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

Software-Defined Manufacturing

Models and digital twins for the VUCA world

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

Presentation Slides

No need to take photos

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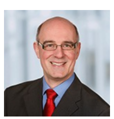
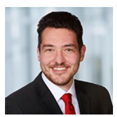


Michael Seyfarth

Research Areas

Software and Engineering Methods



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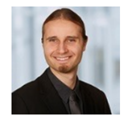
Real-Time Communication and Control Hardware



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David Dietrich
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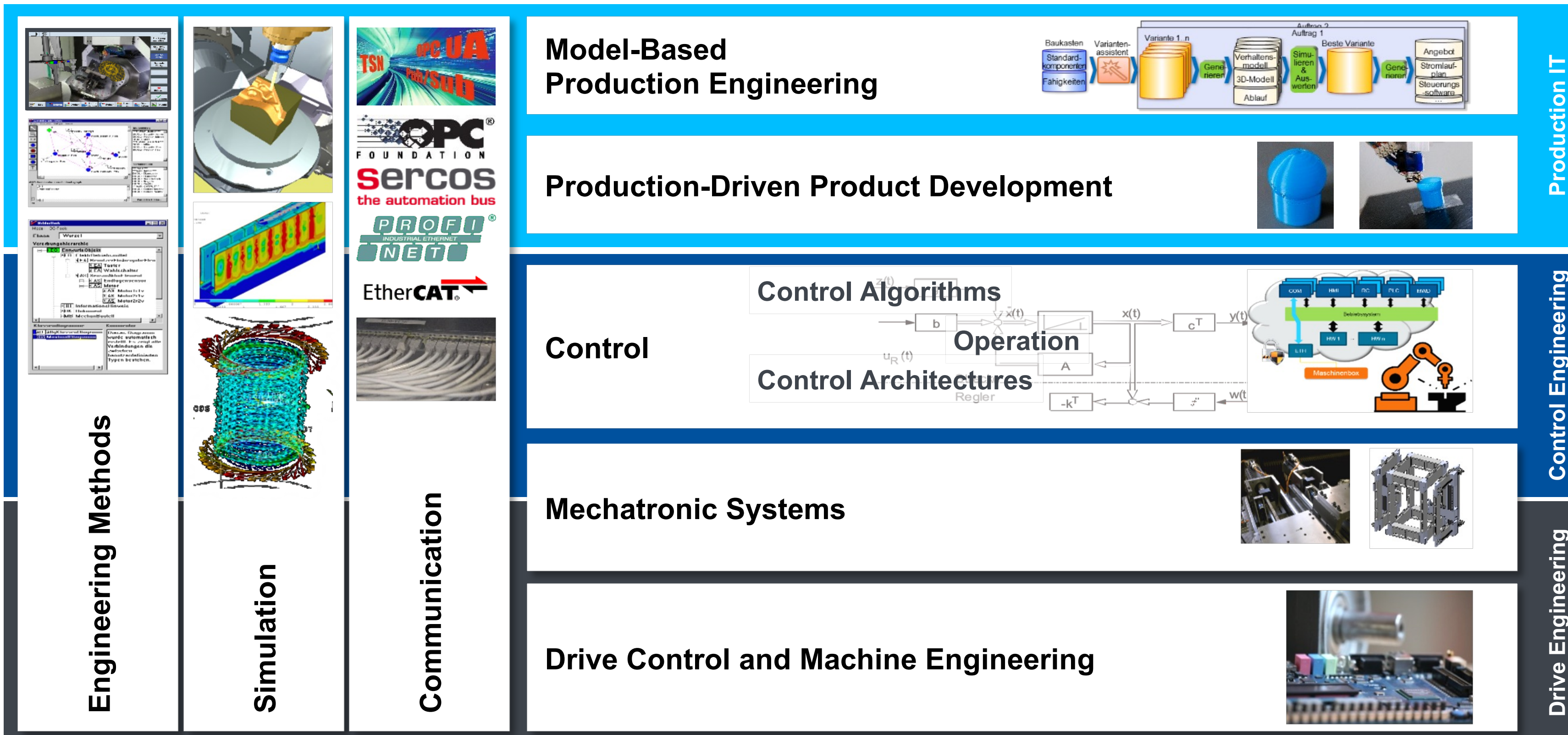
Core Competencies of the ISW



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About the Presenter

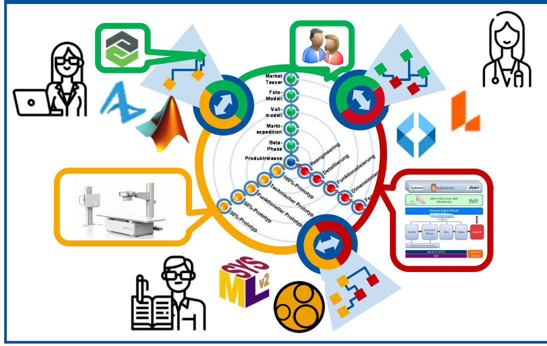
Over a decade of research in model-driven engineering

- Jun.-Prof. Dr. rer. nat. habil. for model-driven development at ISW of University of Stuttgart
- Akad. Oberrat & Venia Legendi at SE of RWTH Aachen University
- Deputy coordinator in Internet of Production excellence cluster
- European Association for Programming Languages and Systems
- Main research interests
  - Model-driven engineering
  - Software language engineering
  - Software architectures
  - Industry 4.0
- 120+ publications (h: 29, i10: 71)
- 8 lectures, 13 seminars/project classes, 70+ theses
- Organization of 20+ international conferences and workshops

Building Better Software more Efficiently

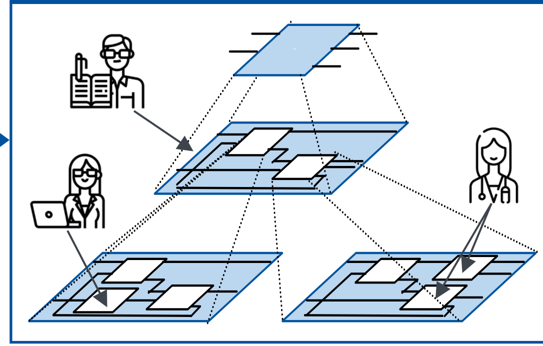
Through better abstraction and automation

Systematic Software Language Engineering



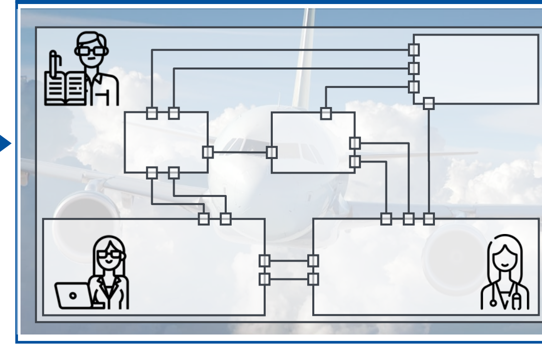
- Component-based language engineering
- Systematic reuse via language product lines
- Improves modeling precision and domain expert integration

Functional Architecture Modeling Methods



- Model-driven, formal C&C architectures
- Semantically-grounded structure and behavior
- Continuous architecting and semantics-aware automation

Methodical Model-Driven Operations

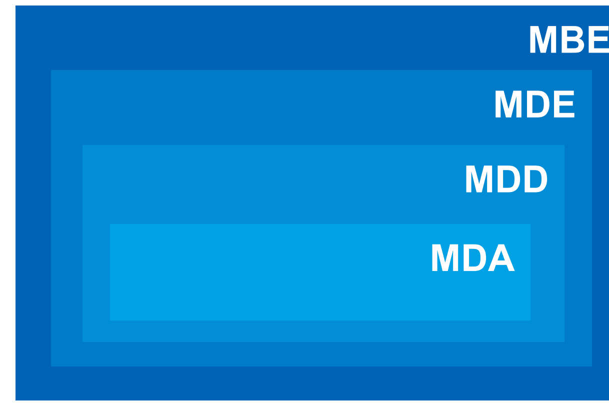


- Digital twins for monitoring, control, optimization
- Integrate explicit models of domain expertise
- Better understanding and more efficient use of CPS

Software-Defined Manufacturing

Is Model-Driven Development in Production

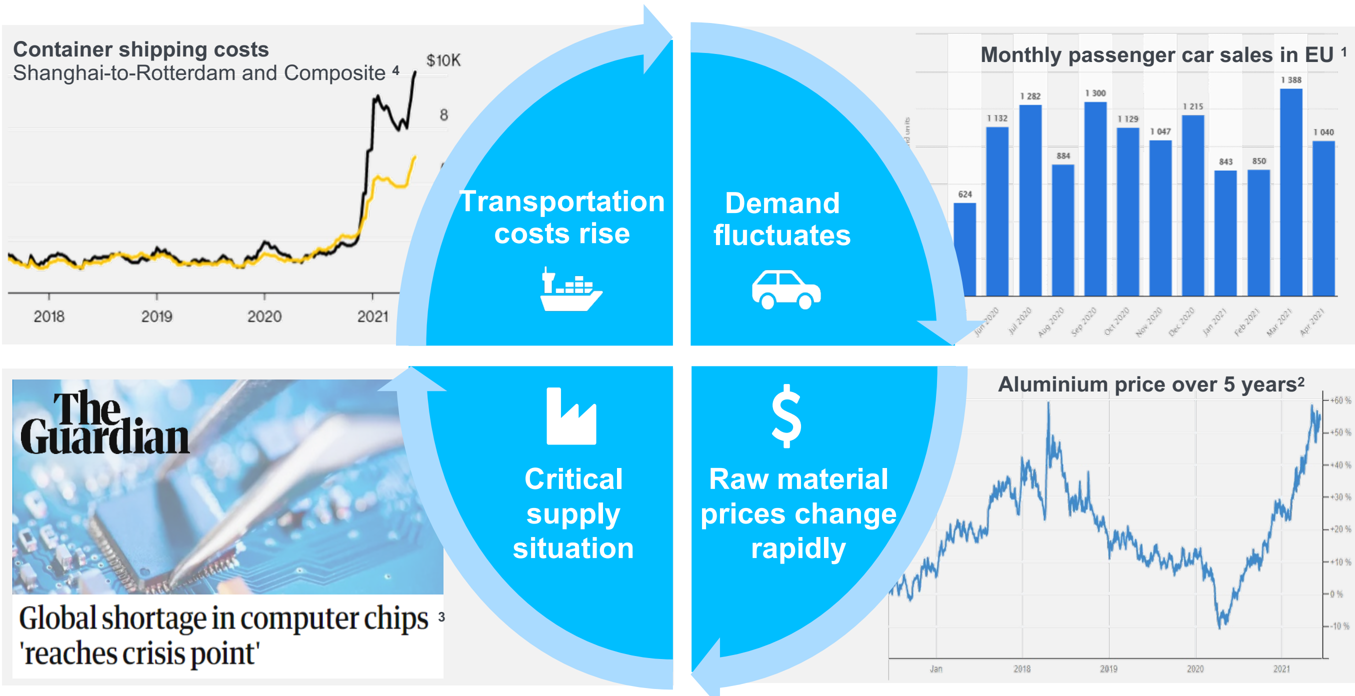
1. **Motivation for Software-Defined Manufacturing**
2. **Vision and Goals of Software-Defined Manufacturing**
3. **Model-Driven Development (MDD), Digital Twins**
4. **Asset Administration Shell as Basis for SDM**
5. **First steps towards realizing SDM in the Stuttgarter Maschinenfabrik**



Source: https://modeling-languages.com/clarifying-concepts-mbe-vs-mde-vs-mdd-vs-mda/

Welcome to the VUCA World

Volatile markets, **U**ncertain operations, **C**omplex processes, **A**mbiguous RQs



External Change Drivers

Internal Change Drivers

- Increase utilization rate of plants
- New technologies available
- Capital commitments
- ...

Source: [1 statista_A 2022; 2 statista_B 2022; 3 guardian 2021; 4 e-ports 2021]

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Volatility and Uncertainty: The New Normal?

Hypotheses on the factory of the future 2030

- Manufacturers will often change the operating point of production equipment due to volatile requirements.
- Reconfigurability of machines and processes vital to react quickly to changing requirements.
- Enablers for major changes: adjust functionality to requirements, degree of change automation.
- Rigid line structures become functional units of dynamically linked value chains linked to product development.
- Competitive advantages in the VUCA world
  - Flexible adaptation to change
  - Easy to implement change
  - Short time-to-market

→ Complex systems
→ Short cycle times
→ High throughput

High Performance Automation

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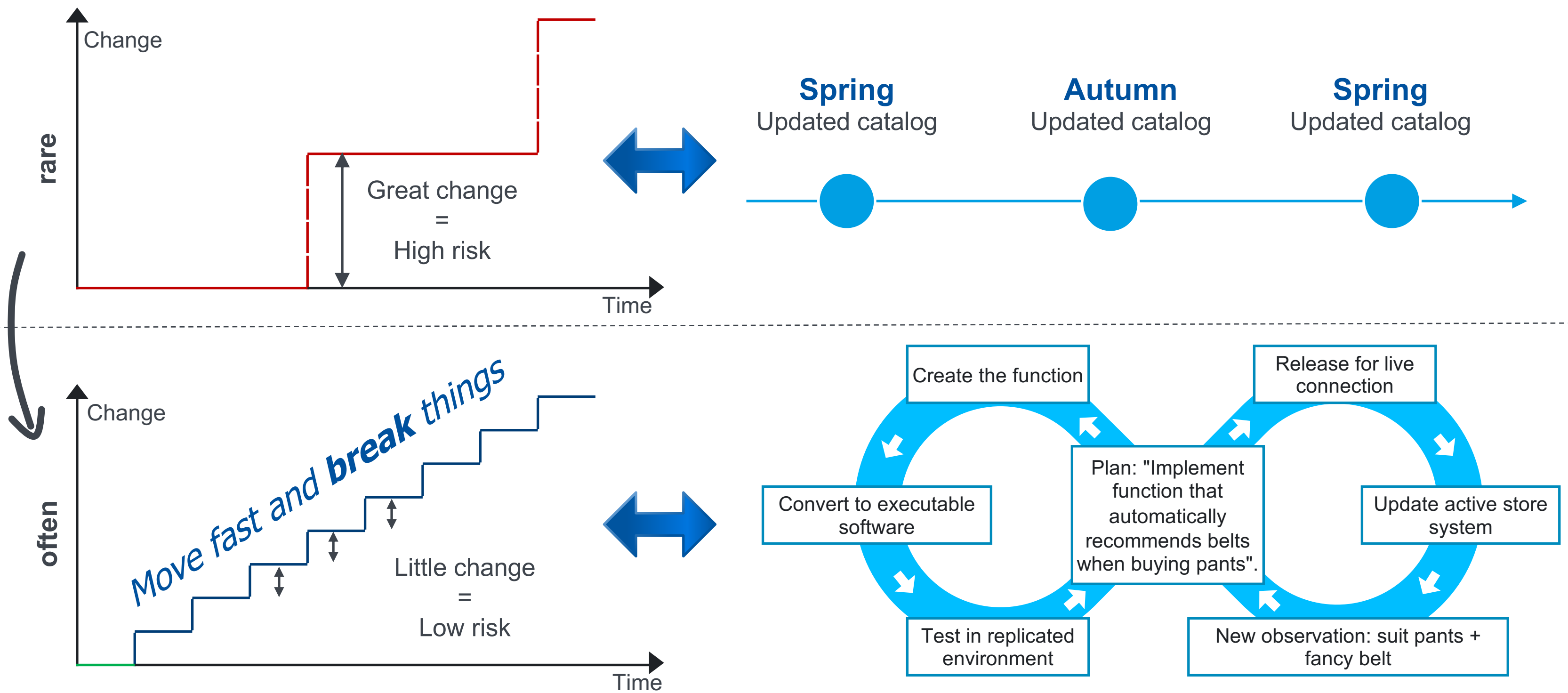
The FAANG World has Lead a Methodological Upheaval

From rare to frequent and informed change

*Facebook (Meta), Amazon, Apple, Netflix, Google (Alphabet)



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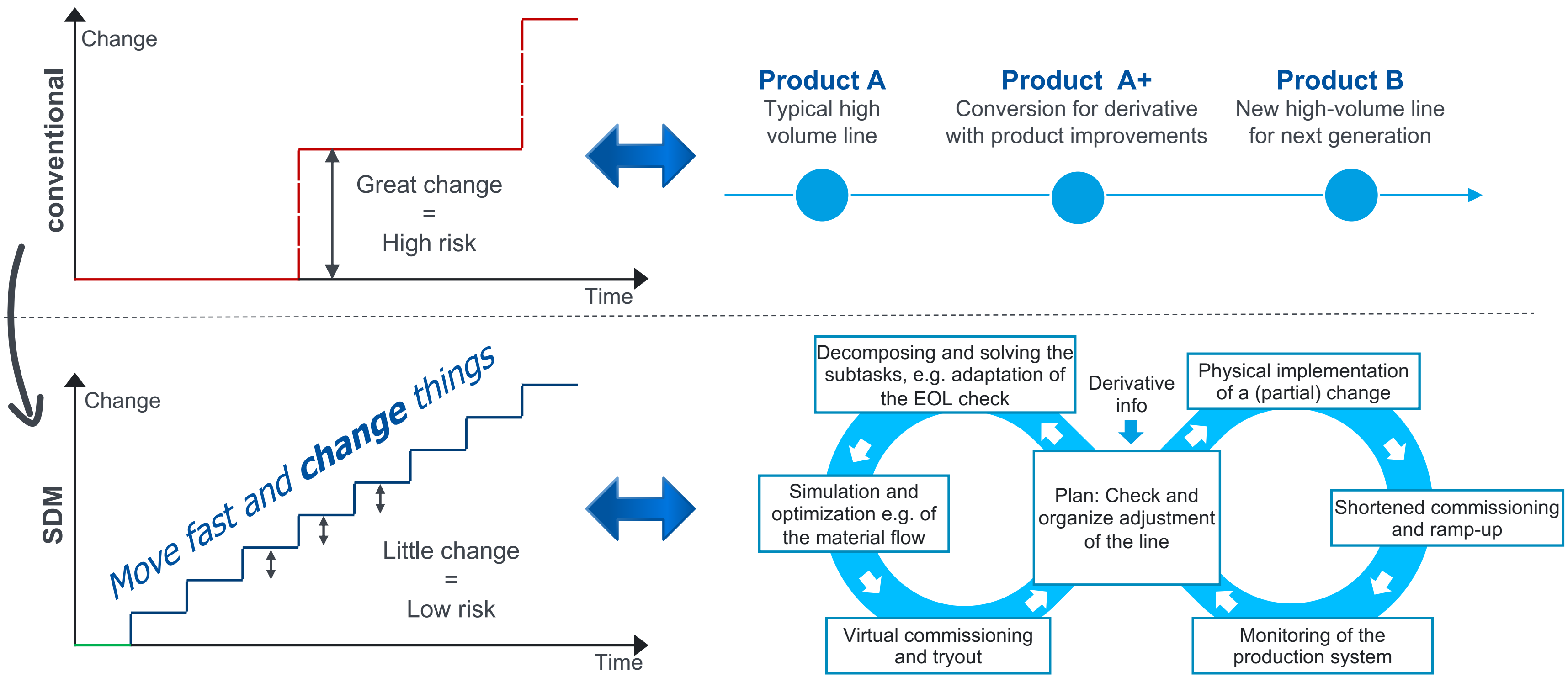
Industrial Production can Learn From This

This is the goal of software-defined manufacturing



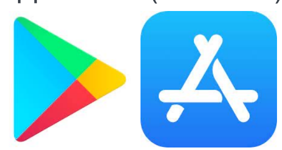
We have Experienced this Transition Already in Person

In household appliances, cars, mobile phones, …

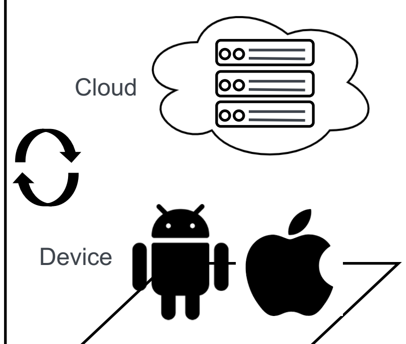
State-of-the-Past

State-of-Practice

Application (Software)



Computing Platform



Computing Hardware

Modifiable Functions

...

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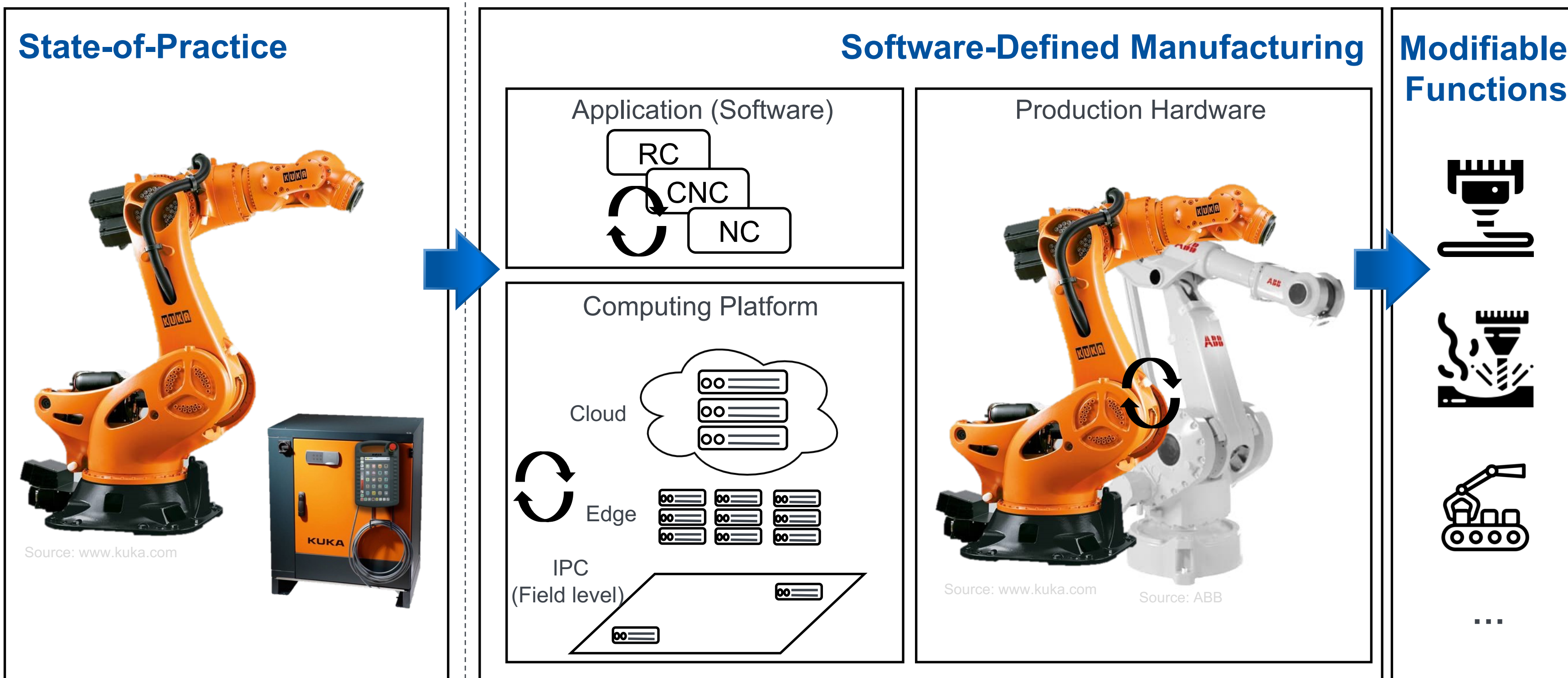
Software-Defined Manufacturing

State-of-the-art and the vision of SDM in detail



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With Software-Defined Manufacturing

Thrive in the VUCA world by decoupling production hardware from software

- Make knowledge about products, processes, resources explicit, machine-processable
- Automate flexible production with less effort
- Decentralize monoliths
- Separate concerns on all production levels and for the entire life cycle
- Manage the complexity of planning and operating production through software
  - Digtialization
  - Abstraction
  - Automation

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Software is Eating the World

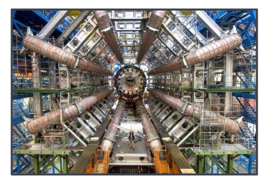
And manufacturing is next on the menu

- Society thrives on cyber-physical systems
  - Communication, energy, home automation, manufacturing, medicine, transportation, …
- Software complexity grows in magnitudes
  - Distributed, self-adaptive, intelligent, …
- Added-value mainly software
- Conceptual gap: problem vs. solution domains
- Model-driven development can[1-3]
  - Overcompensate the growth of complexity
  - Reduce the conceptual gap

Chevy Volt (10 Mio. LoC)

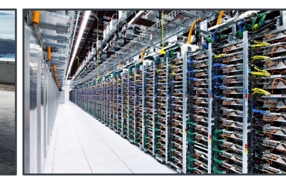
Android OS (12 Mio. LoC)

Boeing 787 (14 Mio. LoC)



LHC CERN (50 Mio. LoC)

High-Value Car (100 Mio. LoC)

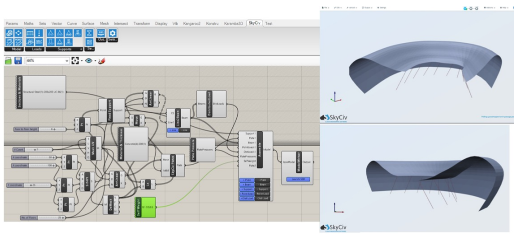


Google Services (2 Bio. LoC)

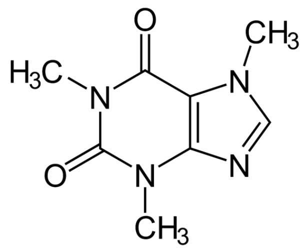
1. Wang, Y., Feng, Y., et al. (2021) The necessity of low-code engineering for industrial software development: A case study and reflections. In ISSREW, IEEE.
2. Neumann, E. M., Vogel-Heuser, et al. (2022). Introduction of an Assistance System to Support Domain Experts in Programming Low-code to Leverage Industry 5.0. IEEE RAL.
3. Tolvanen, J.-P. (2022). Measuring Productivity from Model-Based Development A Tale of Two Companies.

Models are Everywhere and Often Used As Blueprints

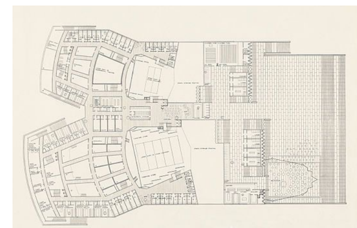
But only few disciplines can automatically translate blueprints into products



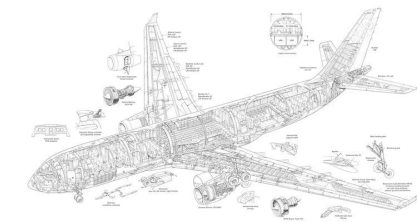
Architecture



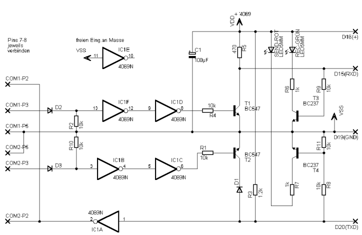
Chemistry



Civil Engineering

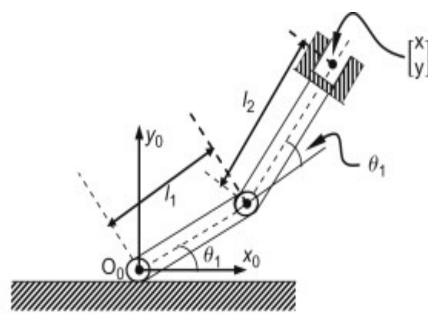


Construction

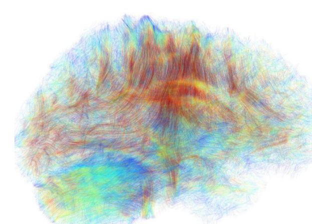


Electronics

Geology



Mechanical Engineering



Medicine

Safety

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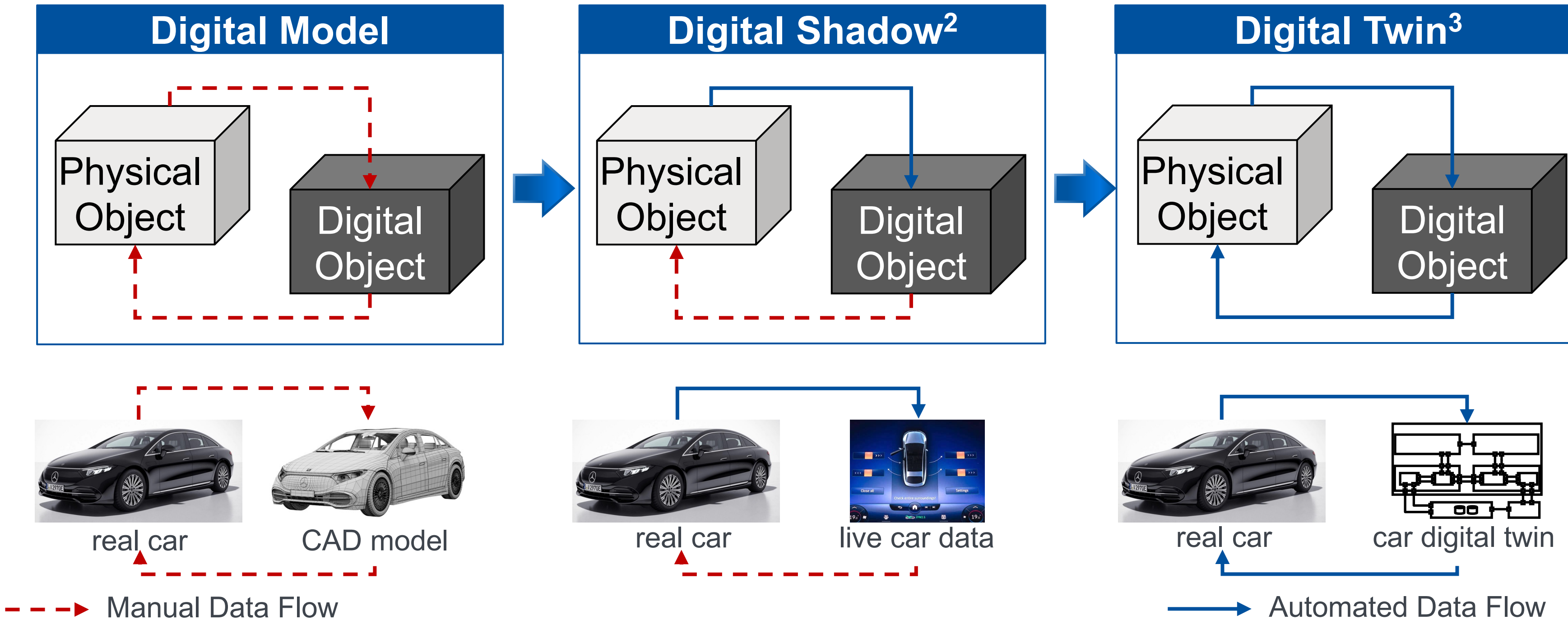
Germany

A Characterization based on Data Flows[1]

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



1. Kritzinger, Karner, Traar, Henjes, Sihn (2018). Digital Twin in manufacturing: A categorical literature review and classification. IFAC-PapersOnLine.
2. Becker, F., ..., Schuh, G., Wortmann, A. (2021). A conceptual model for digital shadows in industry and its application. In Conceptual Modeling: ER 2021, Springer.
3. Dalibor, M., ... Wimmer, M., Wortmann, A. (2022). A cross-domain systematic mapping study on software engineering for Digital Twins. Journal of Systems and Software 111361.

Andreas Wortmann | www.wortmann.ac | @andwor

University of Stuttgart
Germany

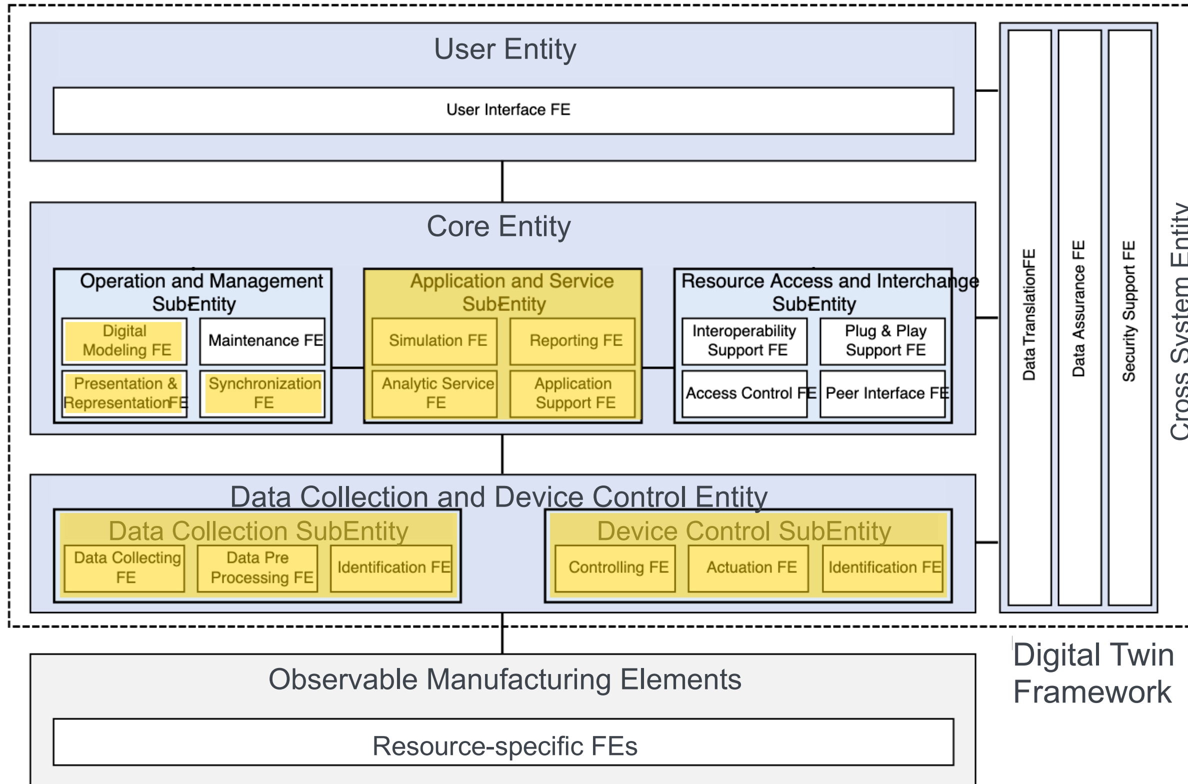
Take-away message

A digital twin is a software system using data, models, and services to purposefully represent and manipulate its original CPS.

Digital Twin Framework for Manufacturing (ISO 23247)

Build on functional entities (= software)

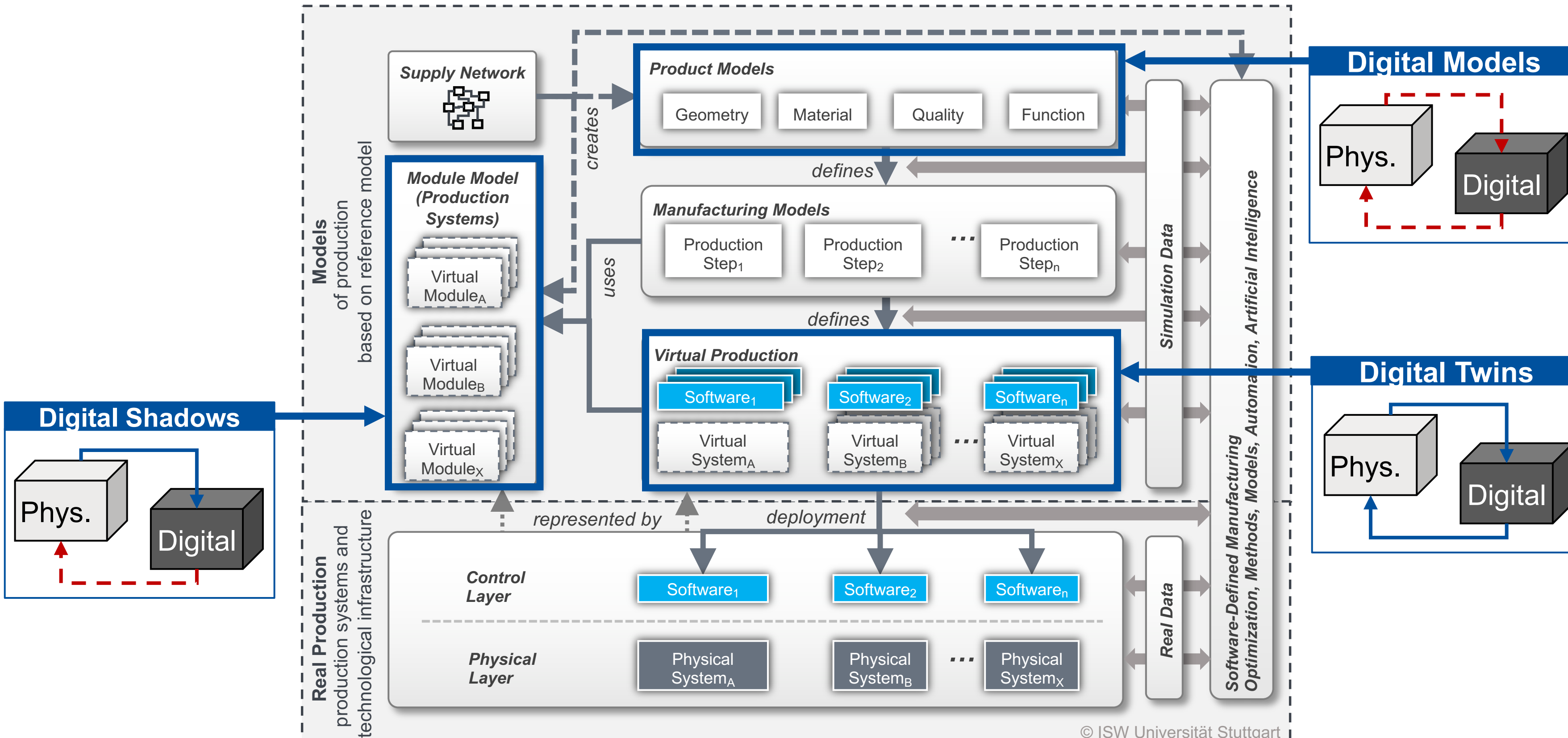
- Published in **2021**
- Part 1: **Overview** and general principles
- Part 2: Reference **architecture**
- Part 3: Digital **representation of manufacturing elements**
- Part 4: **Information exchange**



Source: Automation systems and integration - Digital twin framework for manufacturing - Part 2: Reference architecture

Software-Defined Manufacturing is all about Abstraction

Digital models, digital shadows, and digital twins need to drive production



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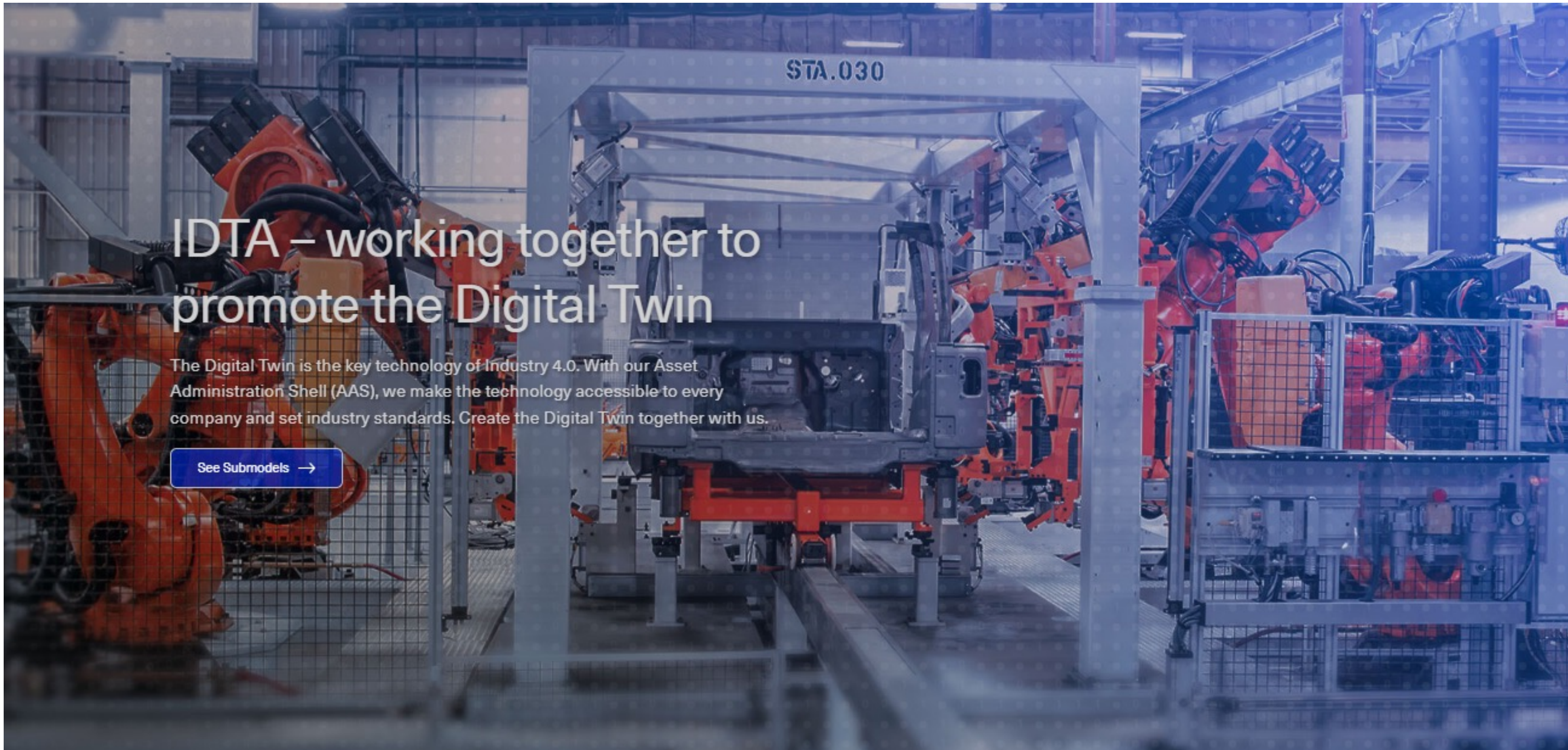
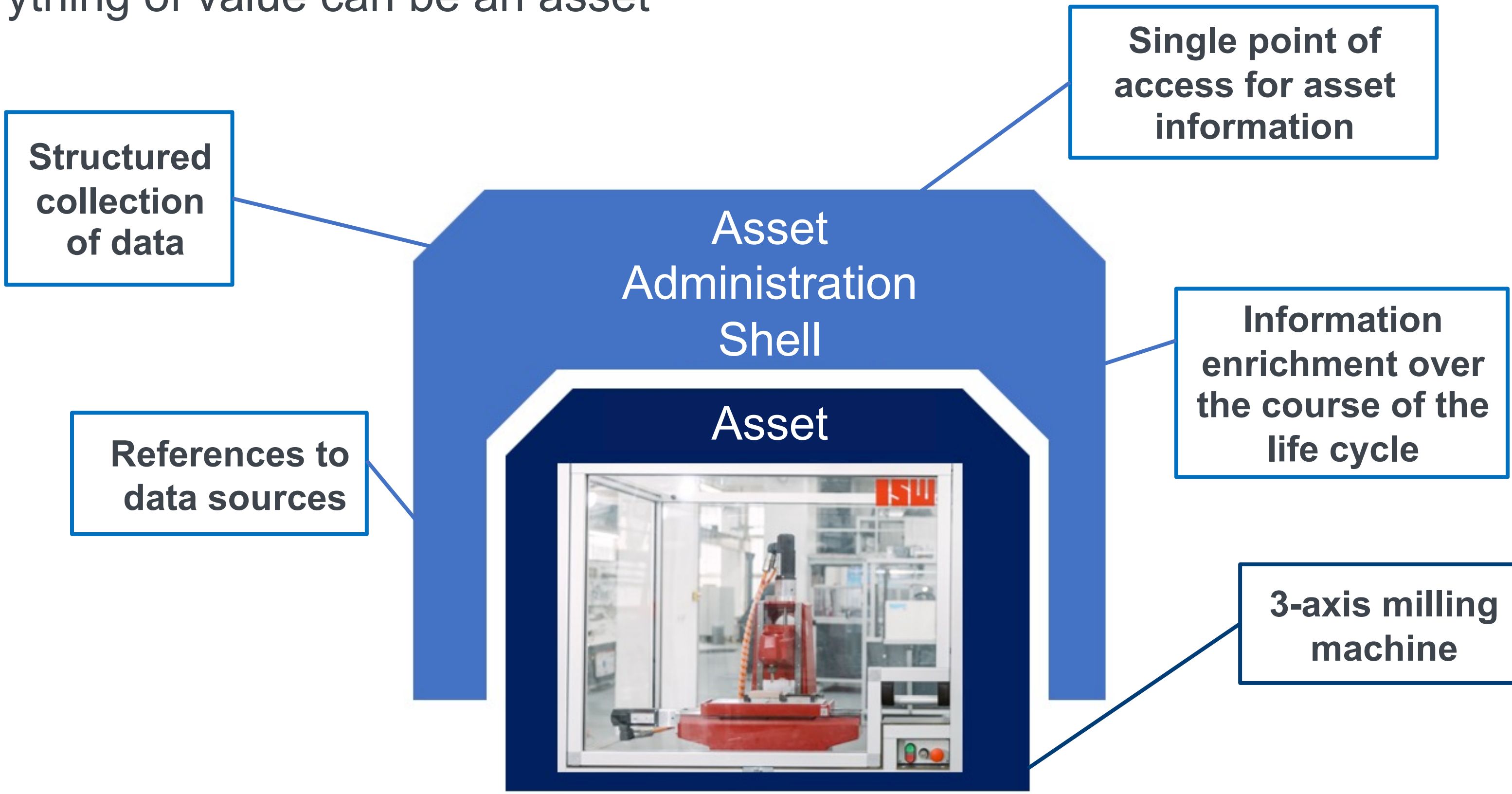
Asset Administration Shells are a Foundation of SDM

Standardized digital representations of assets



Asset Administration Shells

Everything of value can be an asset



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Submodels are the Main Content of Asset Administration Shells

Describe content-related or functional aspects of an asset

Capabilities
- End milling
- Drilling

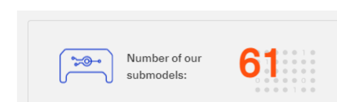
Maintenance
- Cutting time
- Latest service

Operational Data
- Sensor data
- Energy consumption

Technical Data
- Max. spindle speed
- Axis count

Digital Nameplate
- Contact data
- Serial number

3-axis milling machine



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There are 3 Kinds of Asset Administration Shells

And they relate to digital twins

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

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There are 3 Kinds of Asset Administration Shells

And they relate to digital twins

Type 1 AAS	Type 2 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**	• 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 Model	**Digital Shadow**

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There are 3 Kinds of Asset Administration Shells

And they relate to digital twins

Type 1 AAS	Type 2 AAS	Type 3 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**	• 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**	• Extend type 2 AAS • Have active behavior • Can start to communicate & to negotiate on their own • Well-defined language and message structures (VDI/VDE 2193) • Automated dataflows from/to real system • **Software interfacing asset**
Digital Model	**Digital Shadow**	**Digital Twin**

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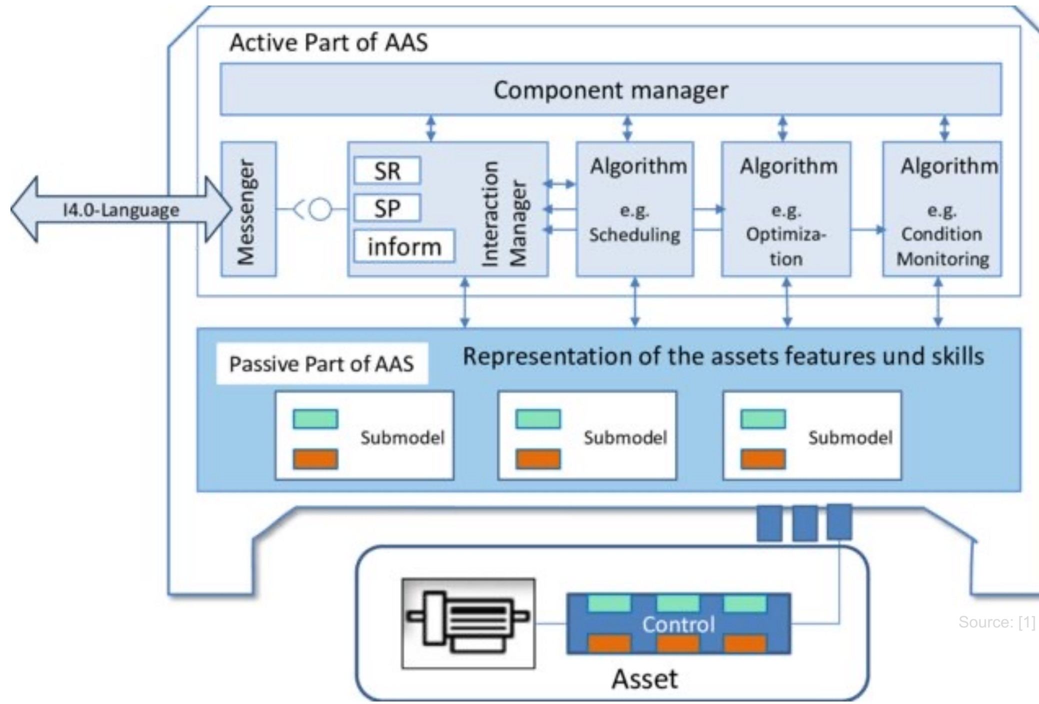
A General Architecture of Type 3 Asset Administration Shells[1]

A potential blueprint for digital twins

- Component manager orchestrates AAS behavior
- Service requester/provider interact with environment
- Algorithms perform computations
- Interact with models and asset
- Reference implementation e.g., with BaSyx
- A lot of JSON…



Source: [1]

1. Belyaev, A., Diedrich, C. (2019). Aktive Verwaltungsschale von Industrie 4.0 Komponenten," in Automationkongress 2019, Baden-Baden.

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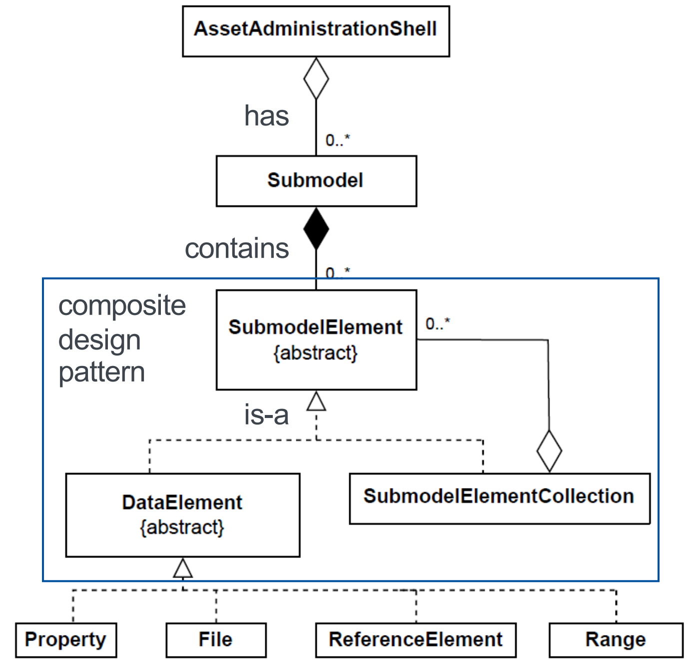
Asset Administration Shells are a Technology, not a Method

Software-defined manufacturing can build on it

- AAS serves as structured collection of the relevant data along the lifecycle of the asset
- Single point of access to all asset information
- Data consistency by referencing data sources/models instead of clone-and-own
  → data can automatically be updated over the lifecycle
- Uniform interfaces for services and applications
- Data integration from different sources by standardization



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Software-Defined Manufacturing for Vehicle & Supplier Industry (SDM4FZI)

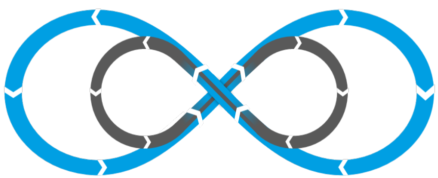
Our ongoing realization of software-defined manufacturing

Software-Defined Manufacturing for Vehicle & Supplier Industry (SDM4FZI)

www.sdm4fzi.de

Software-Defined Manufacturing for Vehicle & Supplier Industry (SDM4FZI)

Core challenges



- Reference model: The model defining the relations between the key aspects of production: products, resources and processes to ensure interoperability between models.
- Technological infrastructure: Architecture integrates hardware, software, communication solutions for SDM.
- Mastering mutability: Methodology for recognizing and mastering mutability.
- Adaptable production systems: Transformability of production systems supported by simulation and optimization on digital twins.
- End-to-end engineering: Continuous digital engineering across the machine/plant lifecycle based on the reference model.
- Virtualized control technology: Automated development and testing of software using digital twins. Orchestration, deployment and operation of software on the technological infrastructure.
- Data-based services: End-to-end information provision and use in networked production systems.

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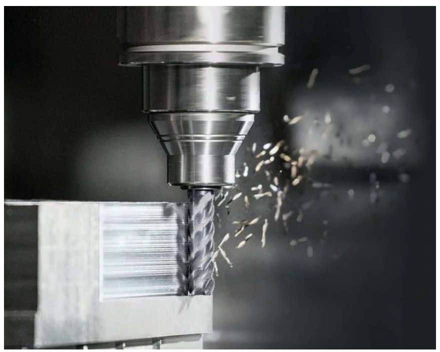
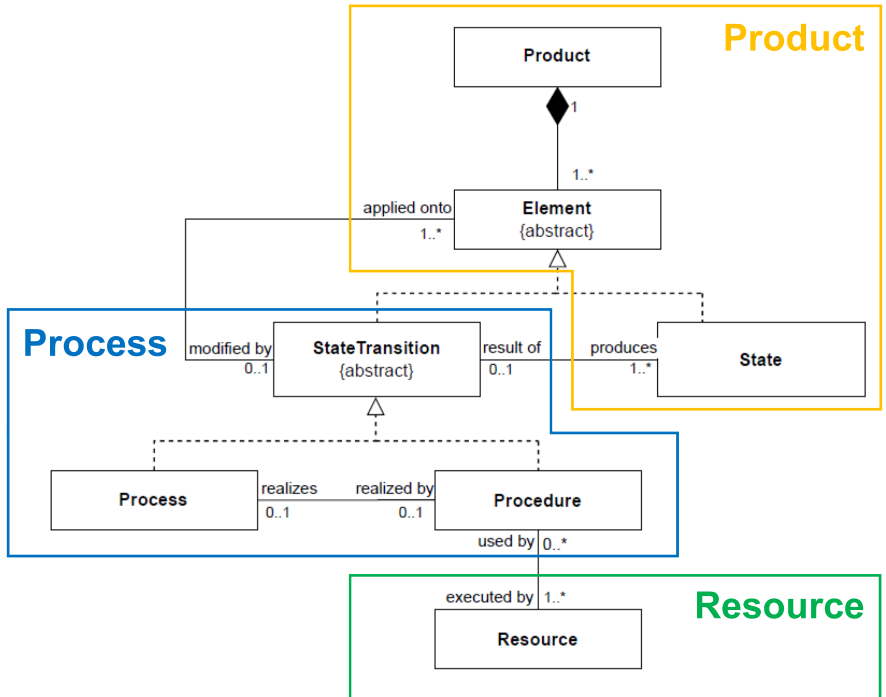
Product-Process-Resource Metamodel[1] for Asset Administration Shells

The foundation of software-defined manufacturing



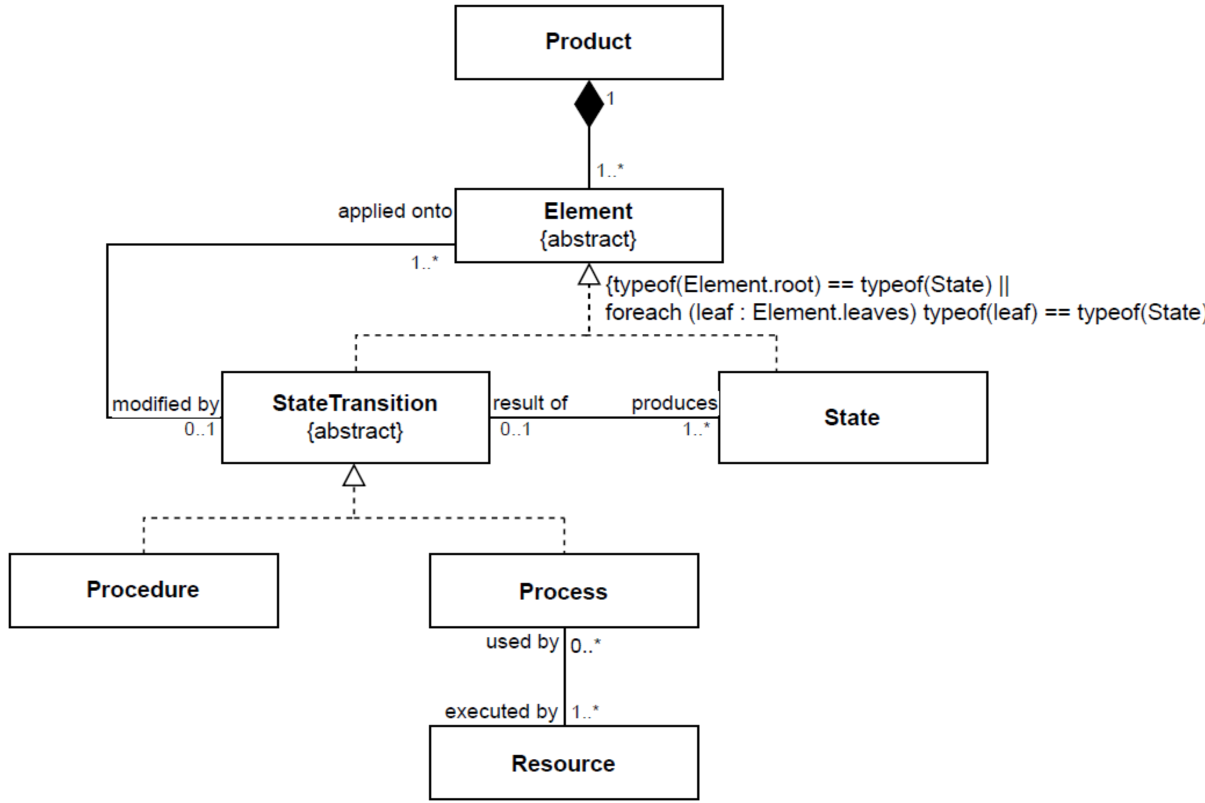
Source: https://mav.industrie.de/



1. Ellwein, C., Neumann, R., Verl, A. (2022). Software-defined Manufacturing: Data Representation. CIRP ICME'22.

Product (Sub-)Modeling in SDM4FZI

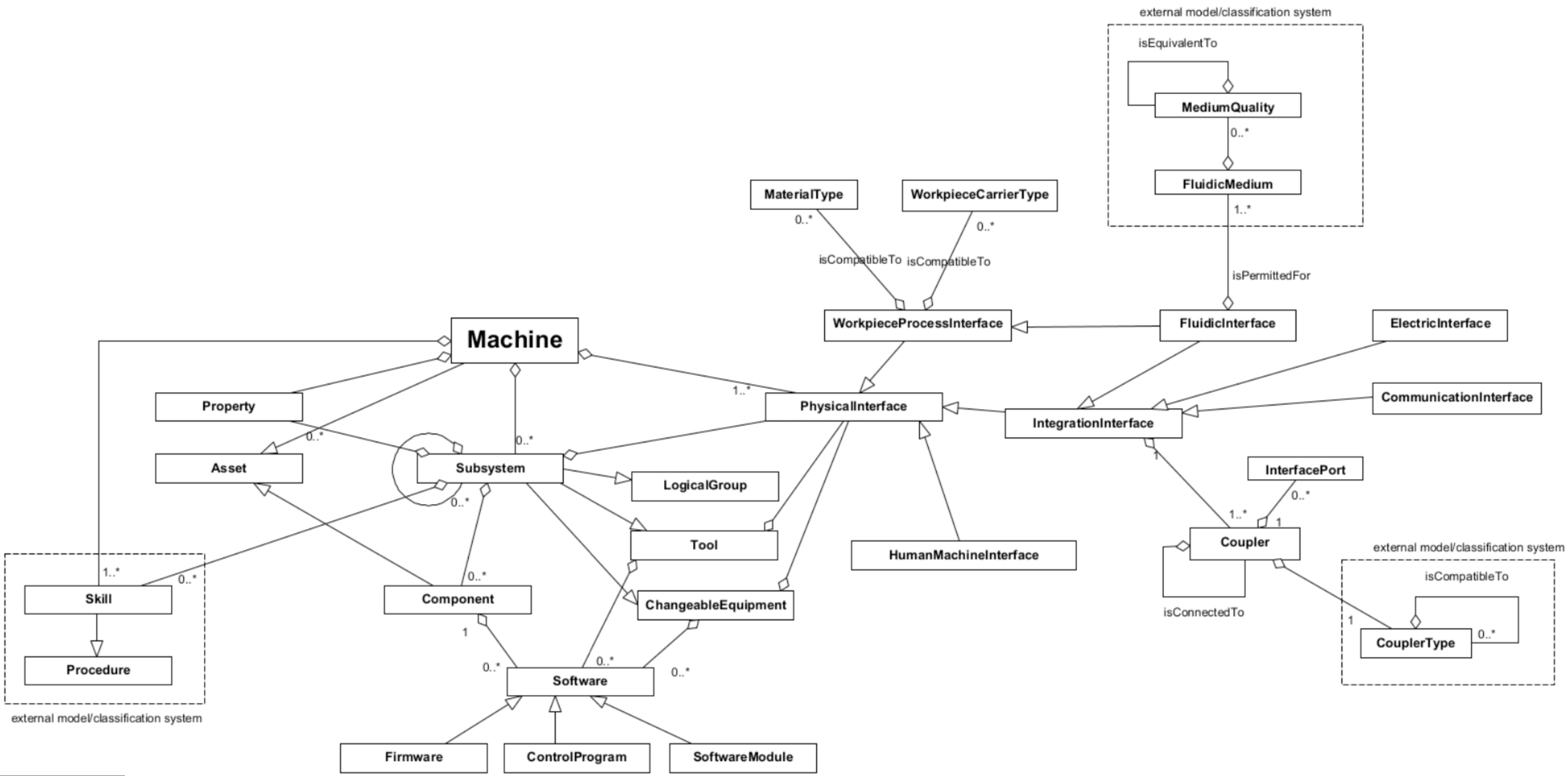
Products consist of elements that went through state transitions



1. Ellwein, C., Neumann, R., Verl, A. (2022). Software-defined Manufacturing: Data Representation. CIRP ICME'22.

Resource (Sub-)Modeling in SDM4FZI

Resources are machines with subsystems, components, software and more.



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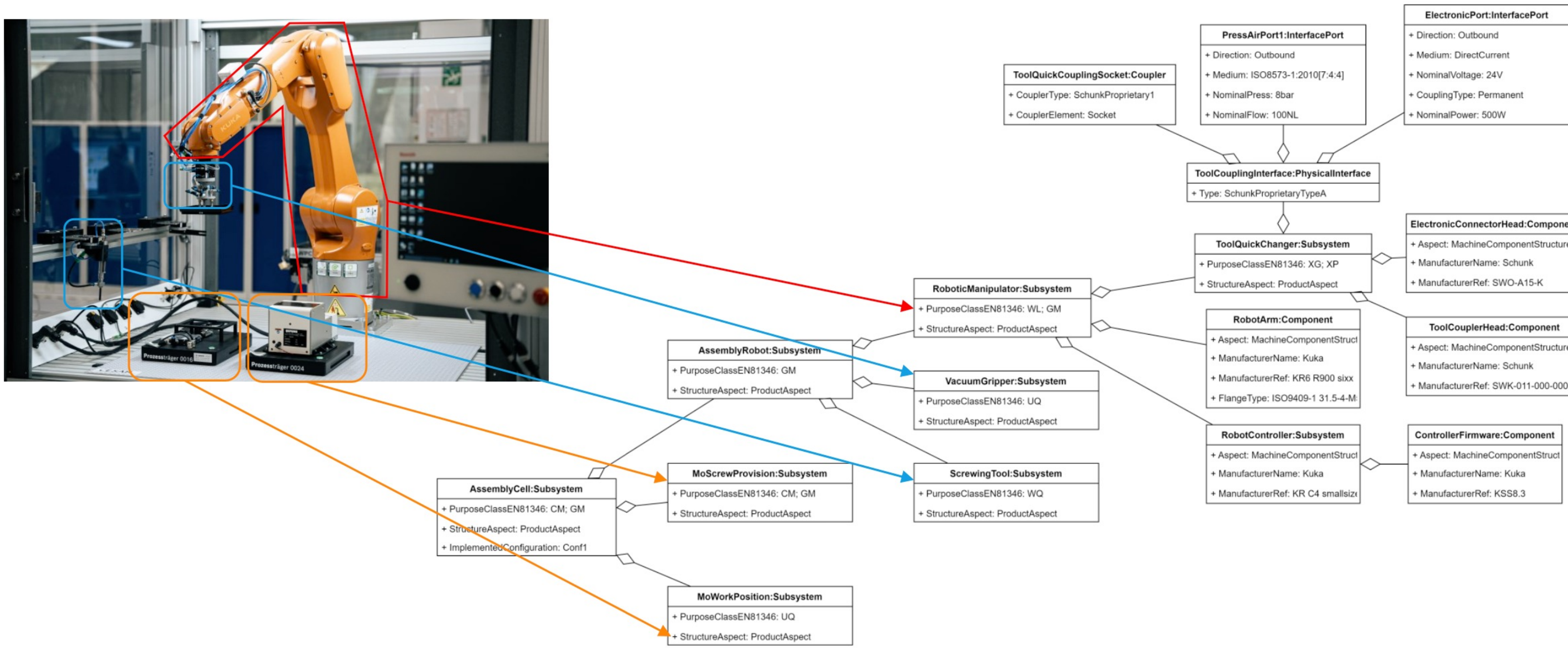
Resource (Sub- Modeling in SDM4FZI

Submodels are linked to production systems



1. Ellwein, C., Neumann, R., Verl, A. (2022). Software-defined Manufacturing: Data Representation. CIRP ICME'22.

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University of Stuttgart
Germany

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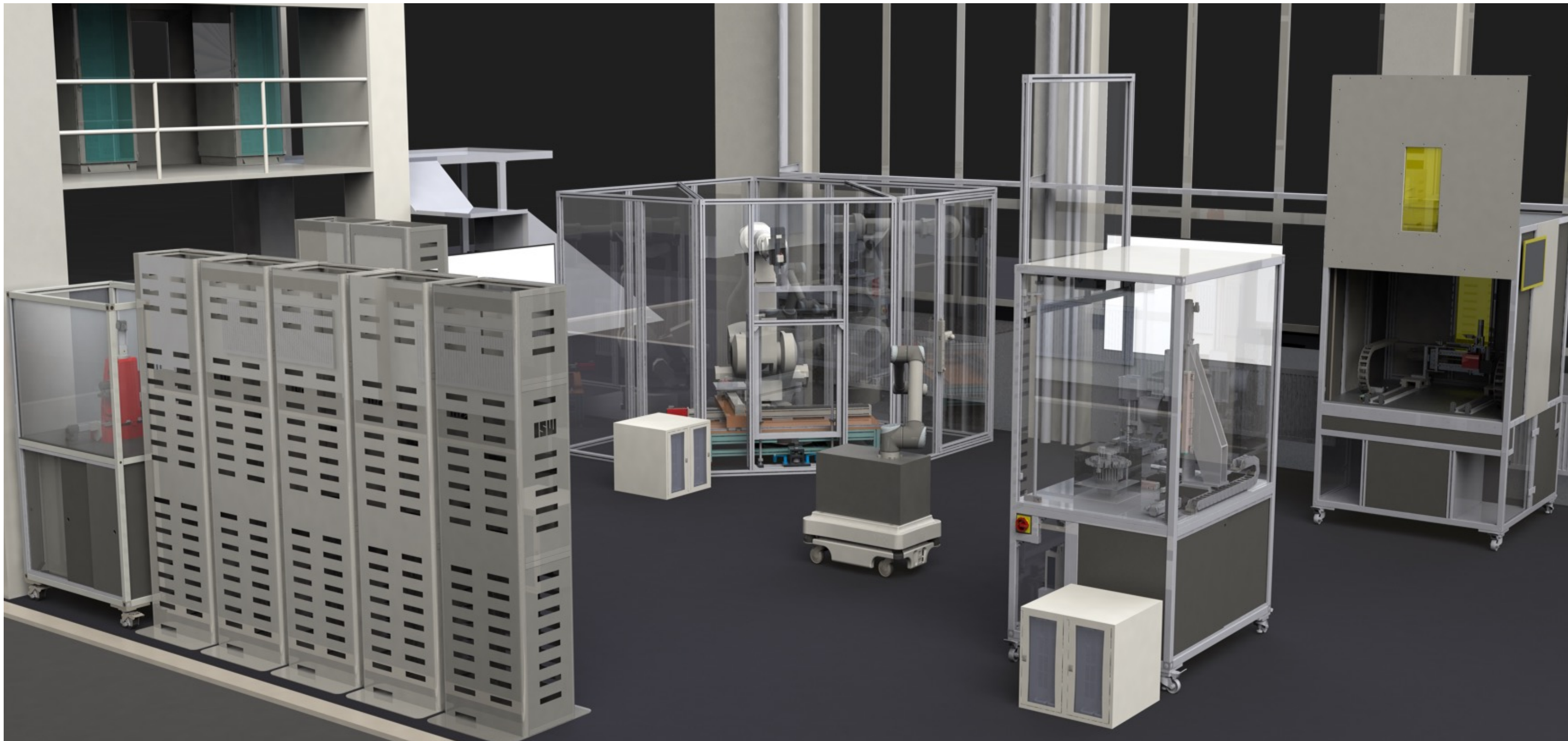
A practical testbed for software-defined manufacturing



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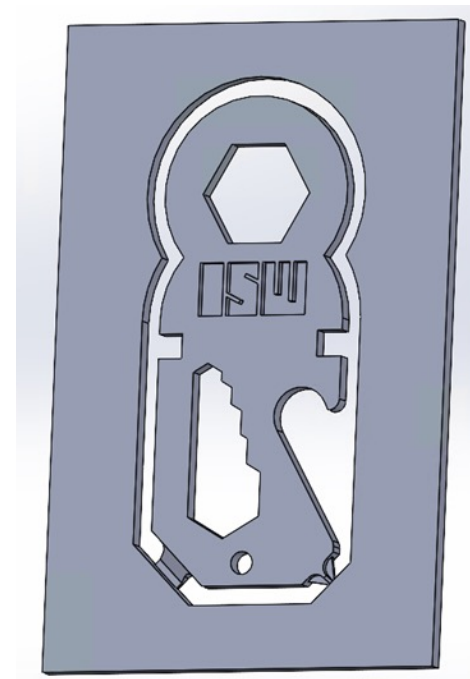
Case study & product

- 1.) Configuration of a personalized multikey tool
  → Automatic instantiation of the AAS
- 2.) CAD-CAM toolchain und iterative manufacturing planning (services)
  → Services use AAS as data source
- 3.) Simulation / validation of planning process
  → Data is saved in AAS
- 4.) Manufacturing of the real multikey tool & documentation
  → AAS includes documentation



Multikey Tool

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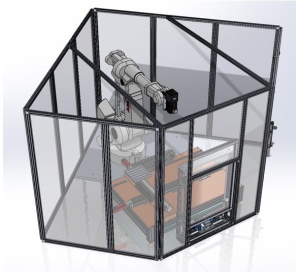
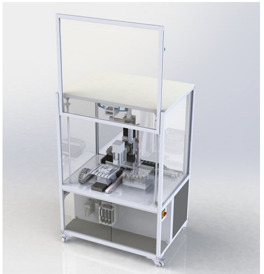
Machines and their asset administration shells

- Potentials of production are determined depending on models
  - workpiece geometry
  - production technology
  - constraints
  - machine status
- Possible production plans are created and evaluated (cost-optimal)
- During manufacturing: execution data is written to the process models
- Iterative planning plans again after each process step (optimization).

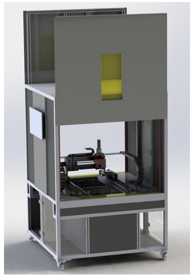
OSACA
3-axis milling machine

HyRob
Hybrid Robot





5X
5-axis milling machine



LarA
Laser processing center

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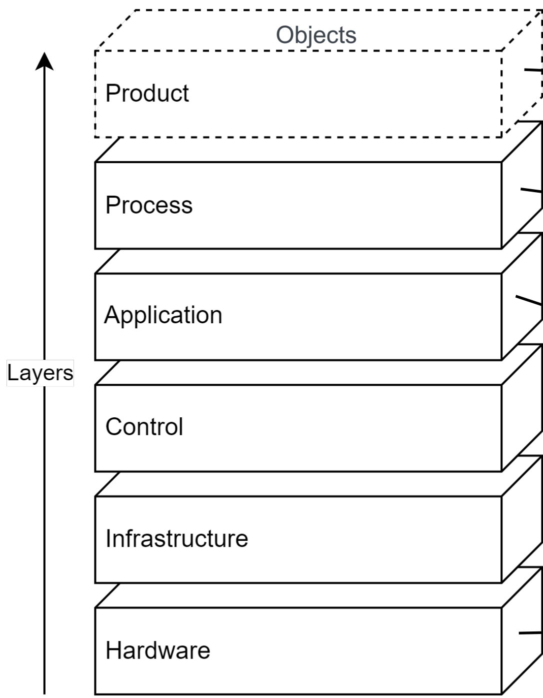
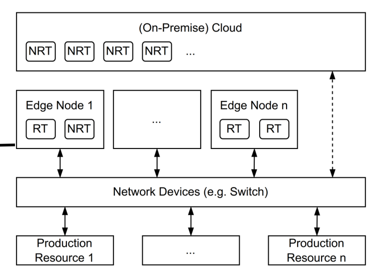
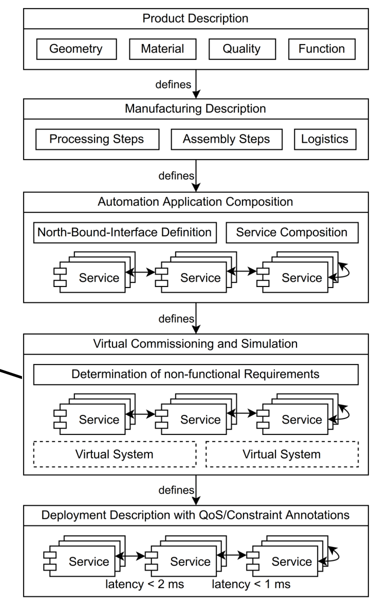
Through the lens of process-product-resource asset administration shells



Quelle: https://mav.industrie.de/





Andreas Wortmann | www.wortmann.ac | @andwor

University of Stuttgart
Germany

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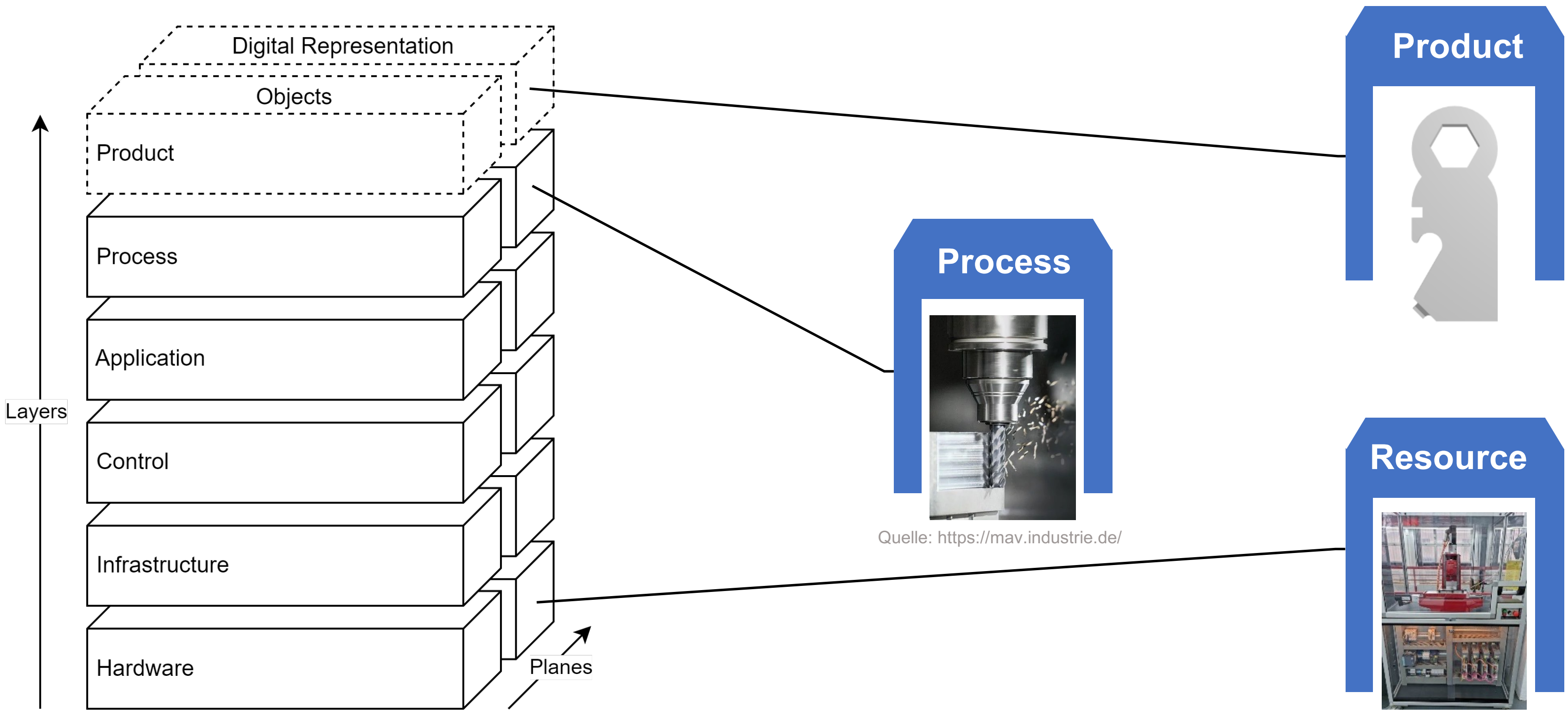

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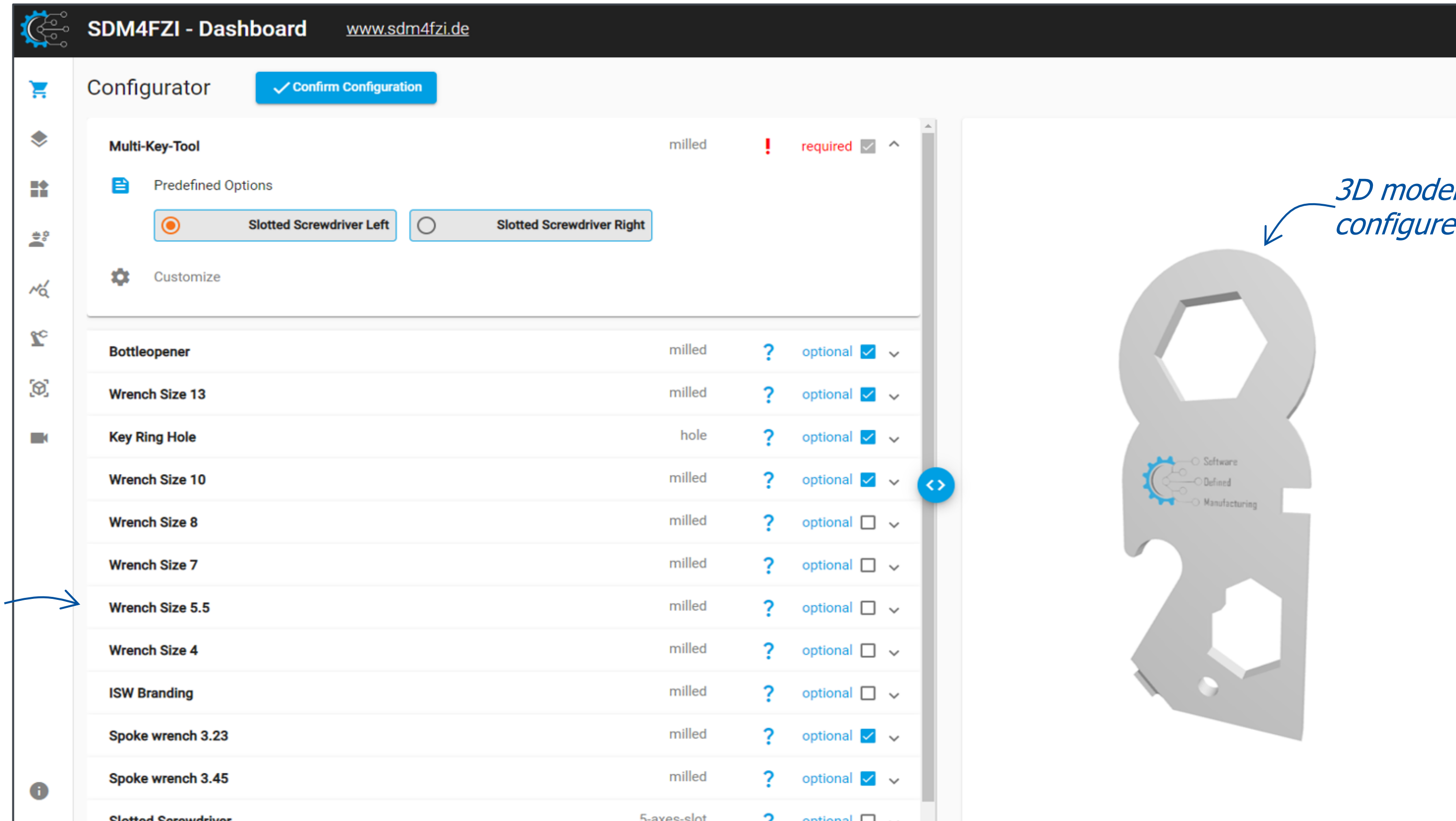
Design-time configuration and prediction of the multikey tool

feature selection



3D model of the configured MKT

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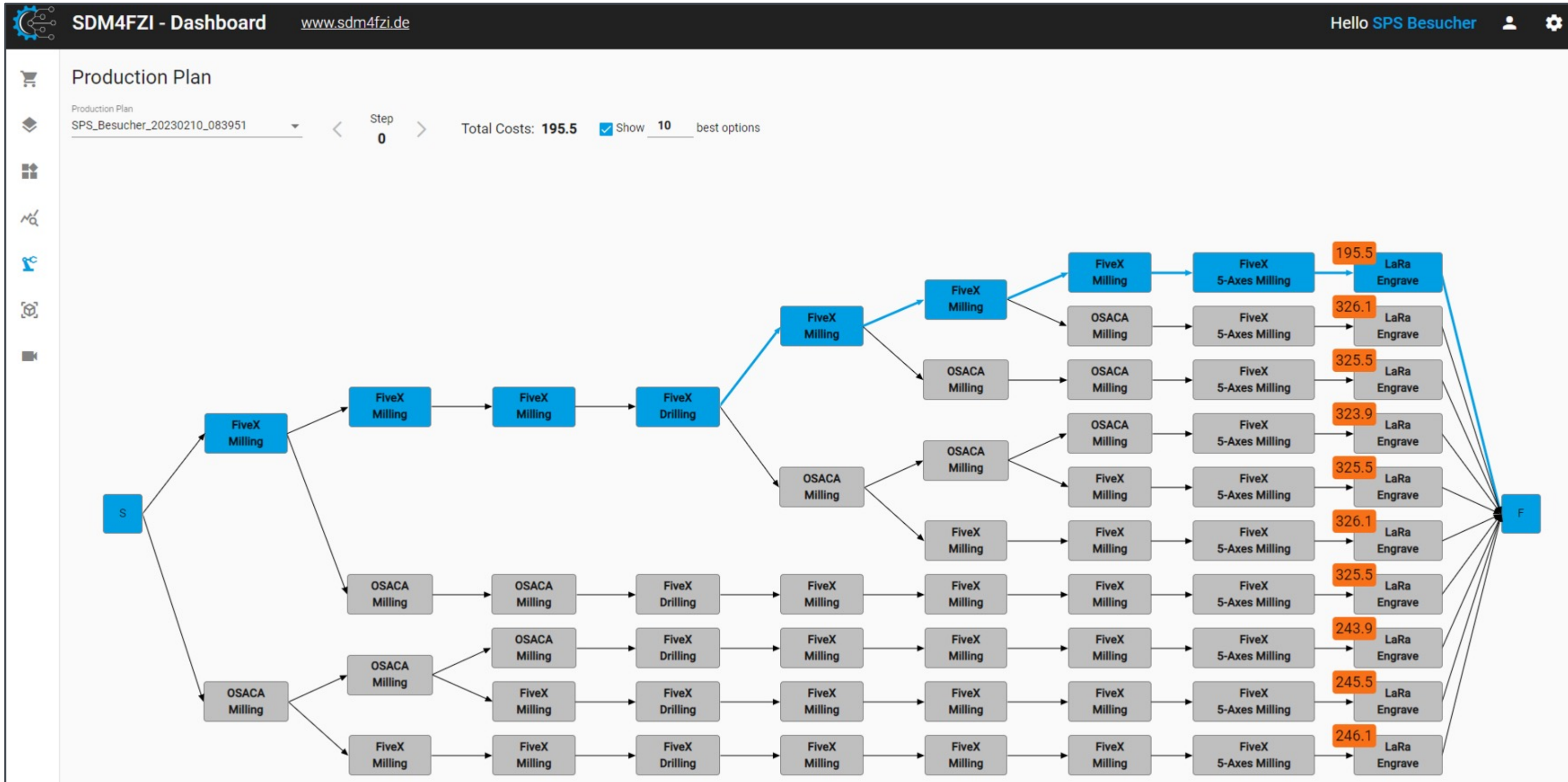
Manufacturing planning and execution



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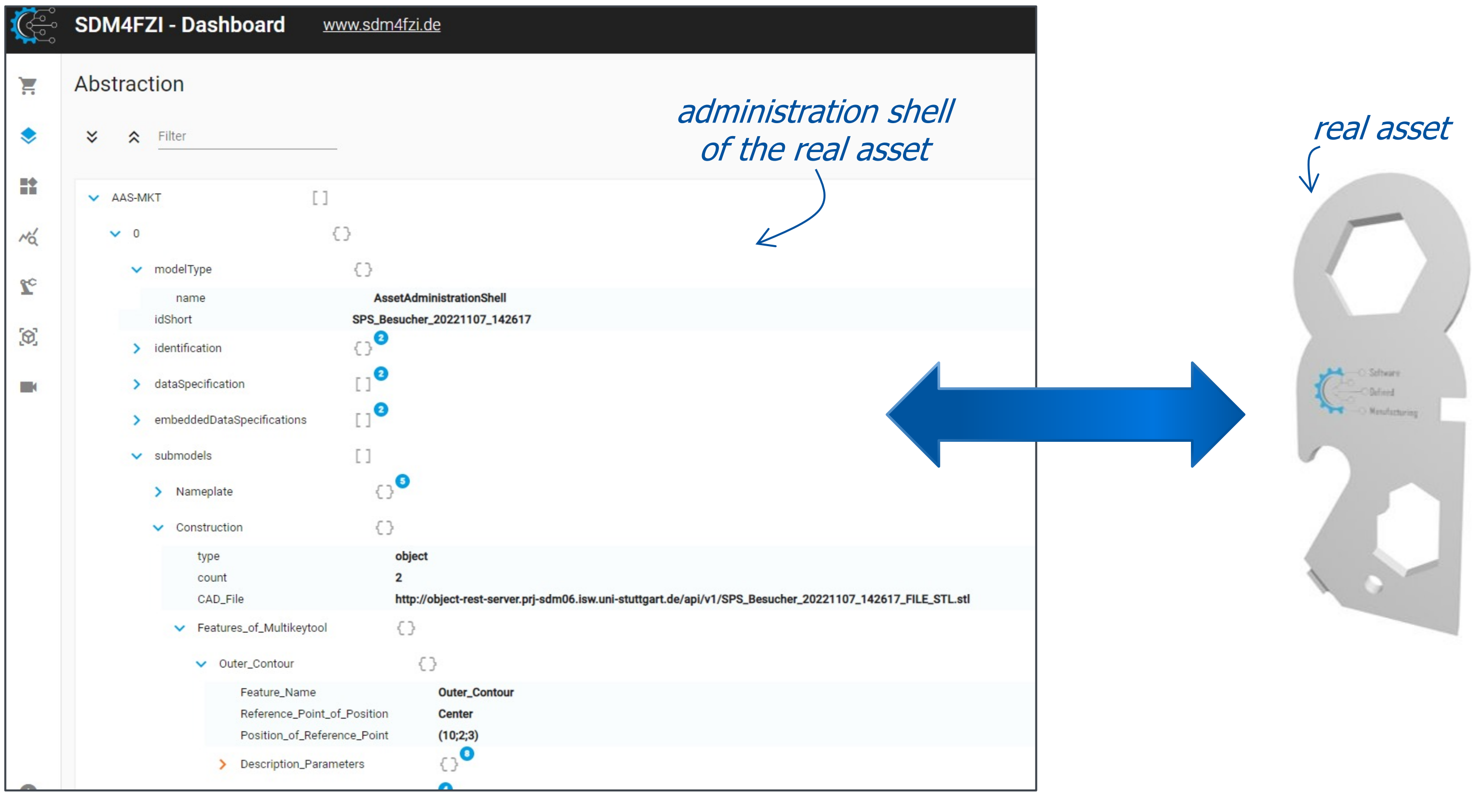
Asset administration shell representing the asset during manufacturing



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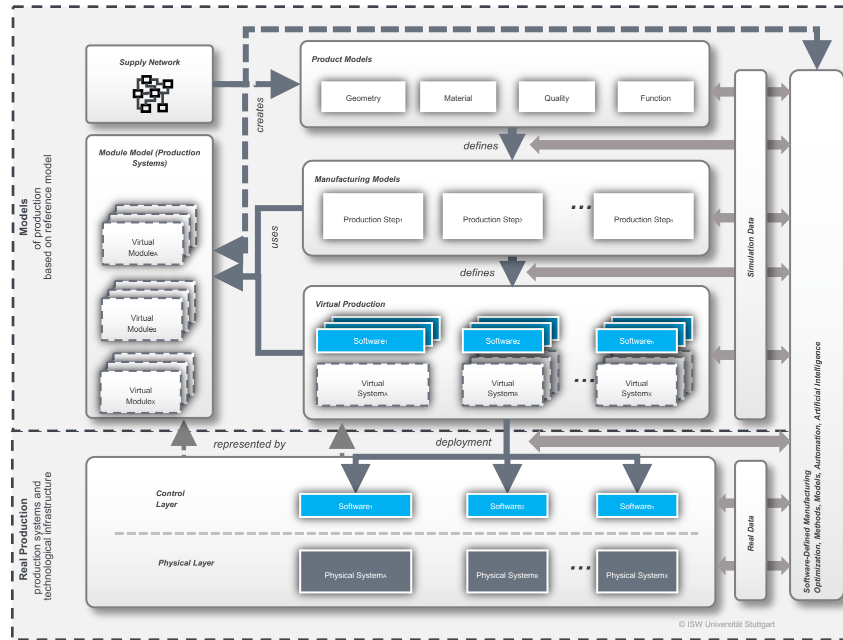
Software-Defined Manufacturing is about Abstraction and Automation

Model-driven development paves the way for it

- Models are key to abstraction and automation
- AAS of product-process-resource (PPR) models decouple production functions from hardware
  - Type 1: Digital Models
  - Type 2: Digital Shadows
  - Type 3: Digital Twins
- PPR AAS ease flexibly reconfiguring production to volatile markets, uncertainties, complexities, …
- Technological and methodical basis for
  - digital twins in
  - software-defined manufacturing



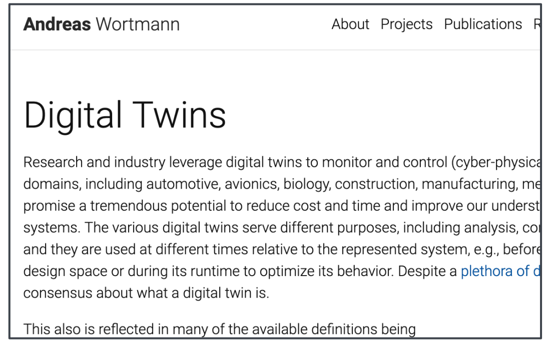
Andreas Wortmann | www.wortmann.ac | @andwor

University of Stuttgart
Germany

Thank You

More on model-driven engineering for production

www.wortmann.ac/presentations



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MODELS'23 Workshop MoDDiT

ICSE'23 Workshop RoSE

ETFA'23 Special Session SECPPS

Software Engineering 2024

Andreas Wortmann | www.wortmann.ac | @andwor

University of Stuttgart
Germany

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

ISW

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

email wortmann@isw.uni-stuttgart.de
web www.wortmann.ac
phone +49 (0) 711 685-84624
twitter @andwor

University of Stuttgart
Institute for Control Engineering of Machine Tools and Manufacturing Units (ISW)
Seidenstrasse 36 • 70174 Stuttgart • Germany