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

Models and AI in Software Engineering for Production

Digital Twins, Generative AI, and Robots

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

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

- Managing director of ISW, University of Stuttgart
- Akad. Oberrat & Venia Legendi at SE, RWTH Aachen University
- Board member European Association for Programming Languages and Systems
- Spokesperson TC AI-Powered Robotics of Robotics Institute Germany
- Co-director of AI Software Engineering Academy
- Research interests
  - Model-driven engineering
  - AI for engineering
  - Digital twins
  - Cyber-physical systems
- 200+ publications
- Organized 40+ conferences, co-founded EDTconf

The ISW has 6 Groups: 4 Conduct Software Research for Production

Head of Institute:

Alexander Verl
Oliver Riedel
Andreas Wortmann
Armin Lechler




Extended Head of Institute:

Florian Frick
Michael Seyfarth


Research fields

Software- and Engineering Methods

Carsten Ellwein

Marc Fischer
Robin Kimmel
Maximilian Koch
Miriam Mack
Rebekka Neumann
Jérôme Pfeiffer
Matthias Richter
Ann-Kathrin Splettstößer
Alexander Uhl
Moritz Walker
Jingxi Zhang

Industrial Control Engineering

Samed Ajdinovic

Tonja Heinemann
Nicolai Maisch
Siddieq Mansour
Matthias Marquart
Christian von Arnim

Real-Time Communication & Control Hardware

Florian Frick

Wolfgang Bubeck
Hannes Grabmann
Philipp Neher
Stefan Oechsle
Manuel Weiss

Drive Systems and Motion Control

Lukas Steinle

Christian Bauer
Marcel Dzubba
Florentin Furcoi
Oliver Jud
Valentin Kamm
Jannik Lehner
Valentin Leipe
Hector-Jair Morales
Lukas Zeh

Mechatronic Systems and Processes

Maximilian Nistler

Johannes Clar
David Dietrich
Nicolas Grupp
David Hecht
Claudius Horsch
Daniel Kurth
Colin Reiff
Haijia Xu
Zexu Zhou

Virtual Methods for Production Engineering

Lars Klingel

Nico Brandt
Shengjian Chen
Annika Kienzlen
Lukas Koberg
Daniel Littfinski
Josip Lozic
Simon Nowinski
Erik-Felix Tinsel

Central Services

Student Affairs
Michael Seyfarth

Accounting
Ingrid Albright
Andrea Bauder
Sonja Cais
Edith Schlenker

Technical Office
Xenia Günther
Inga Deines
Tatiana Motsnaya

Assistance
Anna-Maria Kubelke
Stefanie Lang
Judith Lorch
Hendrik von Linde

Student Applications Laboratory
Georg Ziegler

Electrical Laboratory
Stefan Abel, Arthur Wendland

Mechanical Laboratory
Achim Ringler, Lars Hofmann

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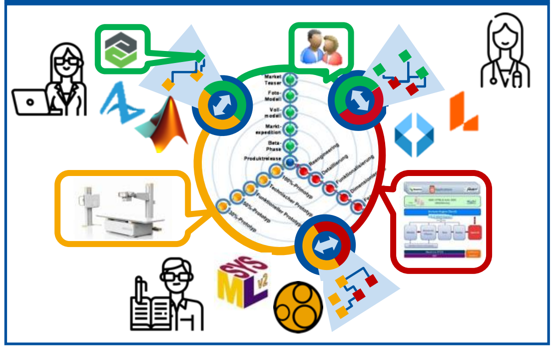
This Keynote Covers five Topics from MDSE over AI to SE for Machinery

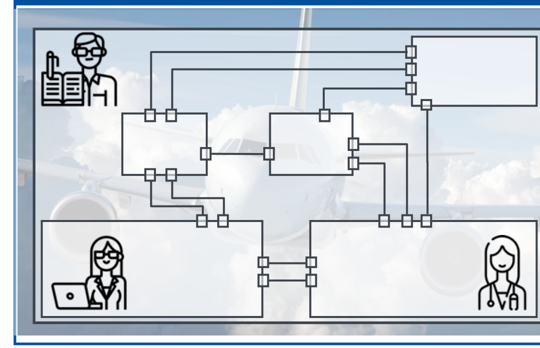
An overview of spotlights across the three main pillars of my research

Model-Driven Software and Systems Engineering



Artificial Intelligence for Engineering

Methodical Model-Driven Operations



1. Digital Twins in Manufacturing
2. Systems Modeling with the Asset Administration Shell
3. Generative AI for Production
4. Machine Connectivity and Information Modeling with OPC UA
5. Software Engineering for Robotics in Production

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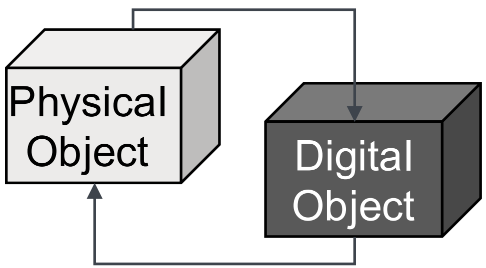
Model-Driven Software and Systems Engineering

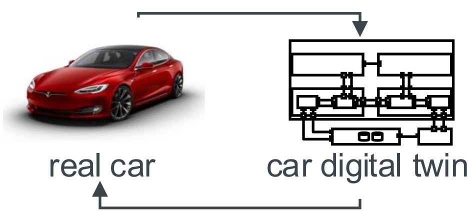
Digital Twins in Manufacturing

Developing DTs is Costly: Minimum 1 million US-$ per DT according to PTC[4]

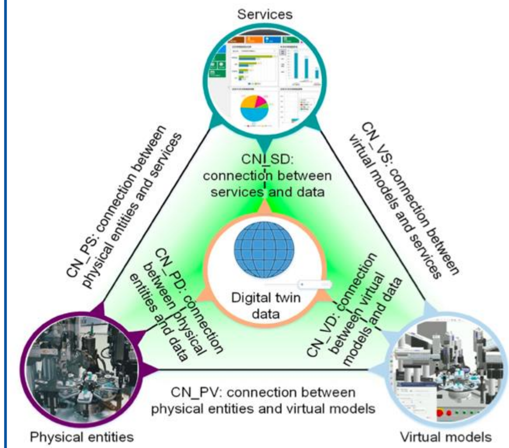
Software engineering can help with that

Flow-Based DT Model[1]



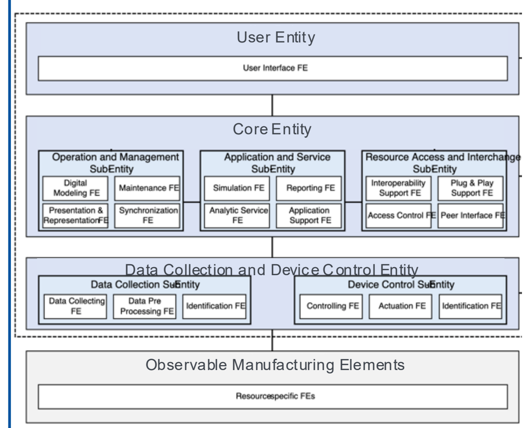


5D Digital Twin Model[2]



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

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.
4. https://www.ptc.com/en/blogs/corporate/roi-of-digital-twin-for-industrial-companies

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 DTs — 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 only 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."

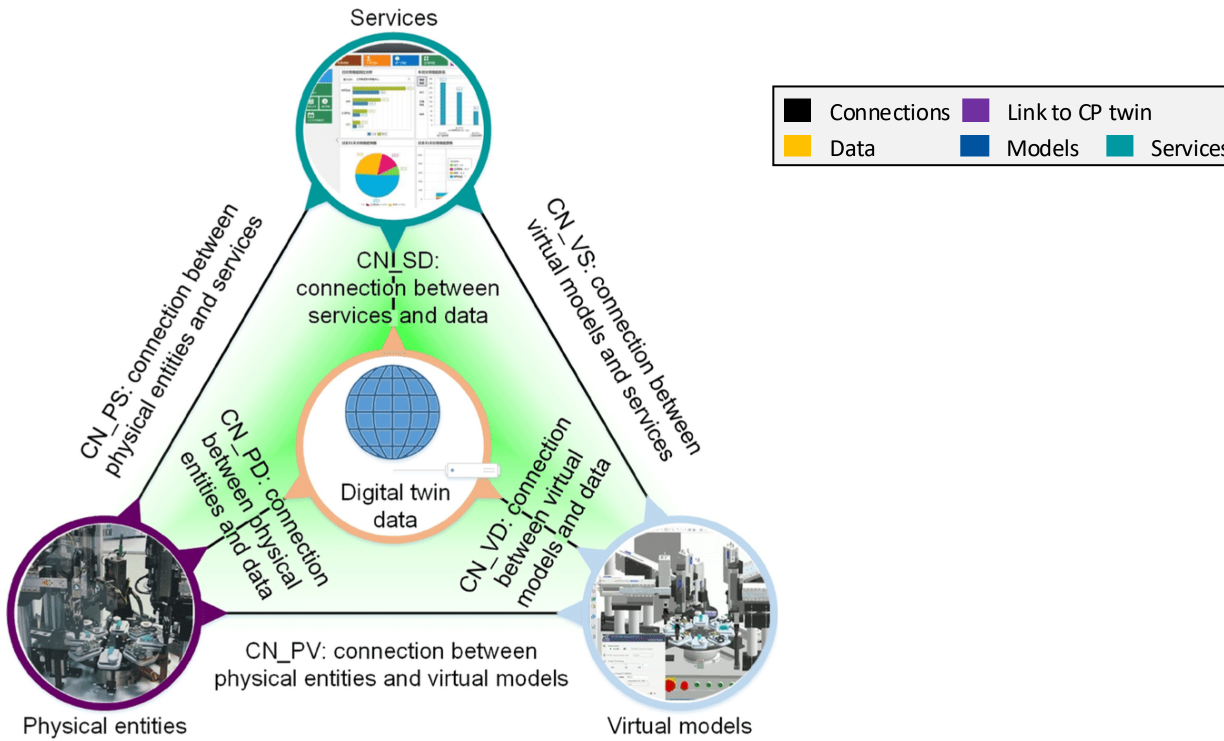
Implications

- 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

A Reference Architecture for ISO 23247 Digital Twins in Manufacturing

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



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

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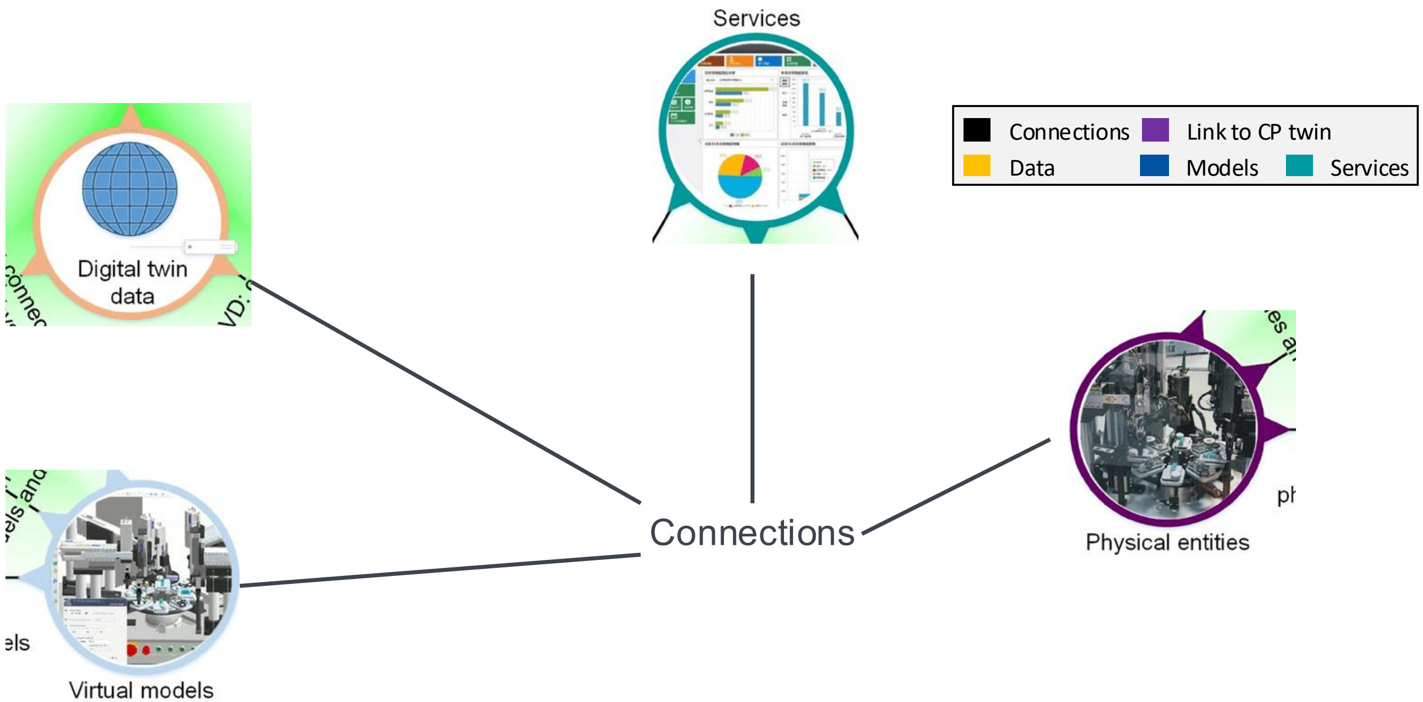

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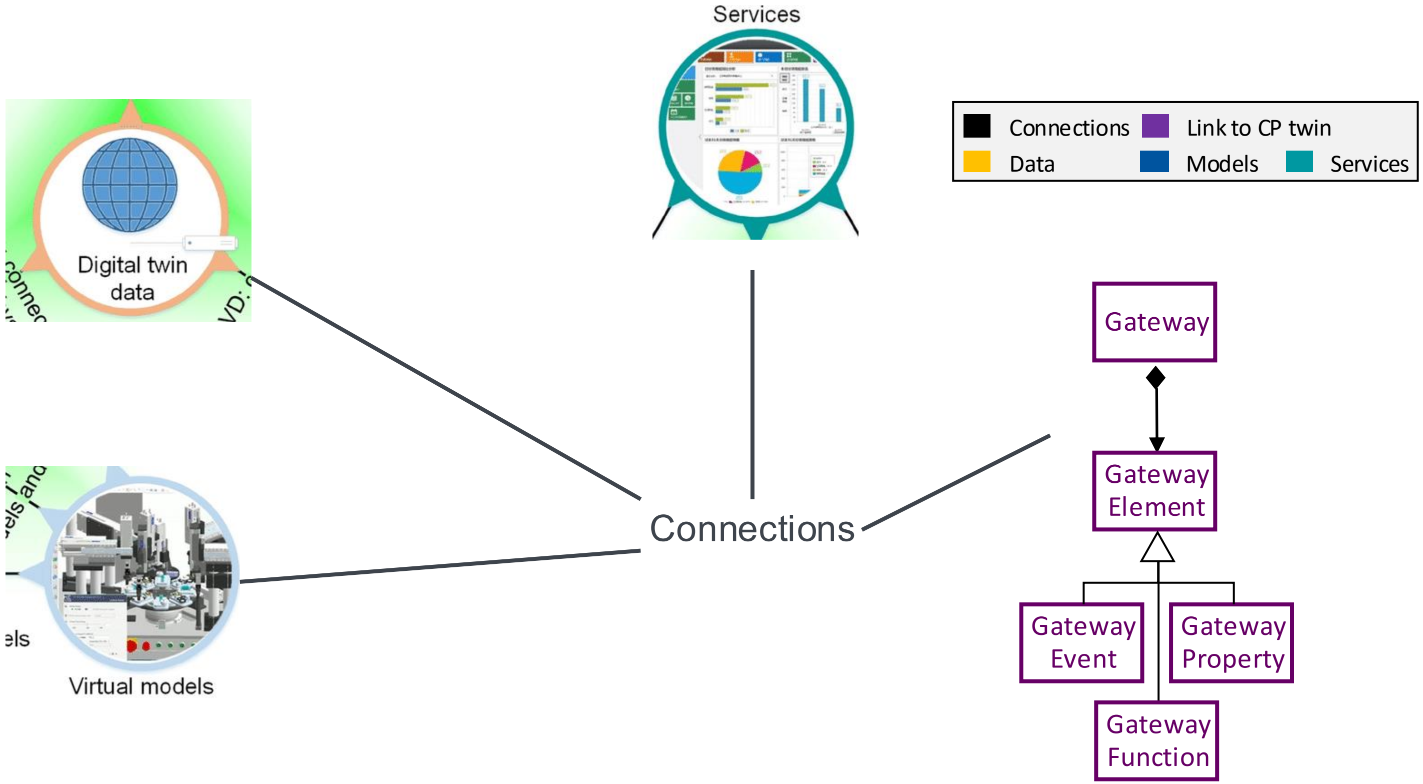

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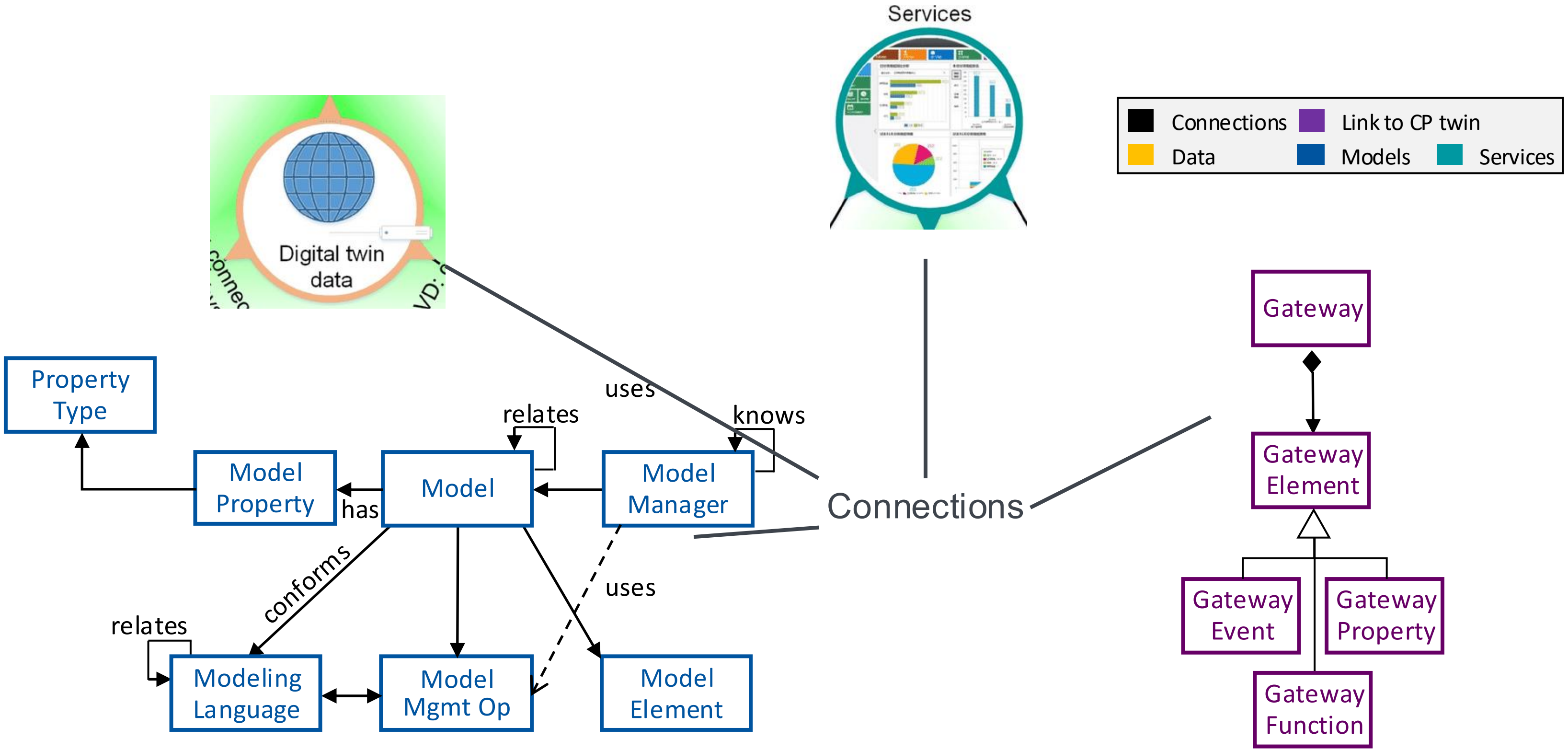

1. Qi et al.: Enabling technologies and tools for digital twin. In: Journal of Manufacturing Systems, Elsevier, 2019

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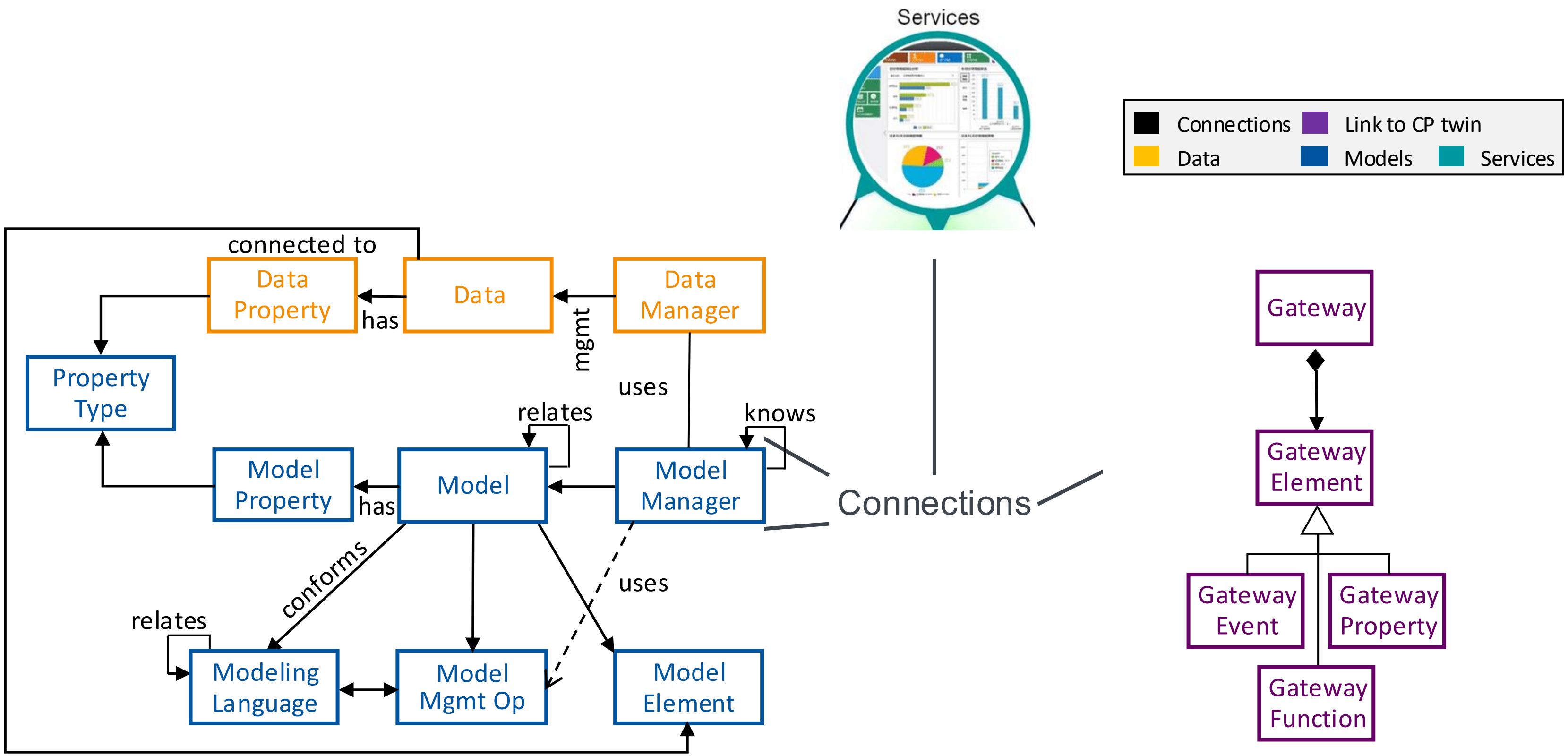

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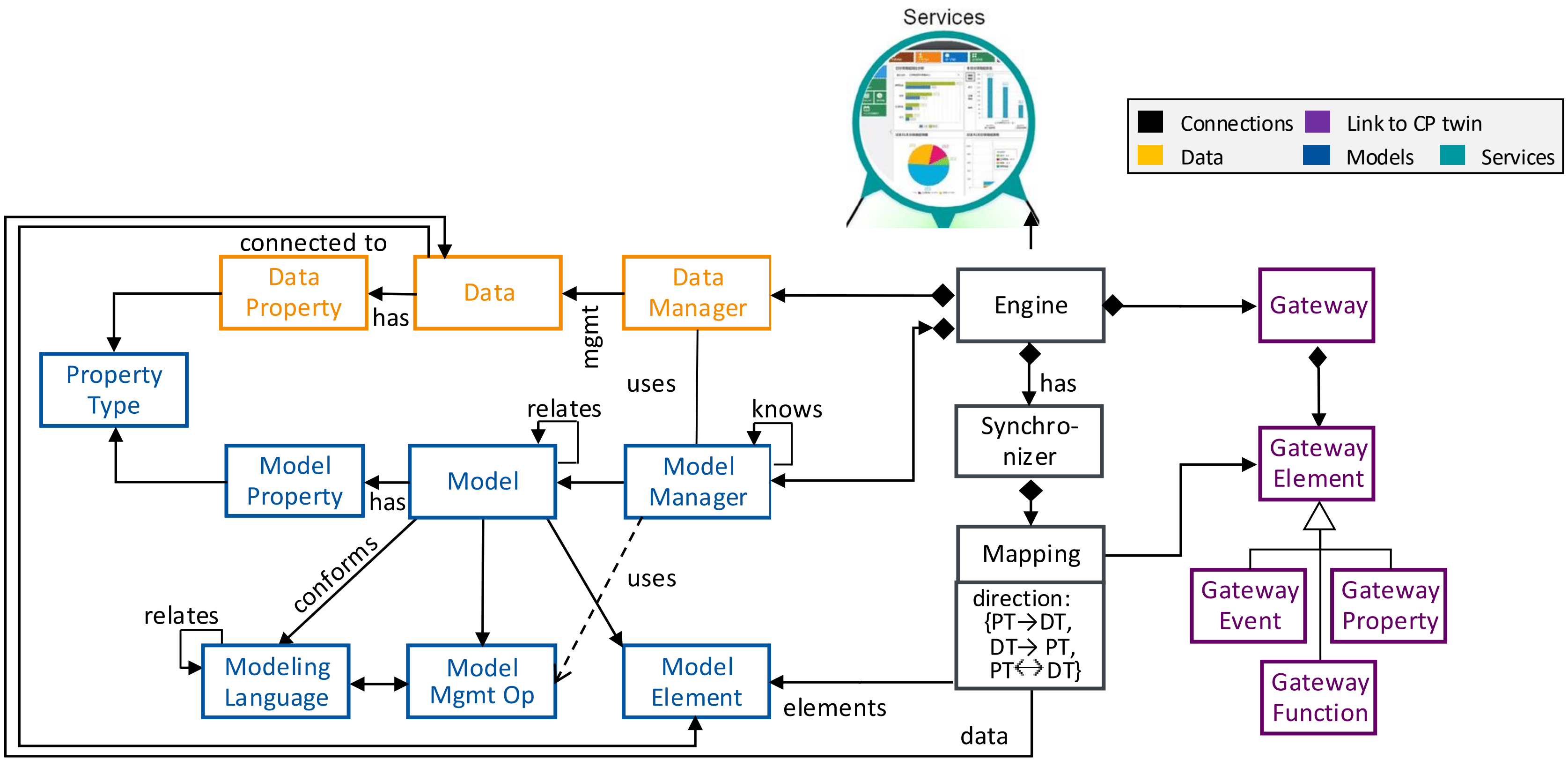

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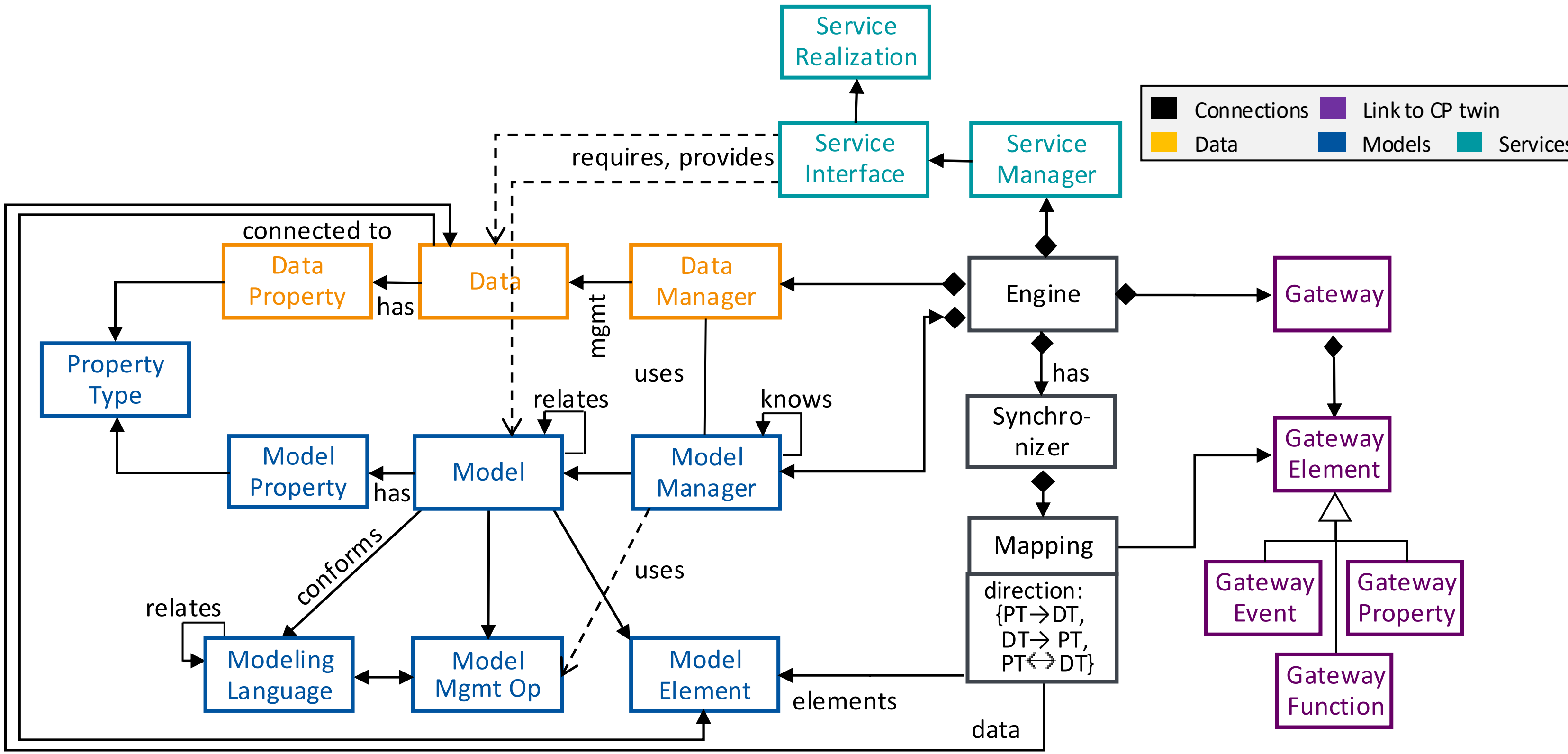

1. Qi et al.: Enabling technologies and tools for digital twin. In: Journal of Manufacturing Systems, Elsevier, 2019

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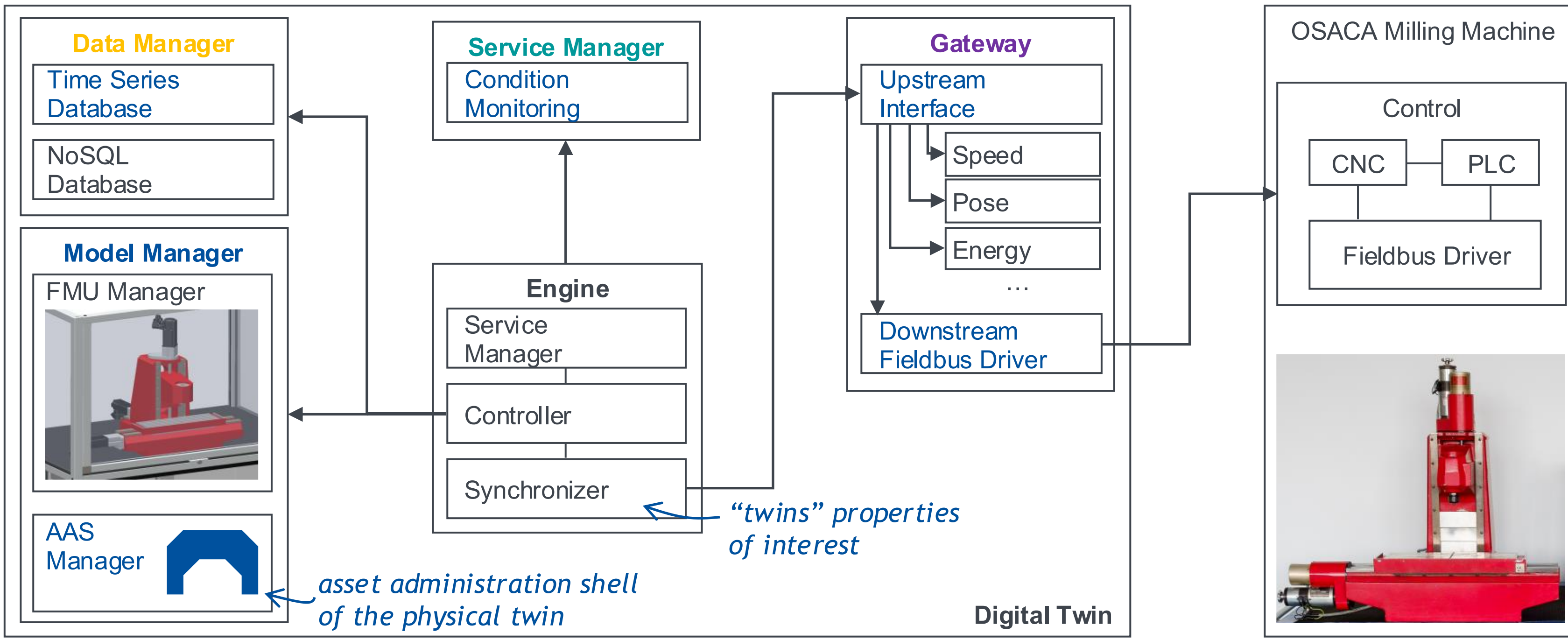
Incarnation of our Reference Architecture for an OSACA Milling Machine

Added value services: condition monitoring



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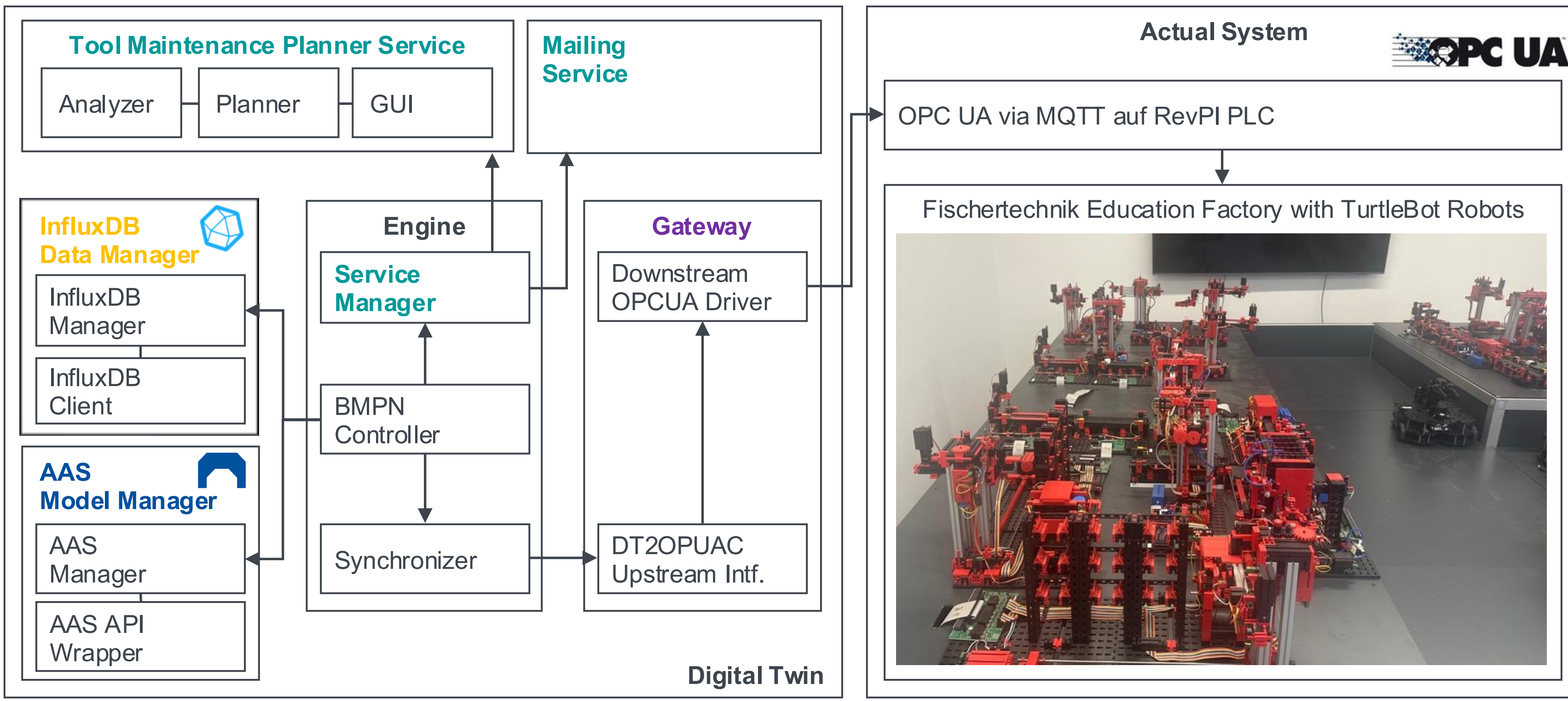
An ISO 23247 Compliant Digital Twin for Production Lines

Added value services: prediction monitoring and service allocation



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There are many Challenges to Systematically Engineering Digital Twins

Focusing on automating their engineering, reusing (parts of) DTs, …

1. **Deriving Twins.** Engineering models comprise vast asset knowledge
   - Challenge: Much needs to be re-developed for the digital twins
   - Opportunity: Derive (parts of) DTs from engineering models
2. **Component Reuse**. DTs process data, models, communication, services
   - Challenge: Reusing their components between DTs hardly possible
   - Opportunity: DT reference architectures with well-defined component interfaces
3. **Digital Twin Reuse.** Complex DTs should comprise sub-DTs.
   - Challenge: The composition of digital twins is far from solved
   - Opportunity: Systematic method to compose DTs into larger ones.
4. **Low-Code Configuration**. DTs are configured and used by domain experts (DEs)
   - Challenge: Expecting experts to grasp object-oriented data models or stack traces is futile
   - Opportunity: Low-code techniques properly configure, represent cross-cutting DT concerns.

Model-Driven Software and Systems Engineering

Systems Modeling with the Asset Administration Shell

Manufacturing must meet Sustainability and Transparency Requirements

Digital product passport (DPP) will be the identity card of products in the EU

- Growing pressure to increase production transparency, as reflected in initiatives:
  - European Green Deal, Agenda 2030
  - Circular Economy Action Plan
- Puzzle piece: digital product passport (DPP)
  - main contents: ID, composition, footprint, circular economy data, compliance, …
- Mandatory rollout timeline from 2027 to 2030
  - industrial & EV batteries (2027)
  - consumer electronics / ICT (2029)
  - others in-between (latest 2030)

- DPP documents the complete product life cycle
  - material origin, supply chain, production
  - facilitates recycling and reuse
- DPP challenges
  - no exemplary realizations or tools
  - no collaborative methodology for creating DPPs
  - aggregating production data into meaningful product information

1. https://commission.europa.eu/energy-climate-change-environment/standards-tools-and-labels/products-labelling-rules-and-requirements/ecodesign-sustainable-products-regulation_en

Main Challenge: Gather and Meaningfully Aggregate all Asset Data

State-of-practice: largely digital documents in silos

Capabilities
- End milling
- Drilling

Maintenance
- Cutting time
- Latest service

Operational Data
- Sensor data
- Energy consumption

Asset

OSACA Milling Machine

Technical Data
- Max. spindle speed
- Axis count

Digital Nameplate
- Contact data
- Serial number

3-axis milling machine

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AASs aim to Locate all Relevant Information About an Asset Centrally

Submodels are the main content of asset administration shells

Capabilities
- End milling
- Drilling

Maintenance
- Cutting time
- Latest service

Operational Data
- Sensor data
- Energy consumption

Asset Administration Shell (AAS)

Asset

OSACA Milling Machine

Technical Data
- Max. spindle speed
- Axis count

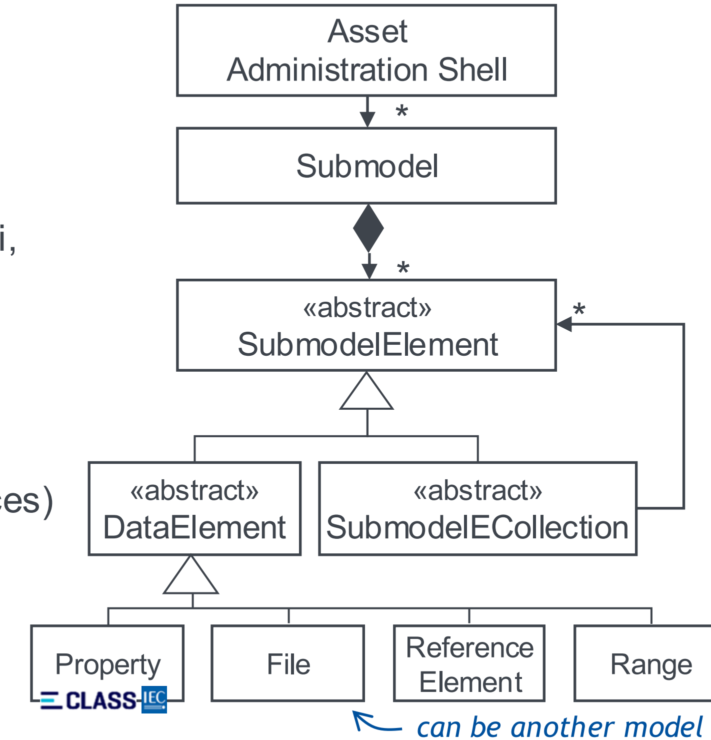
Digital Nameplate
- Contact data
- Serial number

3-axis milling machine

The AAS is an Industrial Modelling Success Story

Every information about an asset in a single place

- Modeling framework for asset information
- Standardized by Industrial Digital Twin Association (IDTA)[1]
- 129 members, incl. ABB, Bosch, Danfoss, Dassault, Hitachi, Huawei, Mitsubishi, PTC; Siemens, SAP, Trumpf, VW, …
- Core metamodel[2] building on industry standards
  - data model based on ISO 13584-42, IEC 61360
  - ECLASS[1] (classification, description of products & services)
- Goal: standard for digital twins in industry[3]
- Eclipse BaSyx for implementation (among others)

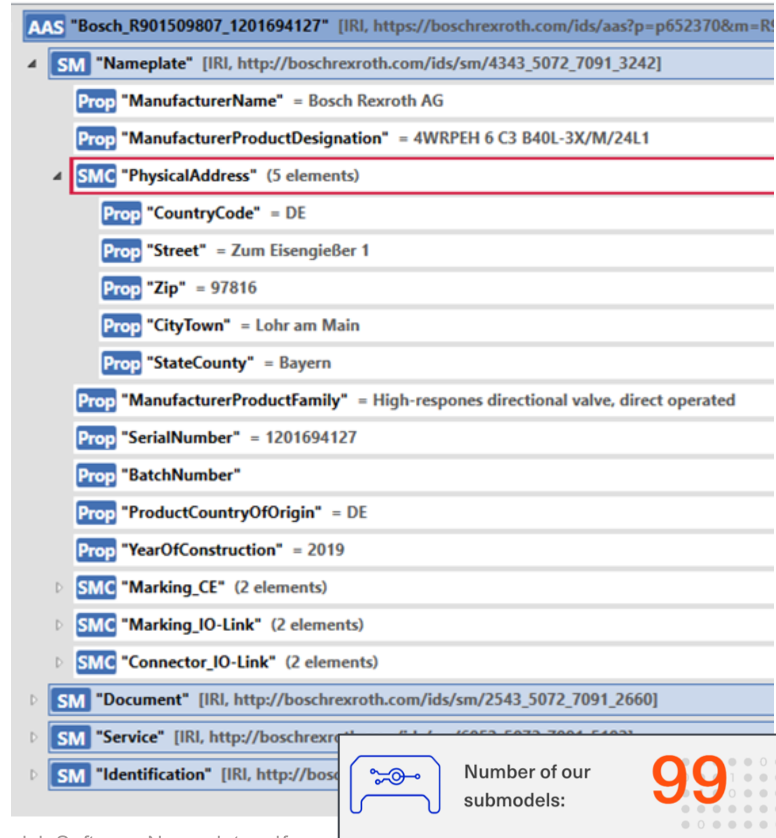


1. ECLASS - ISO/IEC-compliant data standard for products and services: https://eclass.eu/
2. https://industrialdigitaltwin.org/wp-content/uploads/2023/04/IDTA-01001-3-0_SpecificationAssetAdministrationShell_Part1_Metamodel.pdf
3. Zhang, J., Ellwein, C., Heithoff, M., Michael, J., & Wortmann, A. (2025). Digital Twin and the Asset Administration Shell: An Analysis of 3 AASs Types and Their Feasibility for Digital Twin Engineering. *Journal Software and Systems Modeling (SoSyM).*

The Success of AAS Modeling: Standardization with Submodel Templates

Industry working groups standardize data models for use cases of interest

- 40 submodel templates[1] official released, incl.
  - Digital Nameplate
  - Provision of Simulation Models
  - Handover Documentation
  - Bill of Material
  - Asset Interfaces Description
- Rest under development, incl.
  - Software Bill of Materials
  - Nameplate for Software in Manufacturing[2]
  - Digital Battery Passport (rollout 2027)
- Or: build your own submodel templates



1. https://industrialdigitaltwin.org/en/content-hub/submodels
2. https://industrialdigitaltwin.org/en/wp-content/uploads/sites/2/2023/08/IDTA-02007-1-0_Submodel_Software-Nameplate.pdf

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There are 3 Kinds[1] of Asset Administration Shells

And they relate to digital twins differently[2]

Type 1 AAS

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

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

Digital Model

Type 2 AAS

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

→ **Well-informed Dashboard**

Digital Shadow

Type 3 AAS

- Extend type 2 AAS
- Have active behavior
- Can start to communicate & to negotiate on their own
- Well-defined I4.0 language and message structures (VDI/VDE 2193)
- Automated dataflows from and to real system

→ **A software that can control the asset**

Digital Twin

1. Belyaev, A., Diedrich, C. (2019). Aktive Verwaltungsschale von Industrie 4.0 Komponenten," in Automationkongress 2019, Baden-Baden.
2. Zhang, J., Ellwein, C., Heithoff, M., Michael, J., & Wortmann, A. (2025). Digital twin and the asset administration shell. Software and Systems Modeling, 24(3), 771-793.

Modeling Asset Administration Shells Demands Significant Effort

Automating their synthesis and their use in and with digital twins can help

1. **Deriving AASs.** Engineering processes and models comprise vast asset knowledge,
   - Challenge: Much needs to be found, extracted for the AAS
   - Opportunity: Derive parts of AASs from engineering data and models
2. **Combining AAS with DTs**. DT standards and AAS co-exist
   - Challenge: AAS can be models in DTs or shells of DTs or data provided to DTs
   - Opportunity: An AAS might enact different roles for different DTs; needs investigation
3. **Connect AAS with ISO DTs.** Type 3 AASs should be able to integrate with ISO DTs
   - Challenge: The standardization of DT software architectures isn't very precise
   - Opportunity: Use I4.0 language[1] for interfaces between type 3 AASs and ISO DTs
4. **Language engineering**. An AAS can link to other models
   - Challenge: This enables model-based systems engineering with AAS as center piece
   - Opportunity: Apply MBSE principles and practices, language integration, .. to AASs

1. https://www.plattform-i40.de/IP/Redaktion/DE/Downloads/Publikation/hm-2018-sprache.html

Methodical Model-Driven Operations

Machine Connectivity and Information Modeling with OPC UA

Into Rabbit Hole of Operations Technology Connectivity

And modeling is the answer again

IT level

Asset Administration Shell (AAS)
- Standardized representation of assets
- Organizes (un)structured data
- Hierarchical submodels for modular, use-case-driven data structuring
- Consistency and interoperability through a defined metamodel

DPP

OPC UA
- Standard for secure and flexible industrial data communication
- Supports client/server and publish/subscribe interaction models
- Structured data exchange across heterogeneous systems via information models

OT level

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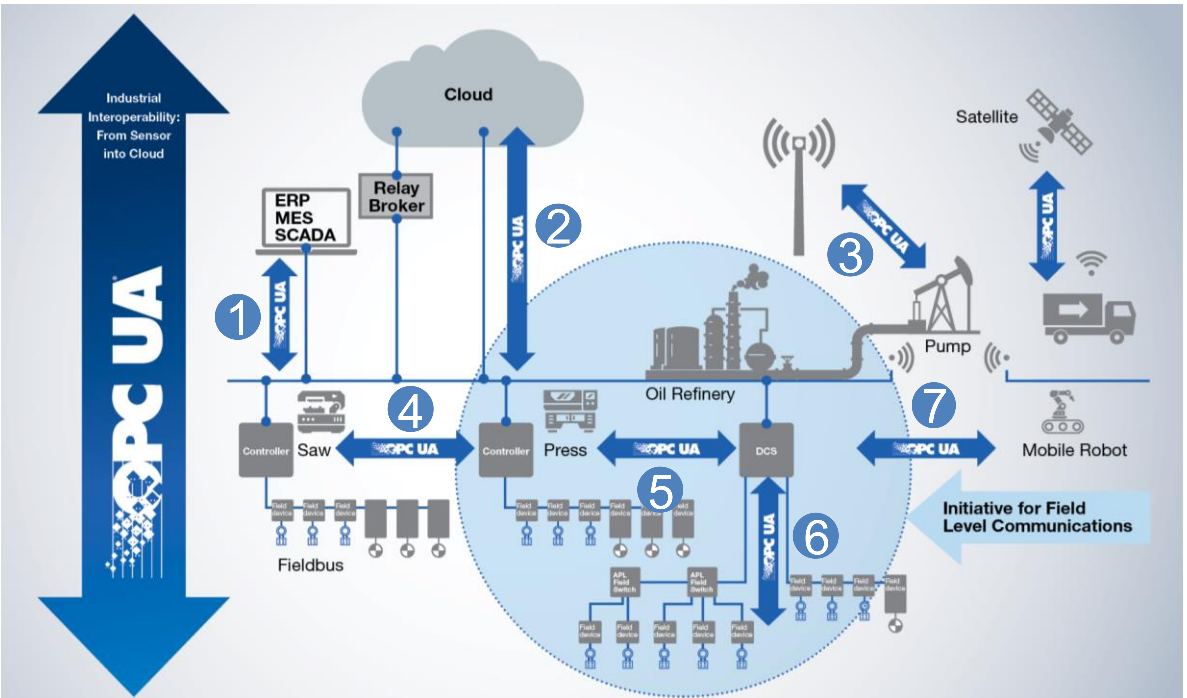
OPC Foundation Advances their Unified Architecture (UA) Successfully

1010 members incl. ABB, Amazon, Google, Honeywell, MS, SAP, Siemens, …



1. IT / OT Communication
2. Cloud Integration
3. Secure Remote Access
4. Local OT Communication
5. Controller to Controller
6. Controller to Field Device
7. Wireless Integration (5G)

The Success of Modeling with OPC UA: (1) Batteries Included

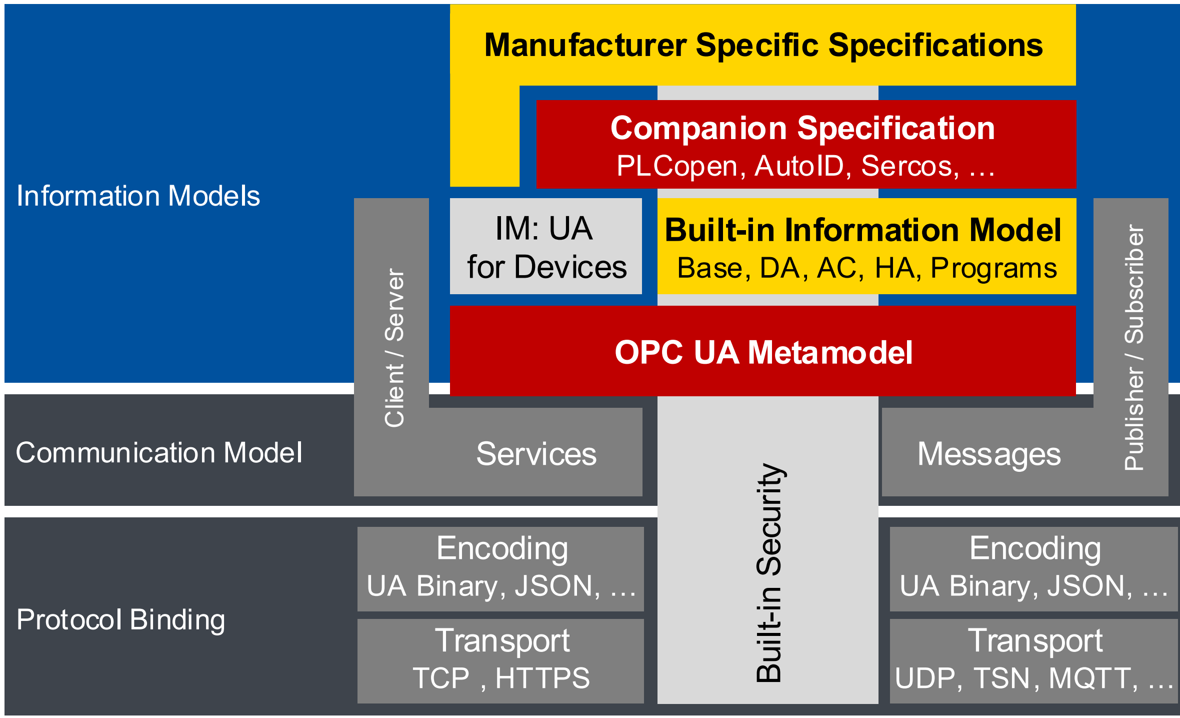
Not: "here's a nice grammar, now build the tools you need yourself"

Expected usage[1]

- production monitoring
- condition monitoring
- virtual commissioning
- remote control

Expected benefits[1]

- replace proprietary interfaces
- standardized communication
- reduce integration effort
- competitive advantages



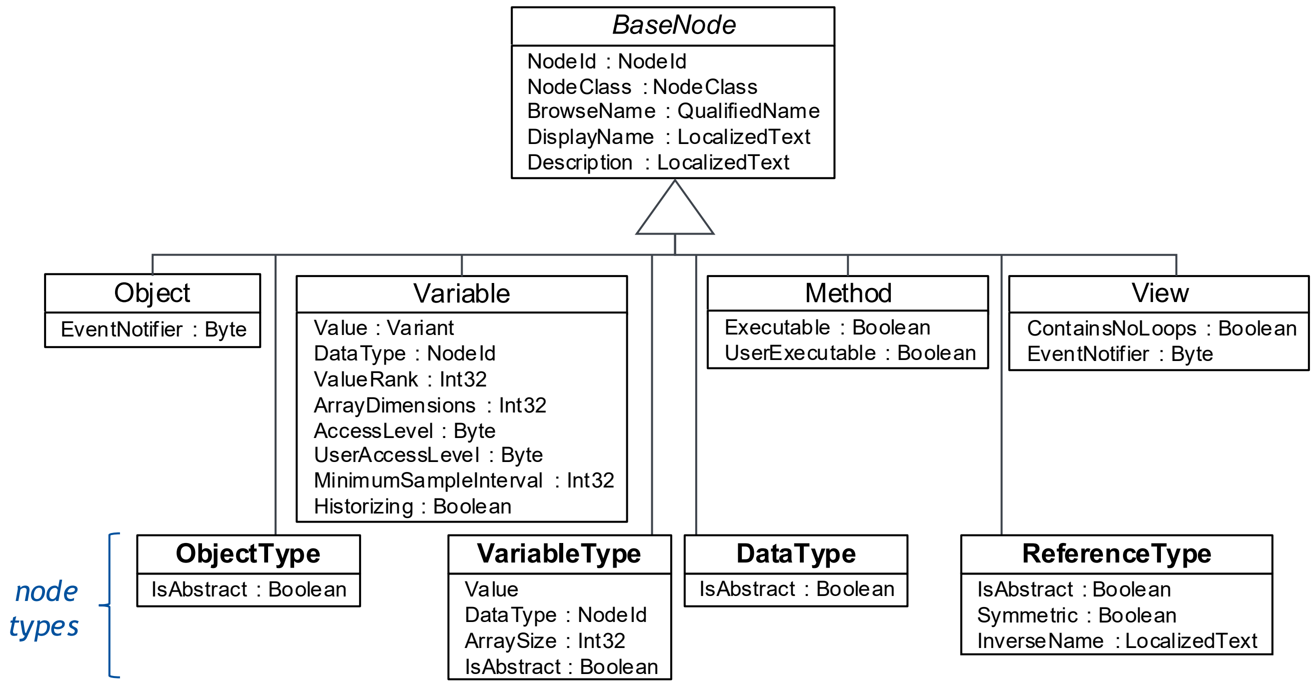
1. VDMA. Studie zur Interoperabilität im Maschinen- und Anlagenbau - Die Weltsprache der Produktion als Grundlage für Industrie 4.0

Source: Hoppe VDMA Interopreability Day 2018

The OPC UA Metamodel is Compact

And mixes type concepts with instance concepts

- Models exist in the address space of OPC UA server
- In the address space, everything is a node
- Non-extensible list of 8 node types
- Each node class has fixed attributes
- Nodes are connected by references



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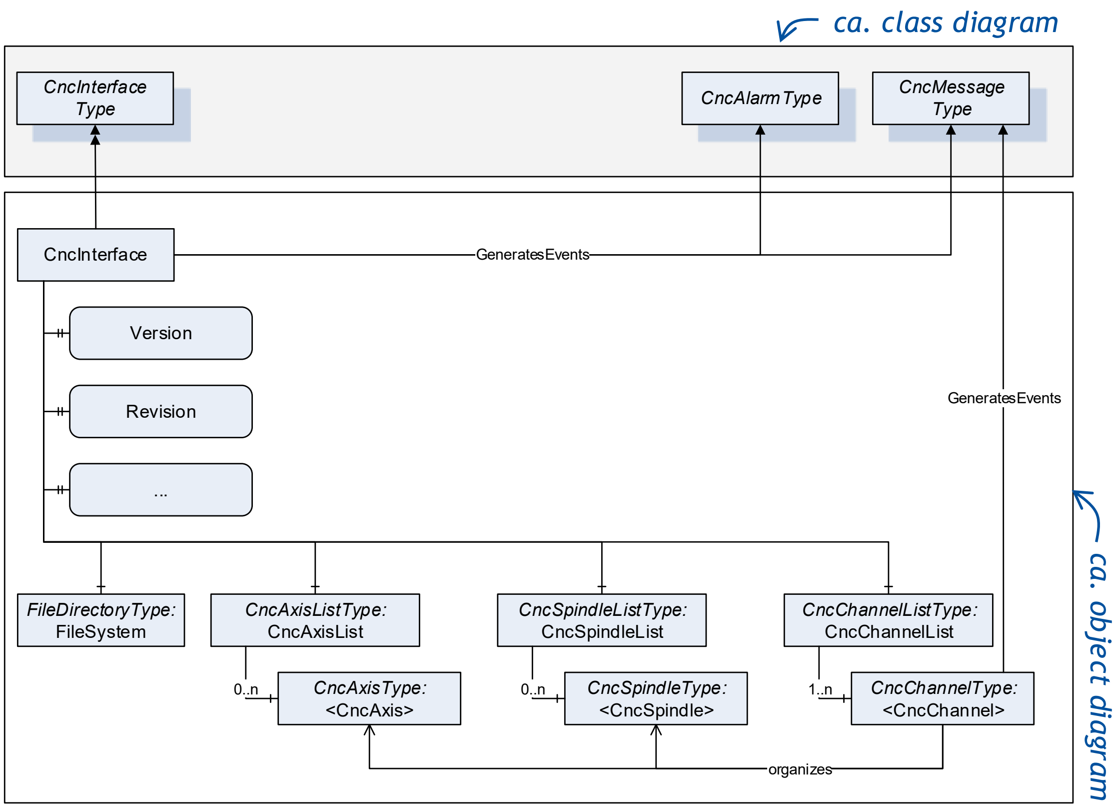
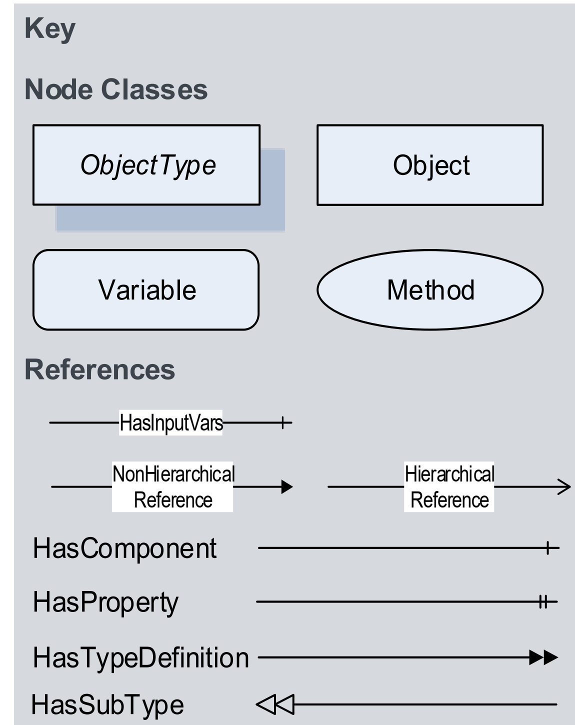
OPC UA Information Models Comprise Type and Instance Information

Consider merging class diagrams with object diagrams plus multi-level modeling





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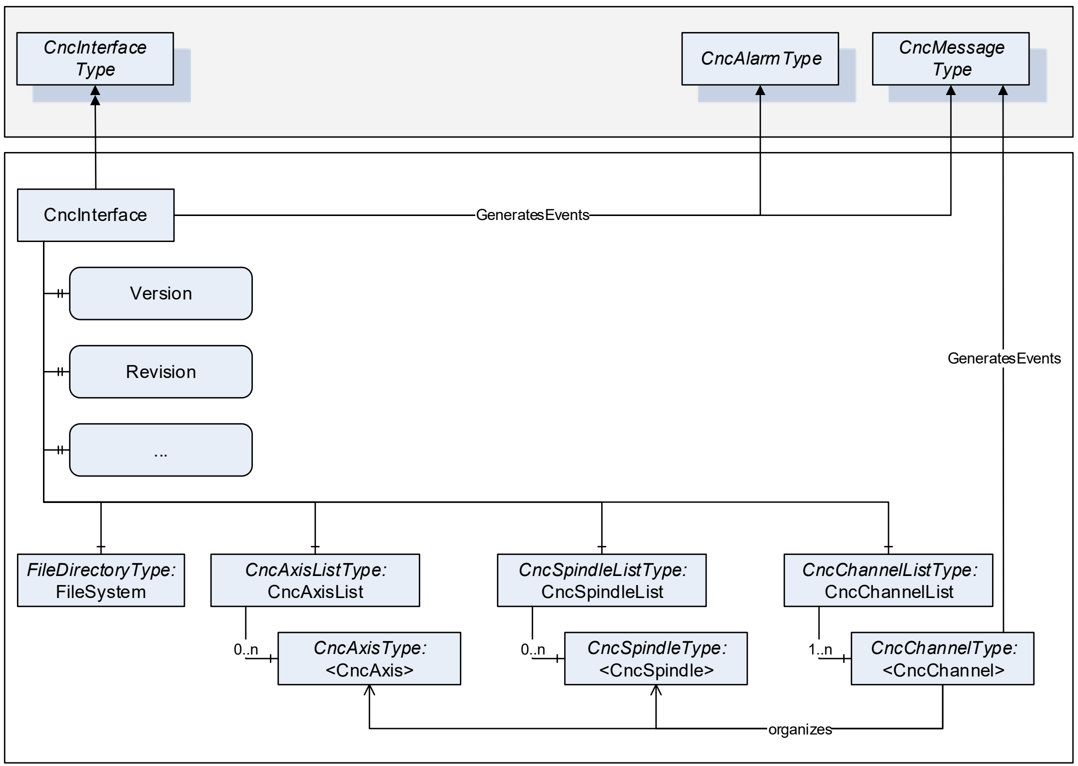
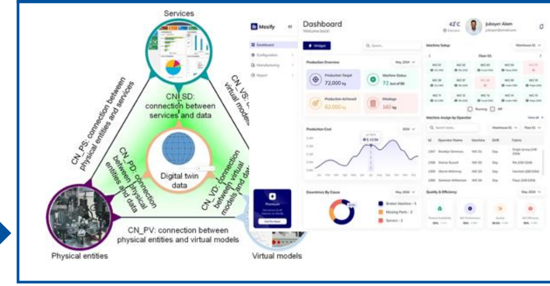
Machinery Provides Information to OPC UA Server, Server to Clients

Clients can send changes back to server and machinery

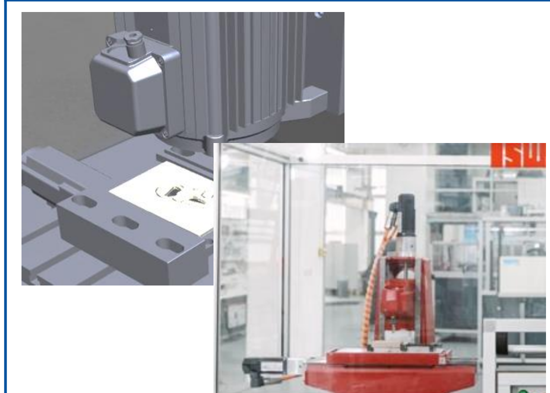
OPC UA Server



OPC UA Clients



Machinery



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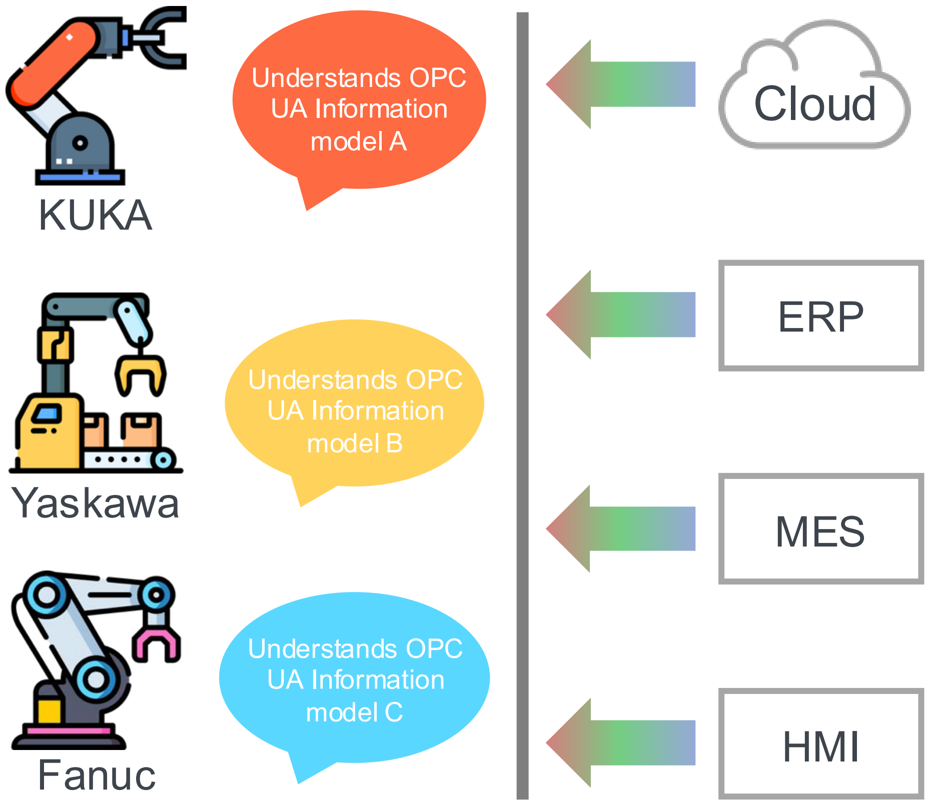
The Success of Modeling with OPC UA: (2) Lightweight Standardization

Industry has modeling working groups to devise companion specifications



- The VDMA with their more than 3000 members started a big initiative for companion specification (CS) definition
- CS are standardized OPC UA models
- Services then share the same information model
- One functionality to communicate
  - orders
  - configuration
  - controlling mechanism
- Systematic integration

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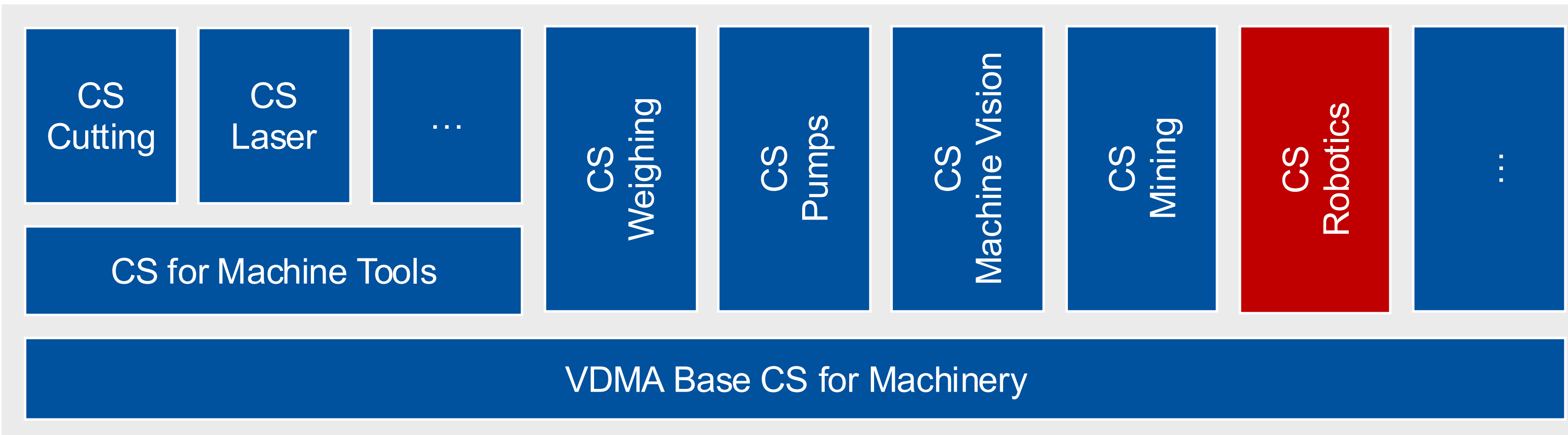
The Success of Modeling with OPC UA: (2) Lightweight Standardization

Companion specifications are standardized OPC UA models



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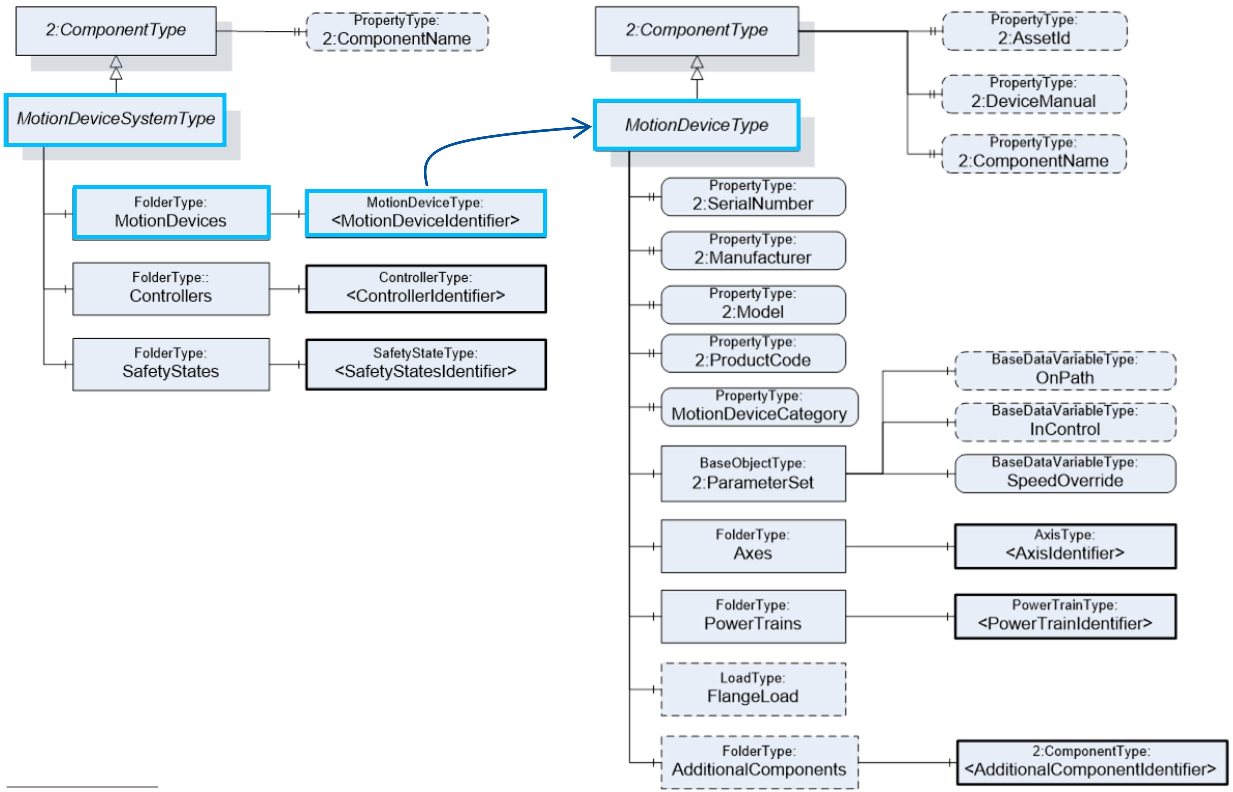
Standardization Within the Scope of the OPC Foundation

Example: OPC Robotics (OPC 40010)



- Make robot OEM transparent for IT
- Driven by ABB, FANUC, KUKA, Yaskawa, Comau, Stäubli, Siemens, Beckhoff Automation, …
- Core components
  - Motion device system (root)
  - controllers
  - axes, power train
- Use cases
  - asset management
  - condition monitoring
  - remove operation

1. https://reference.opcfoundation.org/Robotics/v100/docs/

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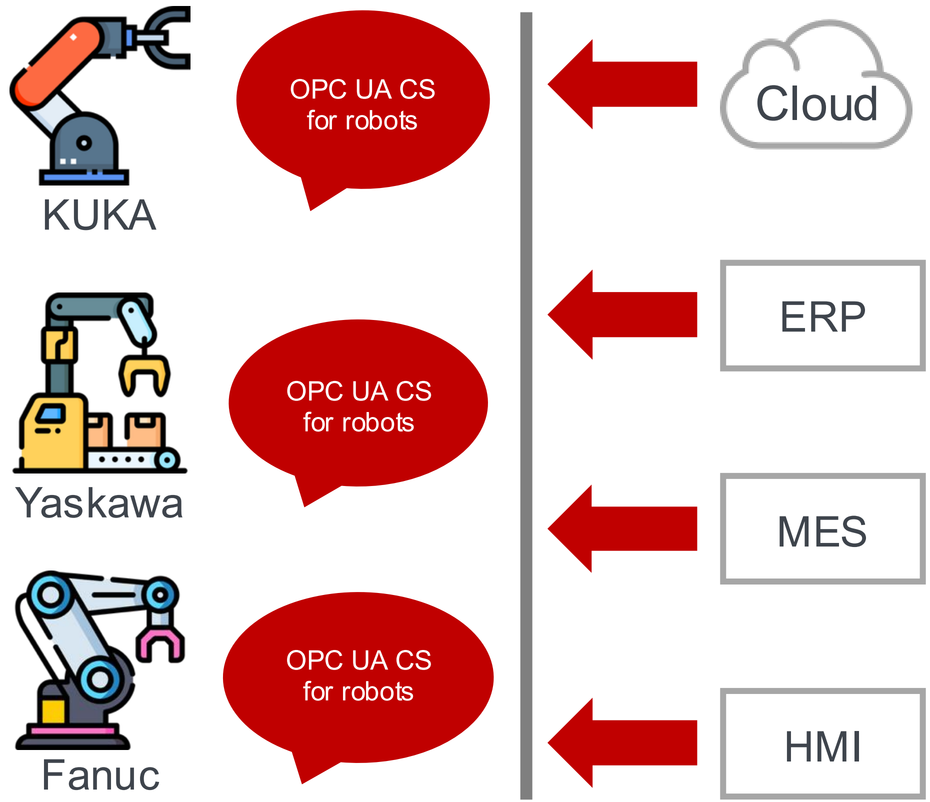
The Success of Modeling with OPC UA: (2) Lightweight Standardization

Industry has modeling working groups to devise companion specifications



- The VDMA with their more than 3000 members started a big initiative for companion specification (CS) definition
- CS are standardized OPC UA models
- Services then share the same information model
- One functionality to communicate
  - orders
  - configuration
  - controlling mechanism
- Systematic integration

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At the Core of OPC UA is Object-Oriented Information Modeling

Yet there are important use cases for which modelers should be supported

1. **Modeling support.** OPC UA often used to check for well-defined KPIs, other established use cases
   - Challenge: Computation might require data from diverse sources
   - Opportunity: Low-code fill-in-the-blank models and smart code generators
2. **Semantic matching**. To bridge terminology mismatches and gaps
   - Challenge: Specific IT (e.g., AASs) demand certain data, but provided differently by OPC UA OT
   - Opportunity: Support modeling with semantic matching (best effort) based on context[1]
3. **Automated model mapping**. Translate proprietary legacy models and data into OPC UA models
   - Challenge: Legacy systems with non-OPC UA documentation need to be integrated
   - Opportunity: Lifting documents to models, semantic matching strikes again
4. **More expressive information models.** OPC UA models are inherently object-oriented
   - Challenge: Interfaces are expressed very weakly (no invariants, pre/postconditions, protocols, …)
   - Opportunity: Adopt the rich interface specification techniques from OO modeling to OPC UA

1. Metović, A., Maisch, N., Ajdinović, S., Lechler, A., Wortmann, A., & Riedel, O. (2026). Industrial Semantics-Aware Digital Twins: A Hybrid Graph Matching Approach for Asset Administration Shells. IDETWIN 2206 (to appear)

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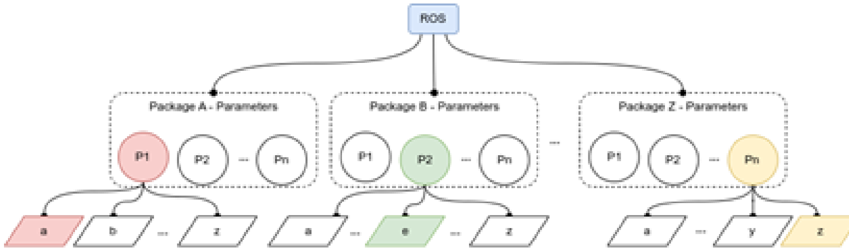
Methodical Model-Driven Operations

Software Engineering for Robotics in Production

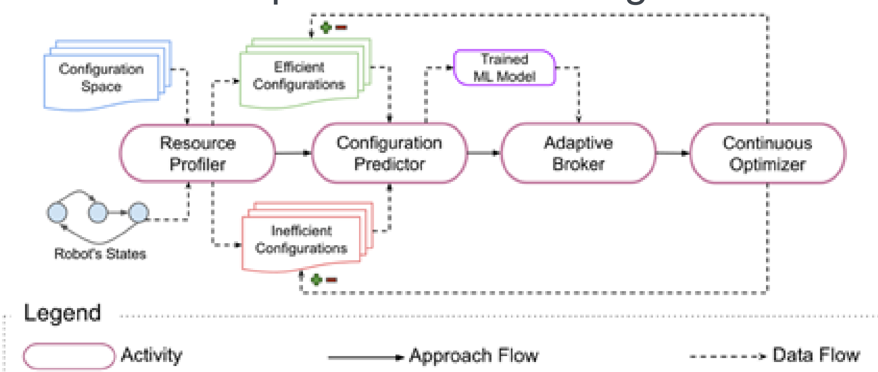
Improving Sustainability of ROS2 Applications

Trading off performance and energy efficiency at runtime

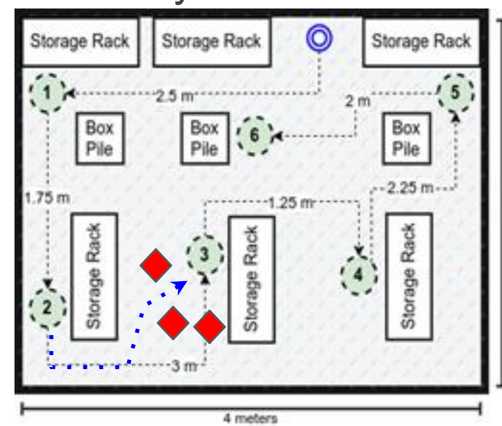
ROS applications are highly-configurable



Continuous optimization of configurations



Operate in dynamic environments



Joint work with

Michel Albonico

Visiting Researcher

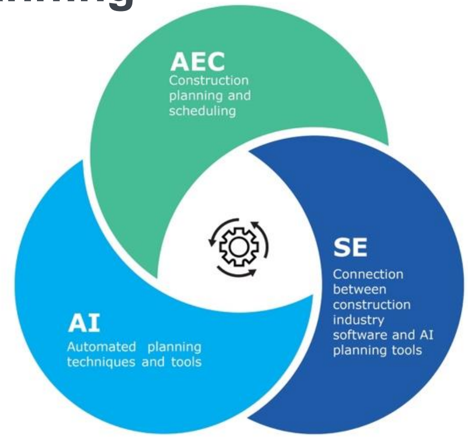
UTFPR

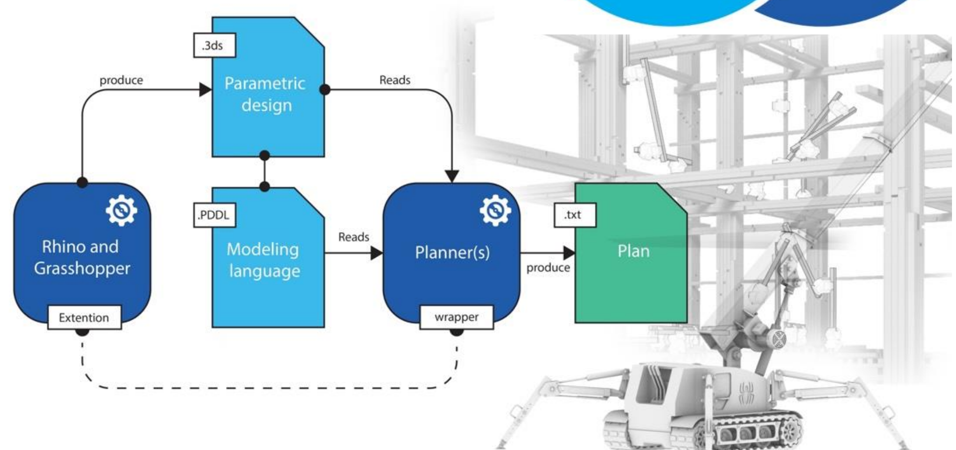
1. Albonico, M., Varela, P. J., Rohling, A. J., & Wortmann, A. (2024). Energy Efficiency of ROS Nodes in Different Languages: Publisher/Subscriber Case Studies (RoSE 24)

Domain-Specific Language for Robotic Construction Planning

Expands behavior tree scaffolds with action plans

- Robotic assembly planning is a hard planning problem[1]
- Requires in-depth expertise in construction, robotics, …
- Modeling methods[2] usable by domains experts
  that a combination of AI planners can use to derive assembly plans
- Based on domain-specific behavior trees that expand based on PDDL



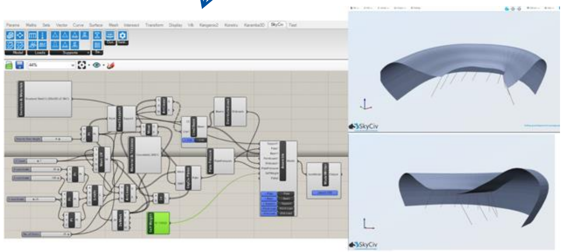


1. Sherkat, S., Garmaroodi, A. A., Wortmann, A., & Wortmann, T. (2023). Residential complex design as a Constraint Satisfaction Problem. Automation in Construction, 154, 104995.
2. S. Sherkat, L. Skoury, A. Wortmann, T. Wortmann (2023). Artificial Intelligence Automated Task Planning for Fabrication. Advances in Architectural Geometry 2023, 249.
3. Sherkat, S., Wortmann, T., & Wortmann, A. (2025). Two Decades of Automated AI Planning Methods in Construction and Fabrication: a Systematic Review. ACM CSUR.

Roboticists often are Domain Experts and Benefit from Software Support

In modeling tools, robot configuration, migration, and much more

grasshopper in rhino3d



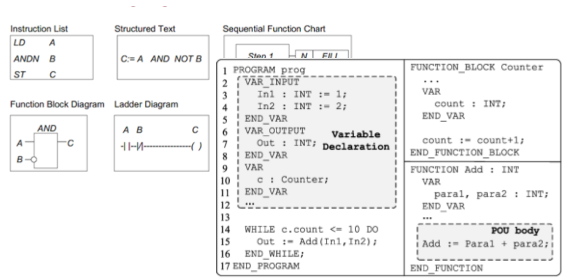
1. **Domain integration.** Architecture has rich tools and methods
   - Challenge: Solutions need integration with BIM, BHoM, Rhino, …
   - Opportunity: Contribute to more sustainable construction with SE
2. **Optimize all the configurations**. SE can support this many domains
   - Challenge: Adoption to other ROS packages, different CPSs, ..
   - Opportunity: Many interesting experiments to make the world a bit better
3. **ROS is legacy.** ROS1 is legacy and ROS2 needs different kinds of artifacts[1]
   - Challenge: Automated support of migration from ROS1 to ROS2
   - Opportunity: Lift ROS code to models[2], optimize, migrate, generate new artifacts
4. **Tailor DSLs to robotics subdomains**. Many different subdomains with specific application contexts
   - Challenge: Existing modeling solutions for robotics (e.g., behavior trees) too generic
   - Opportunity: Leverage language engineering for truly domain-specific solutions

1. Hammoudeh García, N., Chen, Y., Lieb, D., & Wortmann, A. (2025). Evaluation of a model-driven approach for the integration of robot operating system-based complex robot systems. International Journal of Advanced Robotic Systems, 22(4), 17298806251363648.
2. Garcia, N. H., & Wortmann, A. (May). Survey on robotic systems integration. In 2023 IEEE/ACM 5th International Workshop on Robotics Software Engineering (RoSE). IEEE.

Generative AI for Software Engineering in Production

Fundamentals

Programmable Logic Controller (PLC), IEC 61131, Virtual Commissioning (VC)



Programmable Logic Controller

- Industrial computer for machine and process control
- Real-time, deterministic operation
- Interfaces with sensors & actuators
- Widely used in factories and plants
- Producers: Siemens, Beckhoff, Wago etc.

IEC 61131-3

- International PLC programming standard
- 5 languages: LD, FBD, ST, SFC, IL
- Structured Text (ST) basic language similar to Pascal
- Vendor-independent framework
- Tools: TwinCat, TIA, Codesys etc.

Virtual Commissioning

- Test control logic in a virtual environment
- Uses models of machines
- Finds errors before physical startup
- Reduces time & cost of commissioning
- Tools: ISG Virtuos, Omniverse etc.

Language Models for Generating Structured Text (IEC 61131-3)

Preliminary results

FD: Number of failed runs. FT: Successful functional tests. ST: Successful safety tests

Modell	FD	FT	ST	LOC	d.ZZ	max.ZZ	min.ZZ	min.Jitter	max.Jitter	CQ	Doc.	Begründ.
chatGPT	1	100%	67%	25	7	140	3	-244	1951	4	4	4
Claude	2	100%	67%	29	9	169	2	-3744	4522	4	2	4
Gemini	1	100%	67%	26	8	69	3	-1926	3662	4	3	4
LLama	0	100%	100%	36	8	1096	2	-2188	4602	5	4	4
Mistral	1	100%	100%	29	9	204	2	-2990	3988	5	4	4

Results of creating math functions with direct prompting

Modell	FD	FT	ST	LOC	d.ZZ	max.ZZ	min.ZZ	min.Jitter	max.Jitter	CQ	Doc.	Begründ.
chatGPT	1	100%	83%	61	8	111	4	-3430	4657	4.5	4	4
Claude	0	100%	100%	97	11	336	3	-1100	3217	5	4	3
Gemini	3	-	-	-	-	-	-	-	-	-	-	-
LLama	0	100%	100%	30	8	109	2	-1451	4292	5	4	4
Mistral	3	-	-	-	-	-	-	-	-	-	-	-

Results of creating math functions with prompt engineering

Modell	FD	FT	ST	LOC	d.ZZ	max.ZZ	min.ZZ	min.Jitter	max.Jitter	CQ	Doc.	Begründ.
chatGPT	1	100%	100%	24	8	115	3	-1292	2887	5	4	4
Mistral	3	-	-	-	-	-	-	-	-	-	-	-

Results of creating math functions with fine-tuning

Modell	FD	FT	ST	LOC	d.ZZ	max.ZZ	min.ZZ	min.Jitter	max.Jitter	CQ	Doc.	Begründ.
chatGPT	1	100%	83%	28	8	113	2	-1299	3318	4.5	3.5	5
Claude	2	100%	67%	29	8	338	3	-2841	4916	4	4	5
Gemini	1	100%	67%	26	9	172	52	-3891	4297	4	4	5
Mistral	3	-	-	-	-	-	-	-	-	-	-	-

Results o

Modell	FD	FT	ST	LOC	d.ZZ	max.ZZ	min.ZZ	min.Jitter	max.Jitter	CQ	Doc.	Begründ.
chatGPT	3	-	-	-	-	-	-	-	-	-	-	-
Claude	3	-	-	-	-	-	-	-	-	-	-	-
Gemini	3	-	-	-	-	-	-	-	-	-	-	-
LLama	3	-	-	-	-	-	-	-	-	-	-	-
Mistral	3	-	-	-	-	-	-	-	-	-	-	-

Results of creating a motor controller with direct prompting

Modell	FD	FT	ST	LOC	d.ZZ	max.ZZ	min.ZZ	min.Jitter	max.Jitter	CQ	Doc.	Begründ.
chatGPT	2	33%	75%	54	8	102	2	-571	2283	4	4	3
Claude	3	-	-	-	-	-	-	-	-	-	-	-
Gemini	3	-	-	-	-	-	-	-	-	-	-	-
LLama	0	0%	60%	57	7	60	2	-1750	3802	4	4	4
Mistral	3	-	-	-	-	-	-	-	-	-	-	-

Results of creating a motor controller with prompt engineering

Modell	FD	FT	ST	LOC	d.ZZ	max.ZZ	min.ZZ	min.Jitter	max.Jitter	CQ	Doc.	Begründ.
chatGPT	3	-	-	-	-	-	-	-	-	-	-	-
Mistral	3	-	-	-	-	-	-	-	-	-	-	-

Results of creating a motor controller with fine-tuning

Modell	FD	FT	ST	LOC	d.ZZ	max.ZZ	min.ZZ	min.Jitter	max.Jitter	CQ	Doc.	Begründ.
chatGPT	3	-	-	-	-	-	-	-	-	-	-	-
Claude	3	-	-	-	-	-	-	-	-	-	-	-
Gemini	3	-	-	-	-	-	-	-	-	-	-	-
Mistral	3	-	-	-	-	-	-	-	-	-	-	-

- Using more powerful LLMs does not improve performance
- Simply using methods from AI-based SE won’t work

1. Tran, K., Zhang, J., Pfeiffer, J., Wortmann, A., & Wiesmayr, B. (2024). Generating plc code with universal large language models (ETFA 24)

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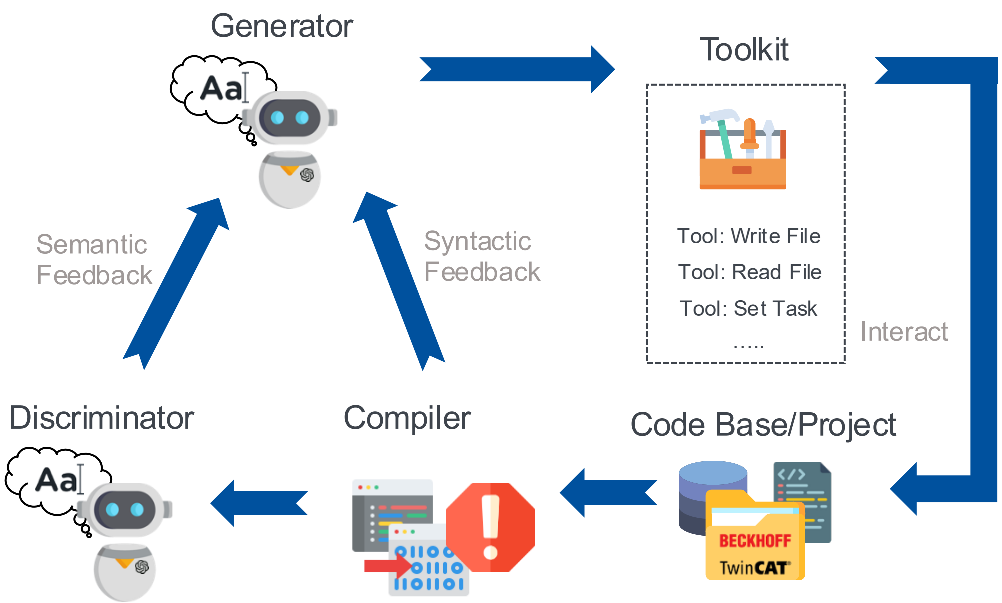
Initial Agent-Based Architecture for PLC Generation

Multiple agents in TwinCat with self-reflection



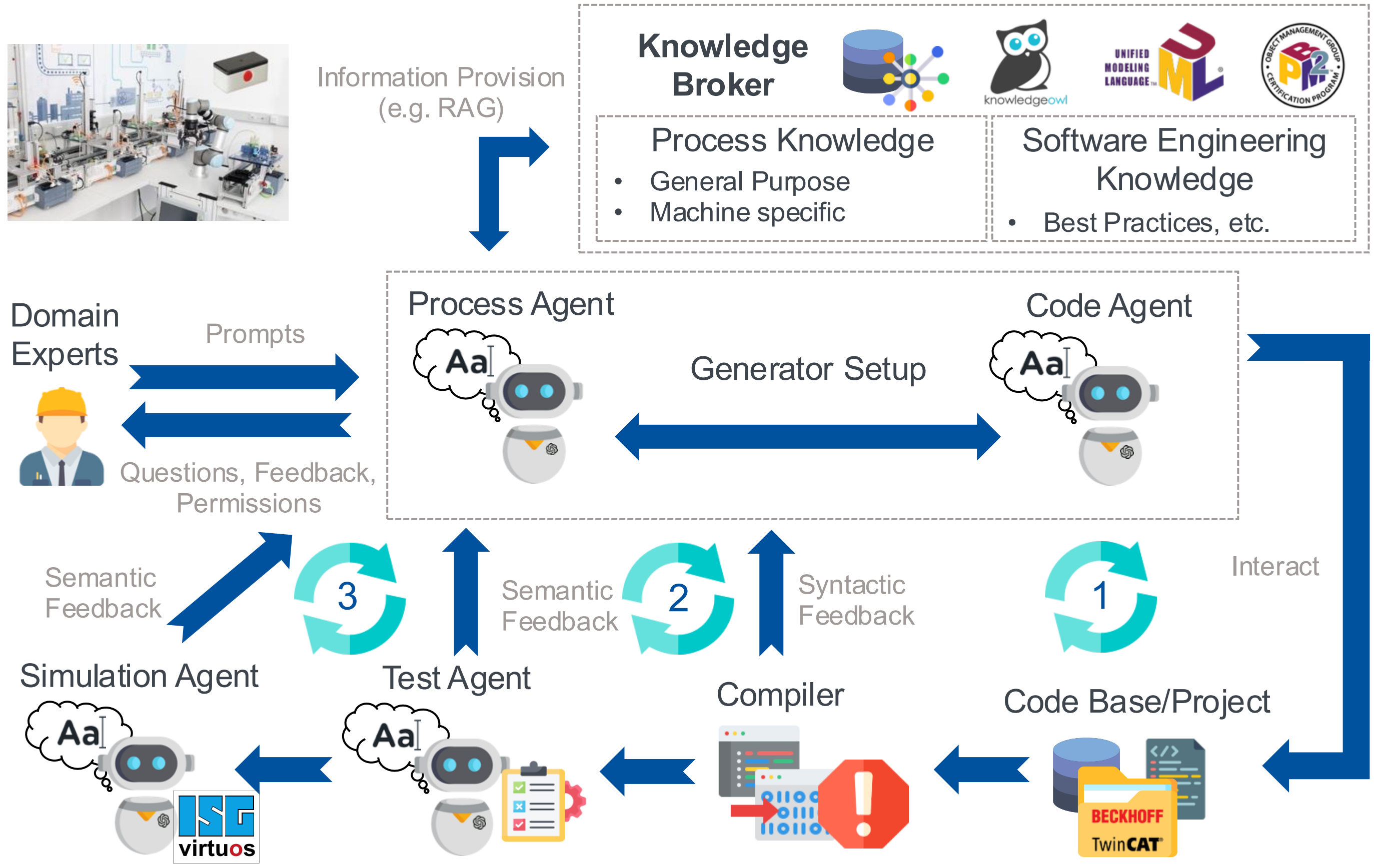
1: Benchmark Dataset for evaluating PLC Code Generation

Kategorie	Titel	Schwierigkeit	pre sem: Anzahl Compilerschleifen	pre sem: Kompilierbar?	pre sem: Semantische Bewertung	post sem: Anzahl Compilerschleifen	post sem: Kompilierbar?	post sem: Semantische Bewertung
Zyklische Standardaufgaben	Stoppuhr	1	0	1	3	1	1	10
			0	1	2	0	1	10
			0	1	4	0	1	8
	PID-Regler	3	0	1	9	0	1	9
			1	1	9	3	1	6
			0	1	10	0	1	10
	Kalman-Filter	5	0	1	3	1	1	5
			3	0	5	0	1	8
			3	0	6	3	0	7
I/O-Standardaufgaben	Linear-Interpolation	1	3	0	3	0	1	8
			1	1	9	0	1	9
			1	1	10	0	1	10
	Primzahl-Checker	2	1	1	2	1	1	7
			3	0	10	3	0	8
			3	1	5	3	1	10
	Quicksort	3	3	0	10	3	0	9
			2	1	4	1	1	7
			1	1	3	3	1	4
	Matrixmultiplikation	3	0	1	10	0	1	10
			3	0	10	1	1	10
			1	1	10	0	1	10
	Eigenwerte	4	3	0	6	0	1	4
			1	1	2	2	1	4
			1	1	3	2	1	3
	Spline-Interpolation	5	1	1	3	2	1	3
			3	0	4	0	1	10
			1	1	3	3	1	3
	Fast-Fourier	5	3	0	2	3	0	2
			1	1	4	3	1	5
			3	0	4	3	0	6
S-Aufgaben	Förderbandsteuerung	2	0	1	9	0	1	10
			0	1	7	0	1	7
			0	1	8	0	1	7
	Kaffeemaschine	1	0	1	4	0	1	5
			0	1	7	0	1	7
			3	0	3	0	1	5
	Autowaschanlage	1	0	1	7	0	1	10
			0	1	8	0	1	10
			0	1	9	0	1	7
	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	4
			[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	6
			[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	6
	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	9
			[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	3
			0	1	3	0	1	9

Base architecture significantly improves PLC code quality with syntactic and semantic feedback

Final Agent-Based Architecture for PLC Generation

Final_rev2_comments5_v2_final?



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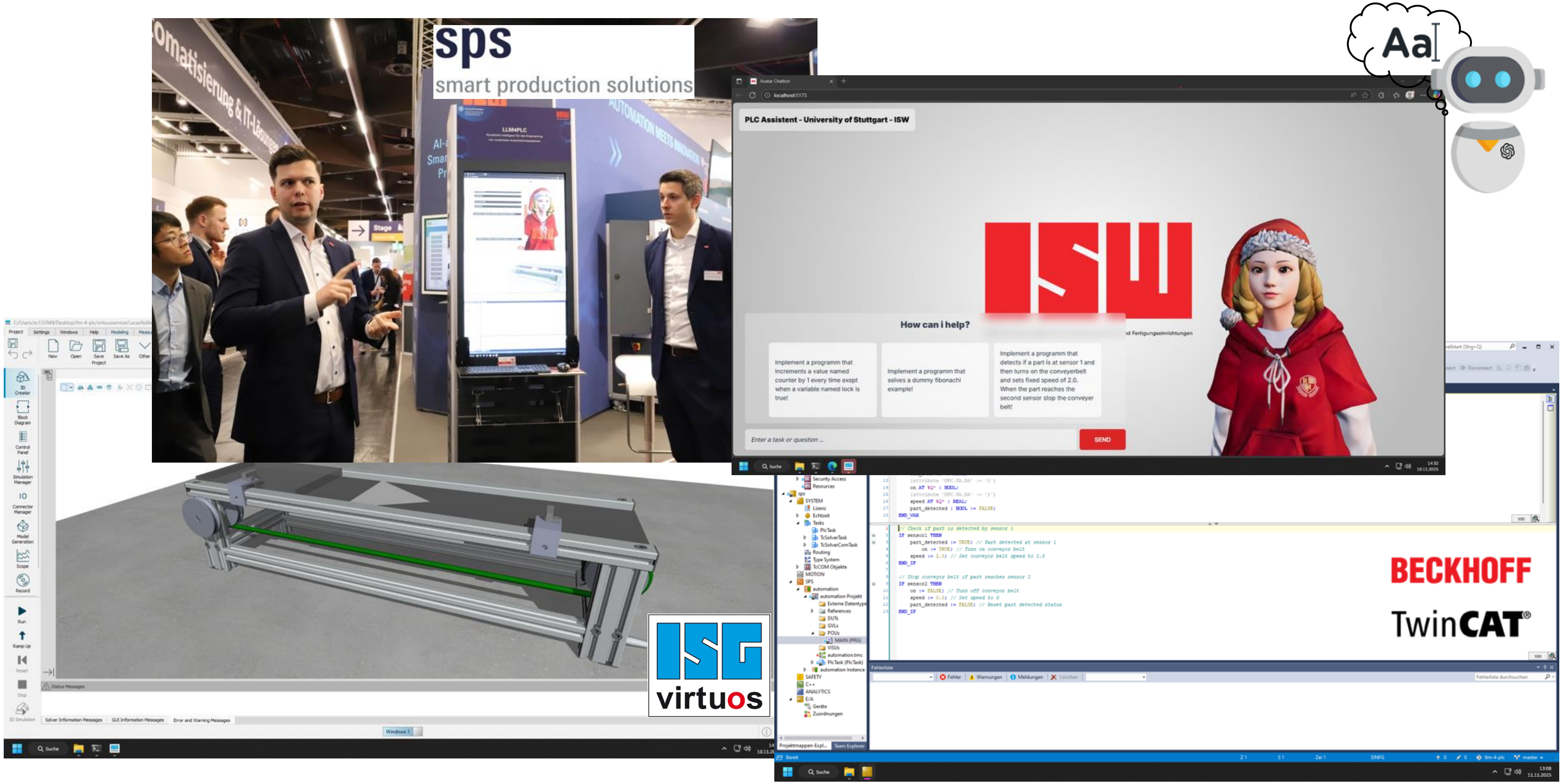
Do Good Things and Speak About it

Prototype agent-based industry 4.0 programming presented at SPS fair 2025



Thank you for your Attention

You‘re invited

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