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


# Model-Driven Industrial Digital Twins and AI

Seminar@SystemX
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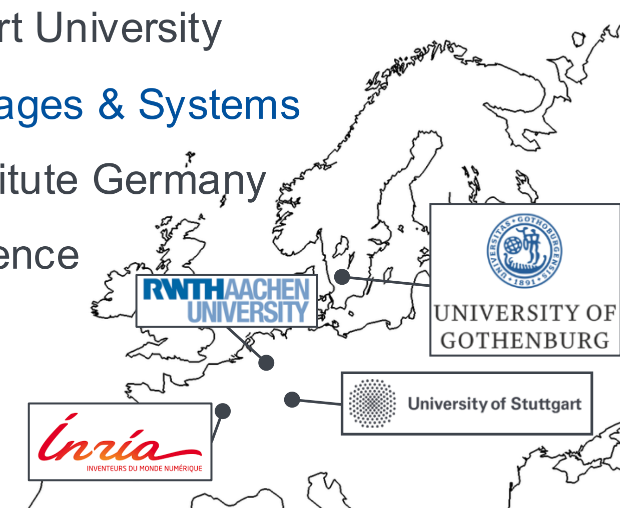
## Institute for Control Engineering of Machine Tools and Manufacturing Units (ISW)

- 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
  - AI for engineering
  - Cyber-physical systems (CPSs)
  - Digital twins



## Head of Institute:

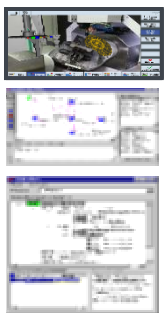
Alexander Verl
Oliver Riedel
Andreas Wortmann
Armin Lechler

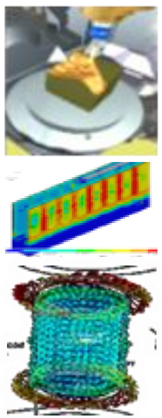
## Extended Head of Institute:

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 |
|---|---|---|---|---|---|



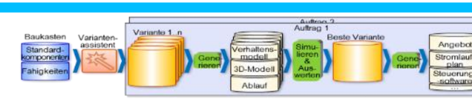


OPC UA TSN Pub/Sub
OPC FOUNDATION
sercos the automation bus
PROFINET
EtherCAT

**Engineering Methods** | **Simulation** | **Communication**

### Production IT

**Model-Based Production Engineering**



**Product Influence**

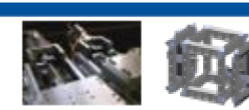
### Control Engineering

**Control**

Algorithms
Operation
Architectures

### Drive Technology

**Mechatronic Systems**

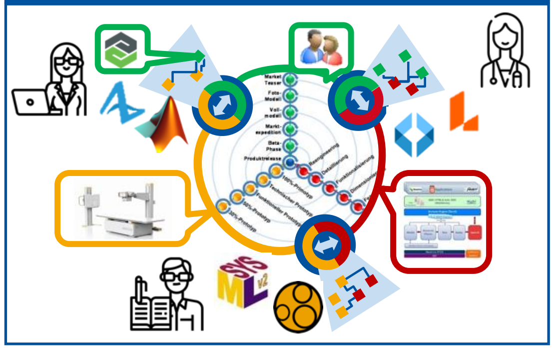


**Drive Control and Machine Technology**

# 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

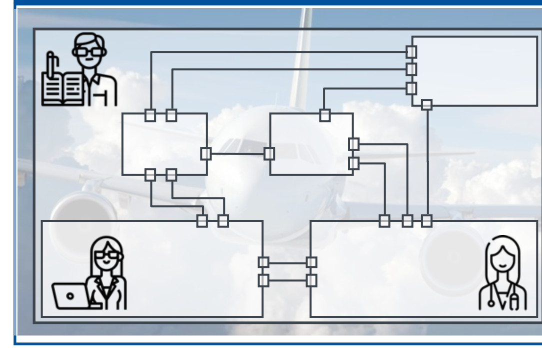


- New software languages
- Modeling techniques
- Model-driven development
- Model analysis, synthesis, code generation

## 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

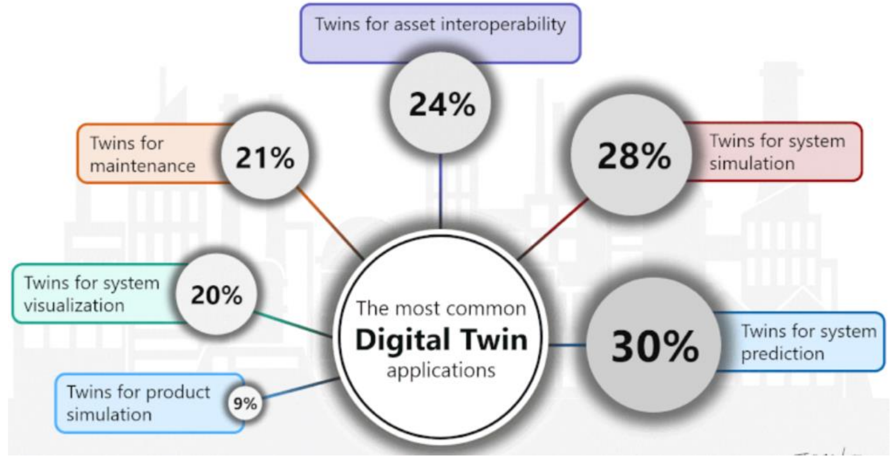
Digital Twins for AI

Challenges

# 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]



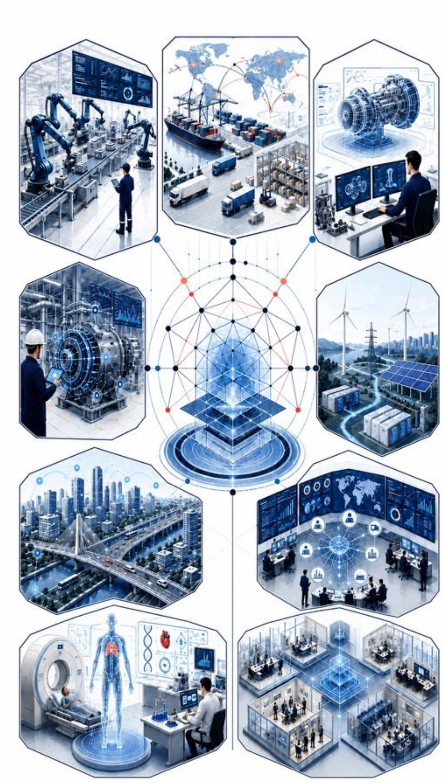

Source: https://www.jeffwinterinsights.com/

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)

# Specific Digital Twin Applications in Manufacturing

## Digital twins have proven real industrial impact on the shopfloor

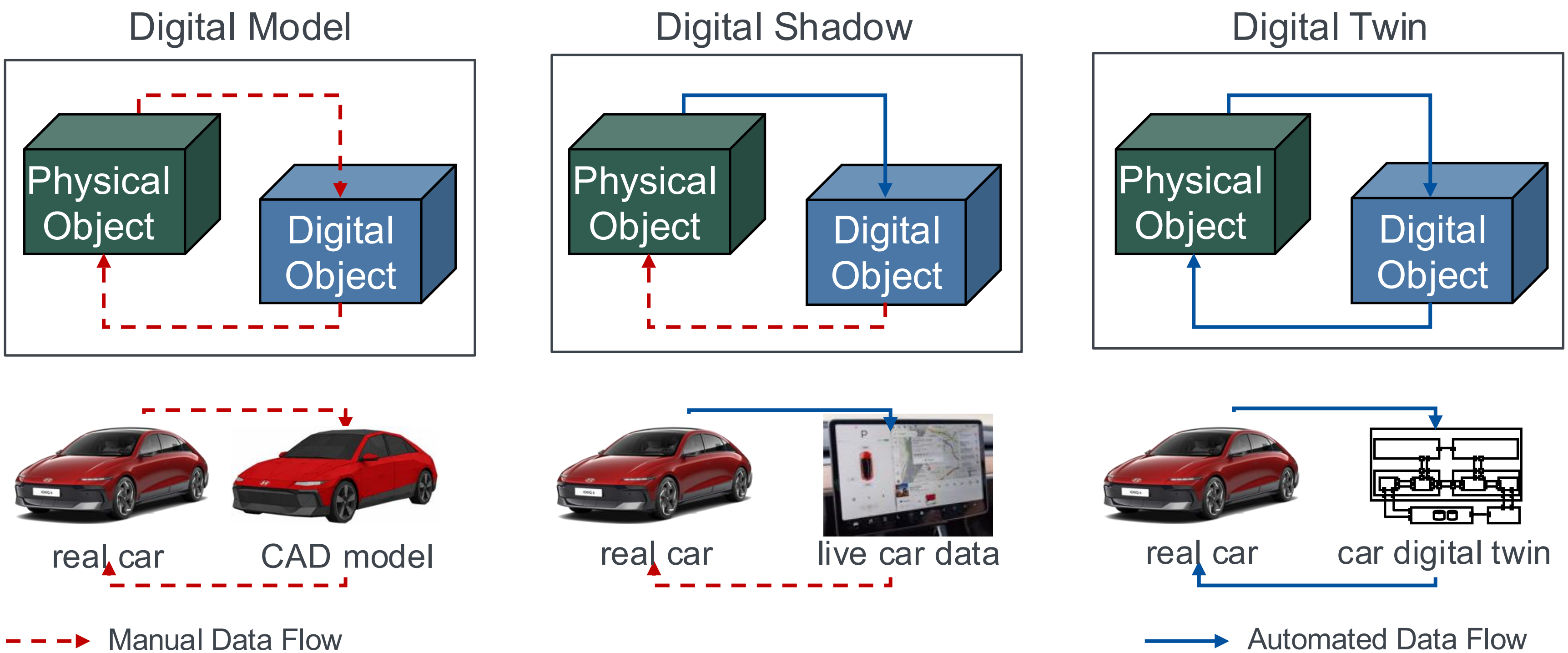
- BMW: 25% reduced time to plan factory operations[1]
- BCG: 3% - 6% procurement cost down with value-chain twins[2]
- Capgemini: 16% improvement in sustainability metrics[3]
- McKinsey: 20% - 50% reduced product development time[4]
- Siemens: 30% service cost down, 8% output increase[6]
- Unilever: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

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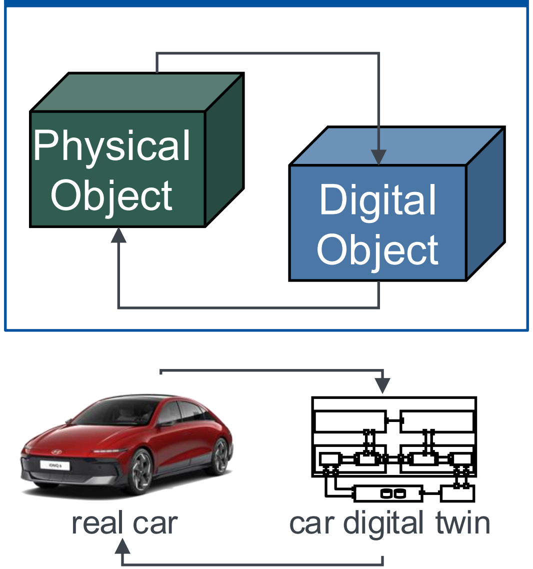
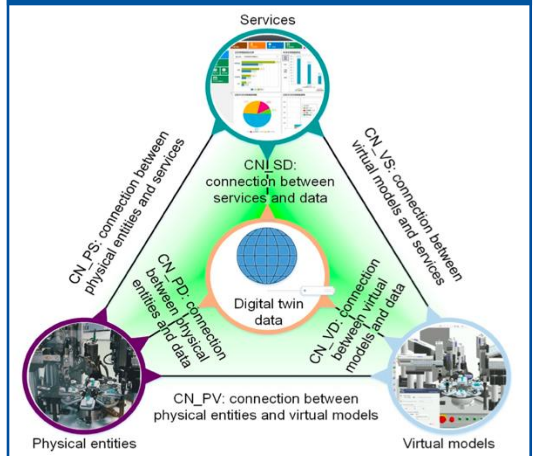
# A digital twin is a software system that uses data, models, and services
to purposefully represent and manipulate the original system during its lifecycle

## Flow-Based DT Model[1]

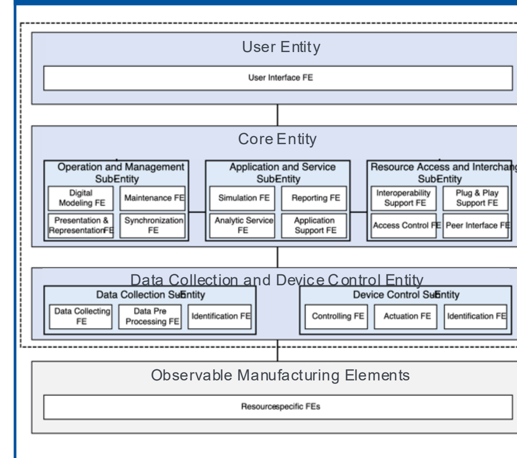



## 5D Digital Twin Model[2]




**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. 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 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/

Conclusion

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

# 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)

# 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 10% of FR GDP
- World-class companies: Airbus, Renault, Saint-Gobain, …
- 99.3% of manufacturing companies SMEs or smaller
- Contribute 23% 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. Insee: Caractéristiques de l'industrie manufacturière selon la taille des entreprises (2023). https://www.insee.fr/fr/statistiques/2015835

# Industrial Digital Twin in a Day using Model-Driven Engineering

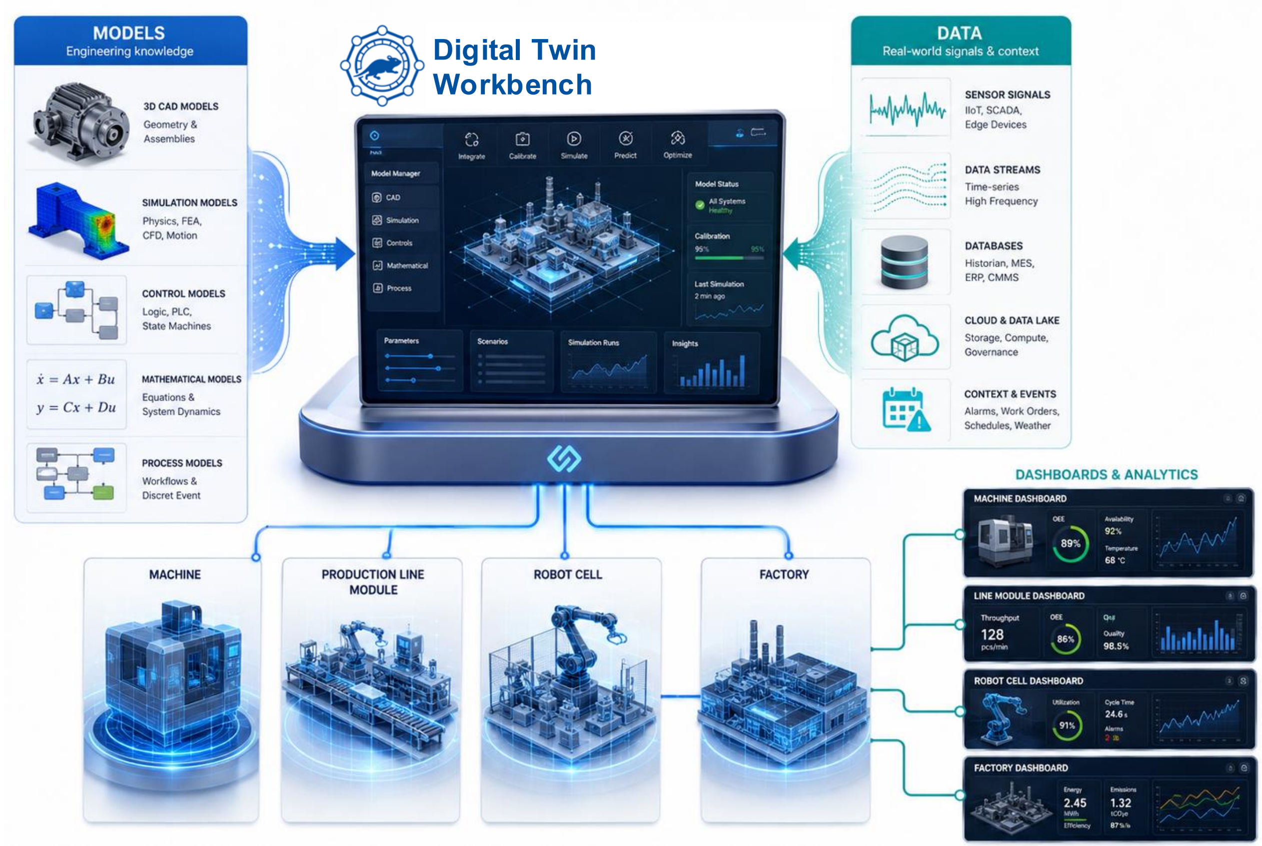
## A low-code-based solution tailored to SMEs and useful for everyone

- 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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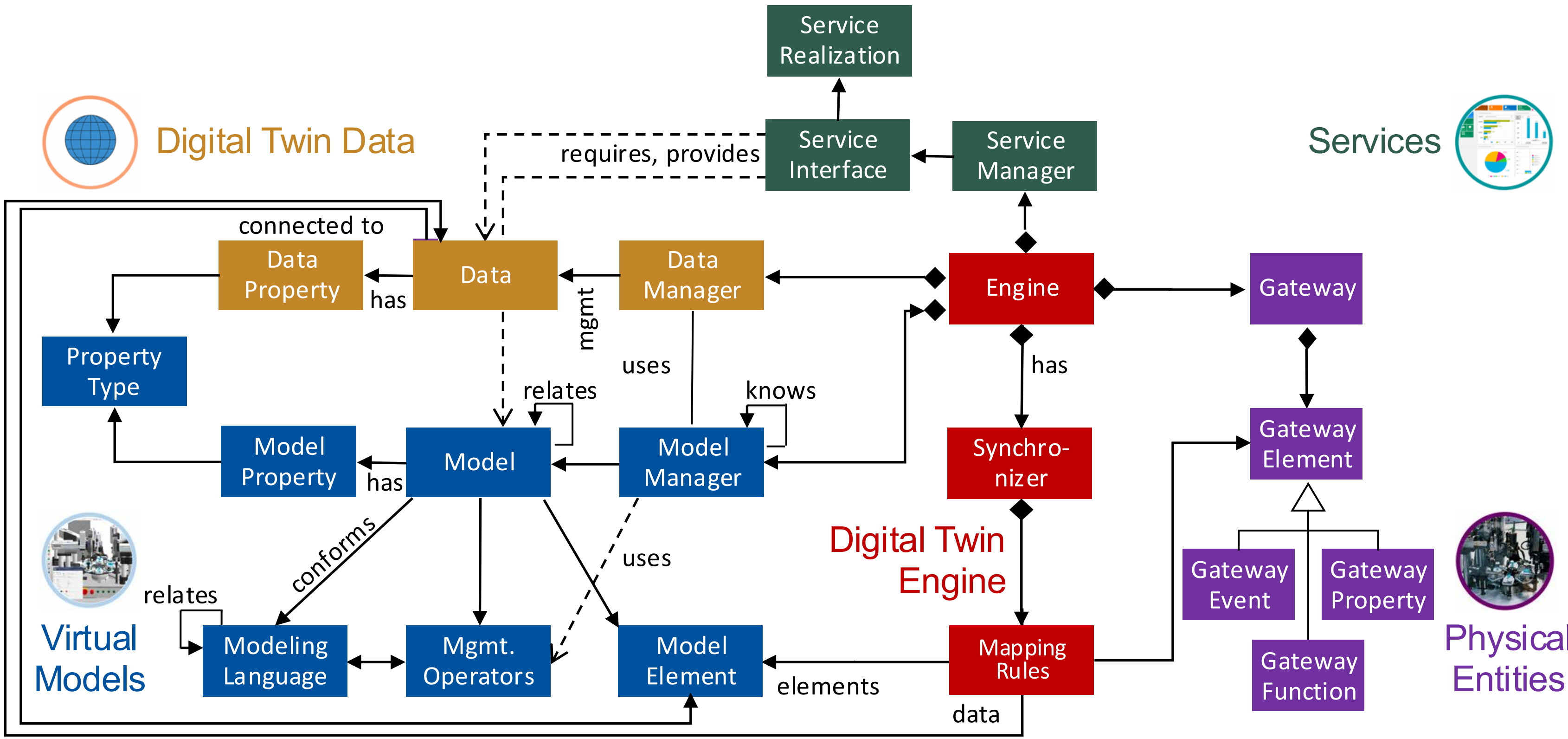
# A Reference Architecture for ISO 23247 Digital Twins in Manufacturing

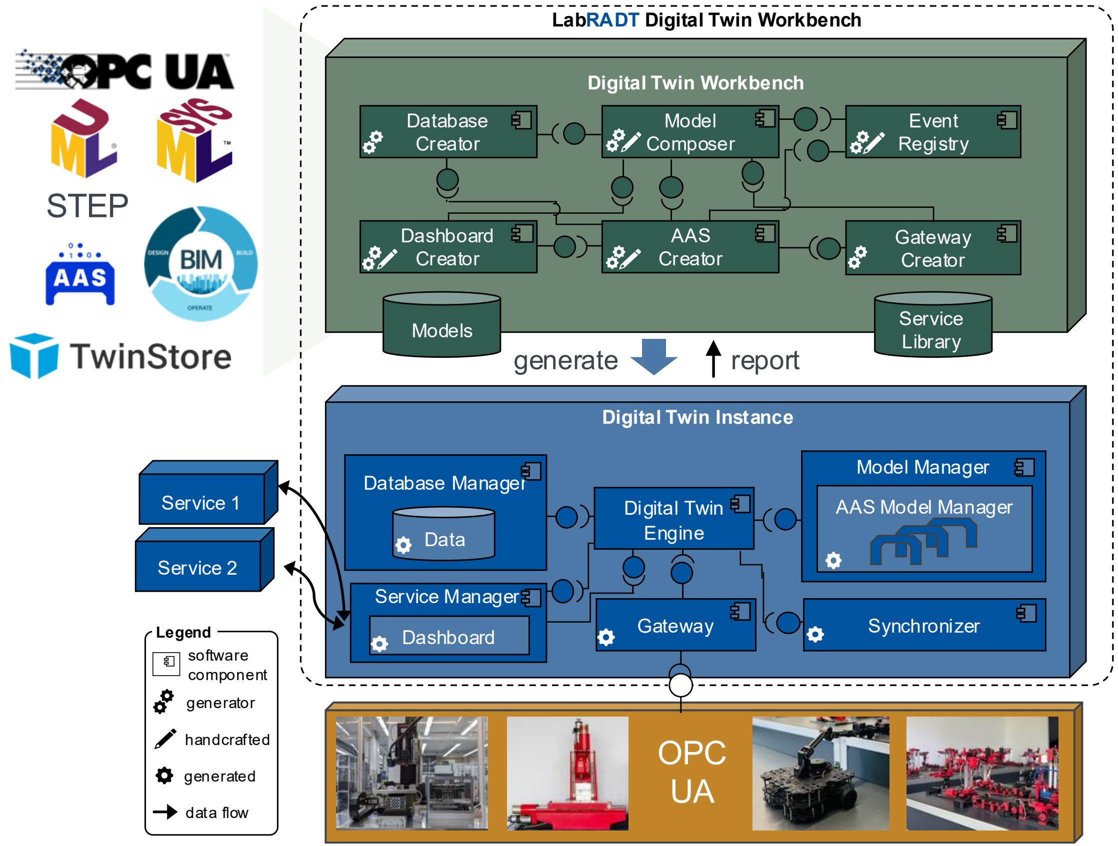
## Based on the 5D model[1] and refined with modeling expertise




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

# 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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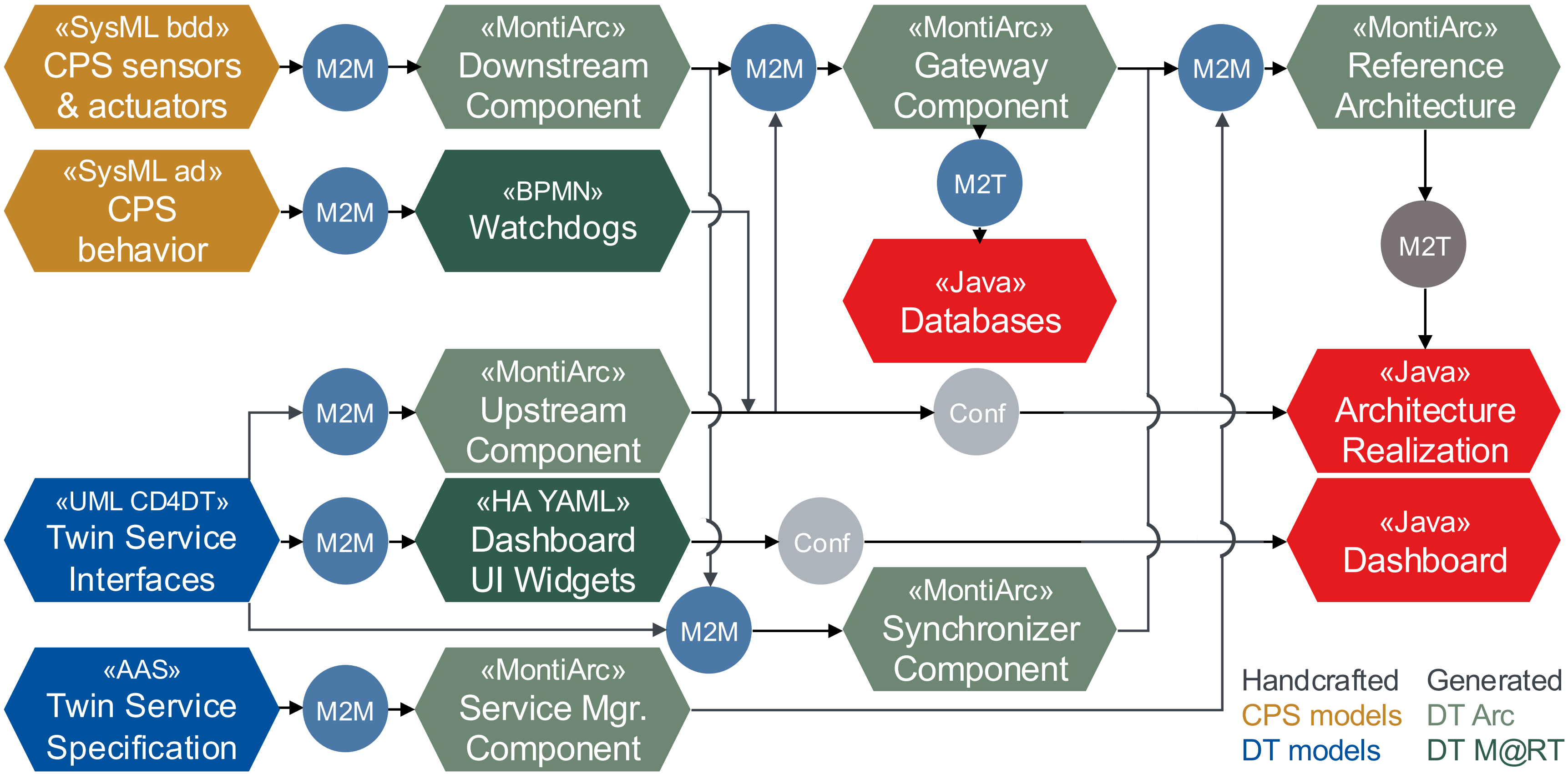
# The Digital Twin is Created via Model Transformations

## A formalism transformation graph overview



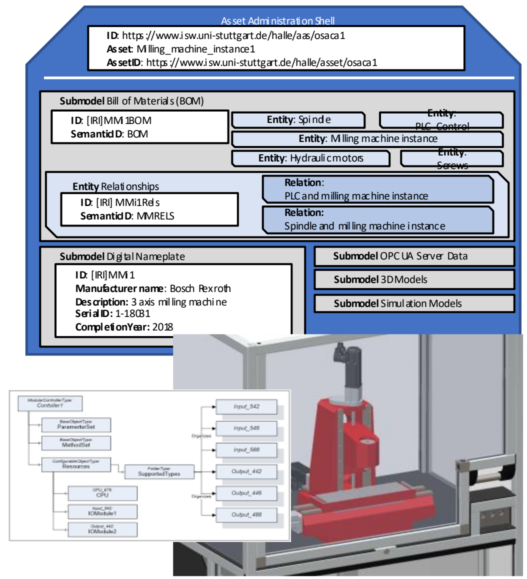
# Case Study 1: OSACA 3-Axis Drilling Machine[1]

## 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

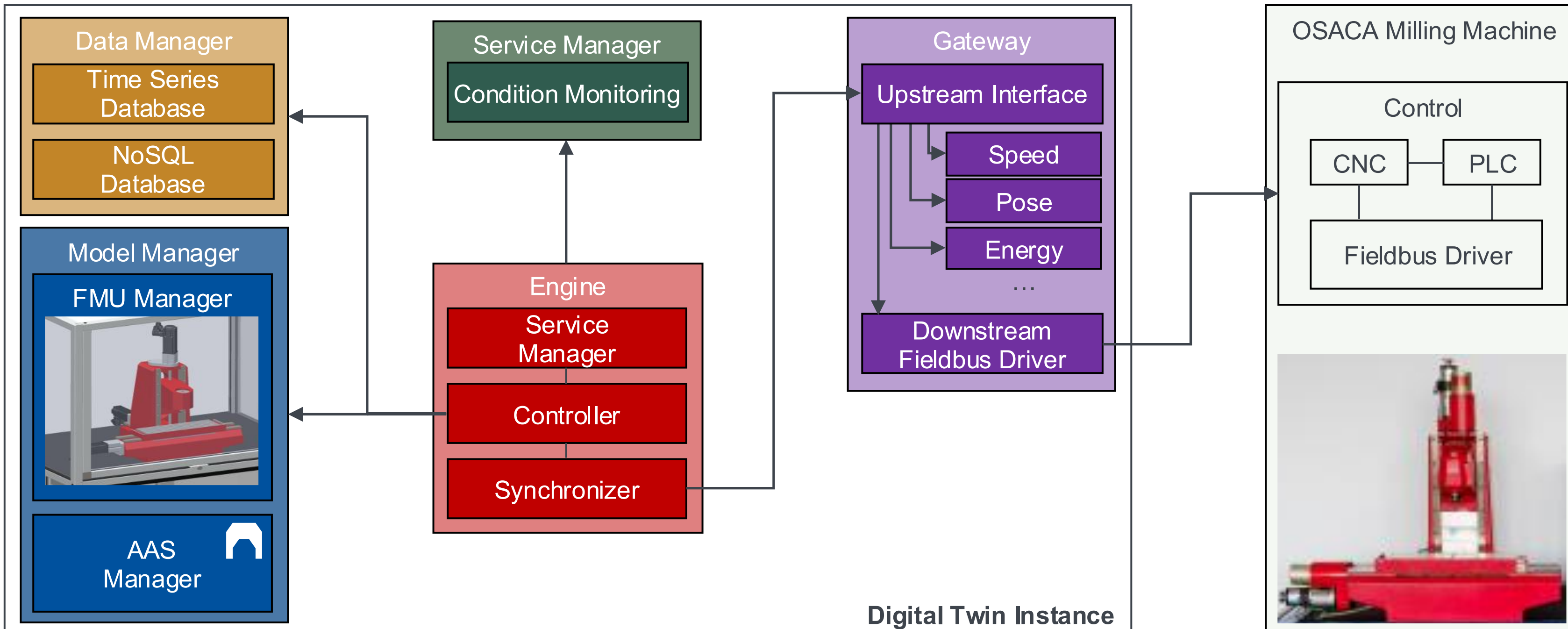



### CYBER-PHYSICAL TWIN

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.

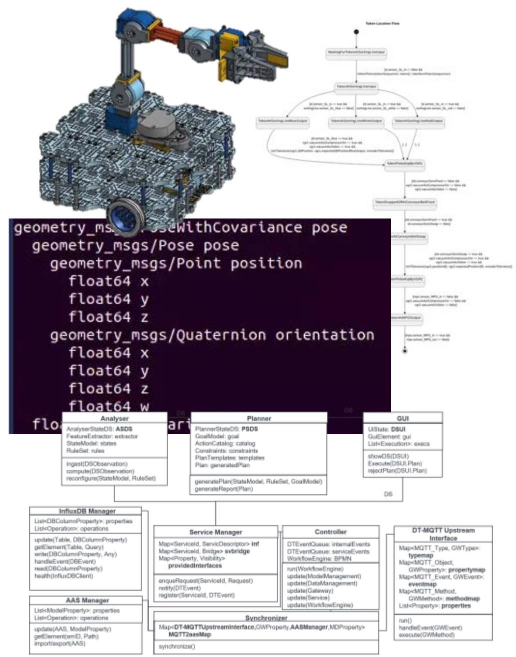
# Case Study 2: Composed Digital Twin of a TurtleBot Robot

## Integrating separate robotic subsystems into a hierarchical Digital Twin

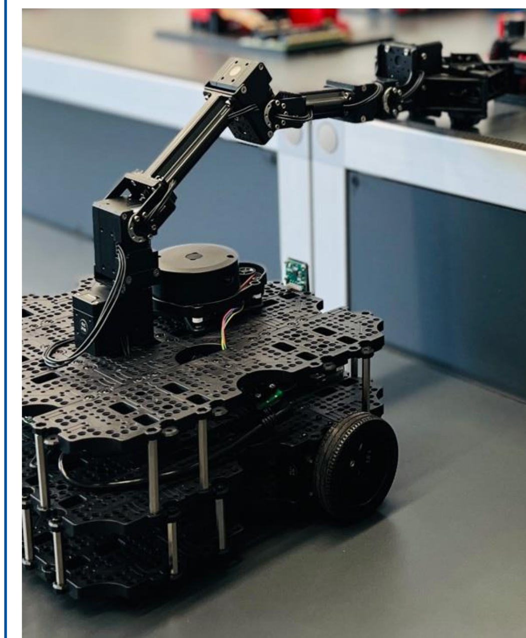
### PURPOSE

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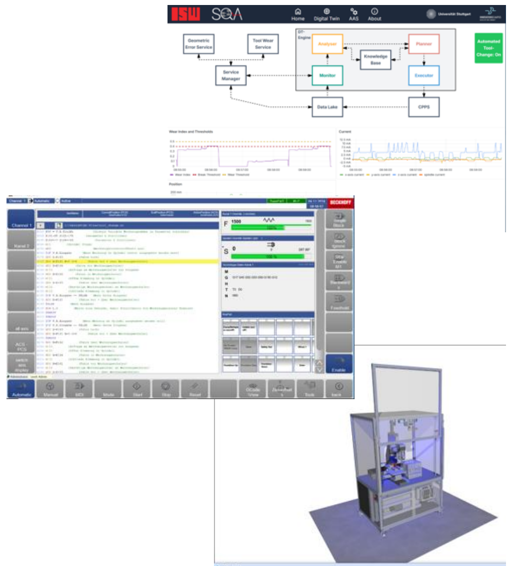
# Case Study 3: FiveX 5-Axis Laser Cutting Machine[1]

## Enabling proactive hardware maintenance and quality control

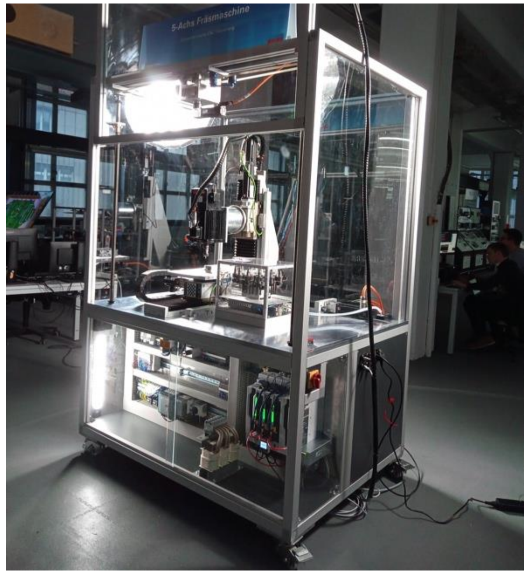
### PURPOSE

- 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.

# 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

# 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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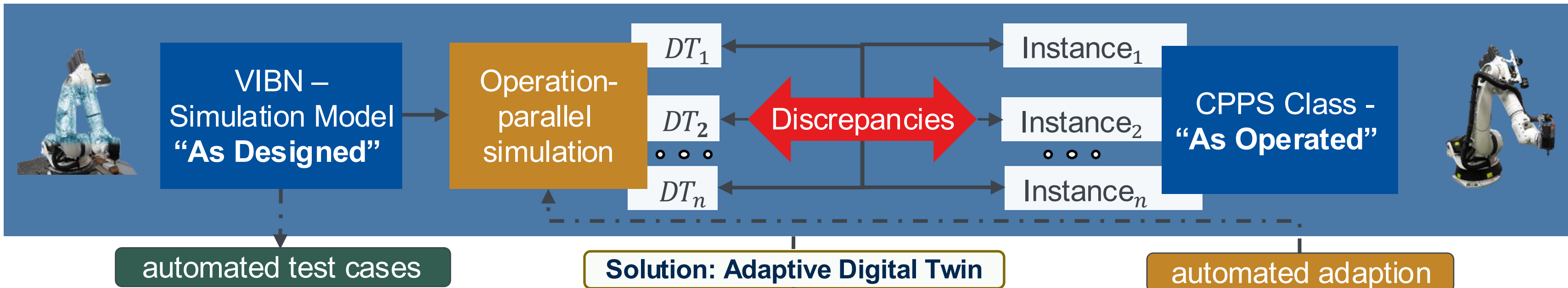
# From Virtual Commissioning to Simulation-Based Digital Twin

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




### Discrepancy Detection

Systematic experiment derivation from simulation

- Analysis of **simulation–reality gaps**
- Model-driven, automated **test program generation**

### Model Adjustment

Sensitivity Analysis & white-box calibration

- **Identification:** dominant parameters
- Discrepancy minimization via **global optimization**

### Continuous Model Adaptation

Self-adaptive digital twin with AI-driven model updates

- **Runtime detection** of behavioral deviations
- **OPC UA & Asset Admin. Shell** integration



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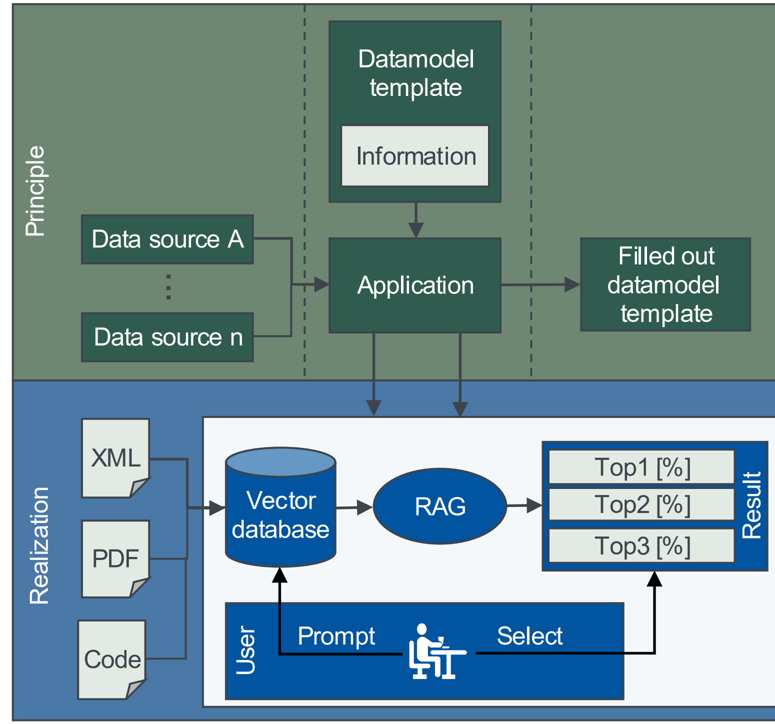
# AI-Powered Semantic Matching and Data Harmonization[1]

## 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

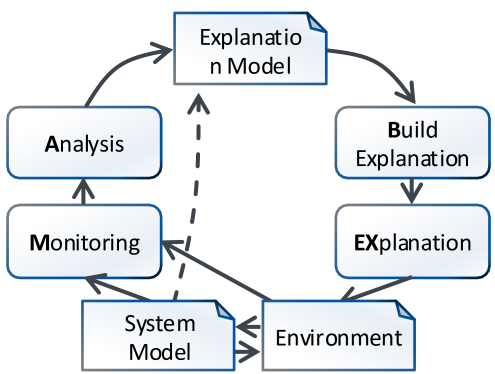


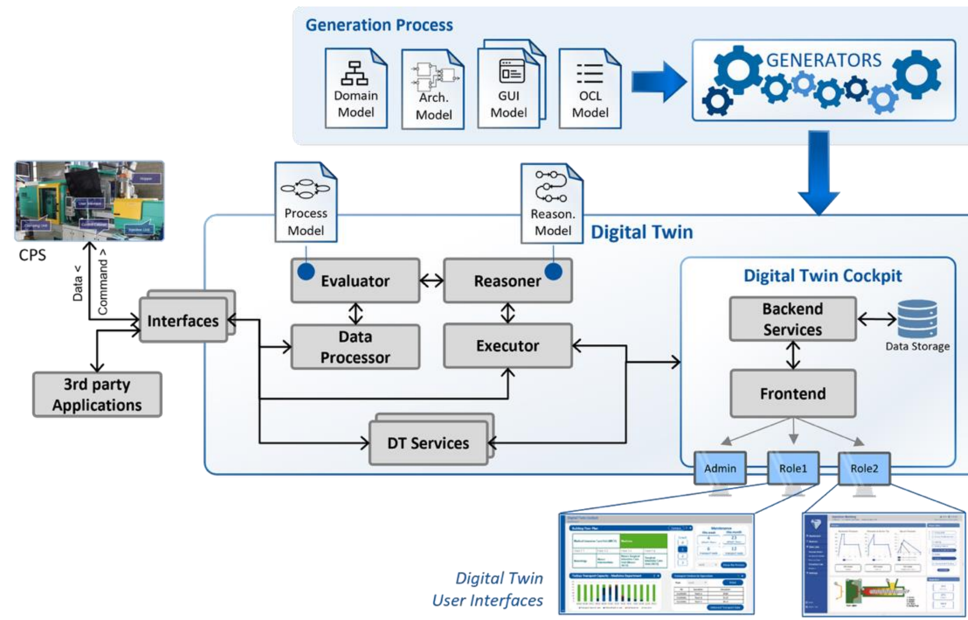

1. Ajdinović, S., Maisch, N., Kimmel, R., Rasouli, T., Lechler, A., Wortmann, A., & Riedel, O. (2025). AI-powered semantic matching and data harmonization for industrial applications with OPC UA & asset administration shells. In 16th International Conference on Mechanical and Intelligent Manufacturing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

# 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.

# 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.

# 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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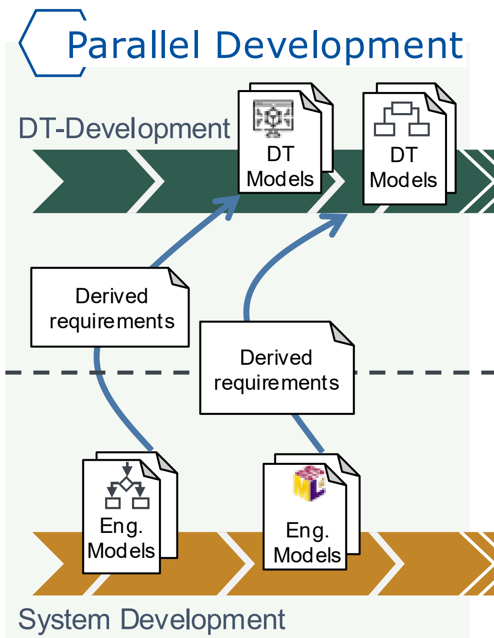
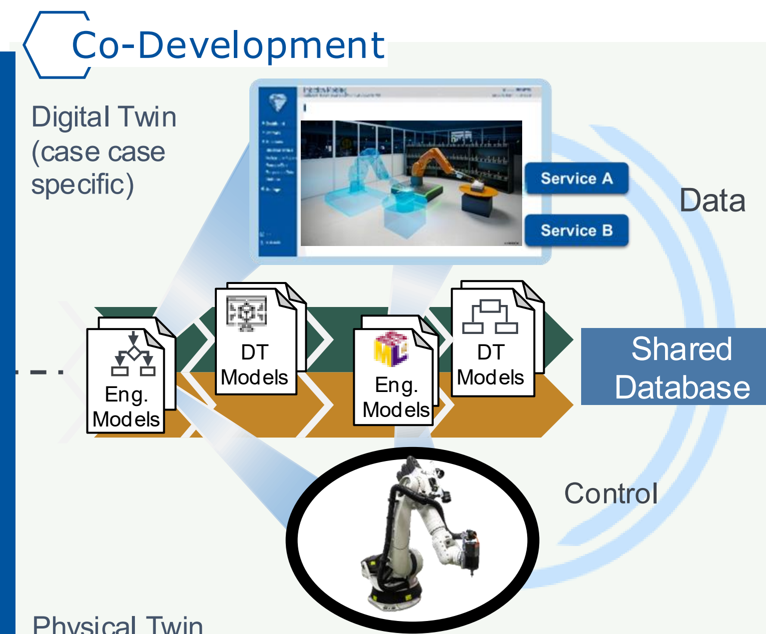
# Co-Development Instead of Re-Development

## Digital twins will be increasingly green-field development projects




- Currently no well-defined co-development process
- Might leverage model-driven engineering
- Reuse of system models
- Off-the-shelf services
- Extensible architecture
- Low-code configuration
- DTs tailored exactly to the specific use cases



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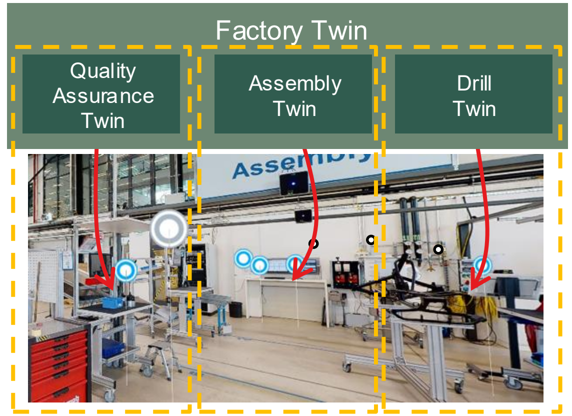
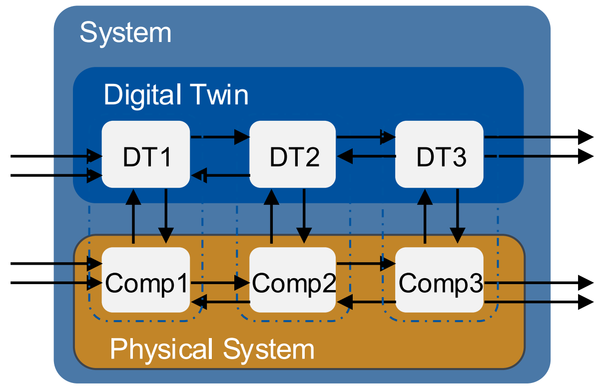
# Composition of Digital Twins is Essential

## 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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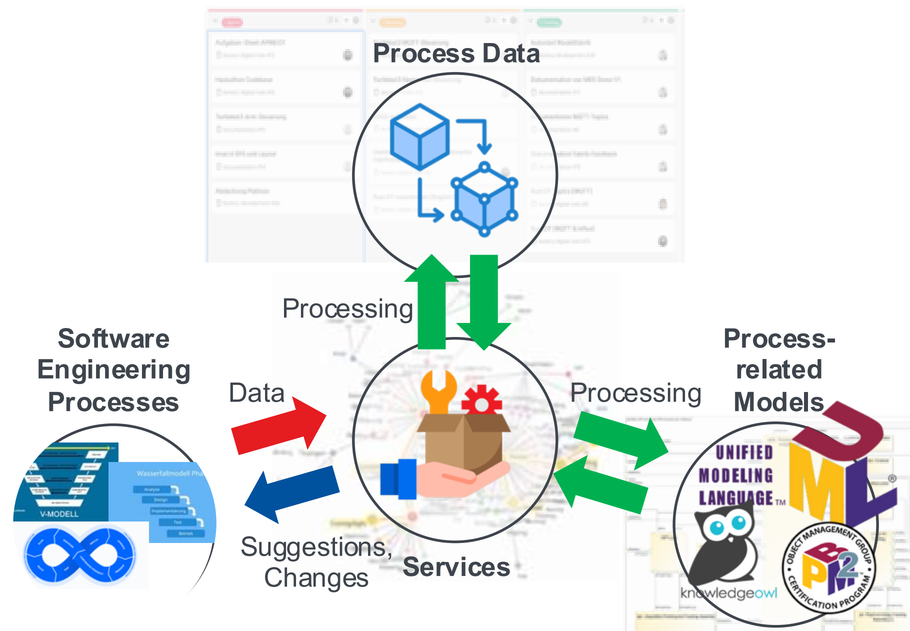
# Digital Twins for Software Engineering Processes[1]

## 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

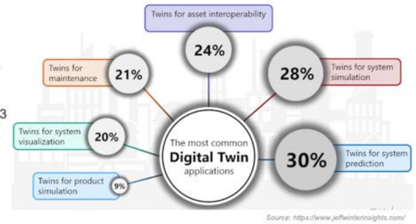



1. R. Kimmel, J. Michael, A. Wortmann and J. Zhang, "Digital Twins for Software Engineering Processes," 2025 IEEE/ACM 47th International Conference on Software Engineering: New Ideas and Emerging Results (ICSE-NIER), Ottawa, ON, Canada, 2025, pp. 16-20, doi: 10.1109/ICSE-NIER66352.2025.00009

## Digital Twins Promise Significant Economic Impact

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

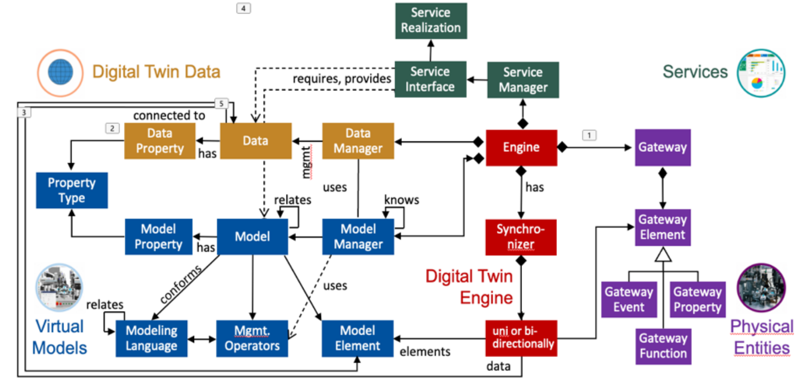
- Digital twins yield benefits of approx. £850 million across a ten-year period[1]
- Manufacturing: impact of DTs estimated[2] to be in the „low tens of billions of dollars“
- EU DT revenue forecast: $49.3B by 2030[3]
- KR DT revenue forecast: $3.8B by 2034[4]
- US DT-based savings of $27.2B / year[2]




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)

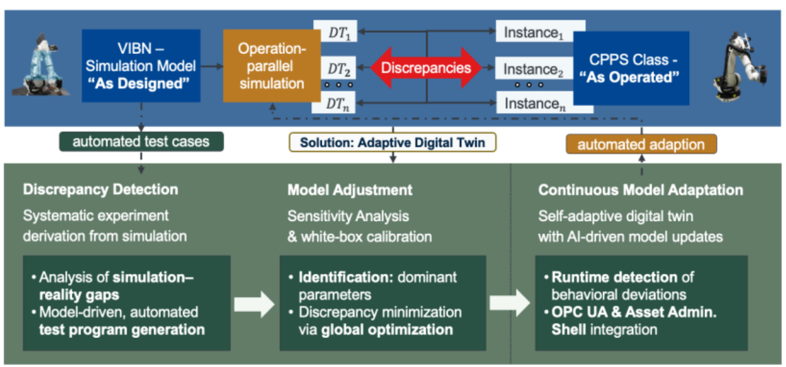
## A Reference Architecture for ISO 23247 Digital Twins in Manufacturing

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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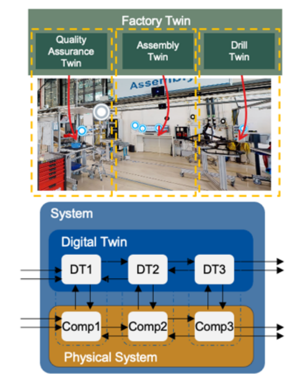



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