production Engineering





Engineering Methods

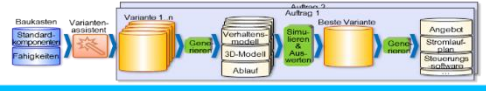

Simulation



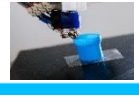



Communication

Model-Based Production Engineering



Product Influence

Production IT

Control

Algorithms
Operation
Architectures



Control Engineering

Mechatronic Systems



Drive Technology

Drive Control and Machine Technology



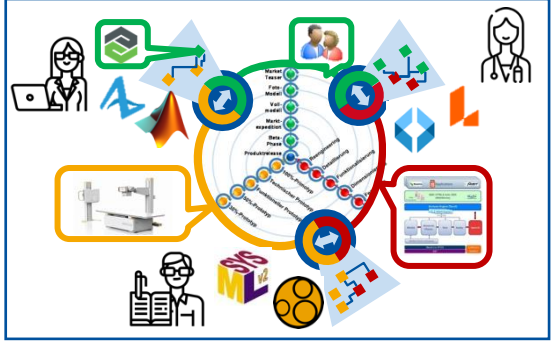
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University of Stuttgart
Germany

Civilization Advances by Extending the Number of Important Operations that we can Perform without Thinking about Them

- Alfred North Whitehead, 1913

Model-Driven Software & Systems Engineering



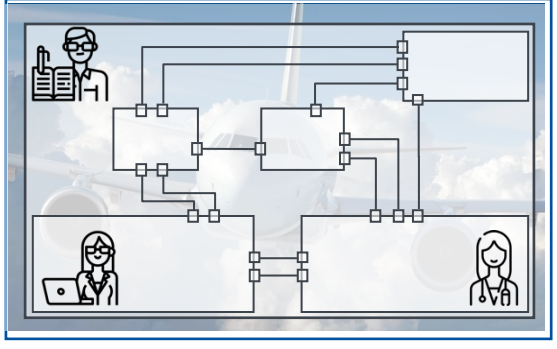
- New software languages
- Modeling techniques
- Model-driven development
- Model analysis, synthesis, code generation

Artificial Intelligence for Engineering



- Sustainable IT/OT through better software
- Automated program optimization
- Modeling assistance

Methodical Model-Driven Operations



- Digital twins for behavior optimization
- More efficient use of CPSs
- Explainable CPS behavior
- MDE for digital twins

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Model-Driven Development of Digital Twins is more Efficient and Reliable

AI can help with this and digital twins can help AI again

Introduction

Motivation

Digital Twins: Disambiguation

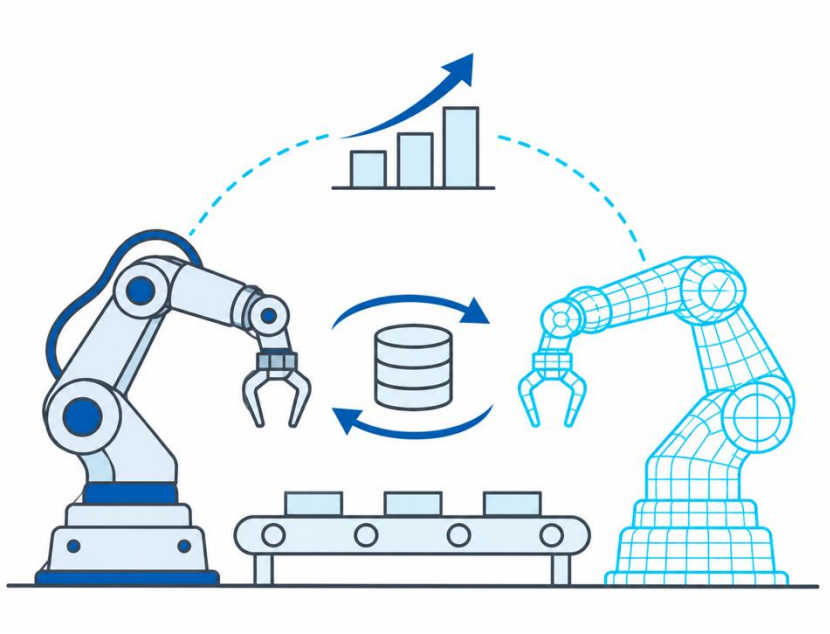
Model-Driven Engineering

Low-Code Development of Digital Twins

AI for Digital Twins

Digital Twins for AI

Challenges

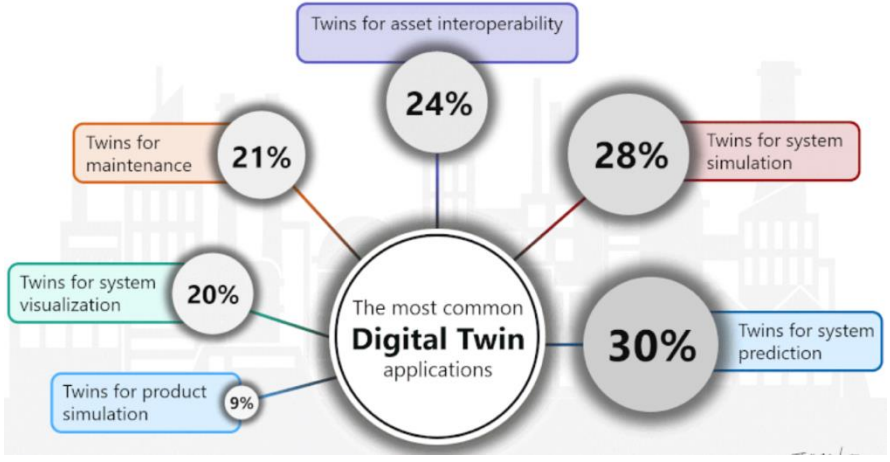


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Digital Twins Promise Significant Economic Impact

Including for behavior prediction, simulation, interoperability, maintenance, …

- Digital twins yield benefits of approx. £850 million across a ten-year period[1]
- Manufacturing: impact of DTs estimated[2] to be in the „low tens of billions of dollars“
- EU DT revenue forecast: $49.3B by 2030[2]
- KR DT revenue forecast: $3.8B by 2034[3]
- US DT-based savings of $27.2M / year[4]



Source: https://www.jeffwinterinsights.com/

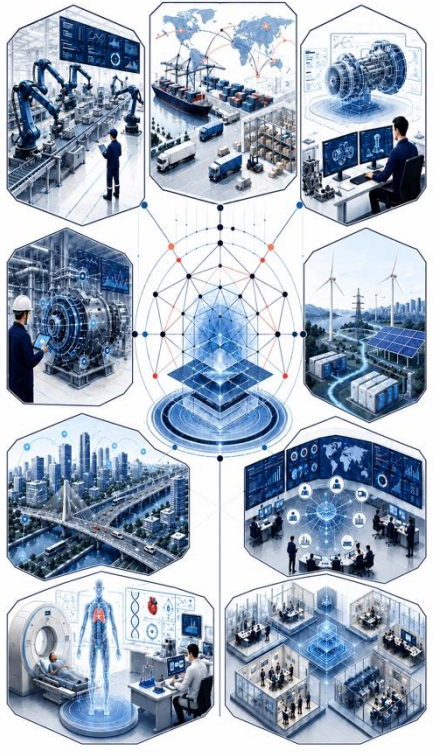
1. https://digitaltwinhub.co.uk/research-on-the-economic-benefits-of-digital-twins-for-integrated-transport-network-management/ (2024)
2. https://www.marketsandmarkets.com/Market-Reports/europe-digital-twin-market-195973825.html (2026)
3. https://www.imarcgroup.com/south-korea-digital-twin-market (2025)
4. National Institute of Standards and Technology (NIST). Economics of Digital Twins. https://tsapps.nist.gov/publication/get_pdf.cfm?pub_id=958153 (2024)

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Specific Digital Twin Applications in Manufacturing

Digital twins have proven real industrial impact on the shopfloor

- BMW: 25% reduced time to plan factory operations[1]
- BCG: 3% - 6% procurement cost down with value-chain twins[2]
- Capgemini: 16% improvement in sustainability metrics[3]
- McKinsey: 20% - 50% reduced product development time[4]
- Siemens: 30% service cost down, 8% output increase[6]
- Unilever: 90% reduction of false maintenance alerts[4]



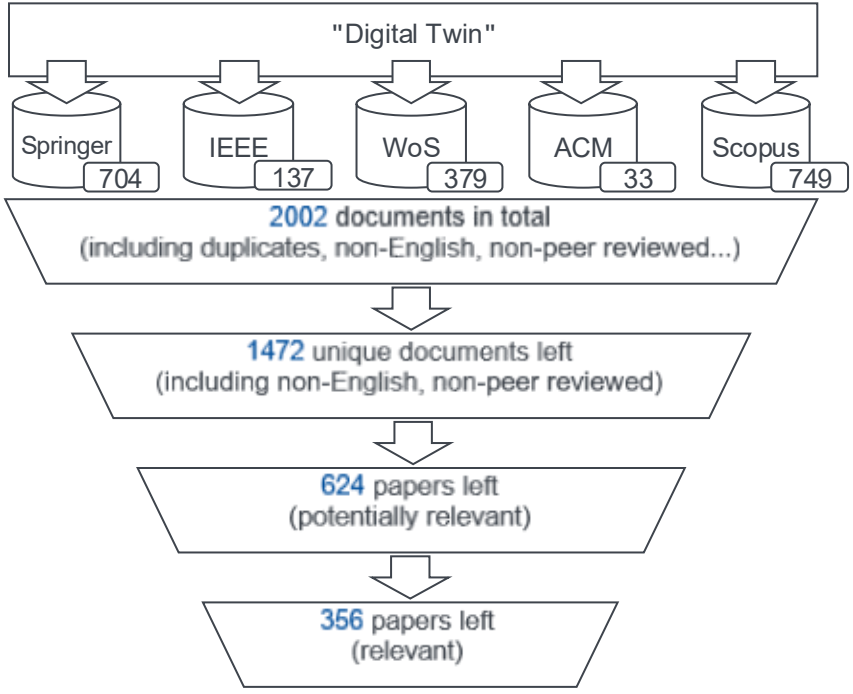
1. TIME Magazine: How Digital Twins Are Transforming Manufacturing, Medicine and More (2021)
2. BGC: Using Digital Twins to Manage Complex Supply Chains (2024)
3. Capgemini: Digital Twins are a catalyst to fulfilling organizations' sustainability agenda (2022)
4. Manufacturing Digital. The transformation of digital twins in manufacturing (2020)
5. McKinsey: Digital twins: The key to smart product development (2023)
6. Siemens Digital Industries Software: Four pillars of the industrial IoT (2020)

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

Research questions and overview

1. Who uses Digital Twins for which purposes?
2. What are 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. Dalibor, M., Jansen, N., Rumpe, B., Schmalzing, D., Wachtmeister, L., Wimmer, M., & Wortmann, A. (2022). A cross-domain systematic mapping study on software engineering for digital twins. Journal of Systems and Software, 193, 111361.

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Most of the 118 Descriptions we Identified of Digital Twins are Problematic

Hampers understanding, discussion, engineering, and operating digital twins

Ambiguous

Refer to **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]

Restricted

Focus **specific kind** of **system or implementation** technology:

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

Unrealistic

Practically **unfeasible**:

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

1. www.wortmann.ac/digital-twin-definitions

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Most of the 118 Descriptions we Identified of Digital Twins are Problematic

What about defining a digital twin as …

… a Model …	… for Simulation …	… of an Existing System
• "defined as the **predictive and validated** model" [128] • "a **software model** which is composed of 3D physical, mechanical, and electrical data" [497] • "**multi-faceted dynamic set of smart digital models** of a system" [719]	• "a […] **simulation model**" [498] • "integrated multiphysics, multiscale, probabilistic **simulation** of an as-built vehicle or system" [1307] • "Digital Twin [...] describes the use of **holistic simulations** to virtually mirror a physical system." [1386]	• "always in sync digital model of **existing manufacturing cells**" [24] • "a digital model of a **real object** containing [...] data, which are synchronized in real-time" [269]

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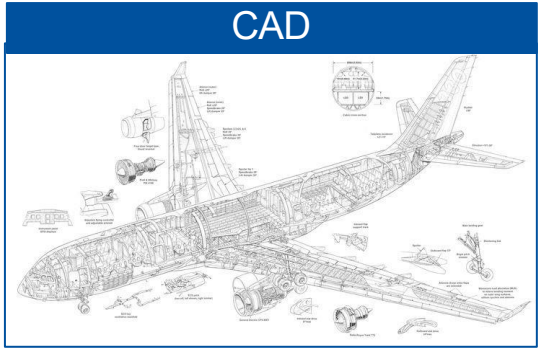
Take-away message

A digital twin must be a simulation model of an existing system

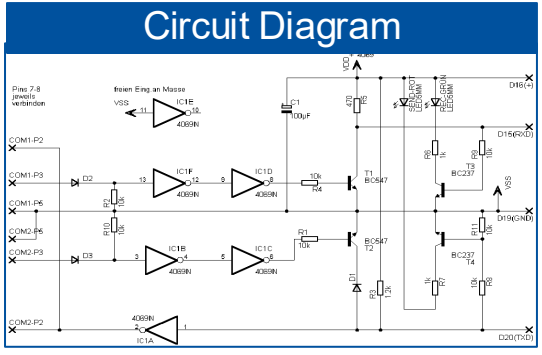
Are these Models Digital Twins then?

All of these models can be used to simulate an existing system

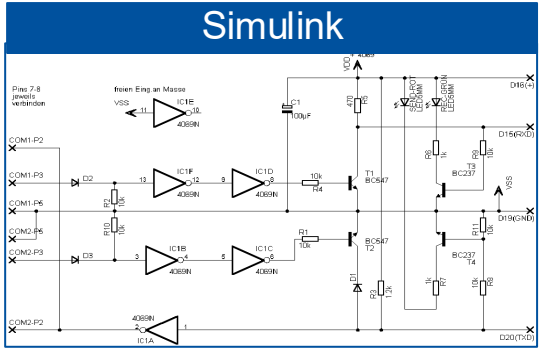
CAD



Circuit Diagram



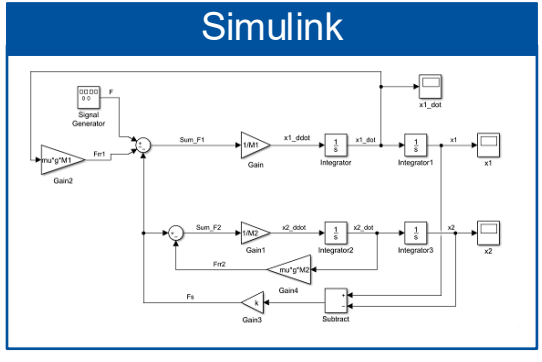
Simulink



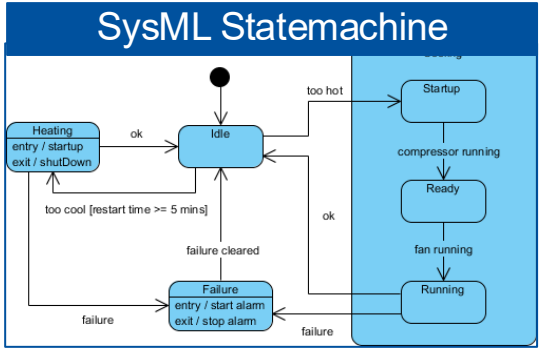
Math

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

Simulink



SysML Statemachine



Andreas Wortmann | www.wortmann.ac

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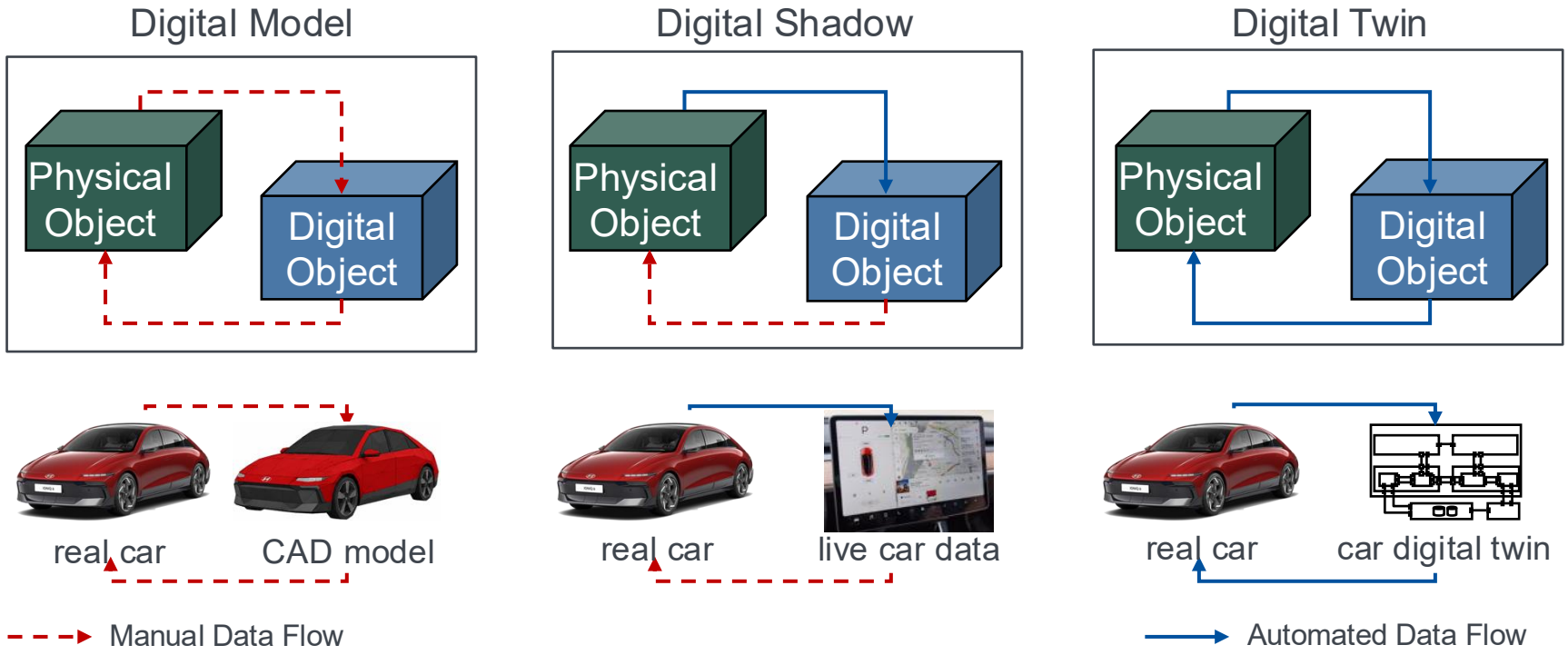
Take-away mess

A digital t st be a simulation model of a ting system



Digital Twins Cannot be mere 3D Simulation Models

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



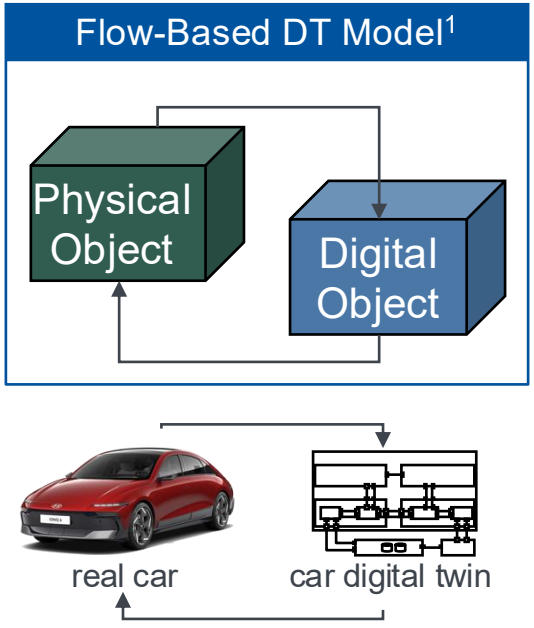
Kritzinger, W., Karner, M., Traar, G., Henjes, J., & Sihn, W: Digital Twin in manufacturing: A categorical literature review and classification. IFAC-PapersOnLine, 2018.

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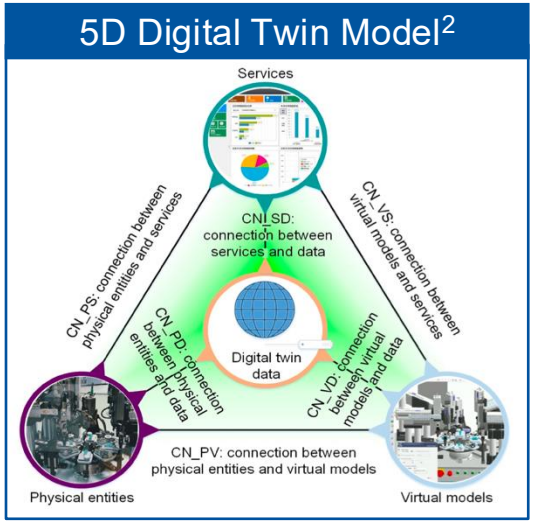
A Digital Twin Comprises Five Dimensions

A connection to the CPS, data from/about it, models of CPS/for DT, services

Flow-Based DT Model[1]

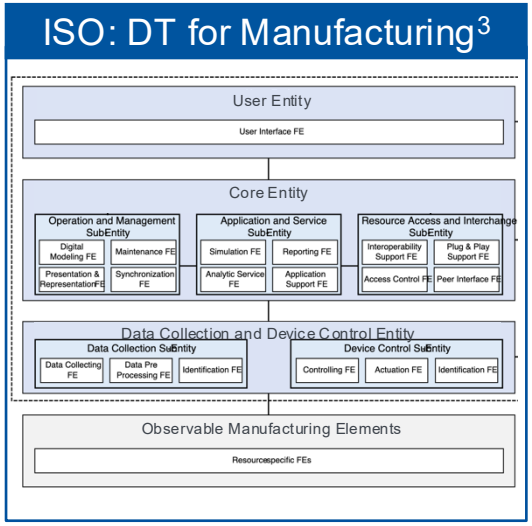


5D Digital Twin Model[2]



5 Dimensions: (1) CPS, (2) data, (3) models, (4) services, and (5) connections

ISO: DT for Manufacturing[3]



Observable Manufacturing Elements: Physical, biological, chemical, virtual, … assets

1. Kritzinger, W., Karner, M., Traar, G., Henjes, J., & Sihn, W: Digital Twin in manufacturing: A categorical literature review and classification. IFAC-PapersOnLine, 2018.
2. Tao, F., Zhang, H., Liu, A., & Nee, A. Y. (2018). Digital twin in industry: State-of-the-art. IEEE Transactions on industrial informatics, 15(4), 2405-2415.
3. ISO 23247. Digital Twin Framework for Manufacturing, 2021.

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Digital twin in industry: State-of-the-art

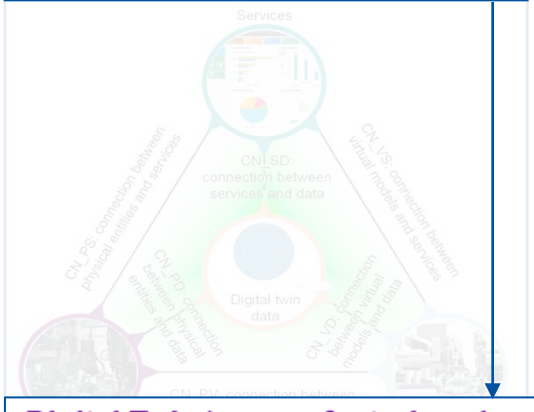
F **Tao**, H Zhang, A Liu, AYC Nee - IEEE Transactions on …, 2018 - ieeexplore.ieee.org

… notions such as the airframe **digital twin** (ADT) and experimental **digital twin** (EDT) [10], [11]. …
Tao, "**Digital twin** and big data towards smart manufacturing and industry 4.0: 360 degree …

☆ Speichern Zitieren Zitiert von: 7192 Ähnliche Artikel Alle 7 Versionen

Flow-Based DT Model[1]

5D Digital Twin Model[2]



ISO: DT for Manufacturing[3]

Digital Twin in **manufacturing**: A categorical literature review and classification

W **Kritzinger**, M Karner, G Traar, J Henjes, W Sihn - Ifac-PapersOnline, 2018 - Elsevier

… in which a **Digital Twin** is implemented, … **Digital Twins** are a major focus of the investigation.
This paper serves as the basis for further work in the field of the **Digital Twin** in **manufacturing**…

☆ Speichern Zitieren Zitiert von: 5795 Ähnliche Artikel Alle 4 Versionen »

1. Kritzinger, W., Karner, M., Traar, G., Henjes, J., & Sihn, W: Digital Twin in manufacturing: A categorical literature review and classification. IFAC-PapersOnLine, 2018.
2. Tao, F., Zhang, H., Liu, A., & Nee, A. Y. (2018). Digital twin in industry: State-of-the-art. IEEE Transactions on industrial informatics, 15(4), 2405-2415.
3. ISO 23247. Digital Twin Framework for Manufacturing, 2021.

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Digital Twins are Supposed to do Everything[1]

From data management to simulation, federated learning, prediction, intelligence

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

1. Digital Twin Consortium. Digital Twin Periodic Table (2026): https://www.digitaltwinconsortium.org/initiatives/capabilities-periodic-table/

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Conclusion

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

Currently 26 ISO Standards Adress or Mention Digital Twins (DTs)

50% directly standardize engineering/use of digital twins, 25% **published**



1. **ISO/IEC 30173:2023** — **DT — Concepts and terminology**
2. **ISO/IEC 30186:2025** — **DT — Maturity model and guidance for a maturity assessment**
3. **ISO/TR 24464:2025** — **Visualization elements of DT — Visualization fidelity**



4. ISO/IEC CD TR 30138 — DT — Fidelity metric of digital twin system
5. ISO/IEC AWI 30153 — DT — Guidelines for digital entity modeling
6. ISO/IEC CD 30151 — DT — Extraction and transactions of data components
7. ISO/IEC CD 30188 — DT — Reference architecture
8. ISO/IEC WD TS 27568 — Security and privacy of digital twins



9. **ISO/TR 23247:2025** — **DT framework for manufacturing**
10. ISO/DTS 25271 — Automation systems and integration — Industrial DT interface architecture



11. **ISO/IEC 20924:2024** — **Internet of Things (IoT) and DT — Vocabulary**
12. **ISO/IEC TR 30172:2023** — **Internet of things (IoT) — DT — Use cases**
13. **ISO/IEC 30194:2024** — **Internet of things (IoT) and DT — Best practices for use case projects**

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Digital Twins are Being Standardized by Various Stakeholder Groups

And it is not the marketing wild west anymore

Definition 3.1.1. (Digital Twin)[1]

"Digital representation (3.1.8) of a target entity (3.1.3) with data connections that enable convergence between the physical and digital states at an appropriate rate of synchronization.

- Note 1 to entry: Digital twin has some or all of the capabilities of connection, integration, analysis, simulation, visualization, optimization, collaboration, etc."

Implications

- Digital representation ⇒ models (in the sense of Stachowiak[2])
- Data connections and some capabilities ⇒ digital twins are software systems
- Convergence between physical & digital ⇒ connected physical twin exists (or a proxy for it)
- Some capabilities ⇒ different DTs of different purposes provide different services

1. ISO/IEC 30173 "Digital twin – Concepts and terminology"
2. H. Stachowiak: Allgemeine Modelltheorie. Springer Verlag, Wien/New York 1973

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Digital Twins (DTs) are Costly: Minimum $ 1M / DT[1]

Including for behavior prediction, simulation, interoperability, maintenance, …

- Capgemini: aerospace & defense invest 2.7% of AR in DTs
- Mid-complexity DTs (e.g., single production line): $500k - 2M costs[3]
- Deployment: 3-6 mo.[4], First value: +4 mo.[5], Scale: +9 mo.[4]
- Hampers adoption and making better use of cyber-physical systems
- Most manufacturing companies have more urgent challenges than setting up digital twins (e.g., digital product pass)



1. https://www.ptc.com/en/blogs/corporate/roi-of-digital-twin-for-industrial-companies
2. Capgemini. Aerospace and defense organizations show growing confidence in Digital Twin technology with 40% invest. increase. (2025)
3. Medium. The Business Case for Digital Twin: Costs, Benefits, and ROI Explained. (2026)
4. Capgemini. REFLECTIOD Digital Twin For Asset Operators (2021)
5. Accenture. How digital twins enable autonomous operations (2022)

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Manufacturing is Driven by SMEs with Limited Software Engineering

Low Code is the key enabler for making digital twins accessible to SMEs

LANDSCAPE[1]

- Manufacturing 20% of DE GDP
- World-class companies: Airbus, Renault, Saint-Gobain, …
- 96.9% of manufacturing companies SMEs or smaller
- Contribute 24% of manufacturing GDP
- More urgent challenges than setting up digital twins
- Impedes better use of CPSs, integrated value chains, …

CHALLENGES

- DTs is costly, time-consuming, and highly complex
- Most manufacturing companies are SMEs with limited IT expertise and resources
- No reusable DT components: ad-hoc, hard-to-maintain solutions
- Implementing standards demands SE expertise

LOW CODE SOLUTIONS

- Vertically integrated model-driven engineering (MDE)
- Tailored modeling techniques for domain experts
- Often little to no software engineering required
- Examples: Appian, Google AppSheet, n8n, NodeRED, Mendix, Microsoft PowerApps, Oracle APEX, OutSystems

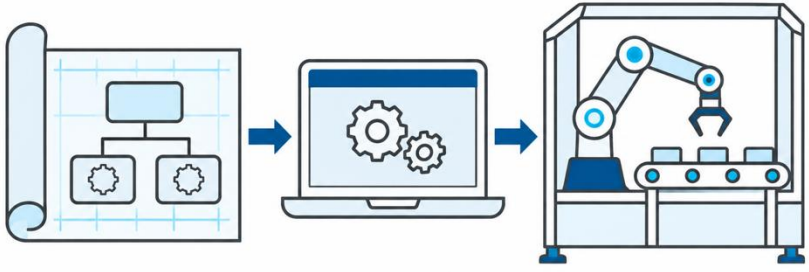
1. Destatis: https://www.destatis.de/Europa/EN/Topic/Industry-trade-services/Industry_GVA.html

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Model-Driven Development of Digital Twins is more Efficient and Reliable

AI can help with this and digital twins can help AI again

- Introduction
- Motivation
- Digital Twins: Disambiguation
- ▶ Model-Driven Engineering
- Low-Code Development of Digital Twins
- AI for Digital Twins
- Digital Twins for AI
- Challenges



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Complexity in Systems Engineering Grows Dramatically Fast

Overcompensating it is crucial

- Society thrives on cyber-physical systems
  - communication, energy, home automation, manufacturing, medicine, transportation, …
- Added-value mainly software
- Software complexity grows in magnitudes
  - distributed, self-adaptive, intelligent, …
- Conceptual gap: problem vs. solution domains
- Modeling can
  - overcompensate the growth of complexity
  - reduce the conceptual gap



Chevy Volt
(10 Mio. LoC)



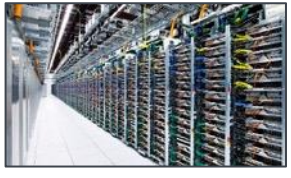
Boeing 787
(14 Mio. LoC)



LHC CERN
(50 Mio. LoC)



High-Value Car
(100 Mio. LoC)

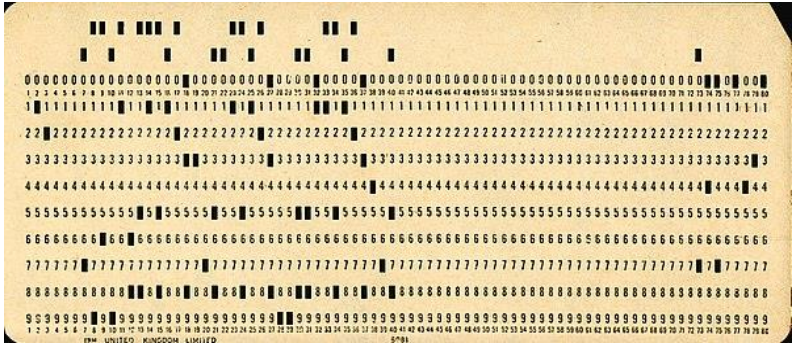


Google Services
(2 Bio. LoC)

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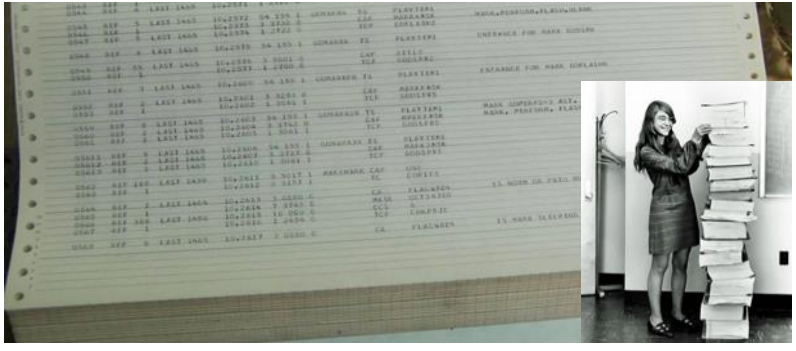
Raising Abstraction in the Engineering of Software-Intensive Systems

What does this program do?



- Punch cards by Herman Hollerith
- First use: 1890 U.S. census
- 9 popular formats (4 x IBM)
- Last use: 2012 voting machines

What does this program do?



- Assembler code
- First use 1949
- Basically, direct memory manipulation
- NASA Apollo 11 guidance computer source code available from https://github.com/chrislgarry/Apollo-11

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Raising Abstraction in the Engineering of Software-Intensive Systems

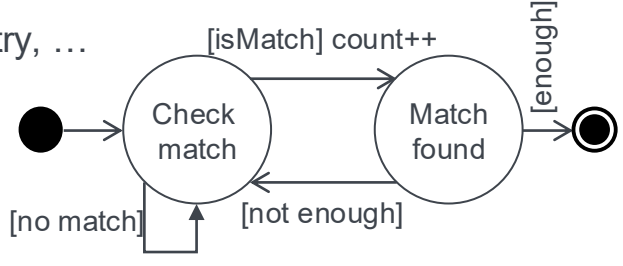


- General purpose programming languages
- Object-oriented, imperative
- Functional, logical
- Code closer to problem domain
  (e.g., medicine, production, robotics, …)

```
const uint8_t req_match_count = match_thre
uint8_t match_count = 0;
for (uint16_t x = 0; x < len; ++x) {
    if (fuzzy_cmp(lhs[x], rhs[x]) == 0) {
        ++match_count;
    }
    if (match_count >= req_match_count) {
        return true;
    }
```



- Modeling languages or domain-specific languages
  - e.g. for structure, behavior, deployment, constraints, physics, kinematics, geometry, …
- Reduce conceptual gap
- Closer to problem domain
- Less accidental complexity

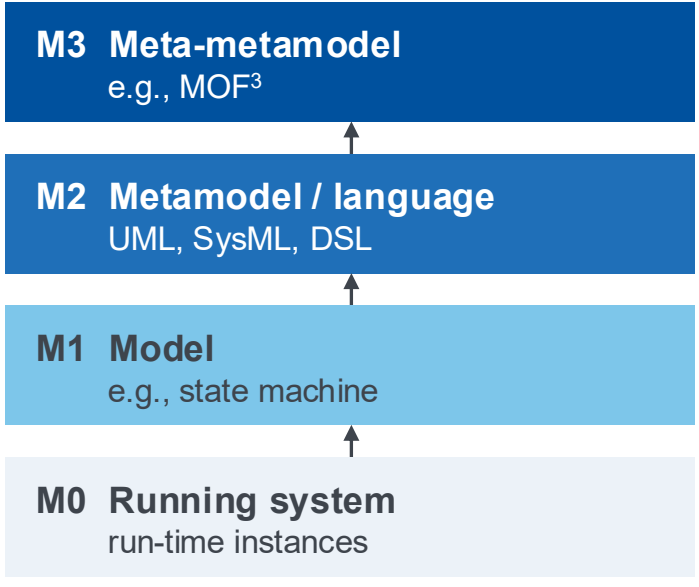


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MDSE Makes Models the Primary Artifacts of Software Development

Definition and core concepts

- Models instead of code as central development artifacts[1]
- Abstraction: problem-domain concepts instead of platform concepts[2]
- Automation: transformations generate code, tests, and documentation[1]
- Languages: general-purpose (UML, SysML) or domain-specific (DSL)[1]
- Equation: models + transformations = software[1]
- Contrast to LLM-based code generation: deterministic



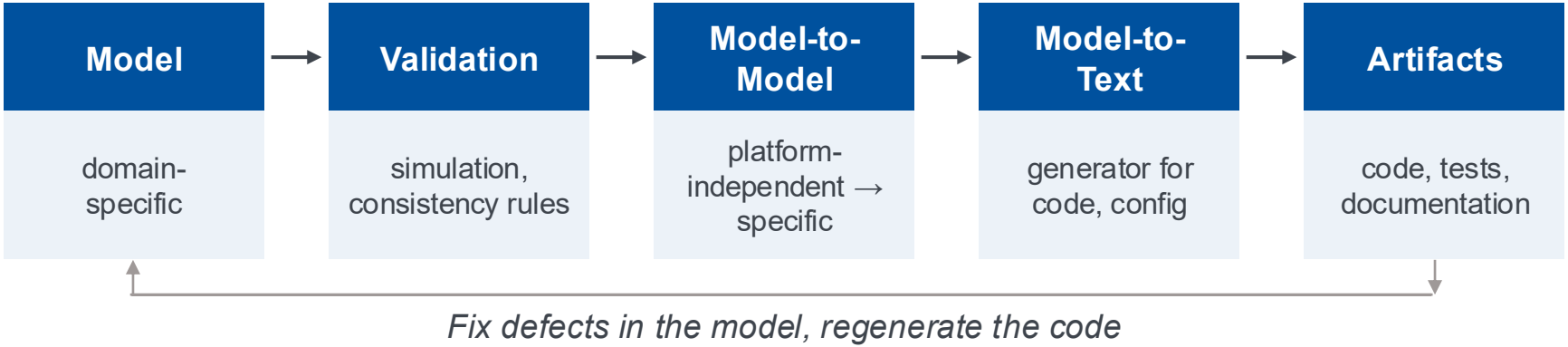
Arrow: "is an instance of"

1. Brambilla, M., Cabot, J., & Wimmer, M. (2017). Model-driven software engineering in practice (2nd ed.). Morgan & Claypool.
2. Schmidt, D. C. (2006). Model-driven engineering. IEEE Computer, 39(2), 25–31.
3. Object Management Group (2016). Meta Object Facility (MOF) core specification, version 2.5.1.

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Transformations Turn Models Step by Step into Executable Software

Basic workflow



Language engineer

defines metamodel, editor, and generators[1]

Domain expert

models, simulates, and generates – (without platform details[2])

1. Brambilla, M., Cabot, J., & Wimmer, M. (2017). Model-driven software engineering in practice (2nd ed.). Morgan & Claypool.
2. Object Management Group (2014). MDA guide, revision 2.0 (ormsc/14-06-01).

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Measured MDE Benefits Range from +20% to 10× – Context Decides

Summary of empirical findings across studies and domains

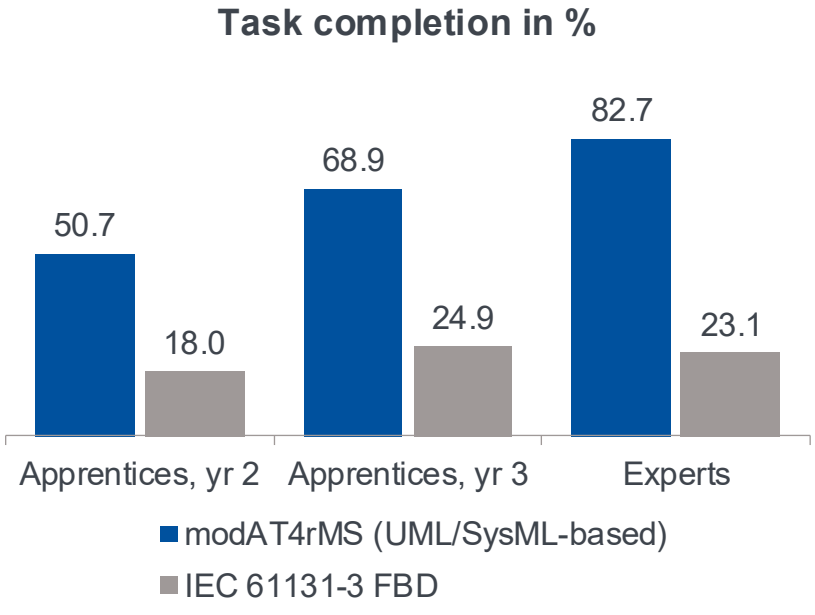
Study / domain	Productivity, cost, and effort	Quality
Practitioner survey (n = 450)	**+20–30%** typical; range −27% to +800%[1]	–
Domain-specific modeling	**5–10×** typical; UML alone: no significant gain[3]	–
Telecommunications (Motorola)	**2–8×** productivity; 65–85% code generated; −33% test case effort[2]	**1.2–4×** fewer defects; **30–70×** faster fixes[2]
Automotive	**−27%** cost, **−36%** time (avg.); < 1 year of experience: higher costs[4]	Earlier defect detection via model tests[4]
Aerospace (Airbus)[5]	Manual coding cut to **30%** (A340)[6]; **−67%** test time (vendor claim)[7]	**< 10** vs. several hundred coding errors per 100 KB[6]

1. Whittle, J., Hutchinson, J., & Rouncefield, M. (2014). The state of practice in model-driven engineering. IEEE Software, 31(3), 79–85.
2. Baker, P., Loh, S., & Weil, F. (2005). Model-driven engineering in a large industrial context – Motorola case study. MoDELS 2005, LNCS 3713, 476–491.
3. Tolvanen, J.-P., & Kelly, S. (2016). Model-driven development challenges and solutions: Experiences with domain-specific modelling in industry. MODELSWARD 2016.
4. Broy, M., Kirstan, S., Krcmar, H., & Zimmermann, J. (2011). Model-based software development – its real benefit. EE Times Europe (global study by Altran/TU Munich).
5. Bochot, T., Virelizier, P., Waeselynck, H., & Wiels, V. (2009). Model checking flight control systems: The Airbus experience. ICSE 2009, Companion Volume, 18–27.
6. Design News (2001). Avionics software joins speed, safety (trade press).
7. MathWorks . Airbus Helicopters accelerates development of DO-178B certified software with Model-Based Design: https://www.mathworks.com/company/user_stories/airbus-helicopters-accelerates-development-of-do-178b-certified-software-with-model-based-design.html

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Manufacturing Automation: Models Ease PLC Programming

Object-oriented models vs. function block diagram (FBD), n = 168[1]



MODELING LANGUAGES

- modAT4rMS (UML/SysML subset), plcML
- Generation of IEC 61131-3 code

USER GROUPS

- Programmable logic controller (PLC) programmers, mechatronics apprentices

BENEFITS

- Up to 3.6× higher task completion
- Lower workload and frustration ($p < 0.001$)
- Limitation: modifying existing code

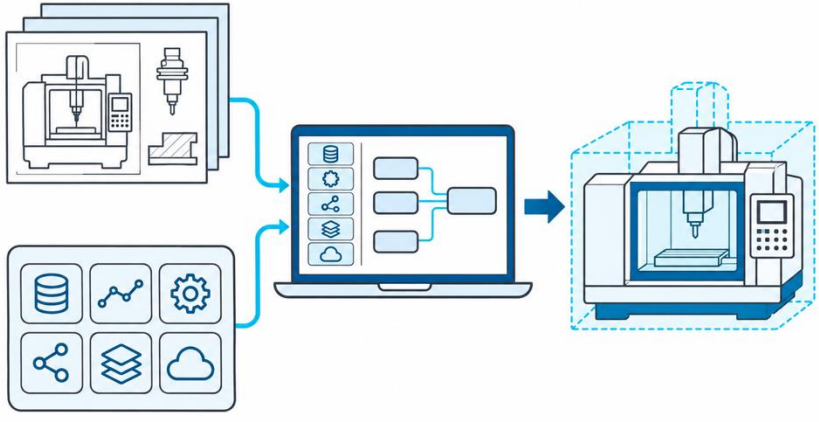
1. Obermeier, M., Braun, S., & Vogel-Heuser, B. (2015). A model-driven approach on object-oriented PLC programming for manufacturing systems. IEEE TII, 11(3), 790–800.

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Model-Driven Development of Digital Twins is more Efficient and Reliable

AI can help with this and digital twins can help AI again

- Introduction
- Motivation
- Digital Twins: Disambiguation
- Model-Driven Engineering
- ▶ Low-Code Development of Digital Twins
- AI for Digital Twins
- Digital Twins for AI
- Challenges



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Low-Code Is MDSE Packaged for Citizen Developers and the Cloud

Same foundations as MDSE, different delivery – which explains its success

WHY IT IS MDSE	WHAT IS SPECIAL	WHY IT SUCCEEDS NOW
• Models drive development; code is generated or interpreted[1] • Model-driven engineering: most cited core technology[2] • No fundamentally new technique[3]	• Targets citizen developers[1] • Cloud: zero setup, hosting, lifecycle[1] • One-shot models, no transformation chains[3]	• Instant cloud deployment[1] • Digital-native domain experts[1] • Shortage of professional developers[1]

$13.8B

low-code revenue in 2021[2]

23% + 22%

of developers used or planned low-code[1]

38%

of peer-reviewed studies validated only by argument[2]

1. Di Ruscio, D., Kolovos, D., de Lara, J., et al. (2022). Low-code development and model-driven engineering: Two sides of the same coin? Softw. Syst. Model., 21(2), 437–446.
2. Bucaioni, A., Cicchetti, A., & Ciccozzi, F. (2022). Modelling in low-code development: A multi-vocal systematic review. Softw. Syst. Model., 21(5), 1959–1981.
3. Cabot, J. (2020). Positioning of the low-code movement within the field of model-driven engineering. MODELS 2020 Companion Proceedings, 76:1–76:3.

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Industrial Digital Twin in a Day using Model-Driven Engineering

A low-code-based solution tailored to SMEs and useful for everyone

- Generate digital twin architecture
- Add business logics from service library
- Configure the remaining parts easily
- Industry standards
- Existing models

Digital twin implementation

- Data infrastructure
- Interfaces
- Dashboard
- Models @ RunTime



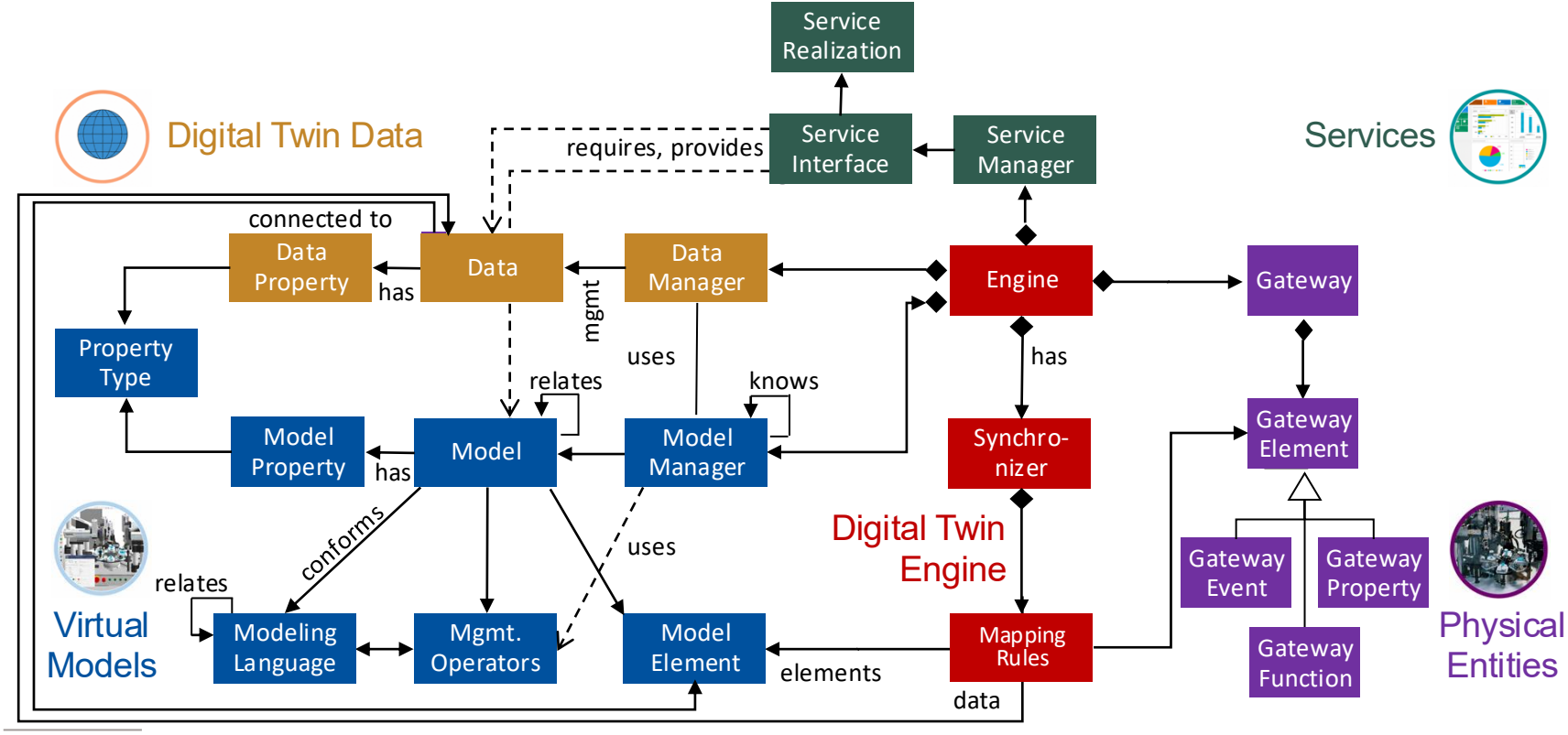
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A Reference Architecture for ISO 23247 Digital Twins in Manufacturing

Based on the 5D model[1] and refined with modeling expertise

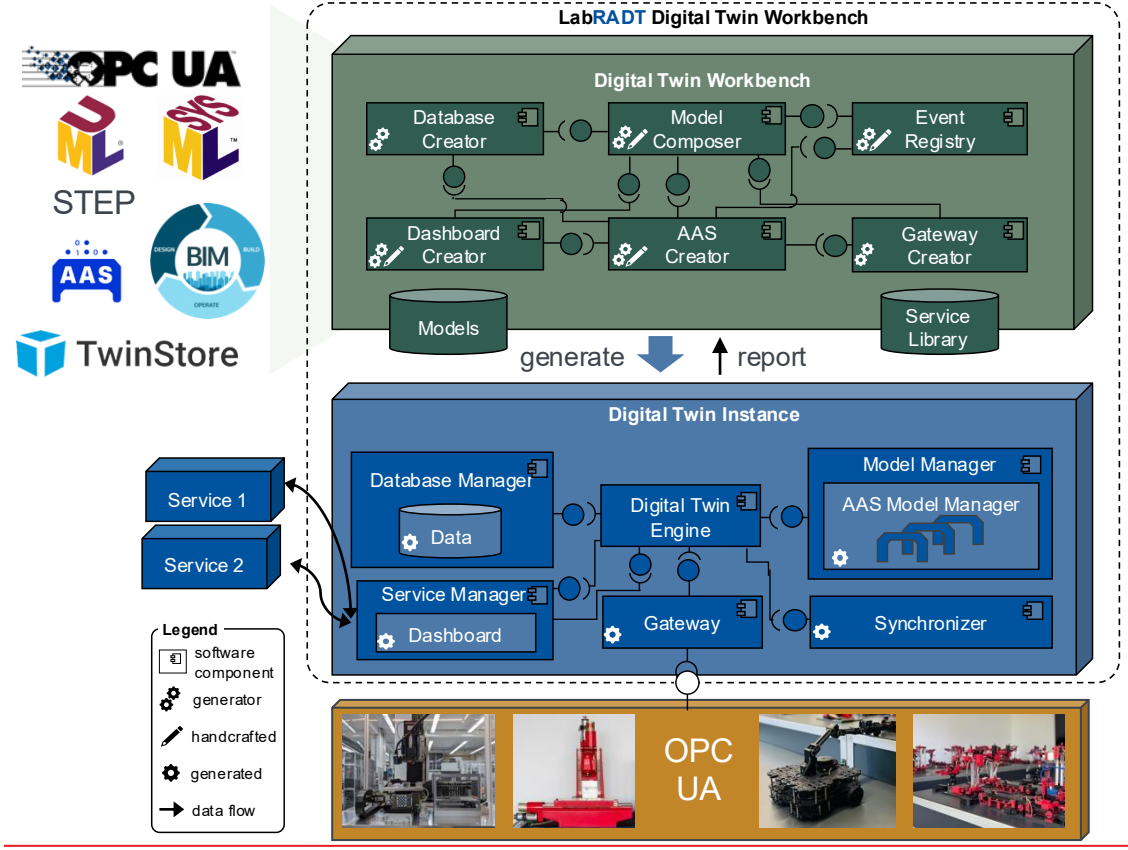


1. Pfeiffer, J., Zhang, J., Combemale, B., Michael, J., Rumpe, B., Wimmer, M., & Wortmann, A. (2025). Towards a unifying reference model for digital twins of cyber-physical systems. In 2025 IEEE 30th International Conference on Emerging Technologies and Factory Automation (ETFA). IEEE

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Our Workbench Employs Models as Blueprint and at Runtime

Ingests engineering models and services, produces digital twin instances



Separation of concerns

- software engineers: workbench, digital twin architecture, services
- domain experts: runtime models, configuration

Workbench

- ingests engineering models
- instantiates DT reference architecture
- creates data infrastructure, UI
- generates DT instance

Digital twin instance

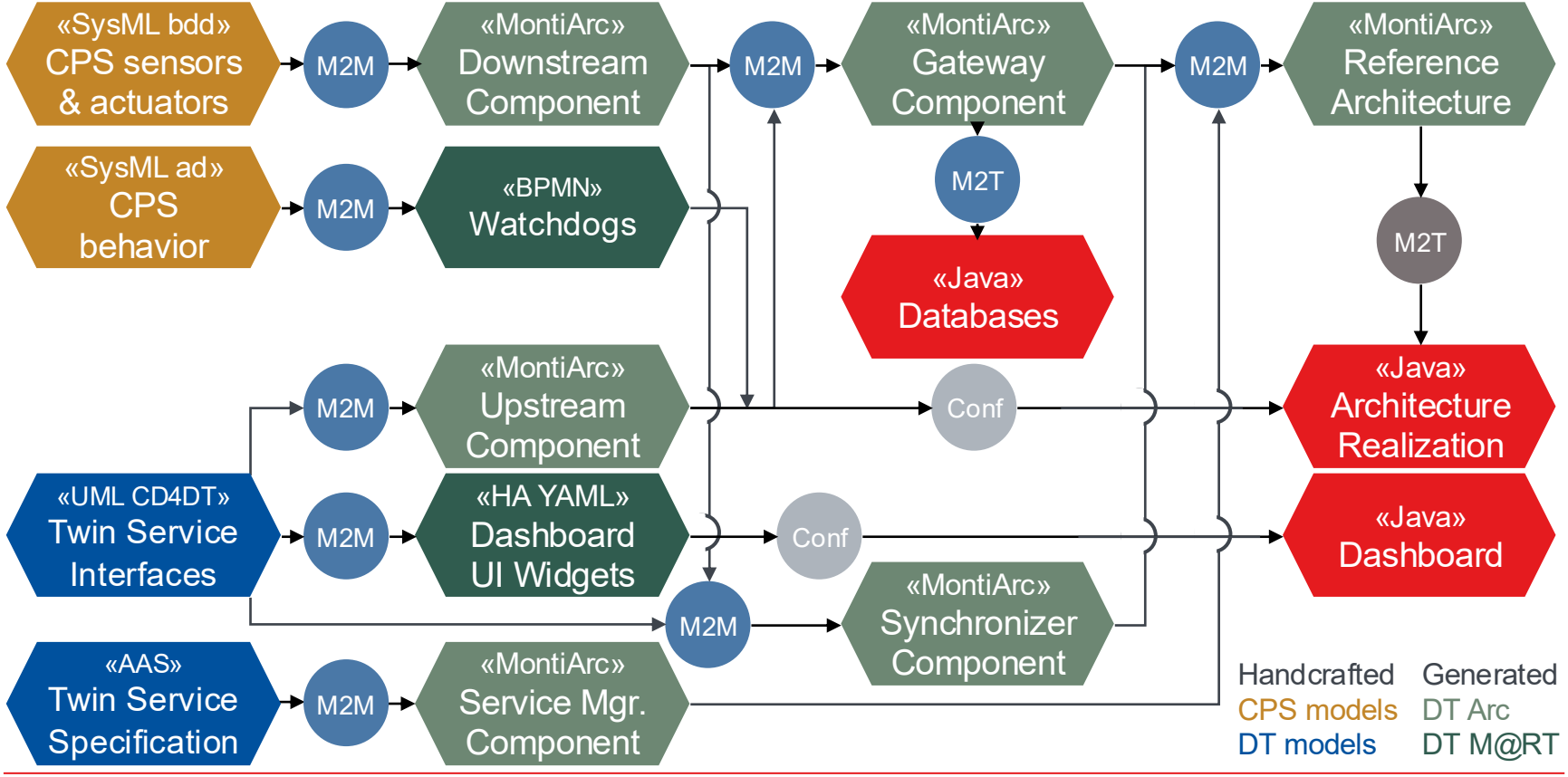
- connects to CPS via OPC UA
- ingests data & controls
- uses added-value services

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The Digital Twin is Created via Model Transformations

A formalism transformation graph overview



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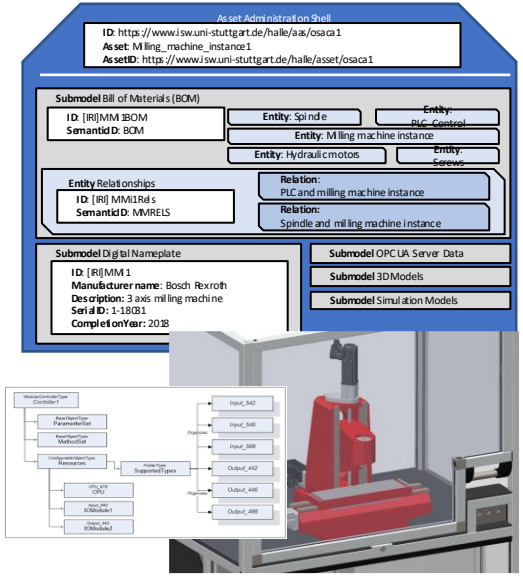
Case Study 1: OSACA 3-Axis Drilling Machine[1]

Computing the CO_2 footprint of a drilling machine via AAS

PURPOSE

- Analyzing energy consumption vs OCL-defined thresholds to detect wear
- Manipulate machine state and spindle speeds to ensure maximum energy efficiency
- Models: virtuos 3D model from virtual commissioning, OPC UA, asset administration shell

MODELS IN THE DT



CYBER-PHYSICAL TWIN

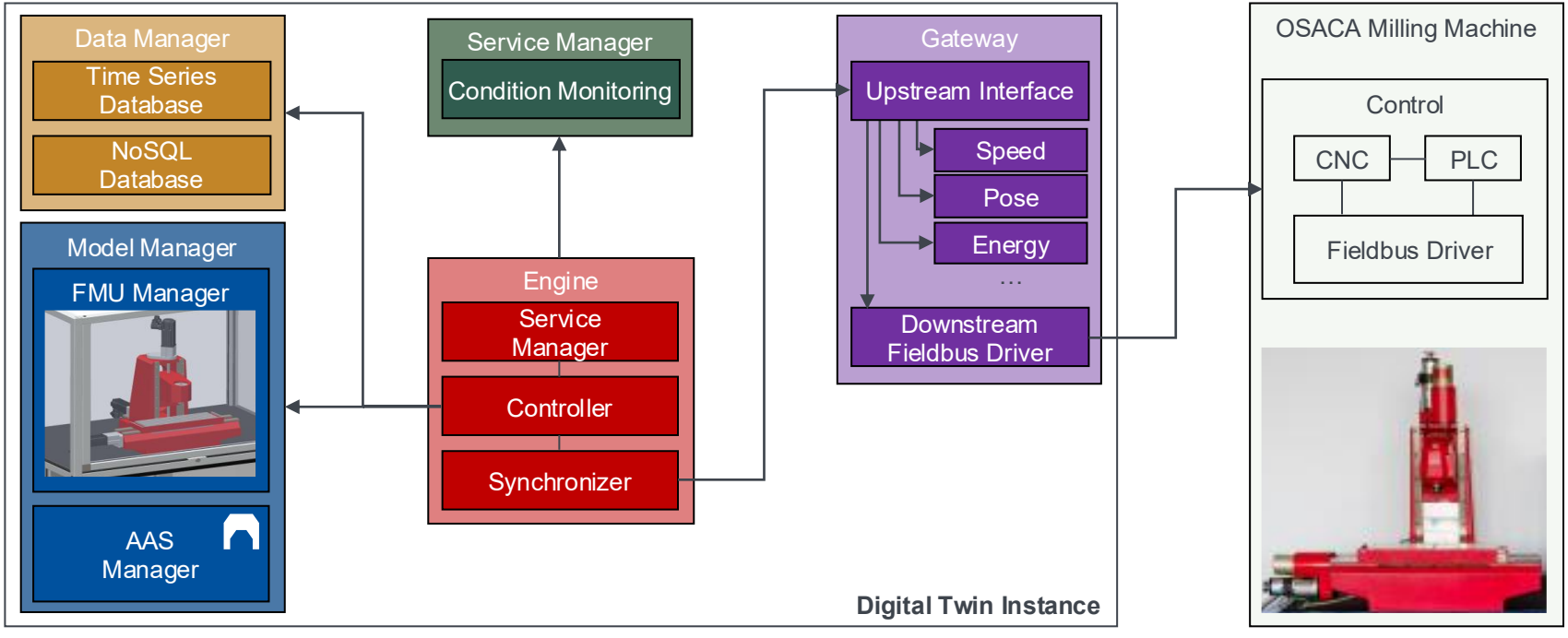


1. Chen, S., Zhang, J., Jud, O., Klingel, L., Verl, A., Wortmann, A., & Ajdinović, S. (2026). A Software Architecture for Real-Time Digital Twins in Machining. In Proceedings of the 8th Workshop on Modeling and Simulation of Software-Intensive Systems.

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Case Study 1: OSACA 3-Axis Drilling Machine[1]

Incarnation of reference architecture for an OSACA sustainability use case



1. Chen, S., Zhang, J., Jud, O., Klingel, L., Verl, A., Wortmann, A., & Ajdinović, S. (2026). A Software Architecture for Real-Time Digital Twins in Machining. In Proceedings of the 8th Workshop on Modeling and Simulation of Software-Intensive Systems.

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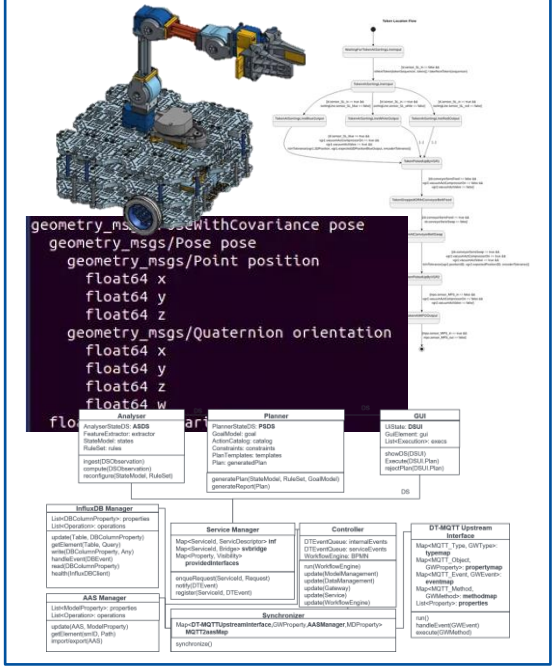
Case Study 2: Composed Digital Twin of a TurtleBot Robot

Integrating separate robotic subsystems into a hierarchical Digital Twin

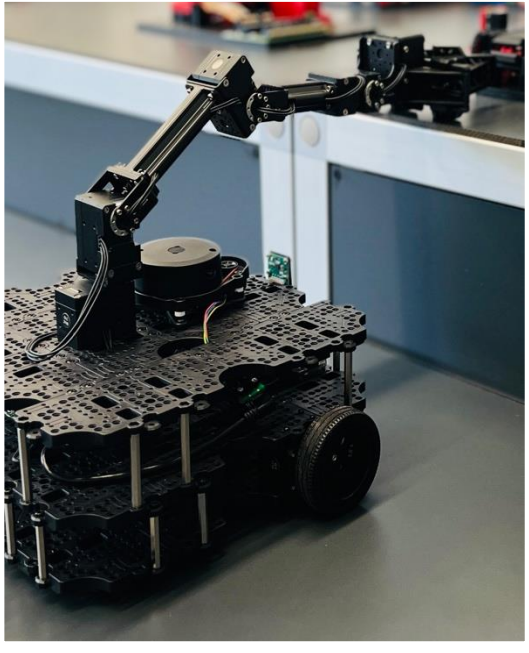
PURPOSE

- Autonomous routing and movement by baseDT
- Object manipulation by armDT coordinated with baseDT for positioning
- Automated docking on low energy by managerDT
- Models: UML class diagram world model, UML activity diagram behavior, OPC UA connection to robot, CAD

MODELS IN THE DT



CYBER-PHYSICAL TWIN



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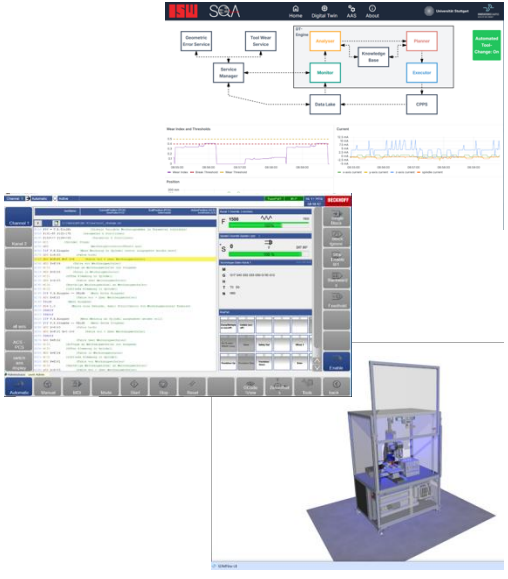
Case Study 3: FiveX 5-Axis Laser Cutting Machine[1]

Enabling proactive hardware maintenance and quality control

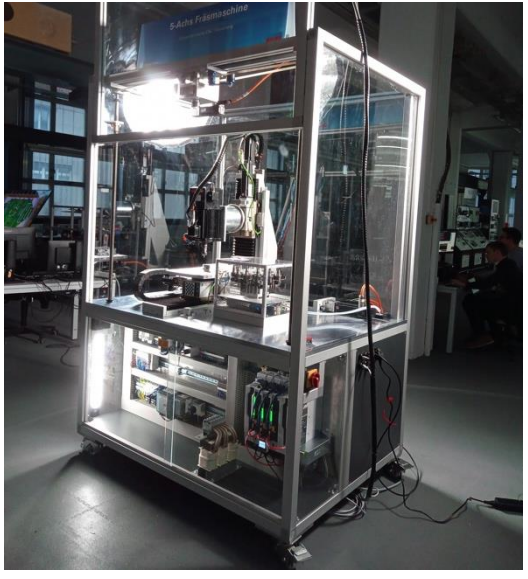
PURPOSE

- Automatically trigger the replacement of lenses
- Simulate heat distribution: predict if the material will warp or distort
- Models: Asset Administration Shell, OPC UA, SysML v2 block definition diagram, CAD, UML class diagram, machine skills

MODELS IN THE DT[1]



CYBER-PHYSICAL TWIN



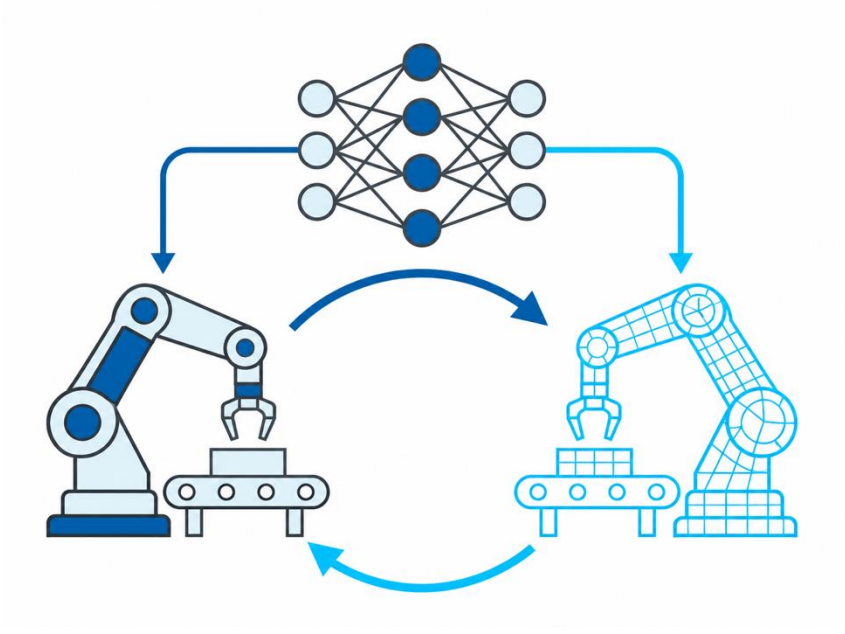
1. Chen, S., Zhang, J., Jud, O., Klingel, L., Verl, A., Wortmann, A., & Ajdinović, S. (2026). A Software Architecture for Real-Time Digital Twins in Machining. In Proceedings of the 8th Workshop on Modeling and Simulation of Software-Intensive Systems.

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Model-Driven Development of Digital Twins is more Efficient and Reliable

AI can help with this and digital twins can help AI again

- Introduction
- Motivation
- Digital Twins: Disambiguation
- Model-Driven Engineering
- Low-Code Development of Digital Twins
- **AI for Digital Twins**
- Digital Twins for AI
- Challenges



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AI can break the 1M USD Per-Twin Cost Barrier that Hampers Adoption

By supporting the creating and integration of models and evolution of code

DERIVING MODELS FROM OPERATION DATA[1]

- Derive integrated system and process models from model silos (CAD, PLC, …)
- Extract constraints from documents, standards, manuals, history data
- Create formal process models from natural language

AI-ASSISTED DOMAIN AND SOFTWARE MODELING[2]

- Check and validate models for the DT in its context
- Recommend history-based changes to models in the DT
  Automated mapping between data and model elements
- Support domain expert in the loop

AGENT-BASED EVOLUTION OF DIGITAL TWIN AND CPS[3]

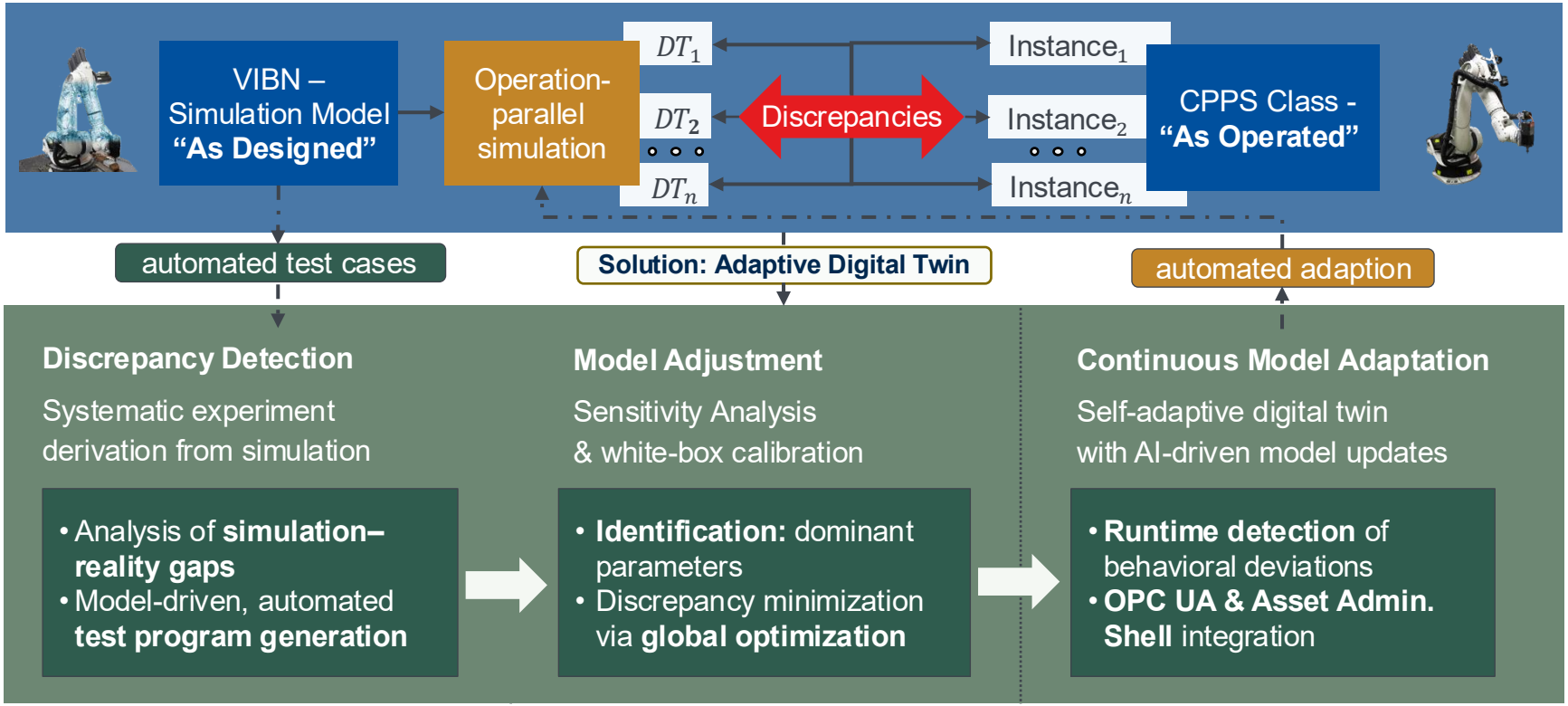
- Train specific SE agents for managing models, data, services, DT architecture
- Agents collaborate for planned change (new sensor → new uncertainty model → new data)
- Create new models, change digital twin source code

1. van der Aa, H., Di Ciccio, C., Leopold, H., & Reijers, H. A. (2019, May). Extracting declarative process models from natural language. In International Conference on Advanced Information Systems Engineering (pp. 365-382). Cham: Springer International Publishing.
2. Kögel, S., Groner, R., & Tichy, M. (2016, October). Automatic Change Recommendation of Models and Meta Models Based on Change Histories. In ME@
3. Dittler, D., Lierhammer, P., Braun, D., Müller, T., Jazdi, N., & Weyrich, M. (2022). An Agent-based Realisation for a continuous Model Adaption Approach in intelligent Digital Twins. arXiv preprint arXiv:2212.03681.

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From Virtual Commissioning to Simulation-Based Digital Twin

Automatically closing the simulation–reality gap via automated white-box simulation

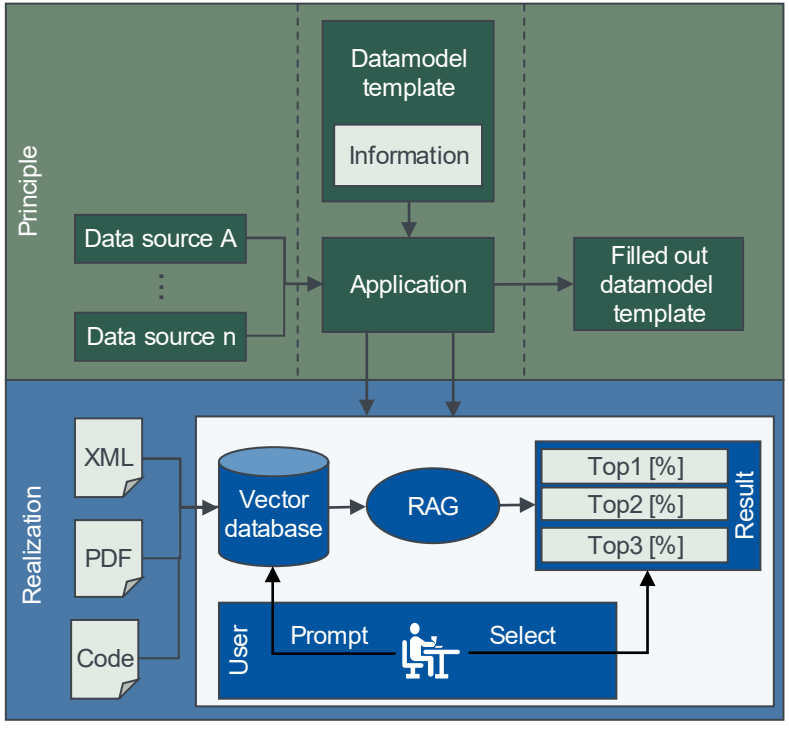


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AI-Powered Semantic Matching and Data Harmonization[1]

Bridging interface mismatches between services and gateway

- Use embeddings of data interfaces to semantically match different representations of
  - gateway upstream vs downstream
  - downstream interface vs. OPC UA server
- Threefold approach
  1. DBSCAN
  2. entity comparison
  3. LLM-assisted evaluation
- 90% accuracy on matching simple attributes
- Requires improvements for large-usage use
- Investigation of HiL learning



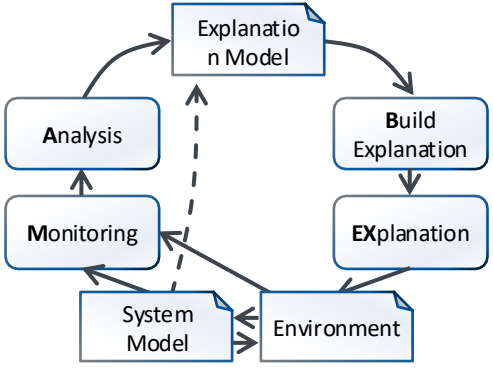
1. Ajdinović, S., Maisch, N., Kimmel, R., Rasouli, T., Lechler, A., Wortmann, A., & Riedel, O. (2025). AI-powered semantic matching and data harmonization for industrial applications with OPC UA & asset administration shells. In 16th International Conference on Mechanical and Intelligent Manufacturing Technologies (ICMIMT). IEEE.

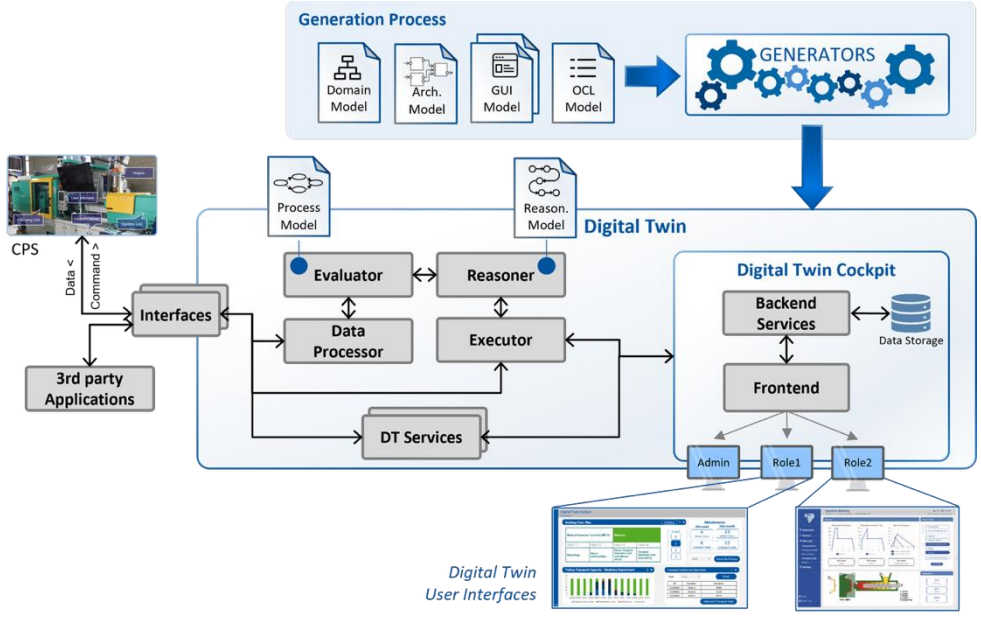
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The Digital Twin can Explain the Behavior of its Cyber-Physical Twin[1]

The operators of digital twins are domain experts who need domain explanations

- MAB-EX[2] makes systems self-explainable
- Case-based reasoning[3] and models create explanations of system behavior
- Variant of the MAPE-K[3] loop





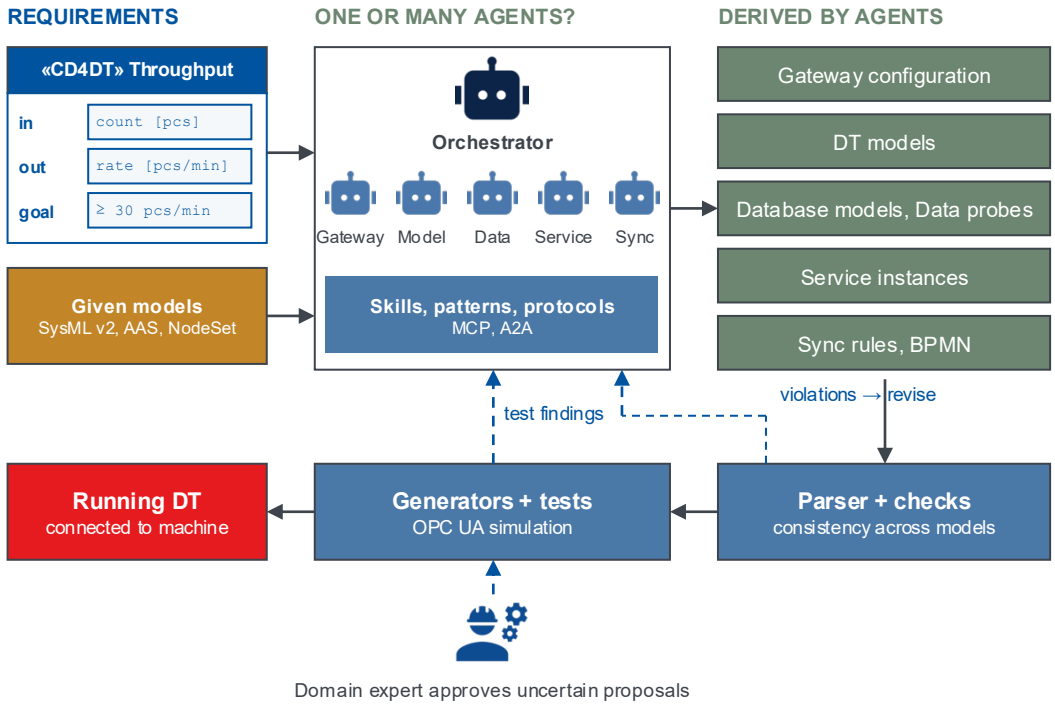
1. Michael, J., Schwammberger, M., & Wortmann, A. (2023). Explaining cyberphysical system behavior with digital twins. *IEEE Software*. IEEE
2. Blumreiter, M., Greenyer, J., Garcia, F. J. C., Klös, V., Schwammberger, M., Sommer, C., ... & Wortmann, A. (2019, September). Towards self-explainable cyber-physical systems. In Proceedings of the 22nd International Conference on Model Driven Engineering Languages and Systems Companion.
3. Bolender, T., Bürvenich, G., Dalibor, M., Rumpe, B., & Wortmann, A. (2021, May). Self-adaptive manufacturing with digital twins. In: SEAMS. IEEE.

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Agents Derive the Digital Twin from Software Requirements

From a low-code specification to a consistent digital twin

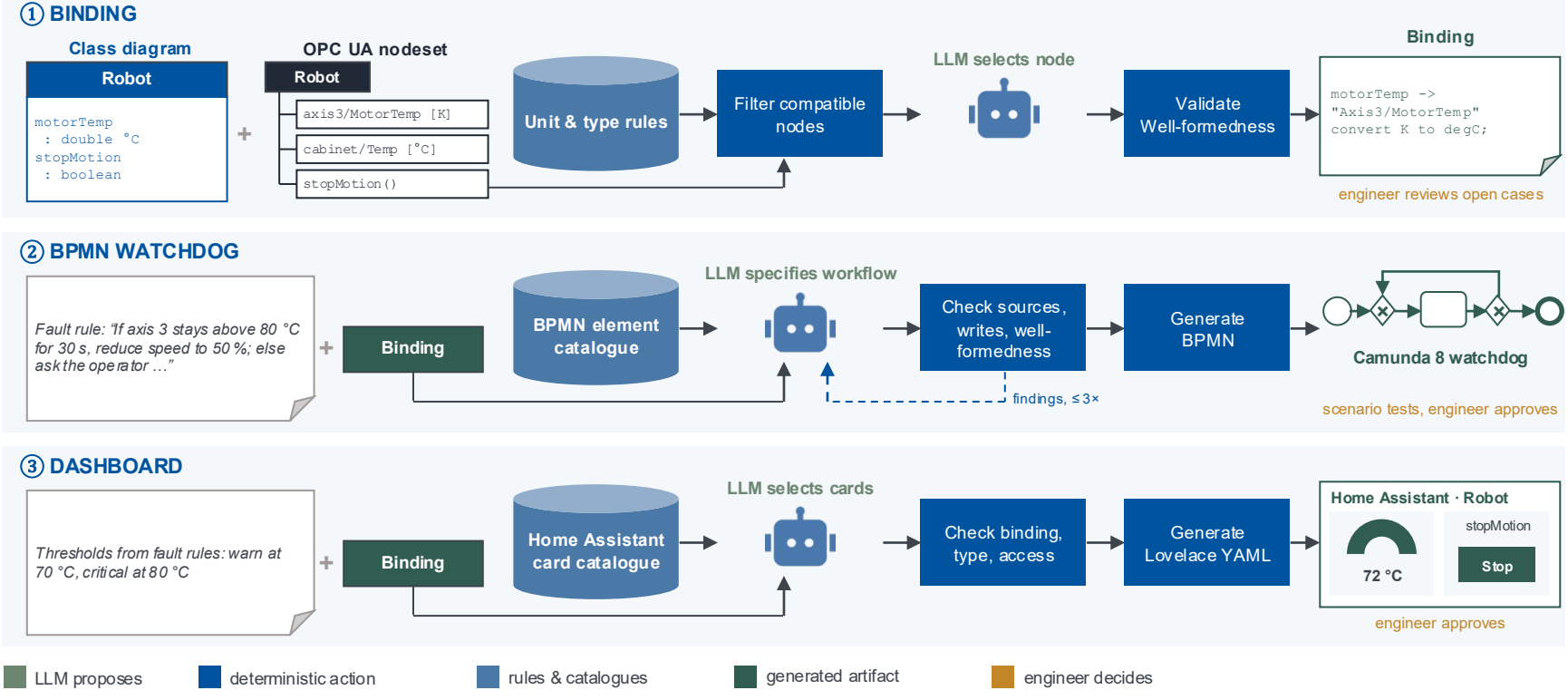
- CD4DT specifies what the software needs: services, inputs, outputs, units, data contracts, and goals
- Agents derive the remaining DT models from this specification and the given engineering models
  - one generalist agent or specialized agents per DT dimension
- Agents collaborate via established patterns and protocols
  - worker and reviewer loops
  - MCP for tools, A2A between agents
- Skills encapsulate model operations, generators, and checks
- Deterministic checks keep derived models consistent and the domain expert approves



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AI-Assisted Engineering of Industrial Digital Twins

LLMs propose and model-based checks decide in three steps



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Digital Twins can Improve and Facilitate using AI in Manufacturing

By giving meaning to data, checking it and including human expertise

FROM DATA SWAMPS TO SEMANTIC DATA[1]

- Give semantics to data points from system models: units, sources, CPS state, process step, … (metadata)
- Better labels using CPS and process models
- Include other data sources: MES, ERP, simulation, …

CONTINUOUS ASSESSMENT OF DATA QUALITY[2]

- Automated plausibility checks using models of CPS and process (ranges, expected signals, timing, …)
- Traceability: metadata
- Identify mismatches between distribution of real data and training data (drift)

FACILITATE CONTINUOUS LEARNING[3]

- Contextualize new data
- Validate new data before retraining
- Human in the loop: ask operator in case of uncertainty, drift, or conflicting data

1. Becker, Fabian, et al. "A conceptual model for digital shadows in industry and its application." International conference on conceptual modeling. Cham: Springer International Publishing, 2021.
2. Saroj, A., Roy, S., Guin, A., & Hunter, M. (2025). Data Quality Assessment Process for Real-Time Data-Driven Traffic Microsimulation of Smart Corridor. In International Conference on Transportation and Development 2025.
3. Son, Y. H., Lee, E. S., & Son, J. Y. (2026). ACL-DT: adaptive continuous learning digital twin framework for resilient manufacturing. The International Journal of Advanced Manufacturing Technology, 1-14.

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Digital Twins can Make AI-Based Manufacturing more Reliable

By acting as proxy between autonomous manufacturing decisions and CPS

DIGITAL TWIN AS SAFEGUARD

- Layer between AI and shopfloor
- Validate AI decisions against explicitly modeled constraints
  - process models
  - CPS models
- Forecast machine health trajectory prior to AI execution

EXPLORATION OF ALTERNATE FUTURES

- Automated concurrent what-if simulation to prevent AI errors
- Choose parameters based on machine and process history
- Have AI systems explain next best course of action

ANALYZE PRODUCTION RELIABILITY

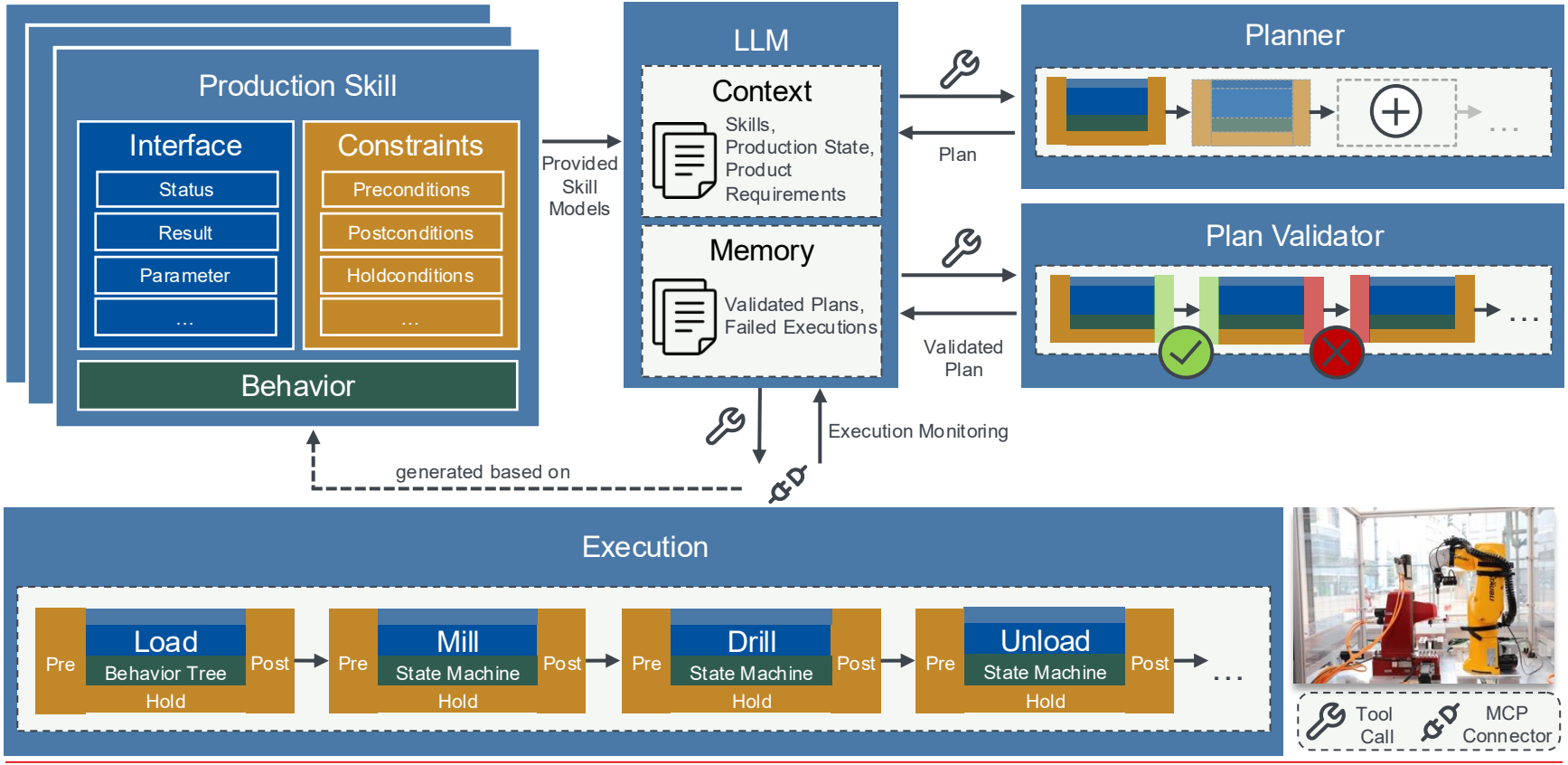
- Simulate CPS problems for connected systems (MES, ERP, SCADA)
- Evaluate effects of problems without having them
- Estimate effects of rare faults
- Learn causes and effects



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Modeling Skills of CPPS for LLM-Driven Production Planning

Planning and Execution with Skill-Aware Digital Twins



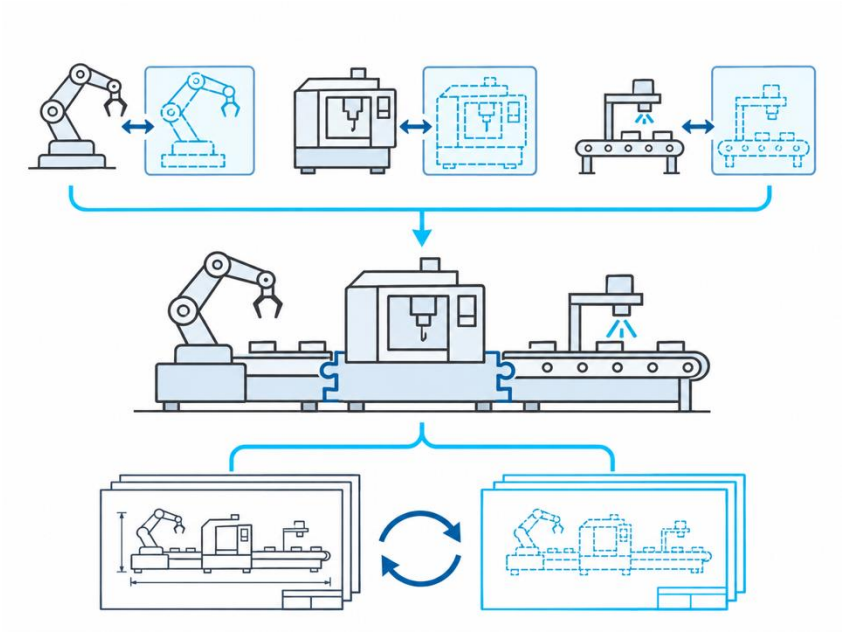
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Model-Driven Development of Digital Twins is more Efficient and Reliable

AI can help with this and digital twins can help AI again

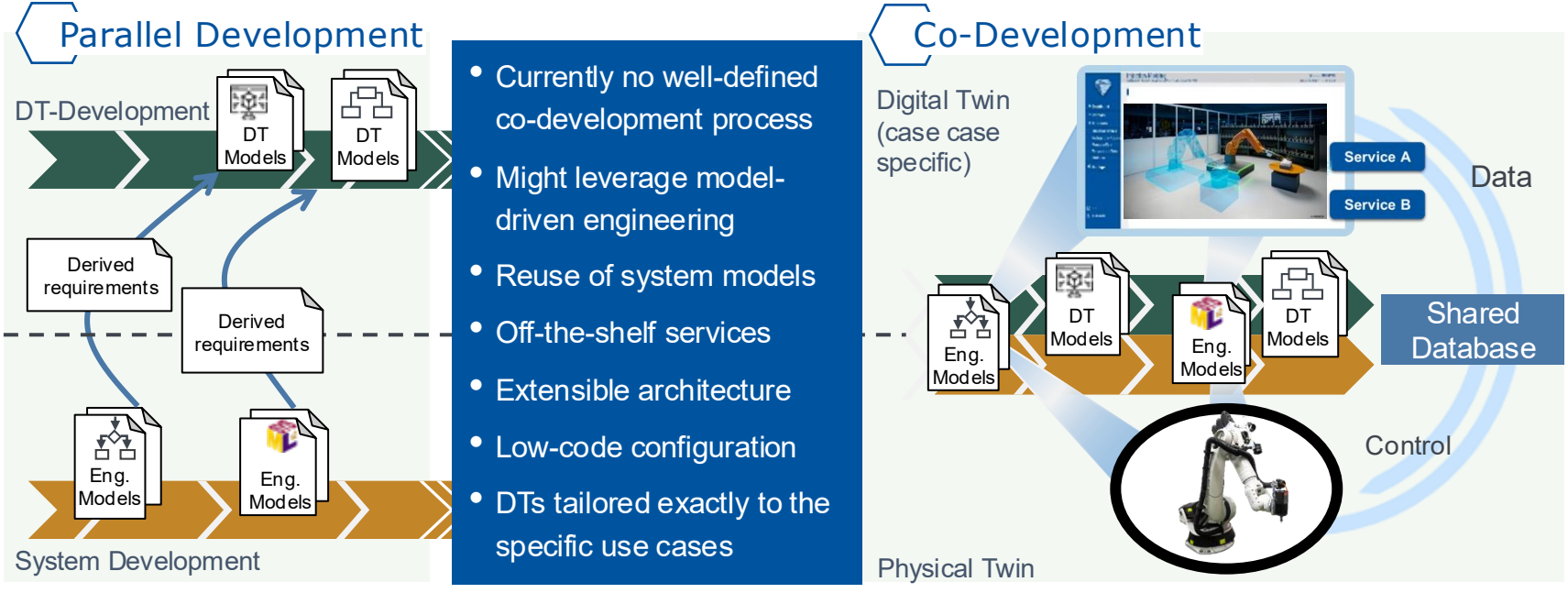
- Introduction
- Motivation
- Digital Twins: Disambiguation
- Model-Driven Engineering
- Low-Code Development of Digital Twins
- AI for Digital Twins
- Digital Twins for AI
- ▶ Challenges



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Co-Development Instead of Re-Development

Digital twins will be increasingly green-field development projects



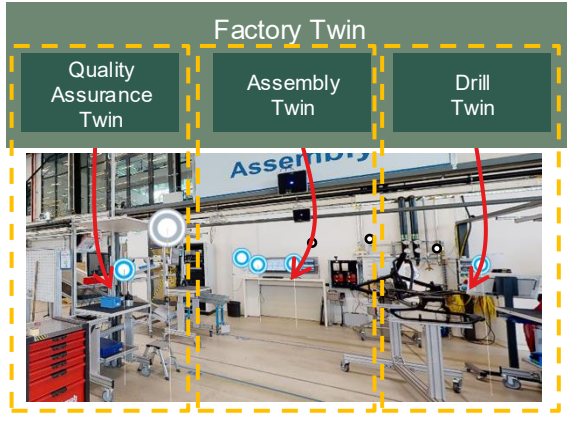
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Composition of Digital Twins is Essential

Combine simple digital twins to build more complicated digital twins

- Composition vital to many disciplines
- Examples: function composition (math), product composition (mechanics), software composition (CS), …
- Efficient software engineering without composition unthinkable
- Idea: When physically composing sensor, machine tool, production line, and factory, compose their digital twin also
- Many open questions:
  - How to compose? (blackbox, whitebox, merge, federate, …)
  - Which parts to compose? (models, data, components, …)
  - What about conflicts? (factual, abstraction, control, …)



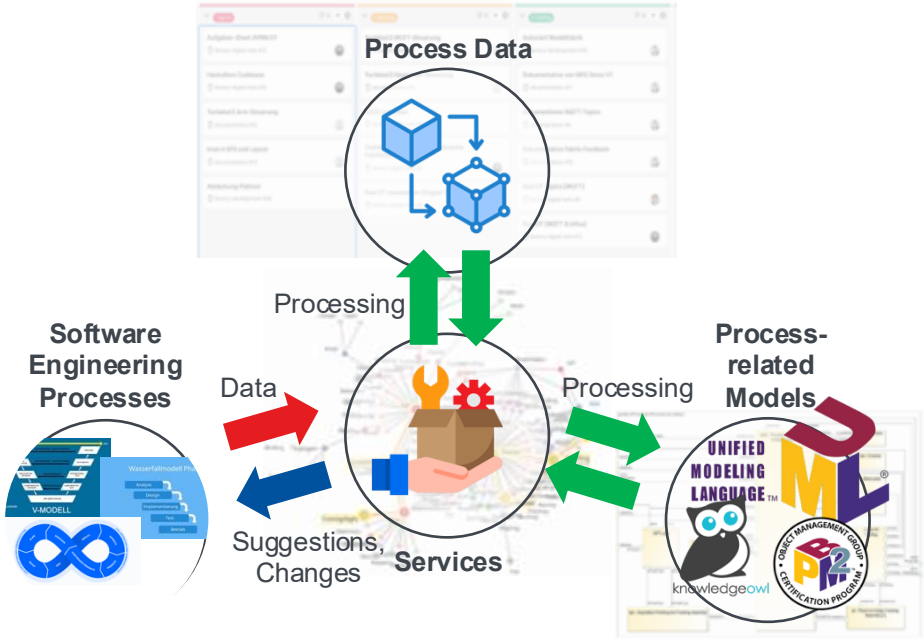
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Digital Twins for Software Engineering Processes[1]

Towards real-time feedback to monitor and steer development processes

- Complex engineering processes slow technological innovation
- Digital twin architecture for processes in a similar manner as to machines
  - process data, e.g., issue board, CI/CD
  - models, e.g., process, data, constraints
  - services, e.g., analysis, assignment, and change proposition
- Autonomous AI-powered process support activities through a standardized model
- SE agents interact with process twin



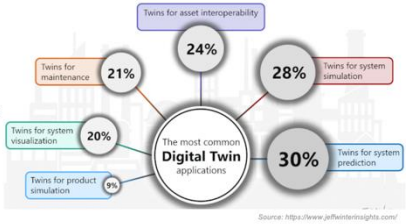
1. R. Kimmel, J. Michael, A. Wortmann and J. Zhang, "Digital Twins for Software Engineering Processes," 2025 IEEE/ACM 47th International Conference on Software Engineering: New Ideas and Emerging Results (ICSE-NIER), Ottawa, ON, Canada, 2025, pp. 16-20, doi: 10.1109/ICSE-NIER66352.2025.00009

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Digital Twins Promise Significant Economic Impact

Including for behavior prediction, simulation, interoperability, maintenance, …

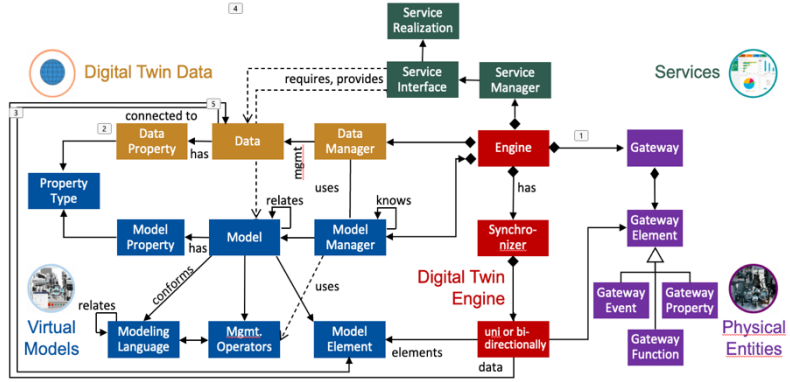
- Digital twins yield benefits of approx. £850 million across a ten-year period[1]
- Manufacturing: impact of DTs estimated[2] to be in the „low tens of billions of dollars“
- EU DT revenue forecast: $49.3B by 2030[3]
- KR DT revenue forecast: $3.8B by 2034[4]
- US DT-based savings of $27.2B / year[2]



1. https://digitaltwinhub.co.uk/research-on-the-economic-benefits-of-digital-twins-for-integrated-transport-network-management/ (2024)
2. National Institute of Standards and Technology (NIST). Economics of Digital Twins. https://tsapps.nist.gov/publication/get_pdf.cfm?pub_id=958153 (2024)
3. https://www.marketsandmarkets.com/Market-Reports/europe-digital-twin-market-195973825.html (2026)
4. https://www.imarcgroup.com/south-korea-digital-twin-market (2025)

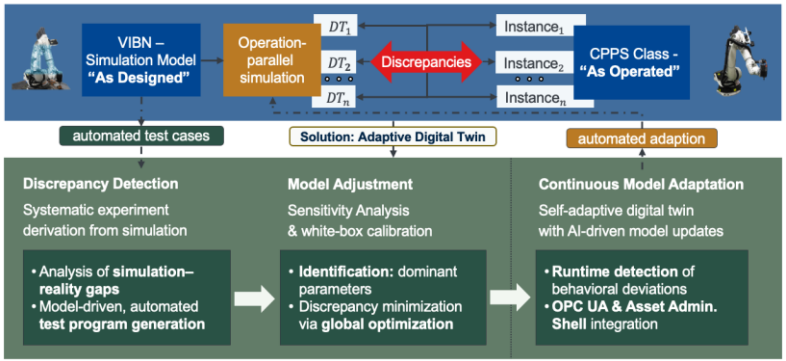
A Reference Architecture for ISO 23247 Digital Twins in Manufacturing

Based on the 5D model[1] and refined with modeling expertise



From Virtual Commissioning to Simulation-Based Digital Twin

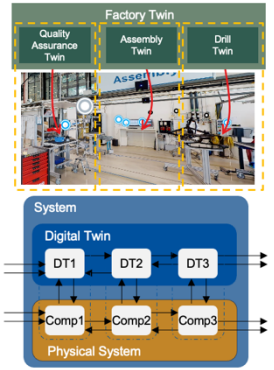
Automatically closing the simulation–reality gap via automated white-box simulation



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