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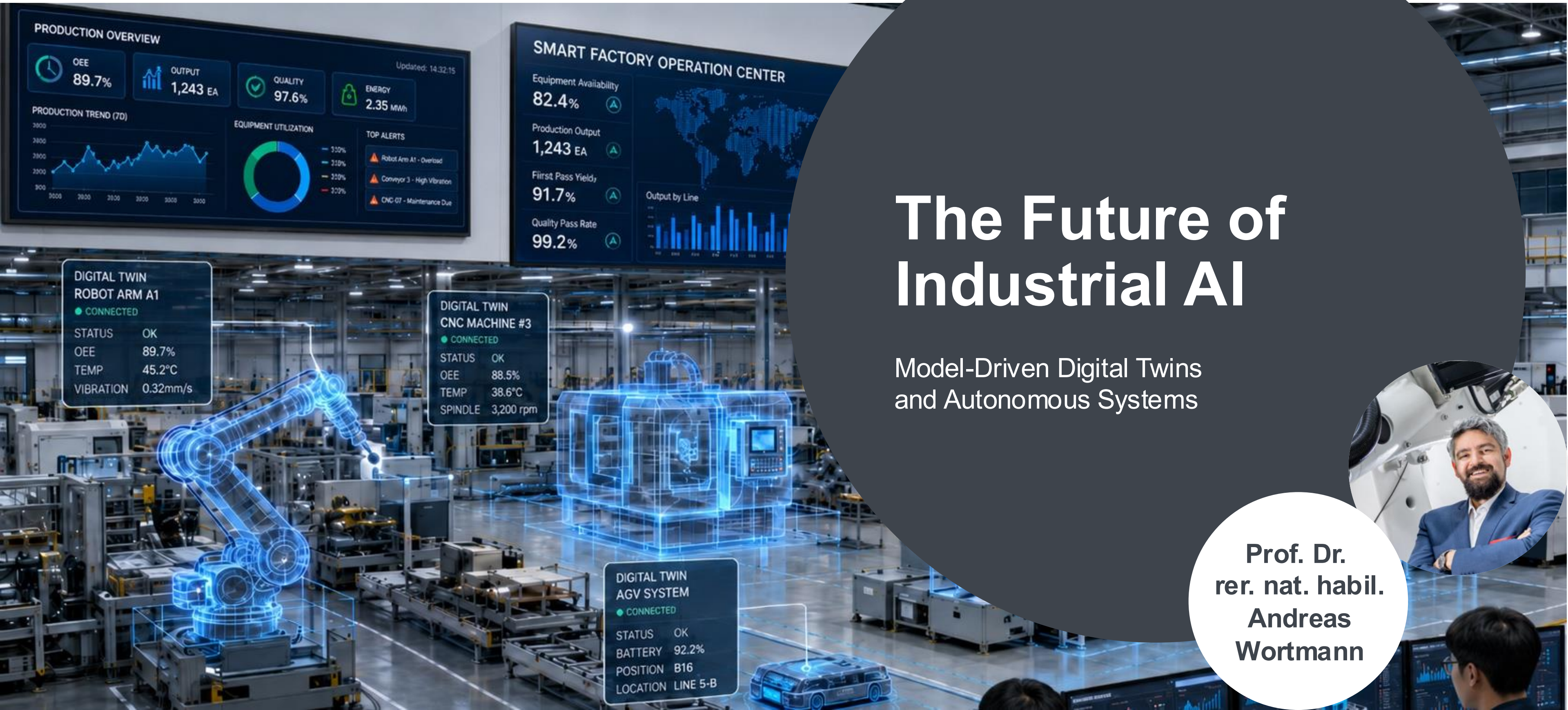
Institute for Control Engineering of Machine Tools and Manufacturing Units (ISW)



The Future of Industrial AI

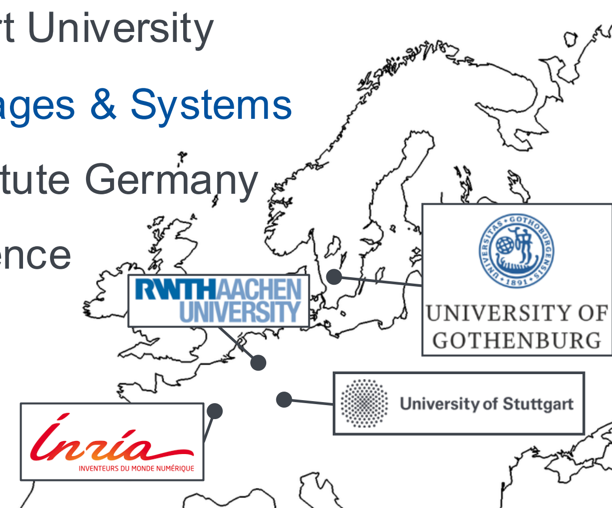
Model-Driven Digital Twins and Autonomous Systems

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



Head of Institute:

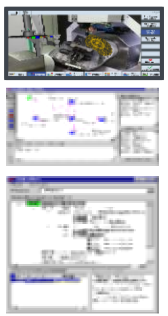
Alexander Verl
Oliver Riedel
Andreas Wortmann
Armin Lechler

Extended Head of Institute:

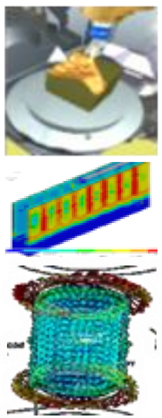
Carsten Ellwein
Florian Frick
Michael Seyfarth

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



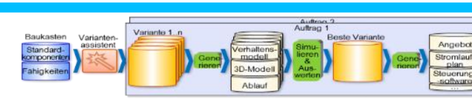
Simulation

OPC UA / TSN / Pub/Sub
OPC Foundation
sercos the automation bus
PROFINET
EtherCAT

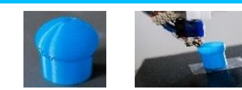
Communication

Production IT

Model-Based Production Engineering



Product Influence



Control Engineering

Control

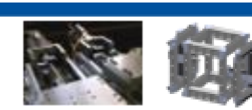
Algorithms

Operation

Architectures

Drive Technology

Mechatronic Systems



Drive Control and Machine Technology

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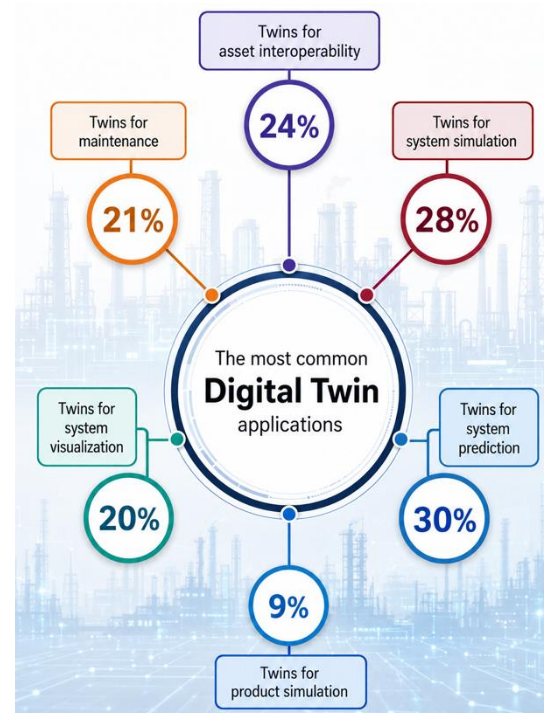
Digital Twins Yield Benefits of £850 Million Across a 10-Year Period[1]

Manufacturing impact of DTs estimated[2] 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]
- BMW: 25% reduced time to plan factory ops[5]
- BCG: 3% - 6% procurement cost reduction[6]
- Capgemini: 16% better sustainability metrics[7]
- Siemens: 30% service reduction, 8% output increase[8]
- Unilever: 90% reduction of false maintenance alerts[9]



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

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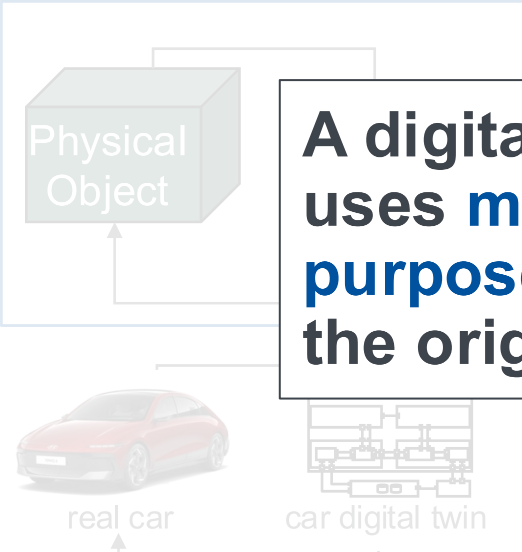
Most Conceptualizations of Digital Twins are not too Useful

Combining flow-based definition with 5D model gives meaning to the concept

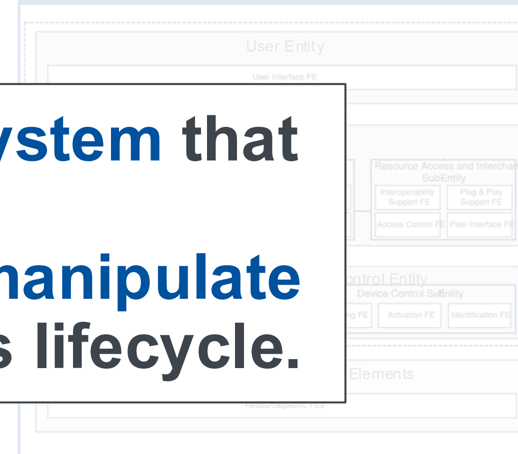
Flow-Based DT Model[1]



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

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

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. Qi et al.: Enabling technologies and tools for digital twin. In: Journal of Manufacturing Systems, Elsevier, 2019
3. ISO 23247. Digital Twin Framework for Manufacturing, 2021.

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

Manufacturing consists of SMEs with limited software engineering expertise

LANDSCAPE[1]

- Manufacturing 27% of KR GDP
- World-class companies: Samsung, Hyundai, LG, …
- 97.3% of manufacturing companies SMEs or smaller
- Contribute 10% of GDP
- Initiatives: Digital Twin National Land, Digital Twin Korea, Smart Farms Testbed, POSCO, POSTECH PIAI & SMART, …

CHALLENGES

- Capgemini[3]: aero & defense invest 2.7% of AR in DTs
- Mid-complexity DTs (e.g., single production line): $500k - 2M[4]
- Deployment: 3-6 mo.[5], First value: +4 mo.[6], Scale: +9 mo.[5]
- Hampers adoption and prevents more efficient use of systems
- Most manufacturing companies face more urgent challenges

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. https://www.ptc.com/en/blogs/corporate/roi-of-digital-twin-for-industrial-companies
2. Ministry of SMEs and Startups. The Status of Small and Medium-Sized Enterprises (2026): https://www.mss.go.kr/site/smba/foffice/ex/statDB/MainSubStat.do
3. Capgemini. Aerospace and defense organizations show growing confidence in Digital Twin technology with 40% invest. increase. (2025)
4. Medium. The Business Case for Digital Twin: Costs, Benefits, and ROI Explained. (2026)
5. Capgemini. REFLECTIOD Digital Twin For Asset Operators (2021)
6. Accenture. How digital twins enable autonomous operations (2022)

Industrial Digital Twin in a Day using Model-Driven Engineering

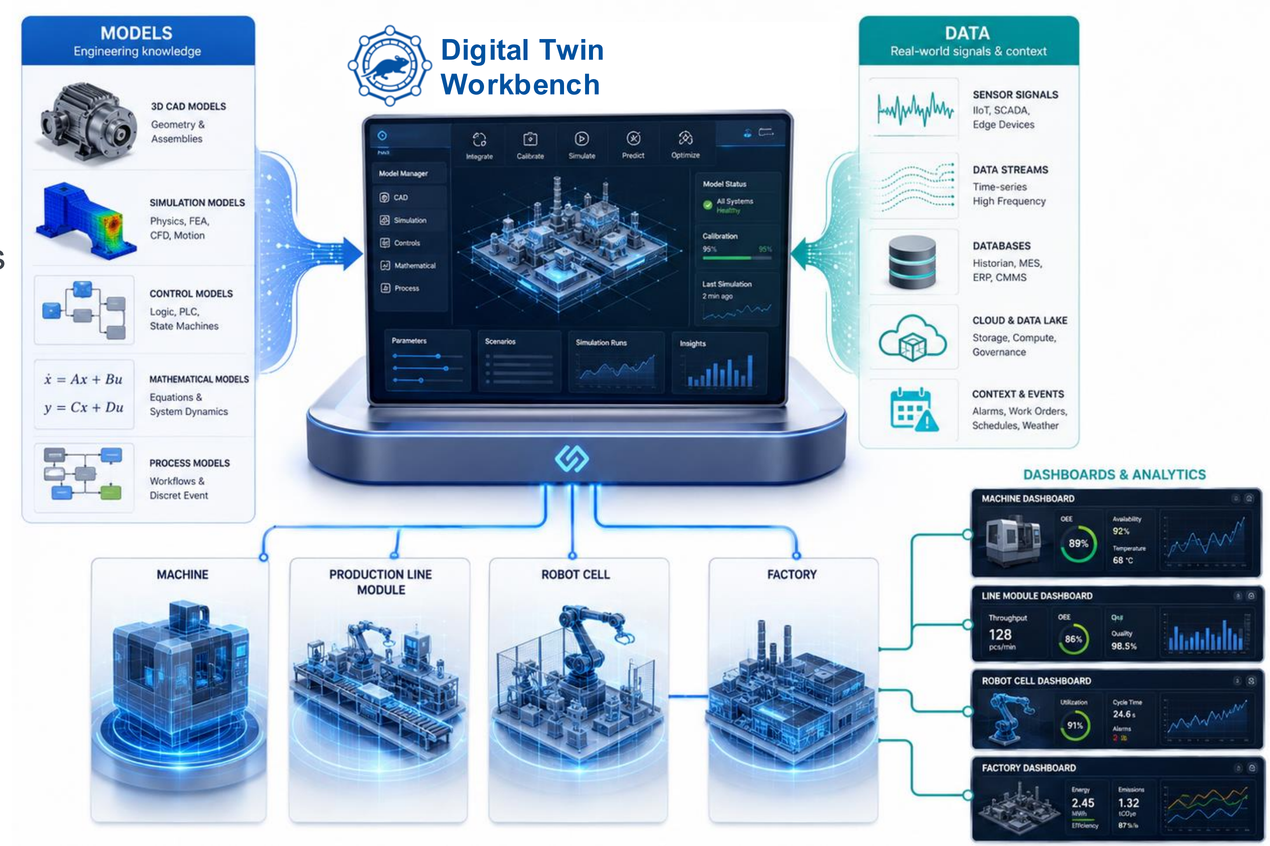
A low-code-based solution tailored to SMEs and useful for everyone

Digital Twin Workbench

- Generate digital twin
- Business logics from service library
- Configure remaining parts Industry standards
- Reuse existing models
- GenAI as support

Digital Twin Implementation

- Data infrastructure
- Interfaces
- Dashboard
- Models @ RunTime
- Data-driven and GenAI



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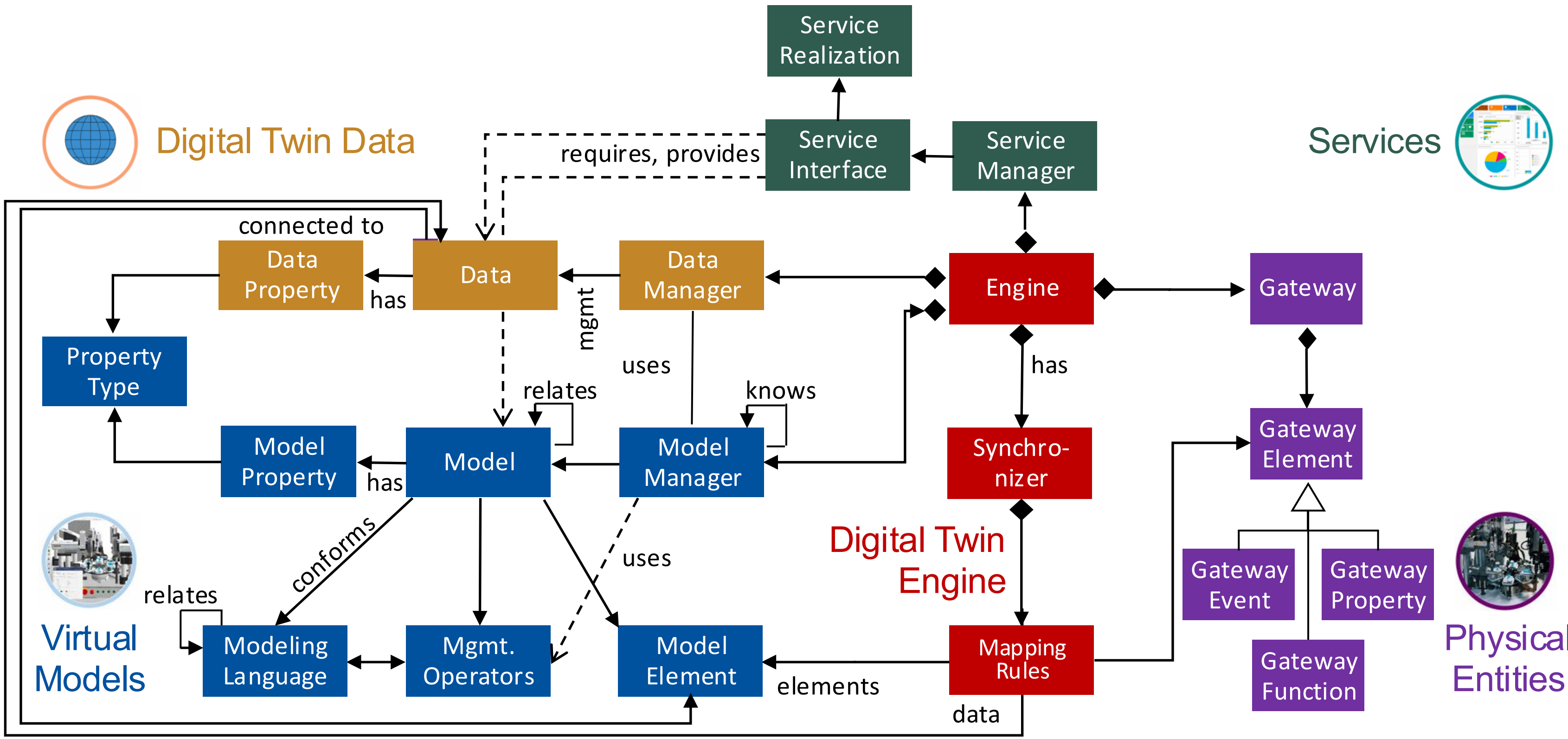
A Reference Architecture for ISO 23247 Digital Twins in Manufacturing

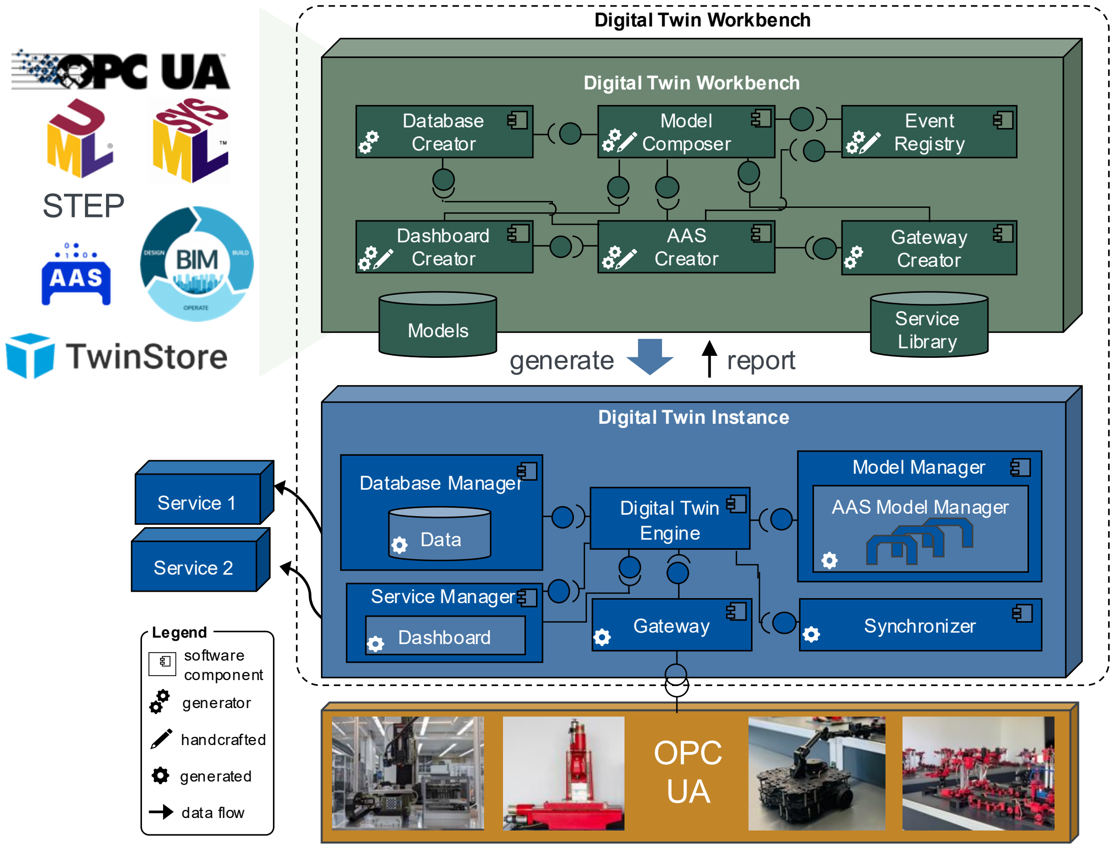
Based on the 5D model[1] and refined with modeling expertise



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

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

Digital Twin Workbench

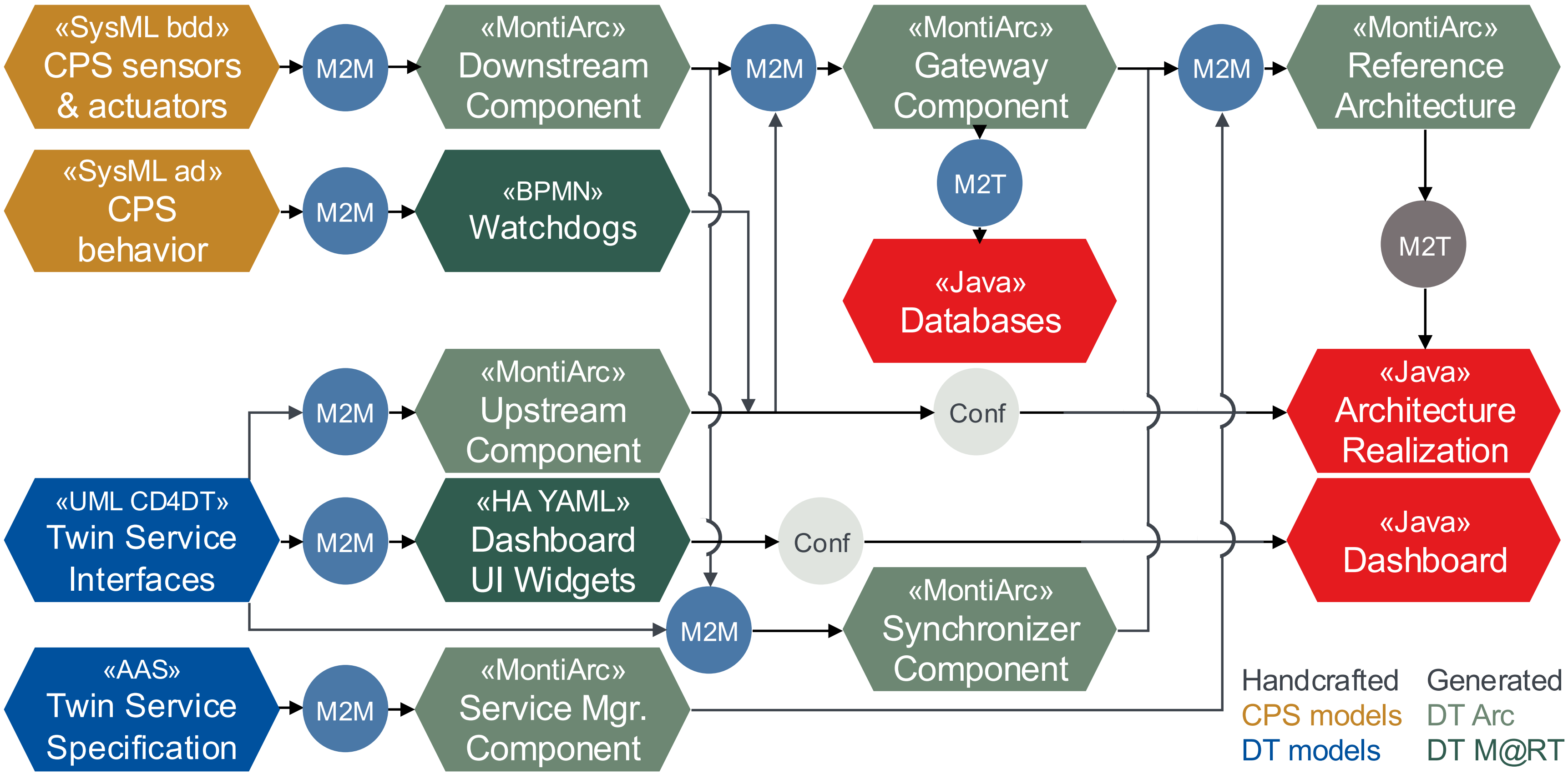
- ingests engineering models
- instantiates DT reference architecture
- creates data infrastructure, UI
- generates DT instance

Digital Twin Implementation

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

The Digital Twin is Created via Model Transformations

A formalism transformation graph overview



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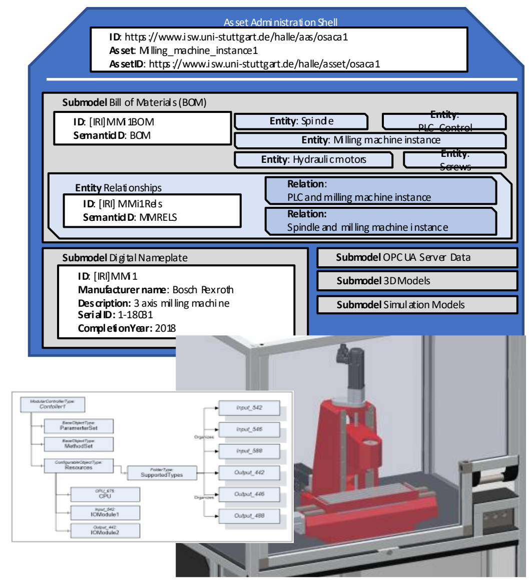
Case Study 1: OSACA 3-Axis Drilling Machine[1]

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

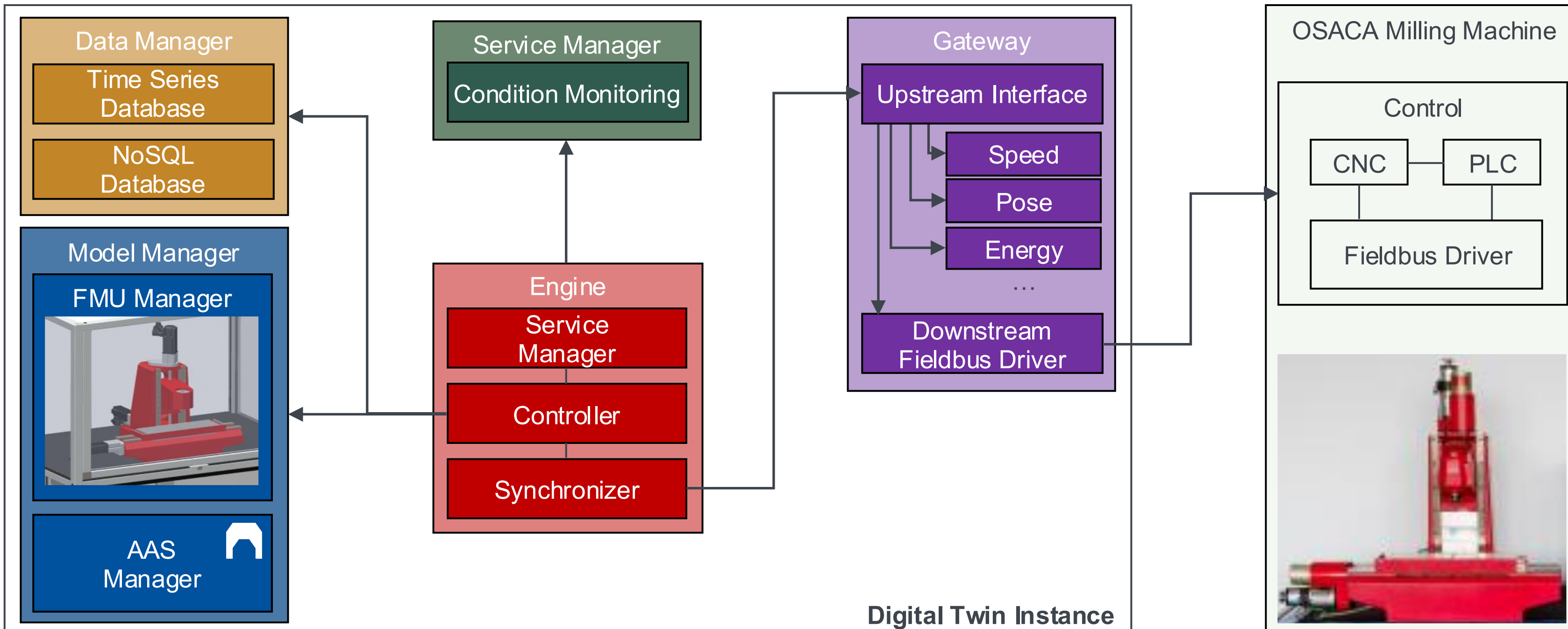


CYBER-PHYSICAL TWIN

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.

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.

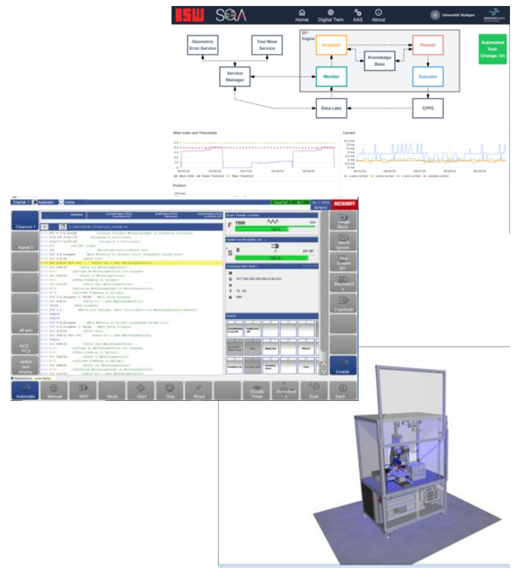
Case Study 2: FiveX 5-Axis Laser Cutting Machine[1]

Enabling proactive hardware maintenance and quality control

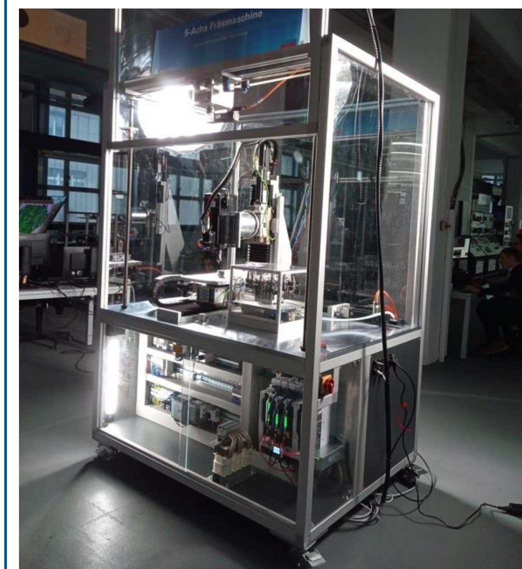
PURPOSE

- 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 skill models

MODELS IN THE DT[1]



CYBER-PHYSICAL TWIN



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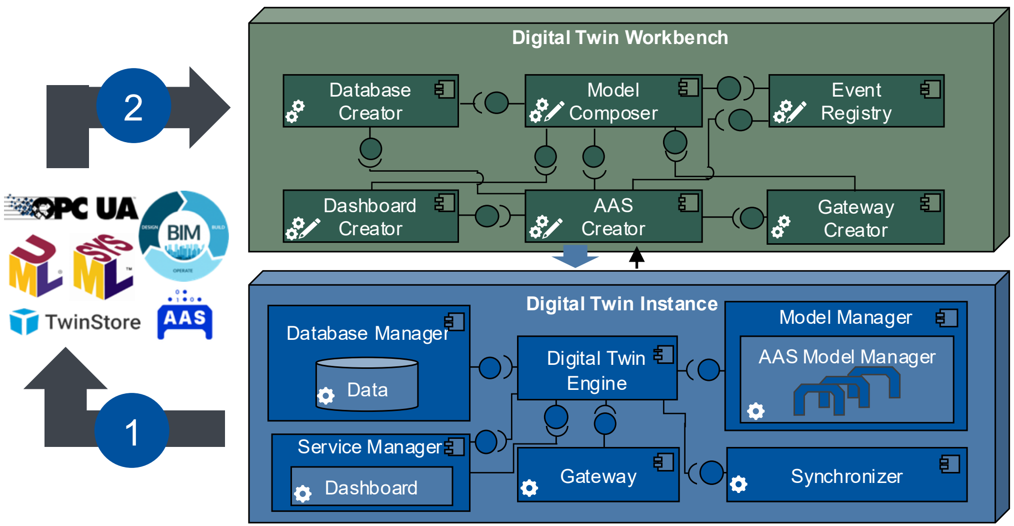
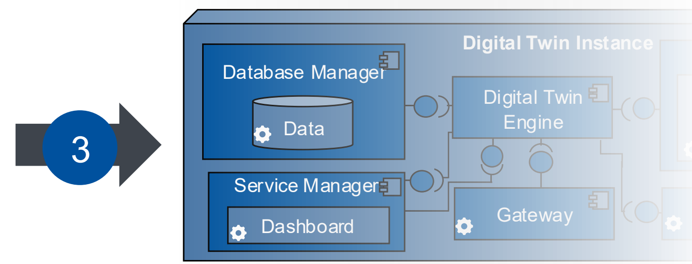
AI4DT: Break the 1M USD Per-Twin Cost Barrier That Hampers Adoption

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



3 Agentic co-evolution of DT and CPS[3]

- SE agents for models, data, services, DT architecture
- Collaborate for planned change
- Create new models, change DT code



1 Deriving models from operation data[1]

- Integrated system/process models from silos
- Constraints from standards, manuals, history
- Formal process models from natural language

2 AI-assisted domain and software modeling[2]

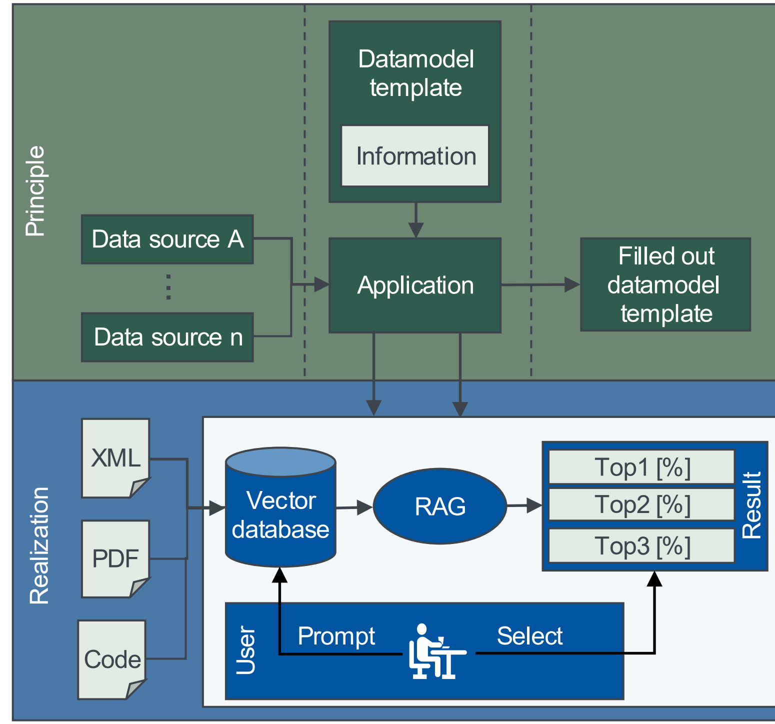
- Validate models for the DT in its context
- Suggest history-based changes to DT models
- Automated data-to-model mapping

1. van der Aa, H., Di Ciccio, C., Leopold, H., & Reijers, H. A. (2019). Extracting declarative process models from natural language. In CAISE. Springer.
2. Kögel, S., Groner, R., & Tichy, M. (2016). Automatic Change Recommendation of Models and Meta Models Based on Change Histories. In ME@MODELS. ACM.
3. Dittler, D., Lierhammer, P., et al. (2022). An Agent-based Realisation for a continuous Model Adaption Approach in intelligent Digital Twins. arXiv:2212.03681.

AI4DT: 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
- But: many different data source kinds
- Integration of HiL learning with cold-start problem

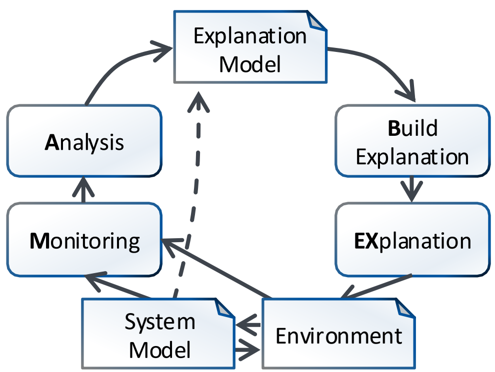


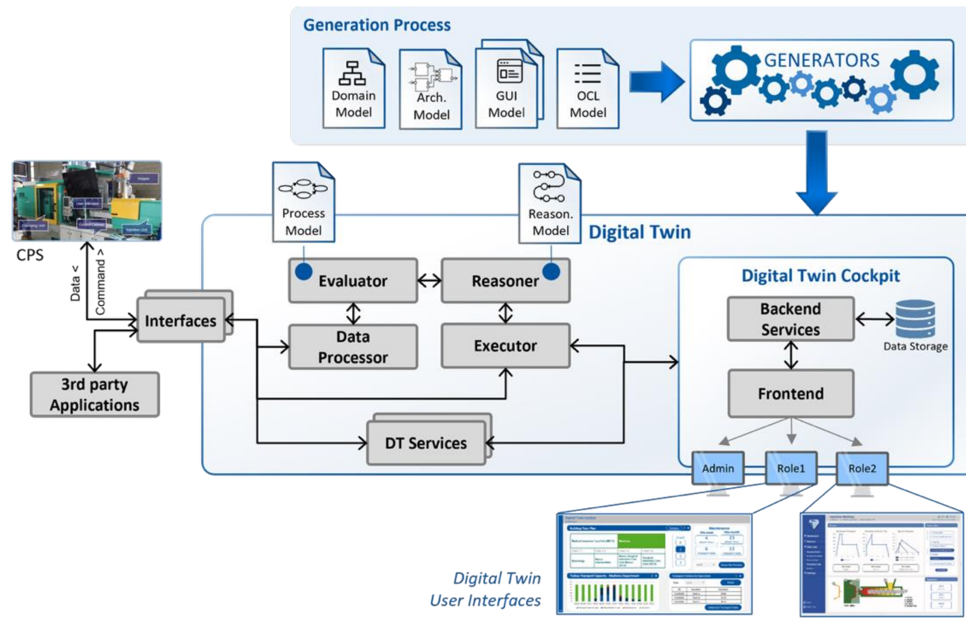
1. Ajdinović, S., Maisch, N., Kimmel, R., Rasouli, T., Lechler, A., Wortmann, A., & Riedel, O. (2025). AI-powered semantic matching and data harmonization for industrial applications with OPC UA & asset administration shells. In 16th International Conference on Mechanical and Intelligent Manufacturing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

AI4DT: Digital Twin Explains 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). 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). Self-adaptive manufacturing with digital twins. In: SEAMS. IEEE.

DT4AI: 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, F., Bibow, P., Dalibor, M., Gannouni, A., Hahn, V., .. & Wortmann, A. (2021). A conceptual model for digital shadows in industry and its application. In International conference on conceptual modeling. Springer.
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.

DT4AI: 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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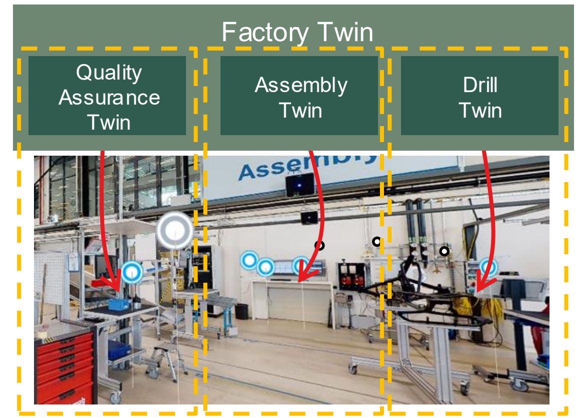
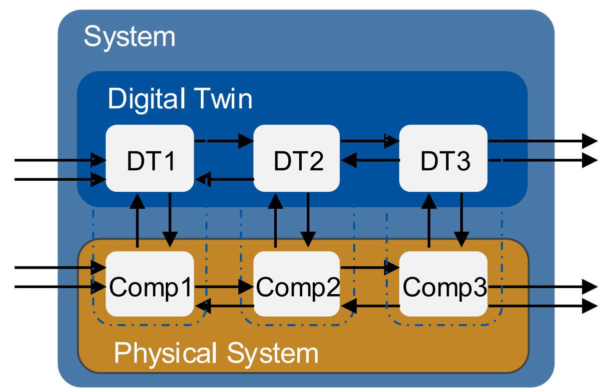
Composition of Digital Twins is Essential

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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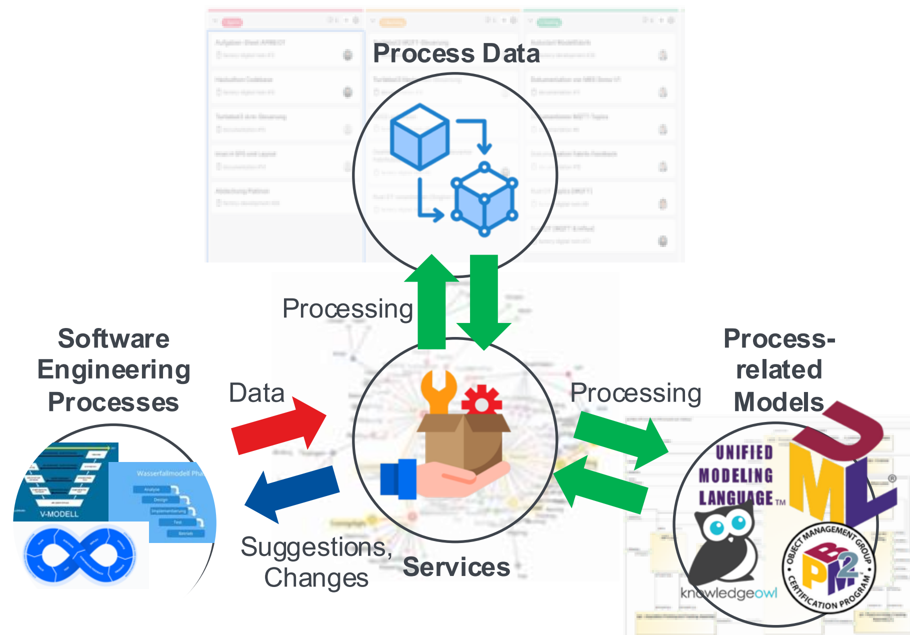
Digital Twins for Software Engineering Processes[1]

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. Kimmel, R., Michael, J., Wortmann, A., & Zhang, J. (2025). Digital Twins for Software Engineering Processes. In 47th International Conference on Software Engineering: New Ideas and Emerging Results (ICSE-NIER). IEEE.

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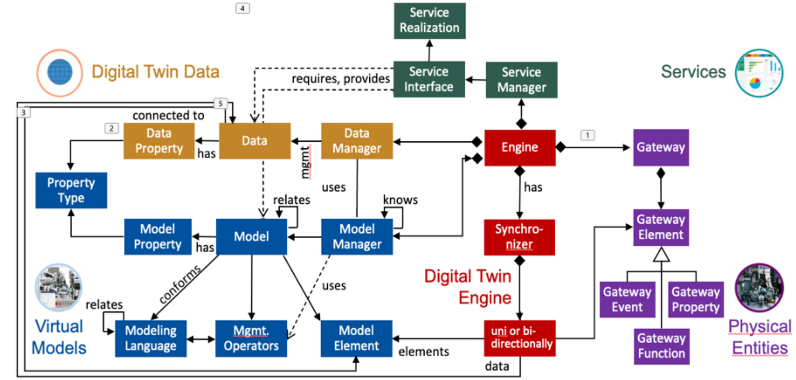

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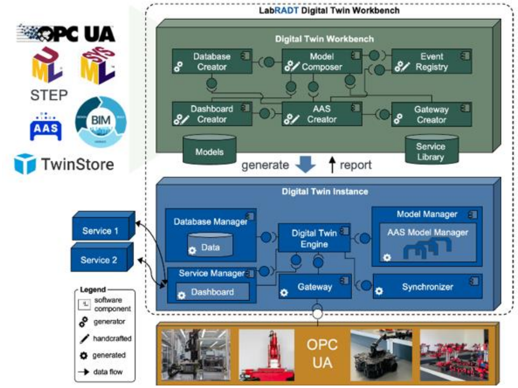

Separation of Concerns

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Digital Twin Workbench

- ingests engineering models
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Digital Twin Implementation

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

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.
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