

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.
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Presentation Slides

No need to take photos

www.wortmann.ac/presentations

The ISW



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Alexander Verl
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Andreas Wortmann
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Extended Head of the Institute

CTO Research



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Software and Engineering Methods



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Real-Time Communication and Control Hardware



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Drive Systems and Motion Control



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Mechatronic Systems and Processes



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Virtual Methods for Production Engineering



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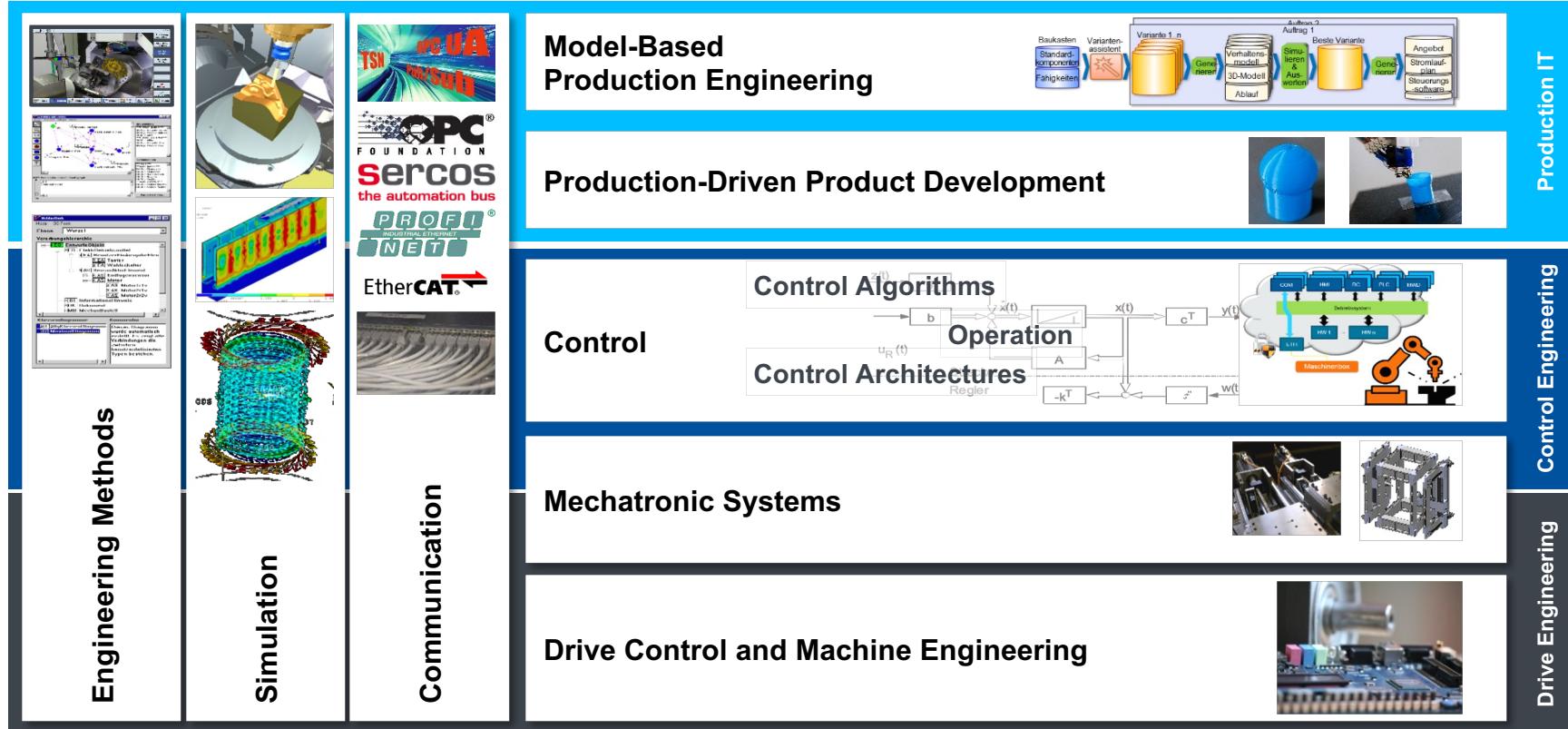
Electric Laboratory

Stefan Abel, Arthur Wendland

Mechanical Laboratory

Achim Ringler, Lars Hofmann

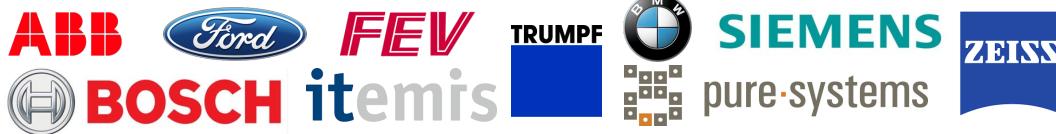
Core Competencies of the ISW



About the Presenter

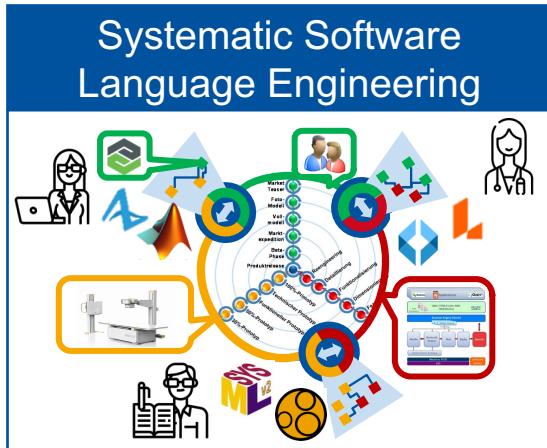
Over a decade of research in model-driven engineering

- 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

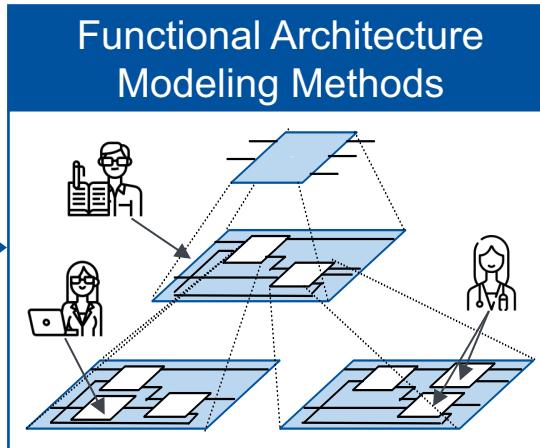


Building Better Software more Efficiently

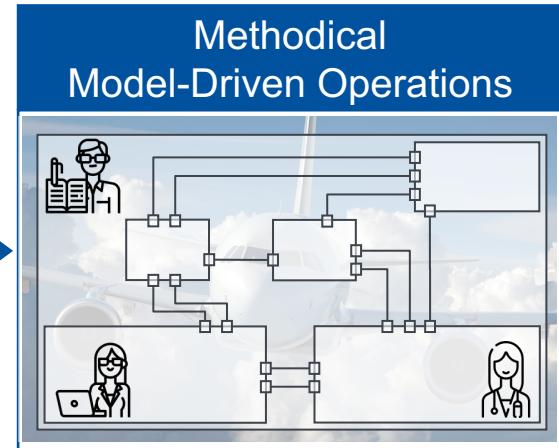
Through better abstraction and automation



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



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



- 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

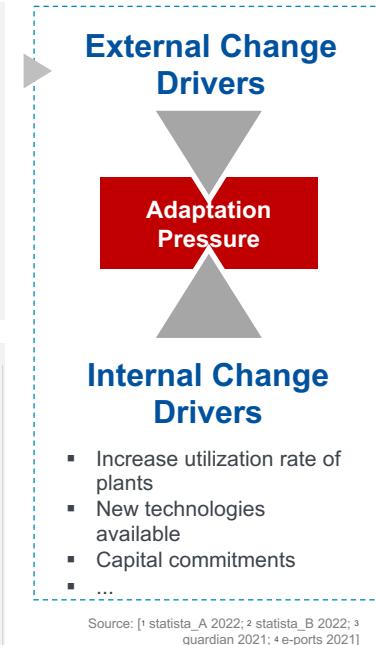
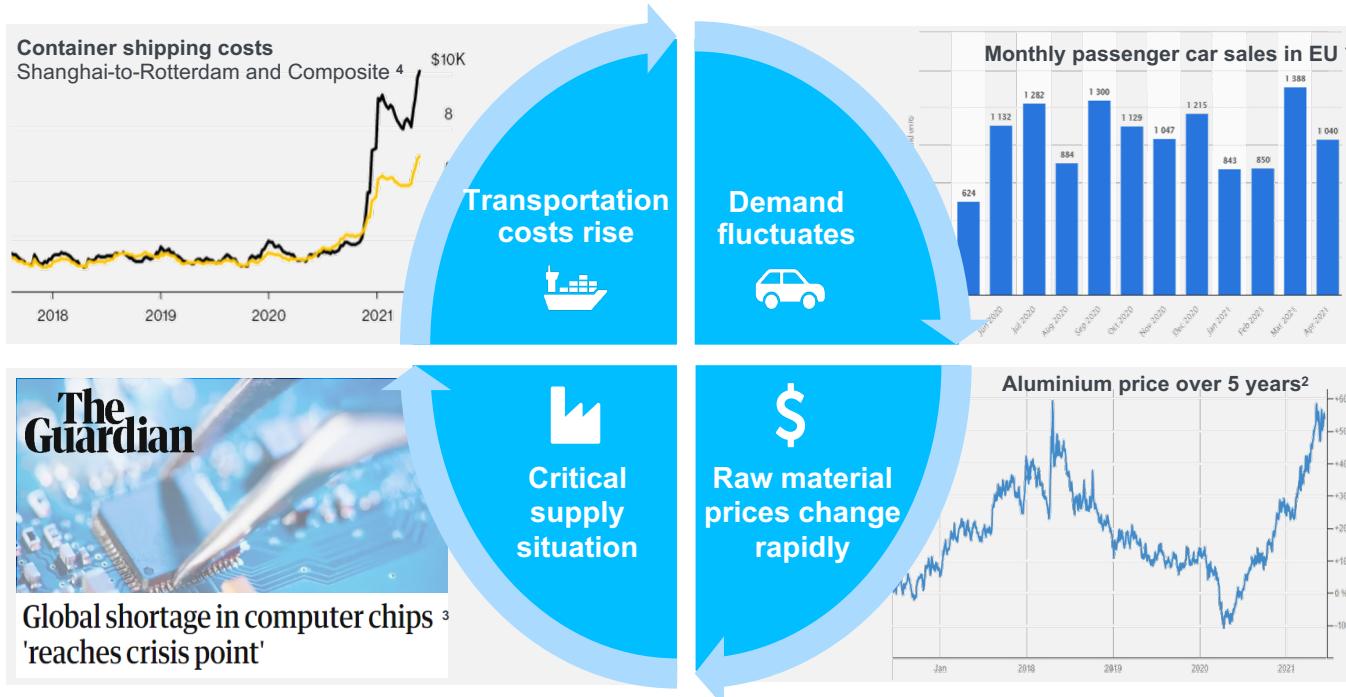
First steps towards realizing SDM in the Stuttgarter Maschinenfabrik



Source: <https://modeling-languages.com/clarifying-concepts-mbe-vs-mde-vs-mdd-vs-md/>

Welcome to the VUCA World

Volatile markets, Uncertain operations, Complex processes, Ambiguous RQs



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



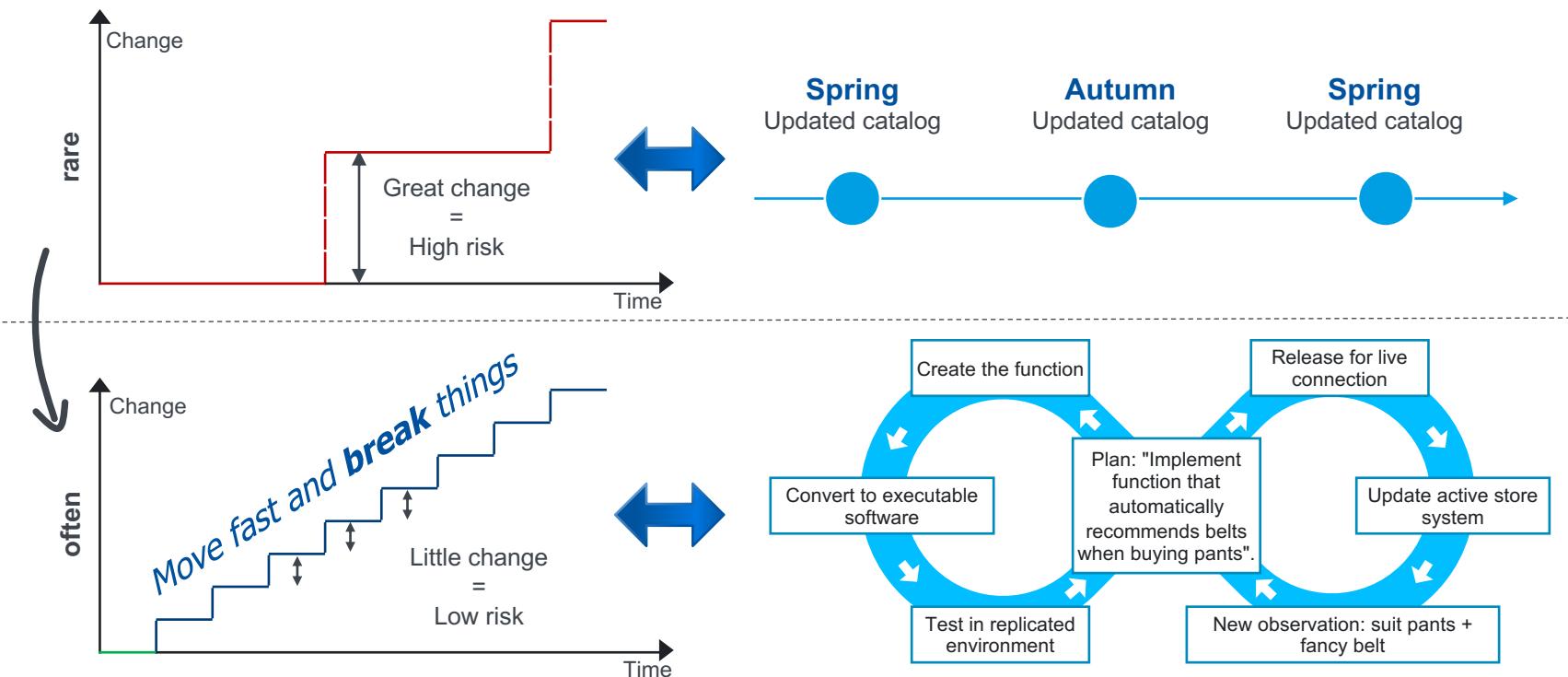
- Complex systems
- Short cycle times
- High throughput



The FAANG World has Lead a Methodological Upheaval

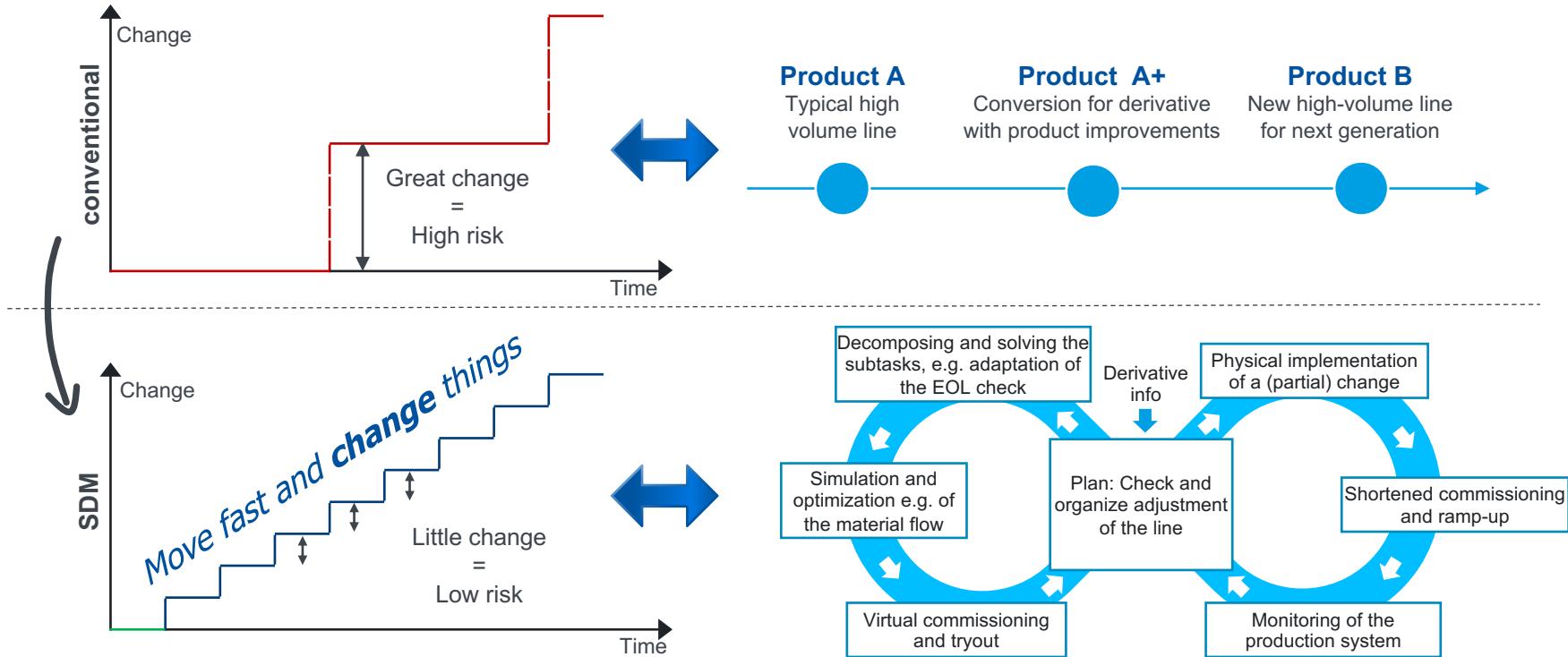
From rare to frequent and informed change

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



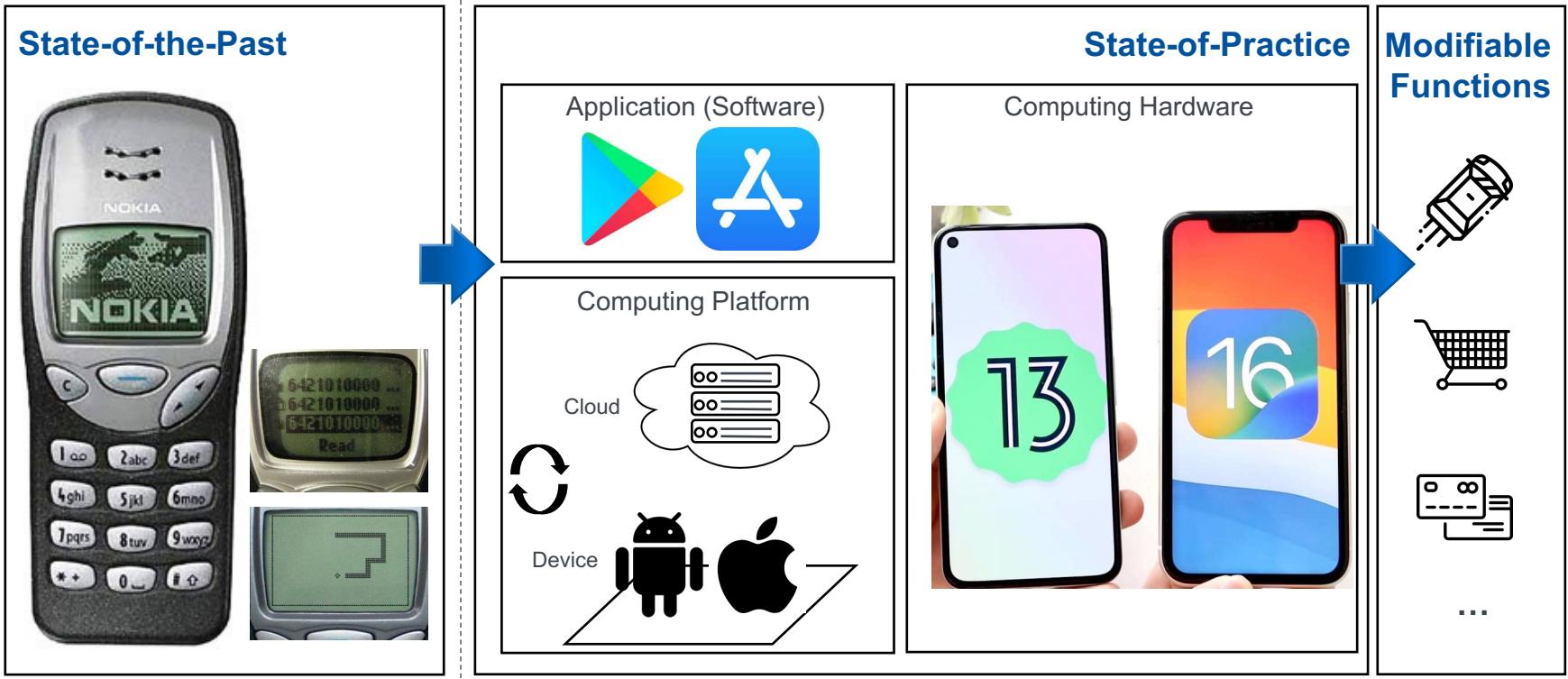
Industrial Production can Learn From This

This is the goal of software-defined manufacturing



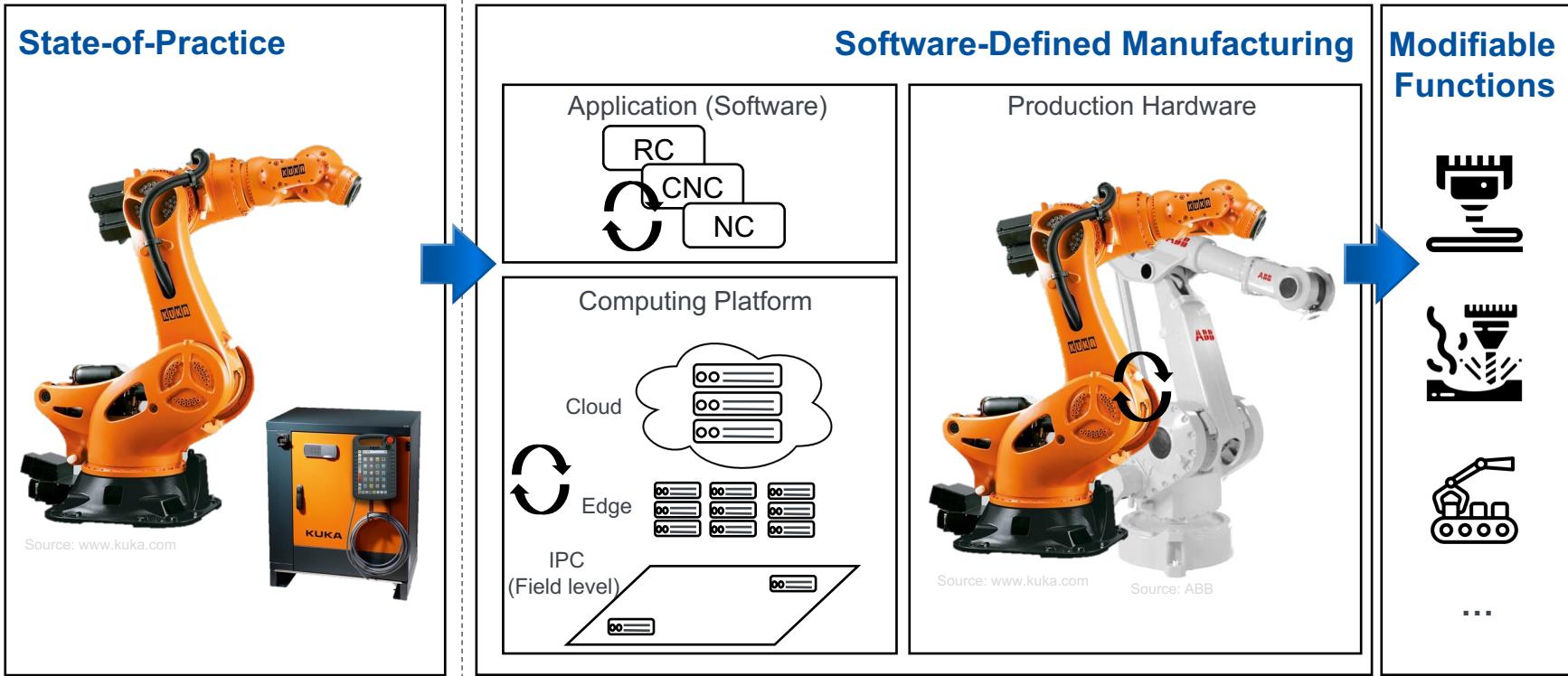
We have Experienced this Transition Already in Person

In household appliances, cars, mobile phones, ...



Software-Defined Manufacturing

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



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
 - Digitization
 - Abstraction
 - Automation



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 can¹⁻³
 - Overcompensate the growth of complexity
 - Reduce the conceptual gap



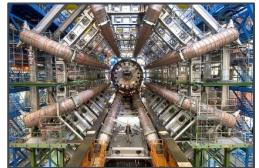
Chevy Volt
(10 Mio. LoC)



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)

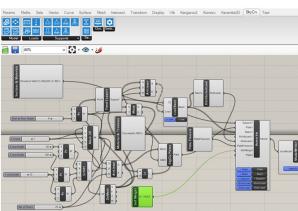
1. Wang, Y., Feng, Y., et al. (2021) The necessity of low-code engineering for industrial software development: A case study and reflections. In ISSREW, IEEE.

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.

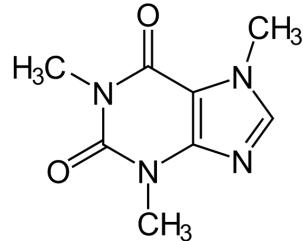
3. Tolvanen, J.-P. (2022). Measuring Productivity from Model-Based Development A Tale of Two Companies.

Models are Everywhere and Often Used As Blueprints

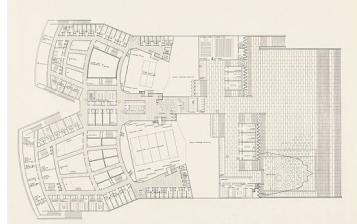
But only few disciplines can automatically translate blueprints into products



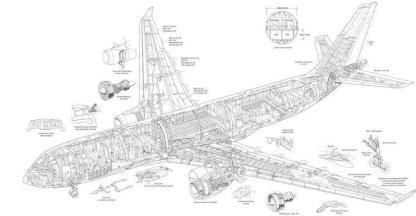
Architecture



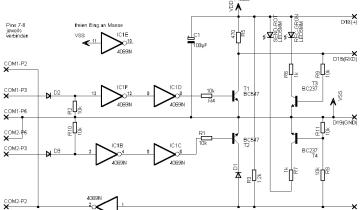
Chemistry



Civil Engineering



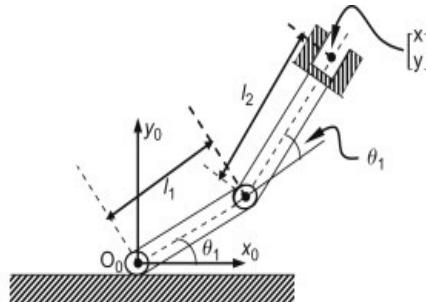
Construction



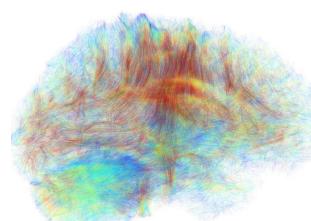
Electronics



Geology



Mechanical Engineering



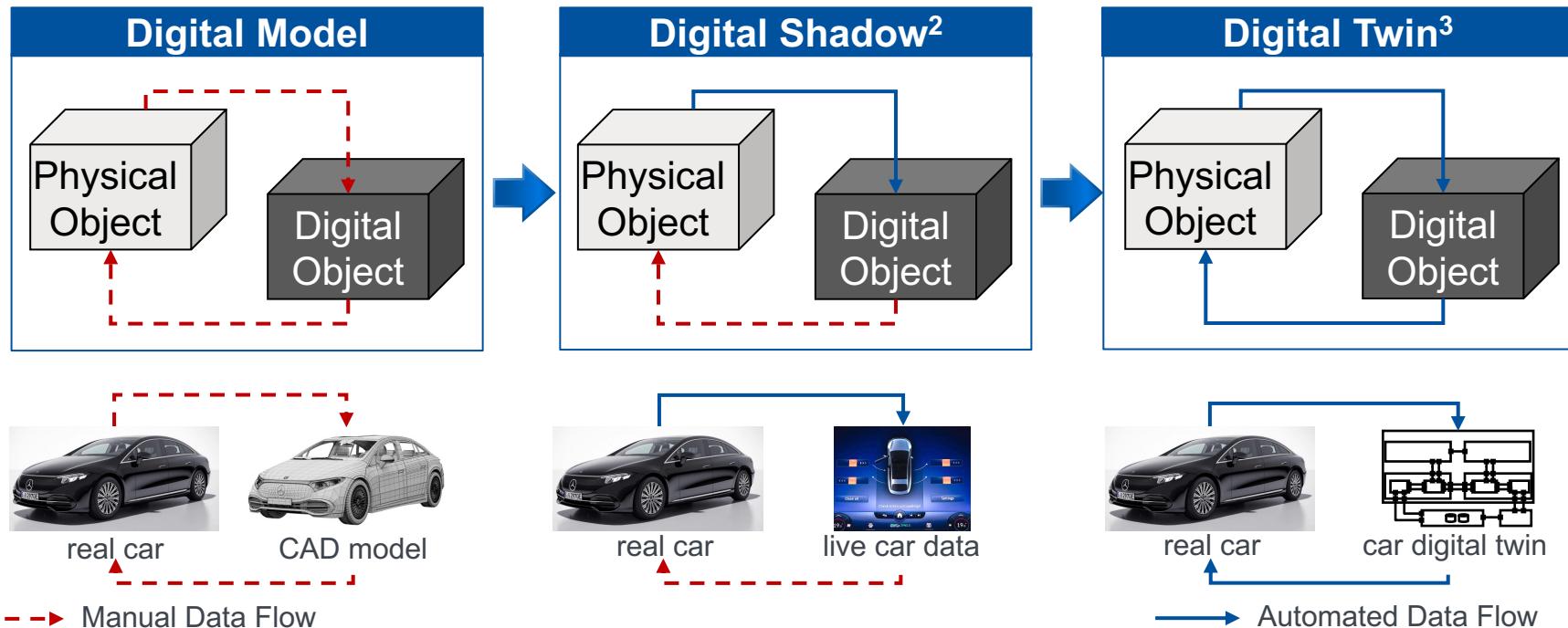
Medicine



Safety

A Characterization based on Data Flows¹

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.

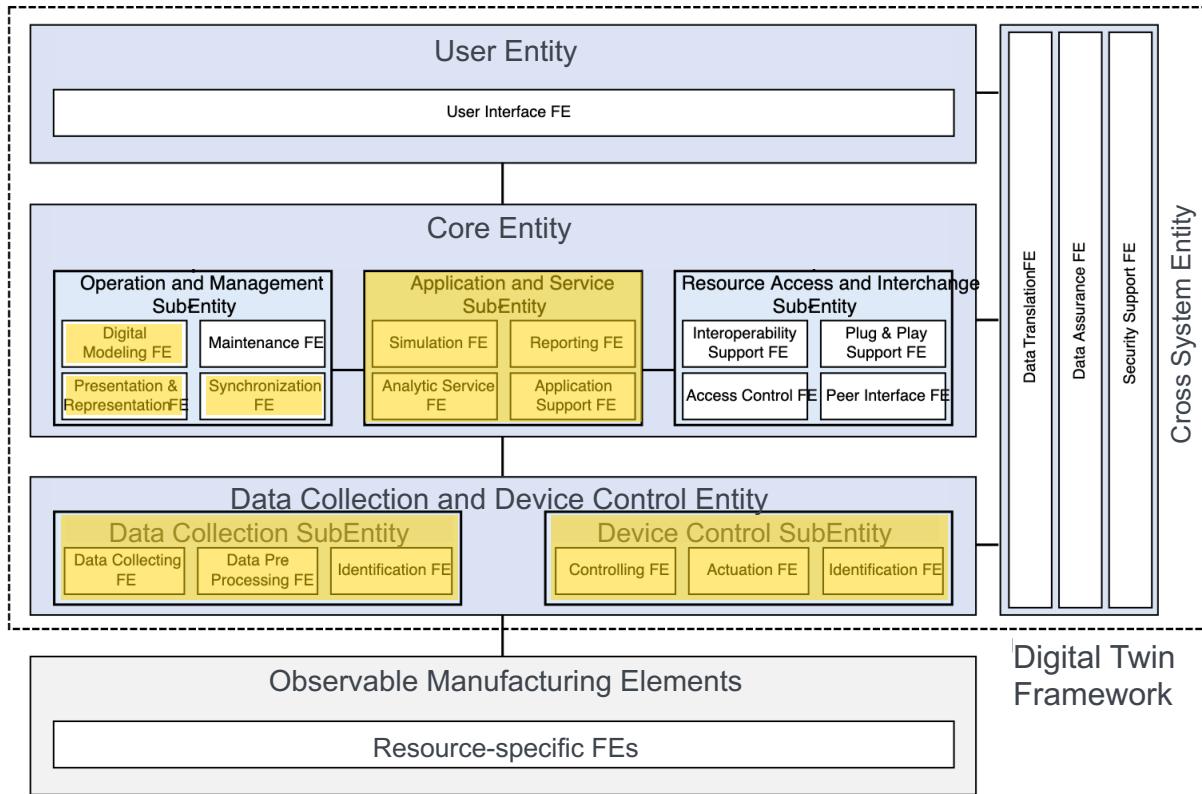
Take-away message

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)

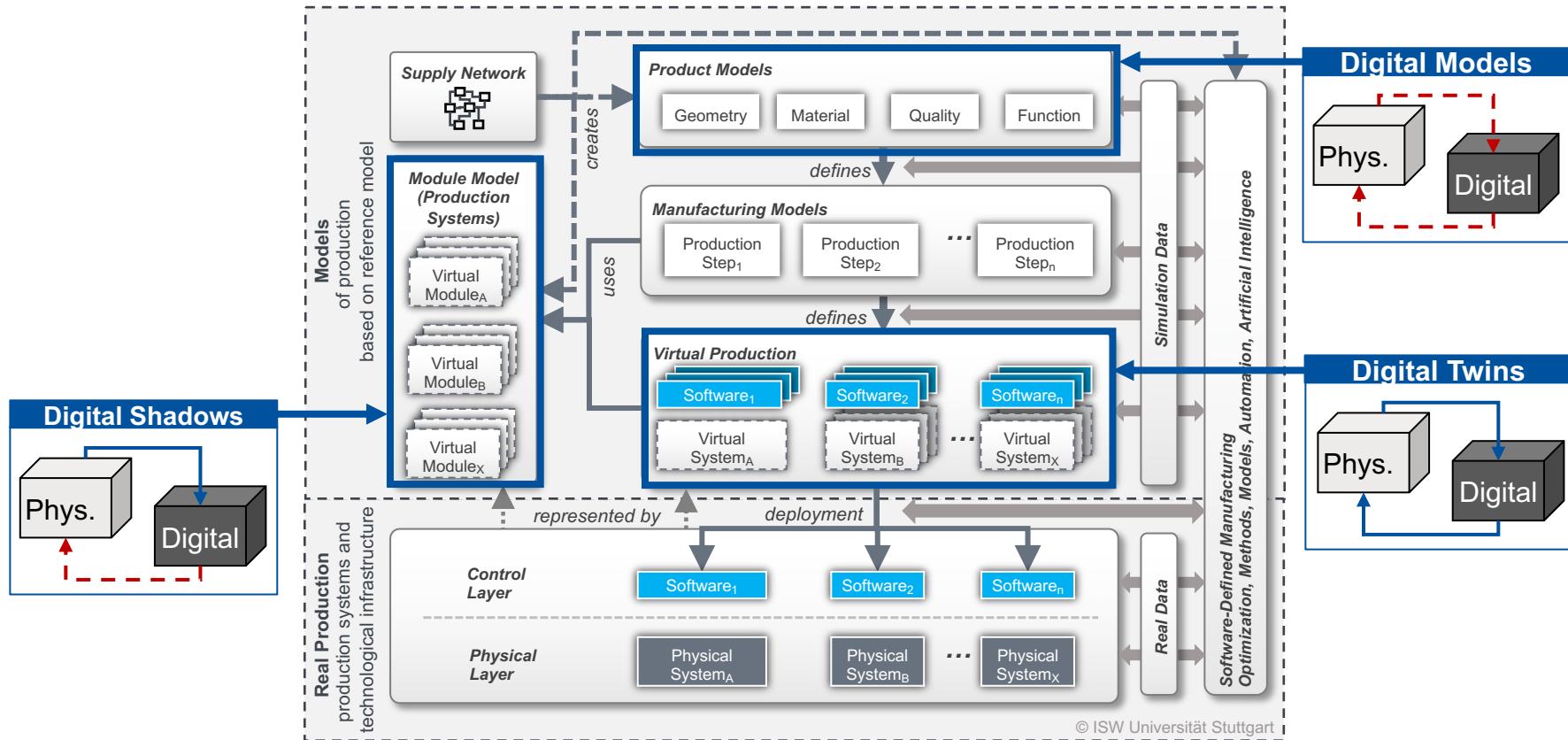
- Published in **2021**
- Part 1: **Overview** and general principles
- Part 2: Reference **architecture**
- Part 3: Digital **representation of manufacturing elements**
- Part 4: **Information exchange**



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

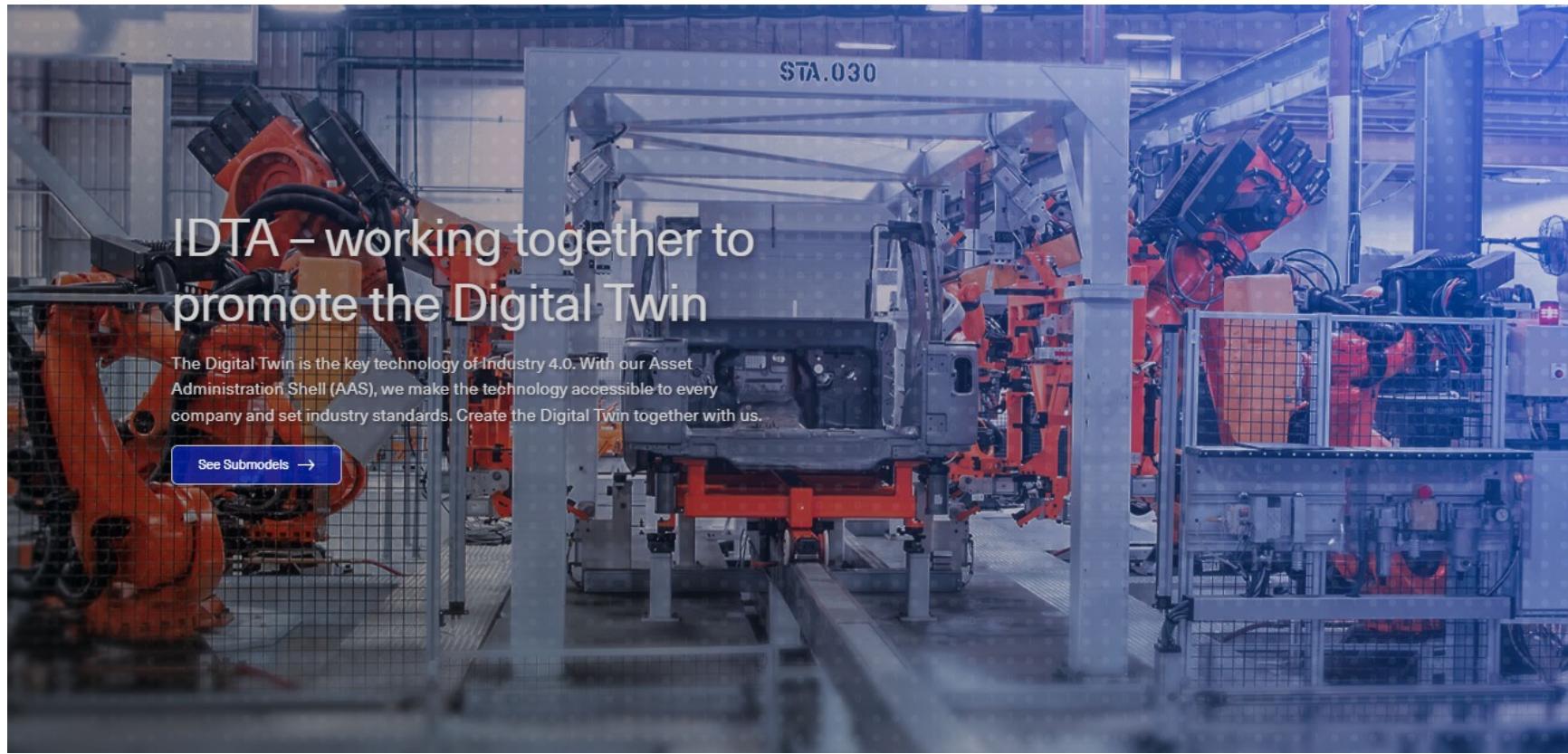
Software-Defined Manufacturing is all about Abstraction

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



Asset Administration Shells are a Foundation of SDM

Standardized digital representations of assets



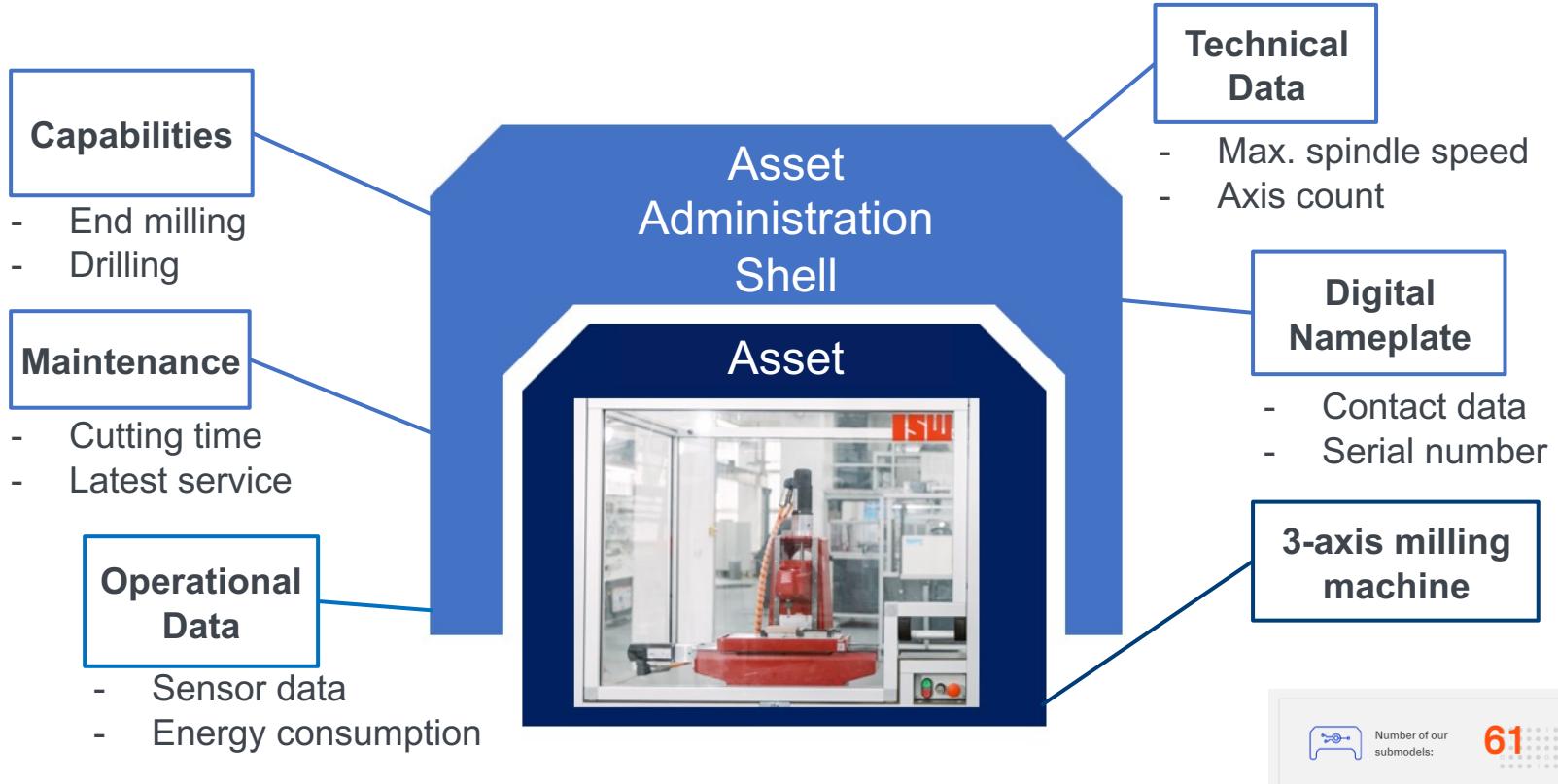
Asset Administration Shells

Everything of value can be an asset



Submodels are the Main Content of Asset Administration Shells

Describe content-related or functional aspects of an asset



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

There are 3 Kinds of Asset Administration Shells

And they relate to digital twins

Type 1 AAS

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→**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

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**
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- **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

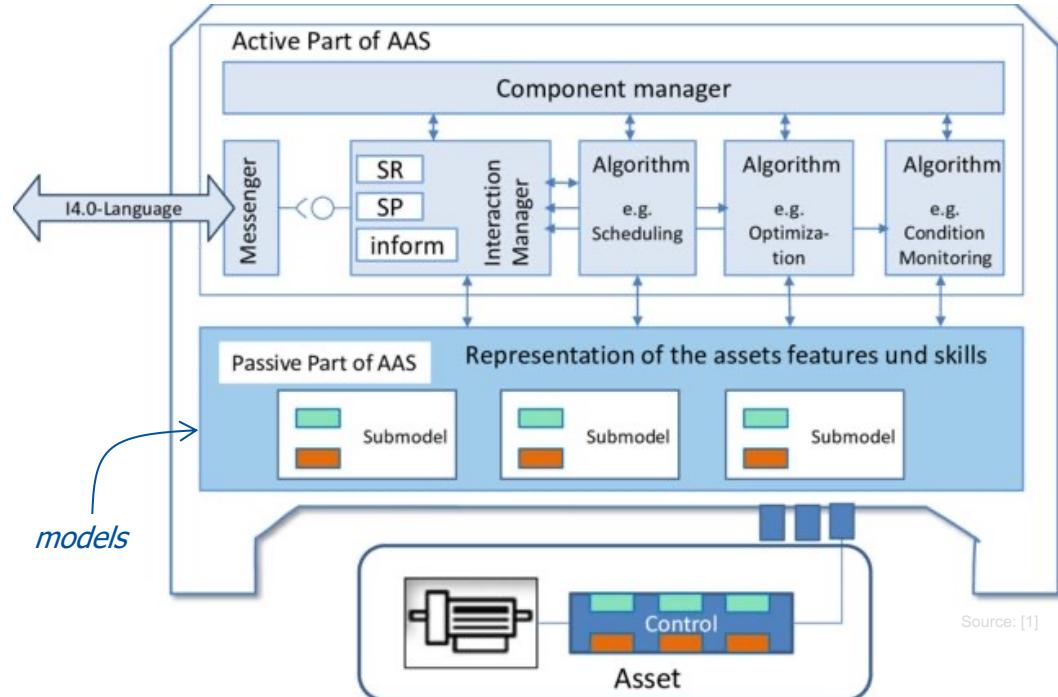
- Extend type 2 AAS
- Have **active behavior**
- Can start to **communicate & to negotiate** on their own
- **Well-defined language** and message structures (VDI/VDE 2193)
- **Automated dataflows from/to real system**
- **Software interfacing asset**

Digital Twin

A General Architecture of Type 3 Asset Administration Shells¹

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...

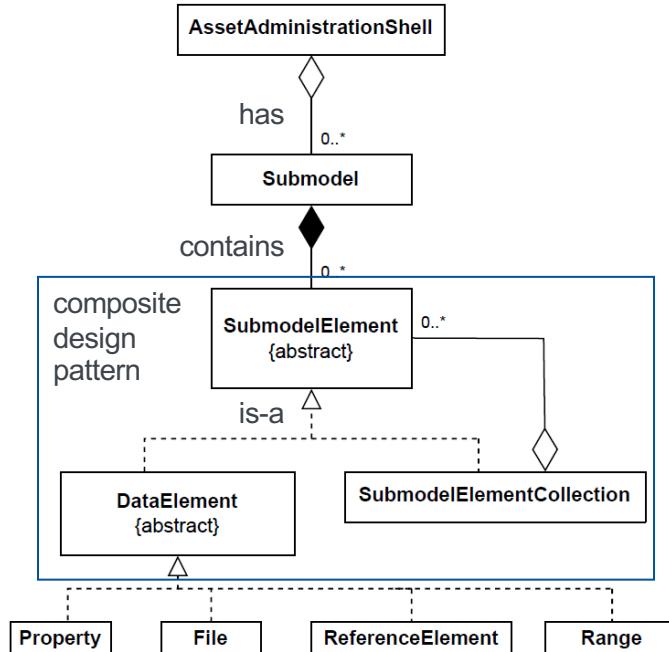


1. Belyaev, A., Diedrich, C. (2019). Aktive Verwaltungsschale von Industrie 4.0 Komponenten,“ in Automationkongress 2019, Baden-Baden.

Asset Administration Shells are a Technology, not a Method

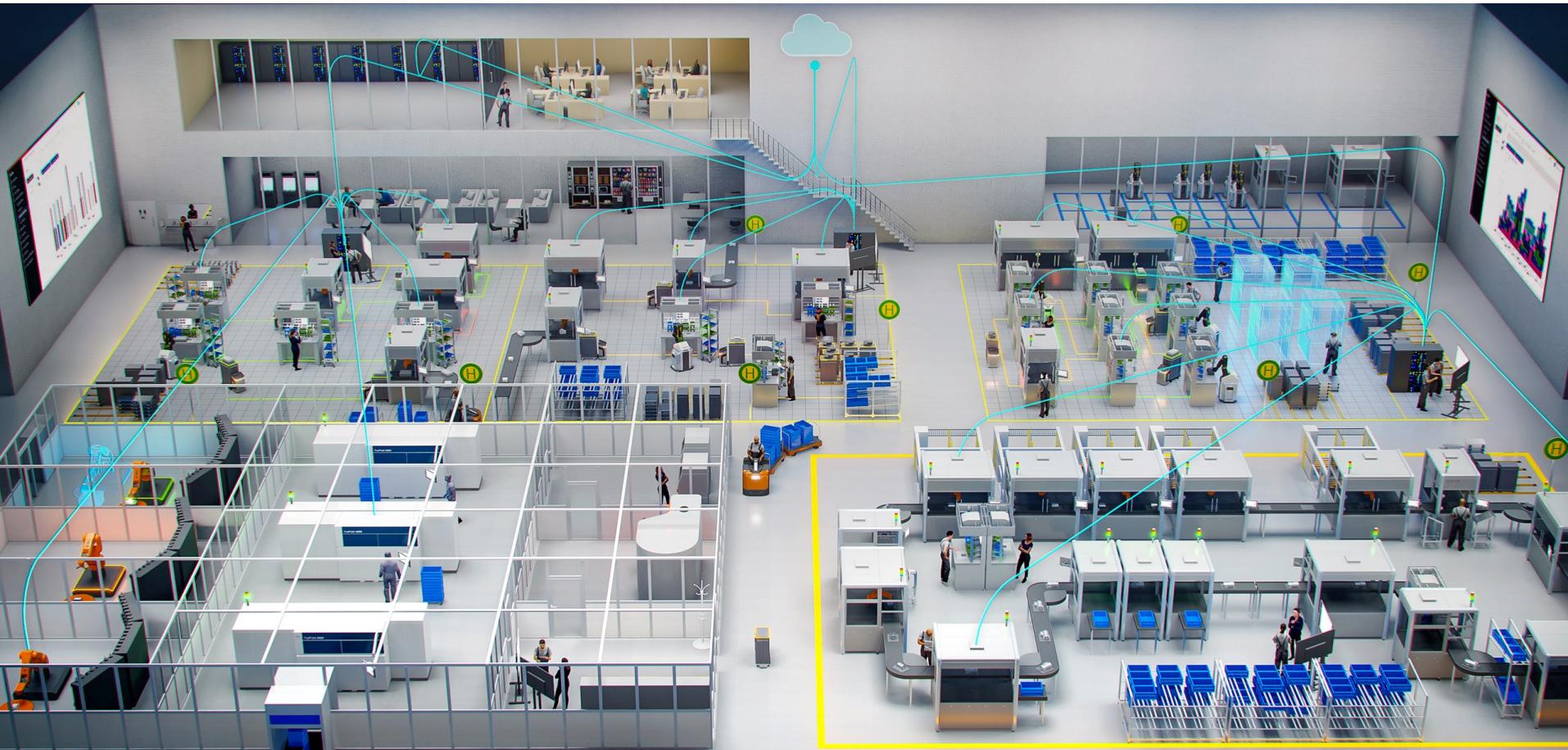
Software-defined manufacturing can build on it

- 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



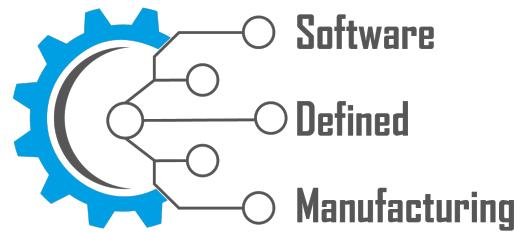
Software-Defined Manufacturing for Vehicle & Supplier Industry (SDM4FZI)

Our ongoing realization of software-defined manufacturing



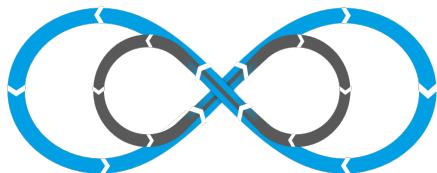
Software-Defined Manufacturing for Vehicle & Supplier Industry (SDM4FZI)

www.sdm4fzi.de



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

Core challenges



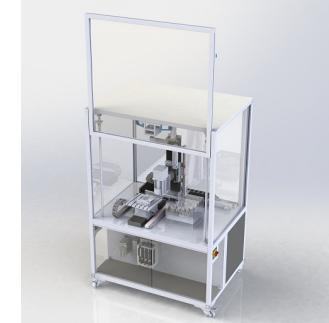
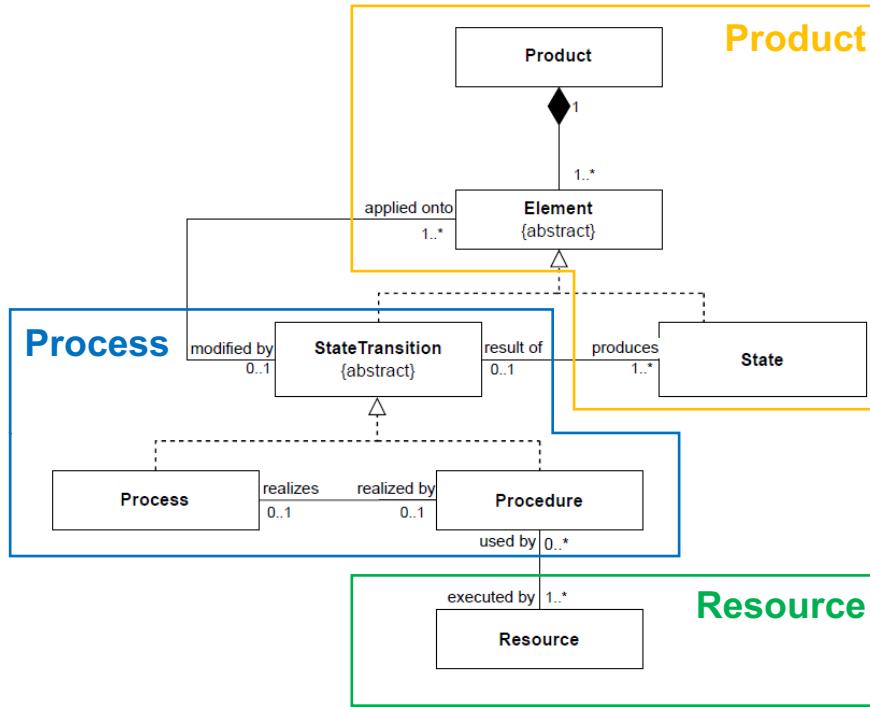
-  Reference model: The model defining the relations between the key aspects of production: products, resources and processes to ensure interoperability between models.
-  Technological infrastructure: Architecture integrates hardware, software, communication solutions for SDM.
-  Mastering mutability: 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.

Product-Process-Resource Metamodel¹ for Asset Administration Shells

The foundation of software-defined manufacturing



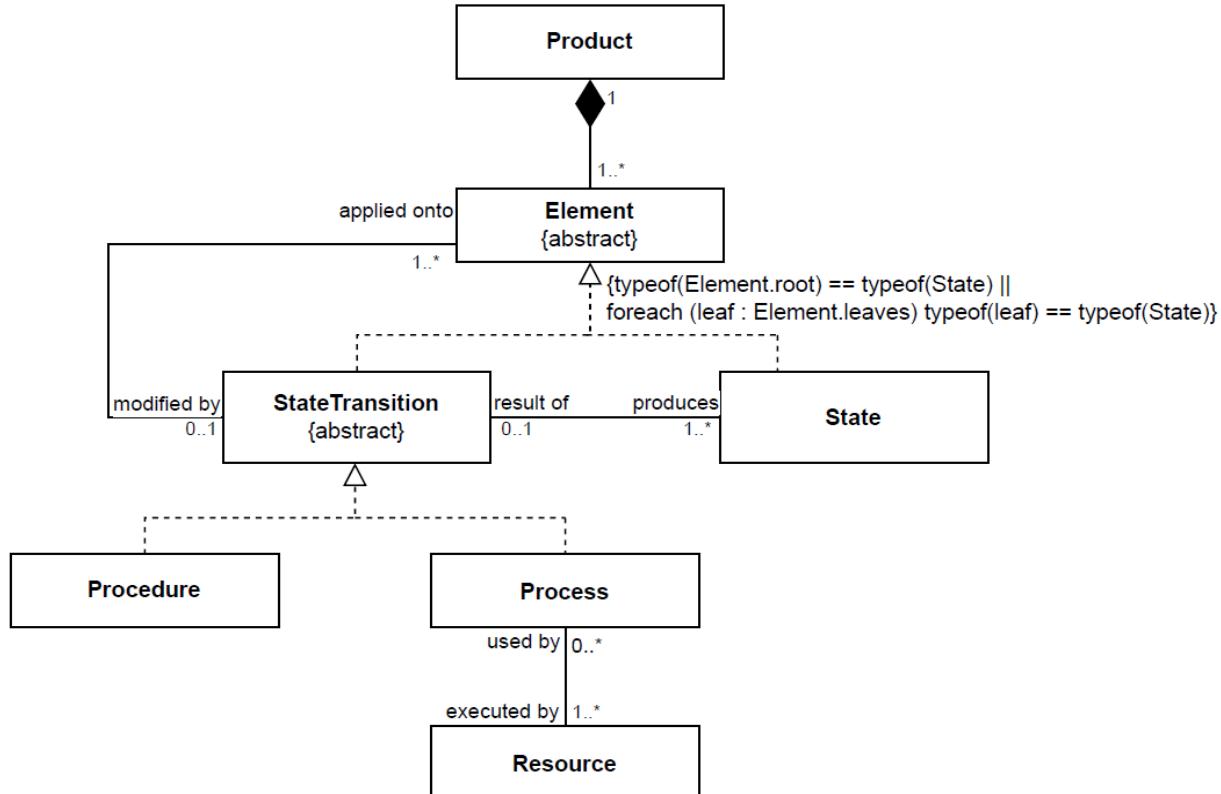
Source: <https://mav.industrie.de/>



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

Product (Sub-)Modeling in SDM4FZI

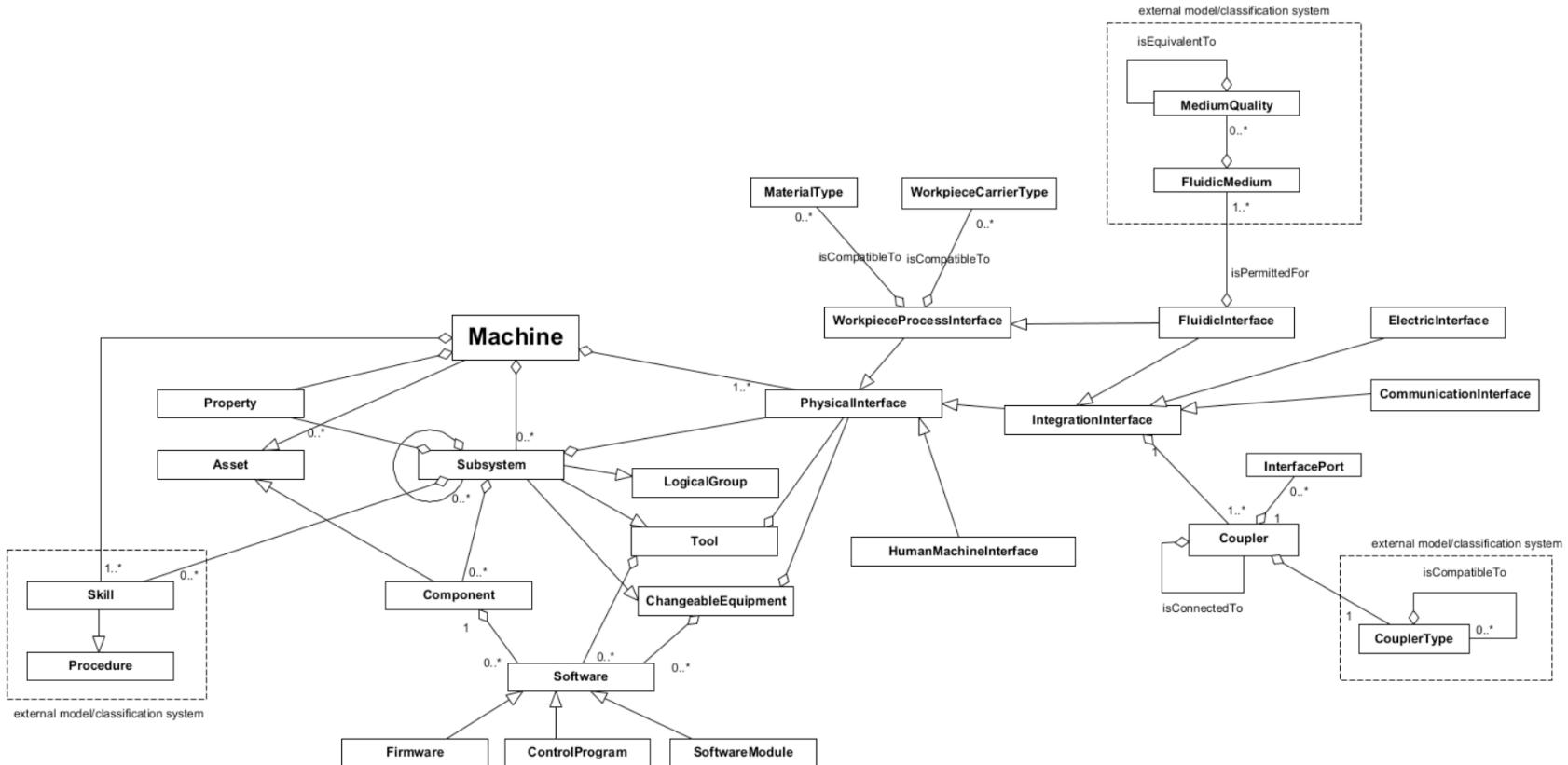
Products consist of elements that went through state transitions



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

Resource (Sub-)Modeling in SDM4FZI

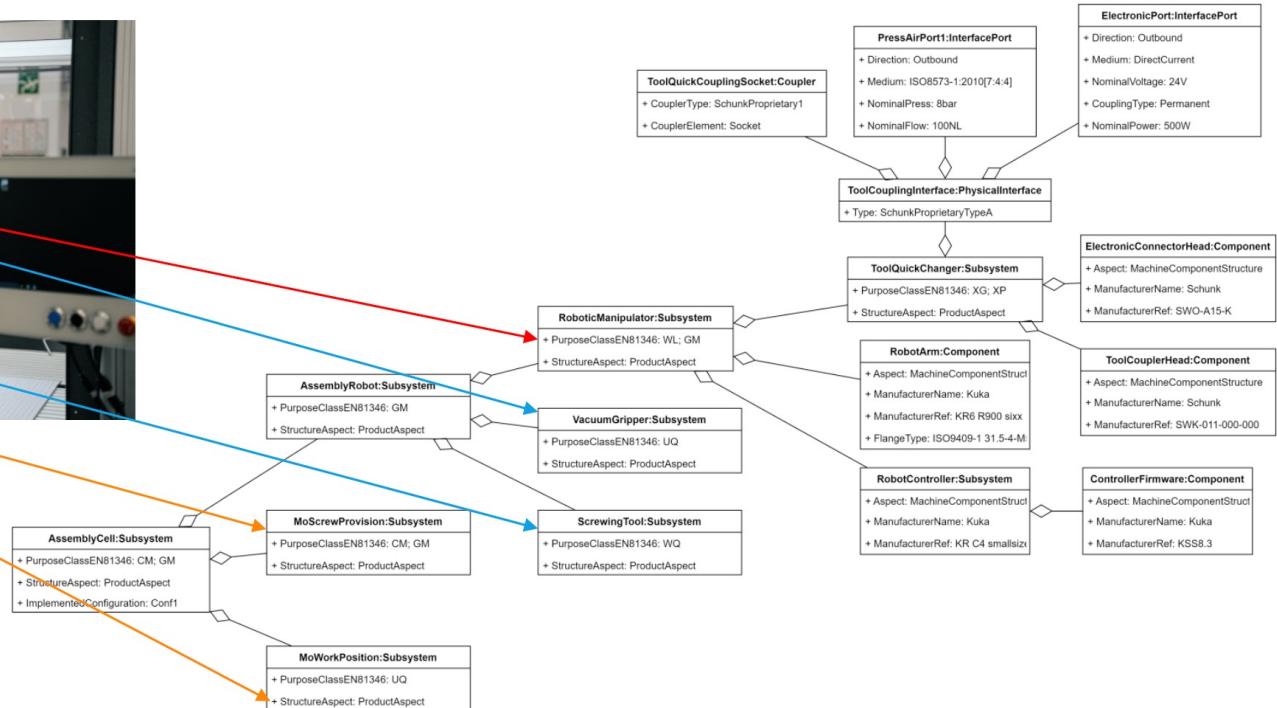
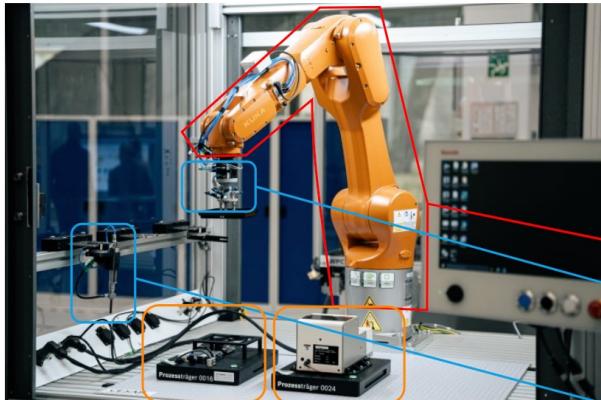
Resources are machines with subsystems, components, software and more.



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

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.

Stuttgarter Maschinenfabrik

A practical testbed for software-defined manufacturing



Stuttgarter Maschinenfabrik

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



Stuttgarter Maschinenfabrik

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



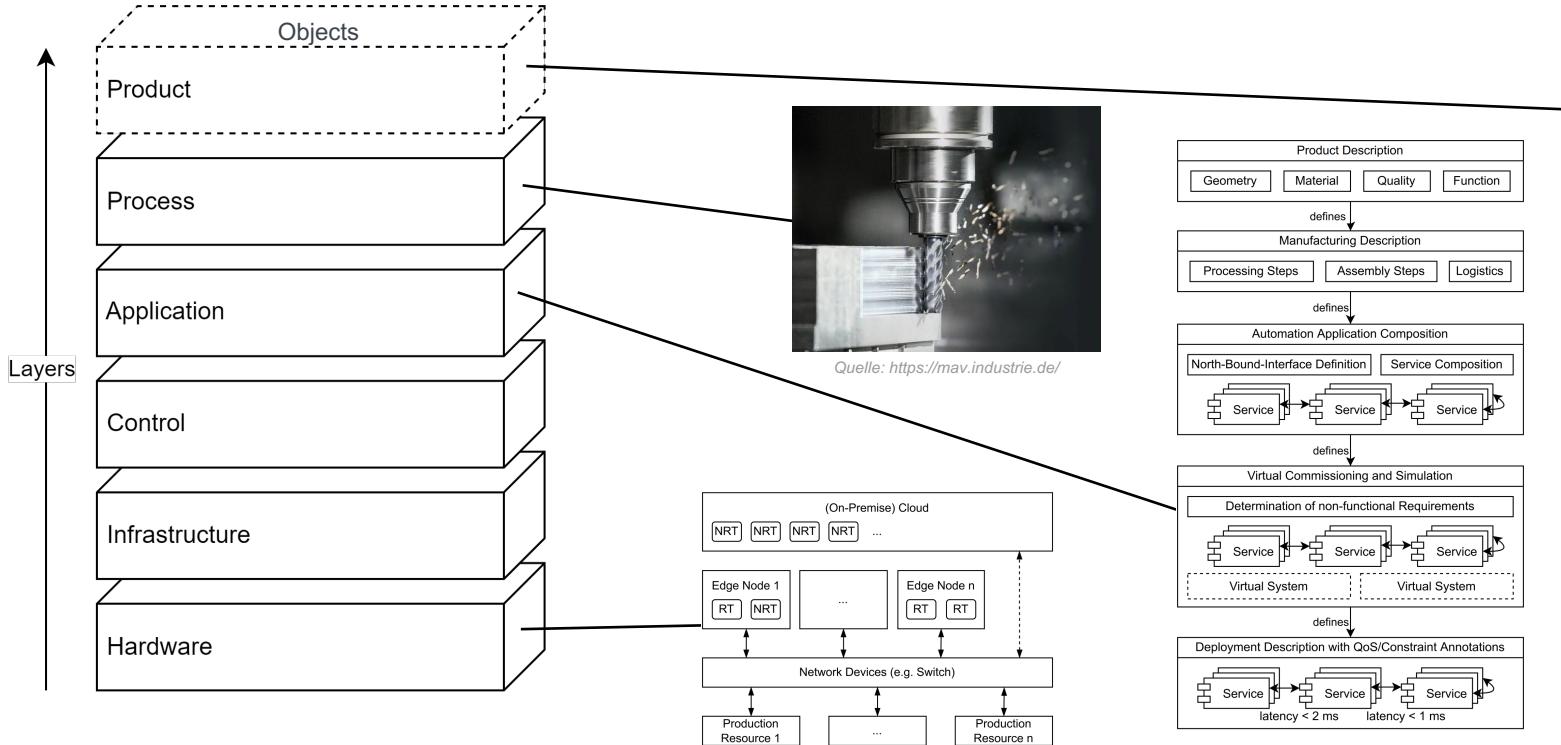
5X
5-axis milling machine



LarA
Laser processing center

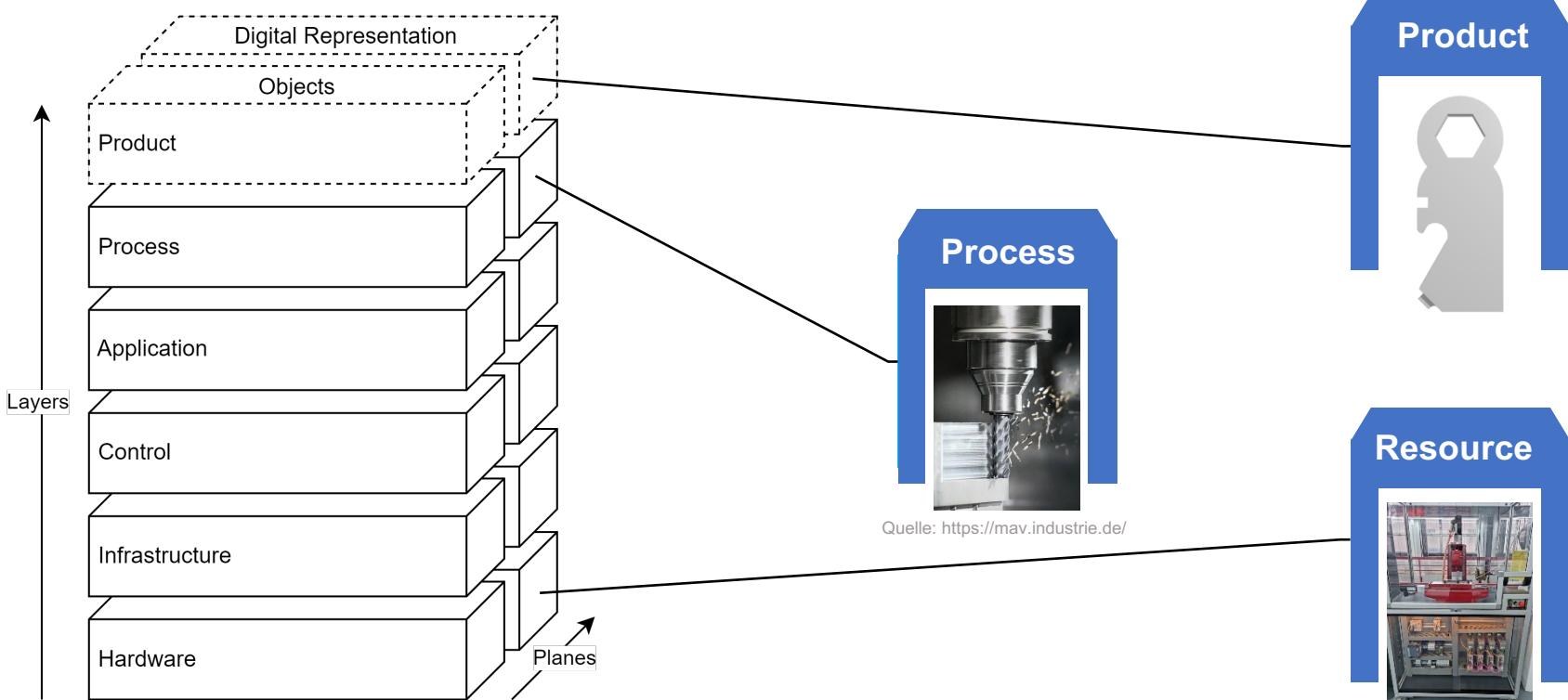
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Through the lens of process-product-resource asset administration shells



Stuttgarter Maschinenfabrik

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



Stuttgarter Maschinenfabrik

Design-time configuration and prediction of the multikey tool

SDM4FZI - Dashboard www.sdm4fzi.de

Configurator ✓ Confirm Configuration

Multi-Key-Tool milled ! required

Predefined Options Slotted Screwdriver Left Slotted Screwdriver Right

Customize

Bottleopener	milled	? optional <input checked="" type="checkbox"/>
Wrench Size 13	milled	? optional <input checked="" type="checkbox"/>
Key Ring Hole	hole	? optional <input checked="" type="checkbox"/>
Wrench Size 10	milled	? optional <input checked="" type="checkbox"/>
Wrench Size 8	milled	? optional <input type="checkbox"/>
Wrench Size 7	milled	? optional <input type="checkbox"/>
Wrench Size 5.5	milled	? optional <input type="checkbox"/>
Wrench Size 4	milled	? optional <input type="checkbox"/>
ISW Branding	milled	? optional <input type="checkbox"/>
Spoke wrench 3.23	milled	? optional <input checked="" type="checkbox"/>
Spoke wrench 3.45	milled	? optional <input checked="" type="checkbox"/>
Slotted Screwdriver	5-axes-slot	? optional <input type="checkbox"/>

feature selection →

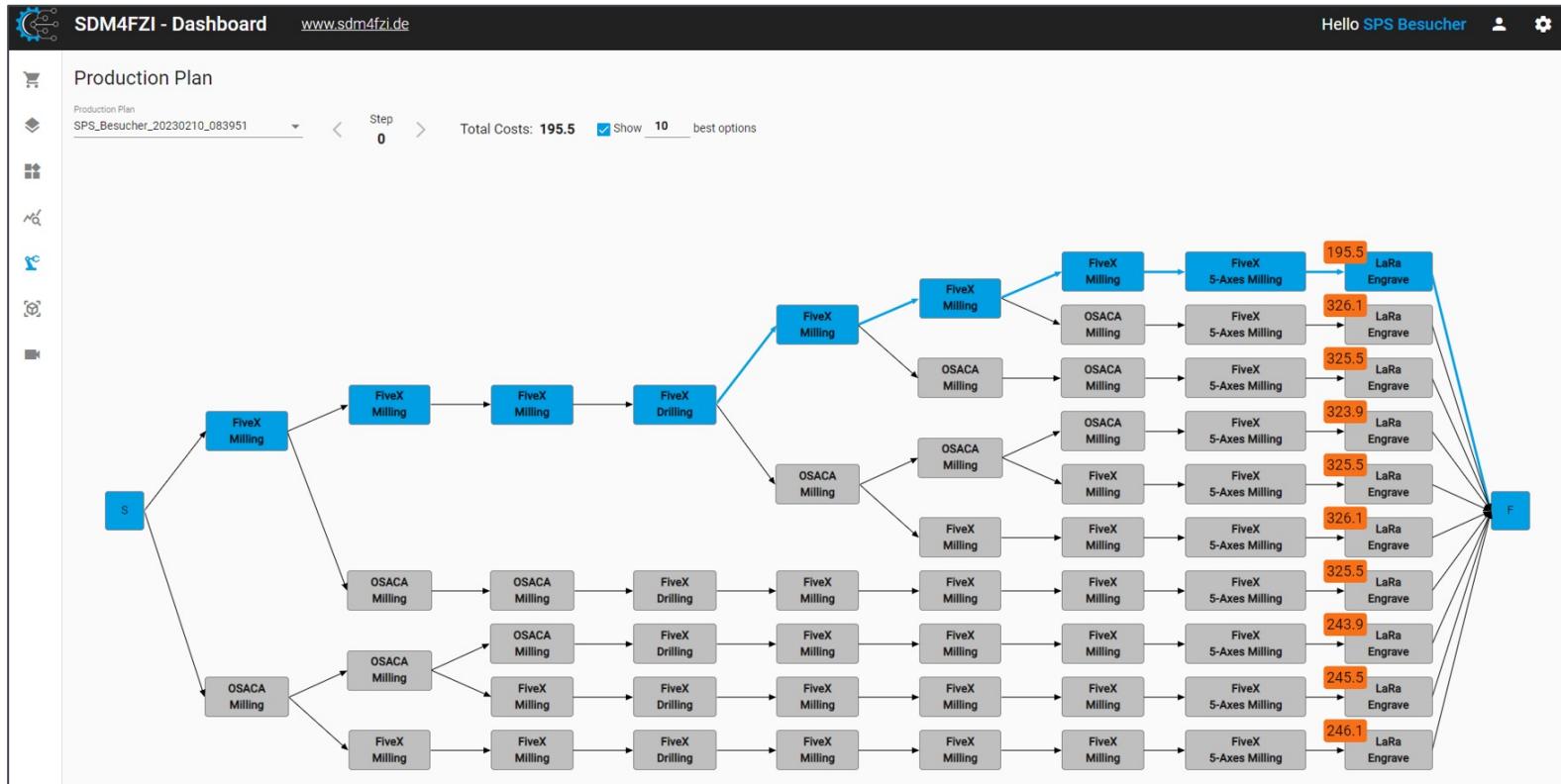
3D model of the configured MKT →



The 3D model of the configured MKT is shown on the right side of the dashboard. It is a multi-functional tool with several different shaped holes and slots, each corresponding to a selected feature from the configuration table. A callout arrow points from the text "3D model of the configured MKT" to the 3D model itself.

Stuttgarter Maschinenfabrik

Manufacturing planning and execution



Stuttgarter Maschinenfabrik

Asset administration shell representing the asset during manufacturing

*administration shell
of the real asset*

real asset

SDM4FZI - Dashboard www.sdm4fzi.de

Abstraction

Filter

AAS-MKT

0

modelType

name: AssetAdministrationShell

idShort: SPS_Besucher_20221107_142617

identification

dataSpecification

embeddedDataSpecifications

submodels

Nameplate

Construction

type: object

count: 2

CAD_File: http://object-rest-server.prj-sdm06.isw.uni-stuttgart.de/api/v1/SPS_Besucher_20221107_142617_FILE_STL.stl

Features_of_Multikeytool

Outer_Contour

Feature_Name: Outer_Contour

Reference_Point_of_Position: Center

Position_of_Reference_Point: (10;2;3)

Description_Parameters

Software

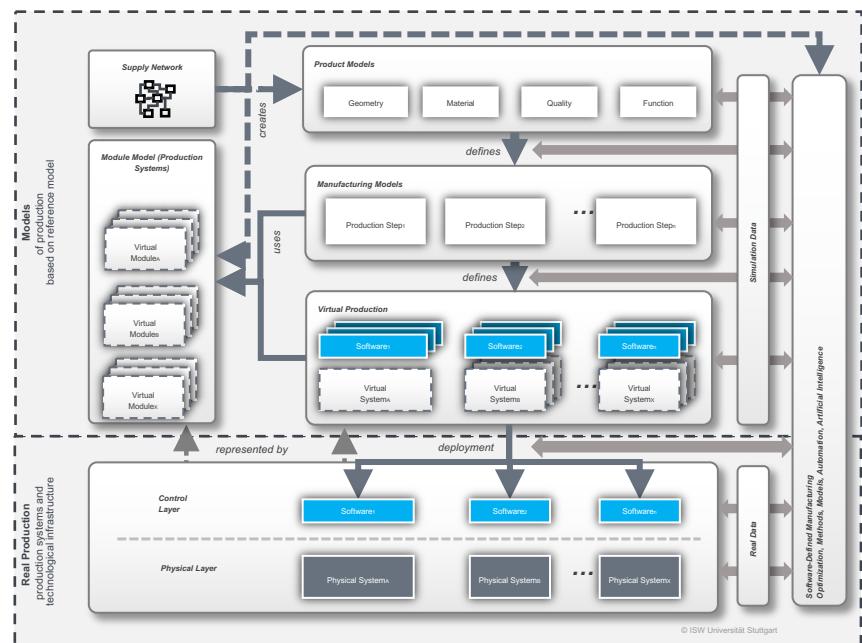
Defined

Manufacturing

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
 - Digital Models, Shadows, Twins
- PPR AAS ease flexibly reconfiguring production to volatile markets, uncertainties, complexities, ...
- Challenges
 - Further standardization of asset representation
 - End-to-end model-driven production
 - Methodical guidelines for implementation
 - Integration with AutomationML, OPC UA,



Thank You

More on model-driven engineering for production



www.wortmann.ac/presentations

RoSE 2023
Official web page of the 5th edition of the RoSE international workshop

5th International Workshop on Robotics Software Engineering (RoSE'23)

- Co-located with [ICSE 2023](#)
- Hybrid event, with collaborative/social session in Melbourne, Australia
- May 15, 2023

Theme & Goals

Increasingly, challenging domains employ robotic applications. Yet, Robotics still is one of the most challenging domains for software engineering. Deploying robotics applications

ICSE'23 Workshop RoSE

Andreas Wortmann

About Projects Publications Research Interests

Digital Twins

Research and industry leverage digital twins to monitor and control (cyber-physical) domains, including automotive, avionics, biology, construction, manufacturing, medicine, and many more domains. Despite the tremendous potential to reduce cost and time and improve our understanding of systems. The various digital twins serve different purposes, including analysis, control, and they are used at different times relative to the represented system, e.g., before design space or during its runtime to optimize its behavior. Despite a plethora of definitions being proposed, there is no consensus about what a digital twin is.

This also is reflected in many of the available definitions being

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ETFA 2023
28th INTERNATIONAL CONFERENCE ON EMERGING TECHNOLOGIES AND FACTORY AUTOMATION
SINAIA, ROMANIA
SEPTEMBER, 12th-15th, 2023

Call for Papers
SS02 - Software Engineering for Cyber-Physical Production Systems (SECPPS)

Organized and Co-Chaired by
István Koren¹, Kristof Meixner², Felix Rinker², Andreas Wortmann³

¹RWTH Aachen University, Germany
²TU Wien, Austria
³University of Stuttgart, Germany

FOCUS: With the emergence of Cyber-Physical Production Systems (CPPS), engineers are currently facing a dramatic increase in the complexity of developing and operating systems. In particular, software plays a crucial role in the effective and efficient operation of CPPSs. Despite the tremendous progress in software engineering approaches and technologies, they do not seem to reach industry. More comprehensive and systematic views on all aspects of systems and their development process are required. The Special Session on Software Engineering for Cyber-Physical Production Systems aims to discuss challenges in adopting state-of-the-art software engineering approaches and technologies to CPPSs, and highlight new methods for the design of software for production systems.

ETFA'23 Special Session SECPPS

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ModDIT 2022 2022, Montreal, Canada

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2nd International Workshop on Model-Driven Engineering of Digital Twins

ModDIT'22
co-located with MODELS 2022

About | Program | Call | Dates | Committees

About the Workshop

Digital twins provide tremendous potential to better understand and make use of cyber-physical systems in automotive, avionics, manufacturing, medicine, and many more domains. Despite many of the twinned systems being developed using models, engineering digital twins currently is ad-hoc and demands integrating different piecemeal technologies, which effectively hinders the application of digital twins. The focus of many digital twins and frameworks to create digital twins is on data acquisition and visualization via dashboards. Current research on digital twins focuses on specific implementations (bottom-up) or abstract models on how digital twins could be conceived (top-down). Yet, there is a huge gap between both views.

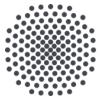
MODELS'23 Workshop MoDDiT

SE | 24
SOFTWARE ENGINEERING

Wir freuen uns darauf, die SE Community vom 26. Februar bis zum 1. März 2024 in Linz willkommen zu heißen!

Diese Seite gleich mal bookmarken - Mehr Infos folgen bald!
Kontakt: se2024@ikl.at (se2024.at/ikl-dnt.at)

Software Engineering 2024



University of Stuttgart

Institute for Control Engineering of Machine
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