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

Reflections about Digital Twins

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

First Things First

Slides available from

www.wortmann.ac/presentations

About Me

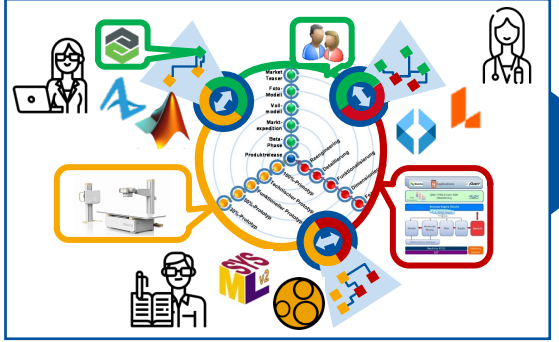
Jun.-Prof. Dr. rer. nat. habil. Andreas Wortmann

- Jun.-Prof. for model-driven software development at ISW
- Habilitation in Computer Science from RWTH Aachen University
- Deputy Coordinator in Internet of Production excellence cluster
- Senior researcher at Chair for Software Engineering or RWTH
- PhD in software engineering on model-driven software architecture
- Research interests
  - Model-driven software
  - Software languages
  - Software architecture
  - Application: CPS, IoT, I4.0
- 100+ publications
- 6 lectures, 12 seminars/project classes, 60+ theses

Enabling Domain Experts to Contributing Machine-Processable Solutions

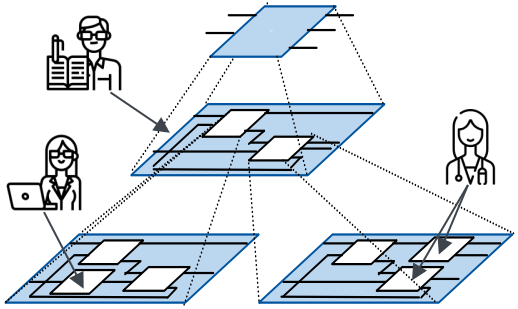
Through better abstraction and automation

Systematic Software Language Engineering



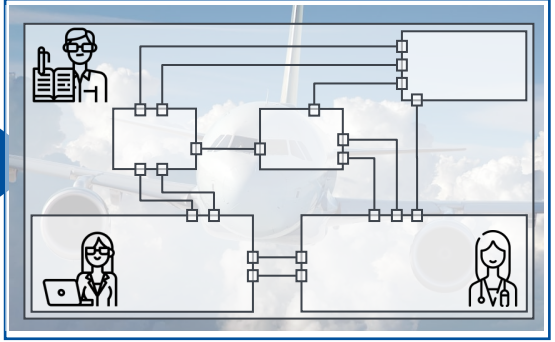
- Component-based language engineering
- Systematic reuse via language product lines
- Improves modeling precision and domain expert integration

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

What are Digital Twins?

A Simple Truth about Digital Twins

A digital twin represents a system

A Simple Truth about Digital Twins

Is it?

A digital twin represents a system

Is it always one?
Can there be many?

Digitalization entails abstraction: how much can we abstract?

What does it mean to be a twin?

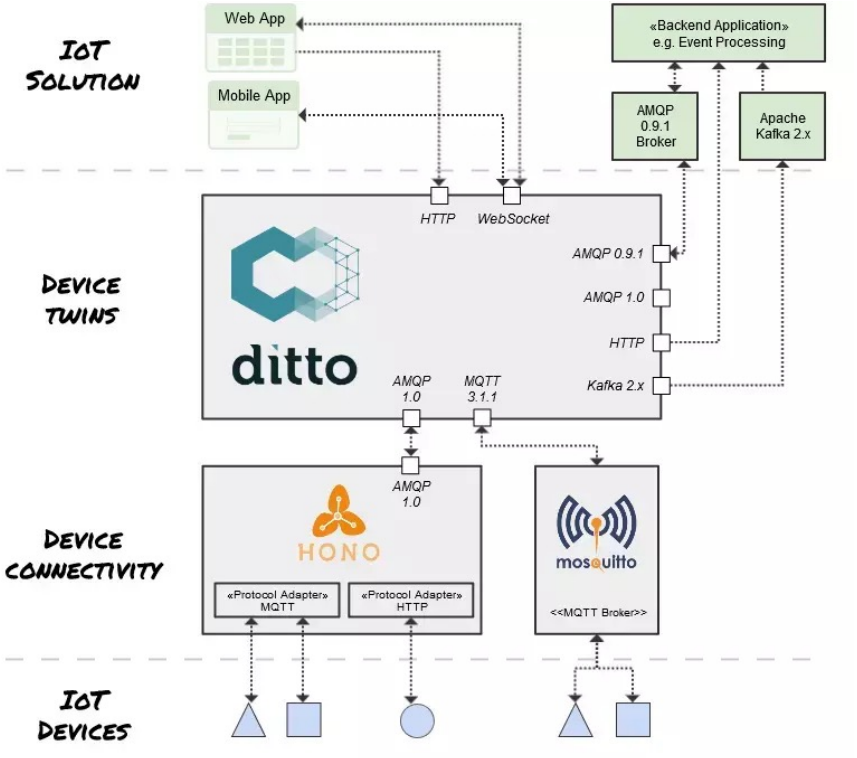
Is this the only purpose?

A single one? Many? Systems-of-systems? Does the system need to exist already?

Does it need to be a CPS? Process twins or person twins?

Digital Twins in the Eclipse Infrastructure

Use Vortho DSL to describe DTs as SW components (ca. function blocks)



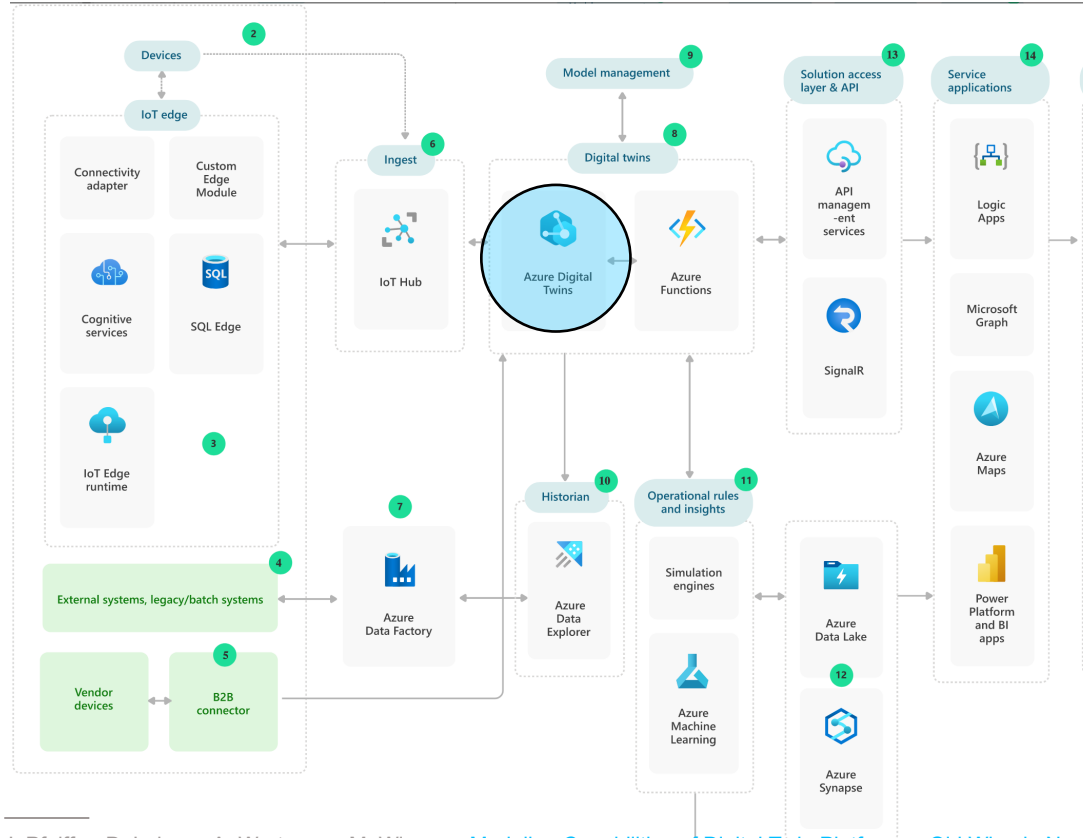
Eclipse Vortho DSL Example

```
namespace com.acme
version 2.0.0
displayname "Raspberry Pi"
description "Raspberry Pi with onboard
sensor and GPS module"

using org.eclipse.vorto.Location; 1.0.0
using org.eclipse.vorto.Temperature; 1.0.0

infomodel RaspberryPi{
functionblocks {

   temperature as Temperature
   location as Location

}
```

J. Pfeiffer, D. Lehner, A. Wortmann, M. Wimmer: Modeling Capabilities of Digital Twin Platforms - Old Wine in New Bottles. Journal of Object Technology, Volume 21, no. 3, 2022.

Digital Twins in Microsoft Azure

Use DTDL to describe interfaces & data structures (ca. UML CD / OPC UA)



Definition: A digital twin is a **digital model** of real-world things, places, business processes, and people

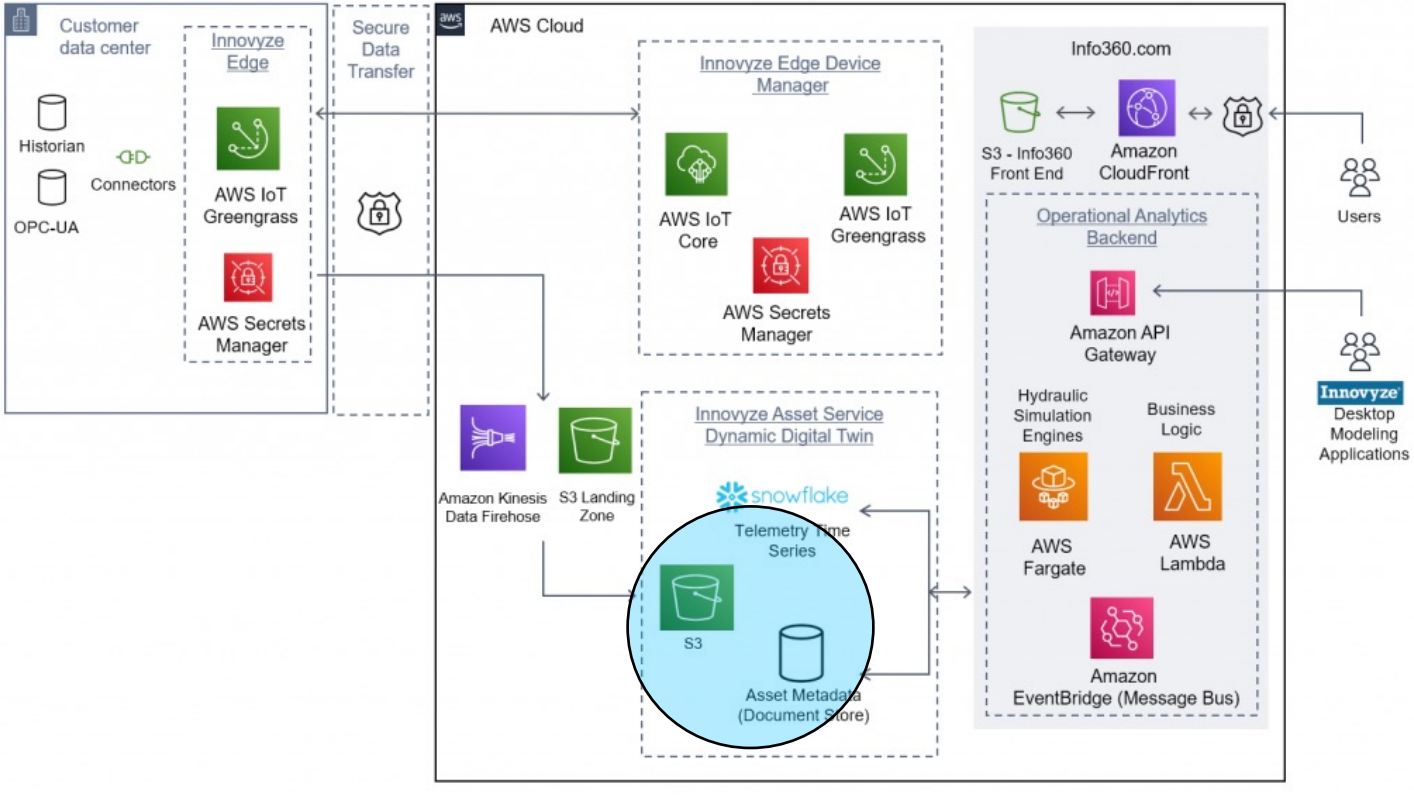
MS DTDL Example

```
{
  "@id": "dtmi:com:example:Building;1",
  "@type": "Interface",
  "displayName": "Building",
  "contents": [
    {
      "@type": "Property",
      "name": "name",
      "schema": "string",
      "writable": true
    },
    {
      "@type": "Relationship",
      "name": "contains",
      "target": "dtmi:com:example:Room;1"
    }],
  "@context": "dtmi:dtdl:context;2"
}
```

J. Pfeiffer, D. Lehner, A. Wortmann, M. Wimmer: Modeling Capabilities of Digital Twin Platforms - Old Wine in New Bottles. Journal of Object Technology, Volume 21, no. 3, 2022.

Digital Twins in Amazon AWS

The digital twin is data in an S3 database or document store



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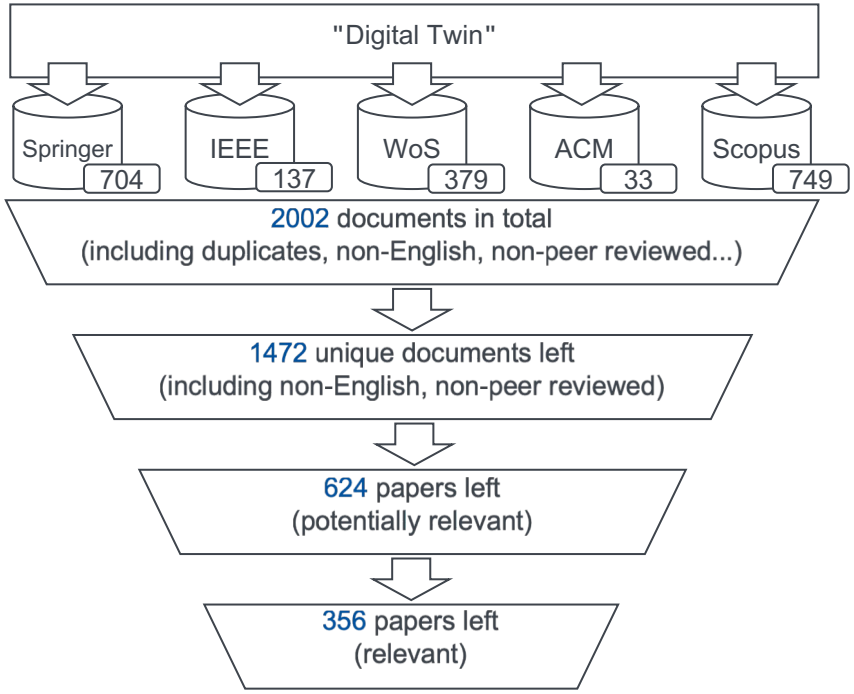
A Systematic Cross-Domain Mapping Study for Digital Twins

Research questions and overview

1. Who uses Digital Twins for which purposes?
2. What are the conceptual properties of Digital Twins?
3. How are Digital Twins engineered?
4. How are Digital Twins deployed?
5. How do Digital Twins operate?
6. How are Digital Twins evaluated?

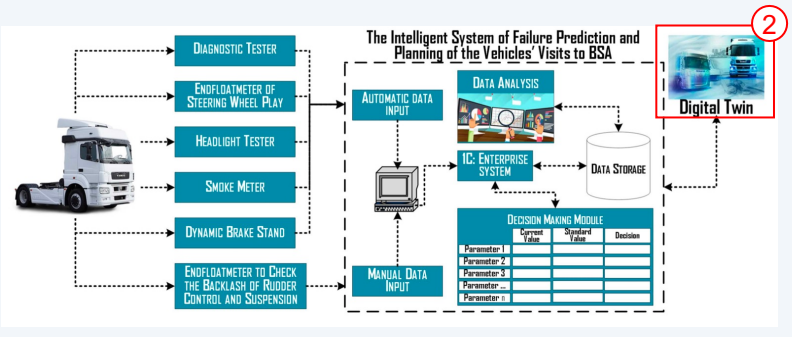


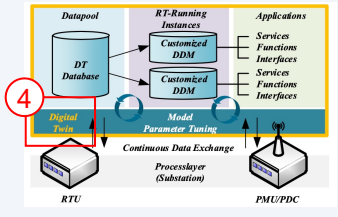
M. Dalibor, N. Jansen, B. Rumpe, D. Schmalzing, L. Wachtmeister, M. Wimmer, A. Wortmann: *A Cross-Domain Systematic Mapping Study on Software Engineering for Digital Twins.* Journal of Systems and Software, 111361, 2022.

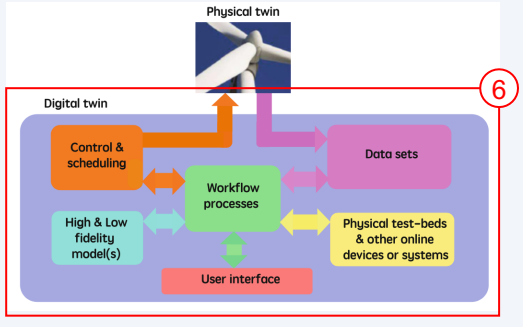
Digital Twins come in a Spectrum of various Shapes and Purposes

And are used at different times throughout systems engineering

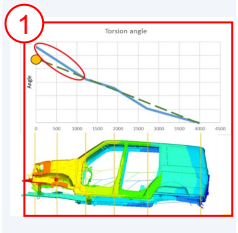
Active

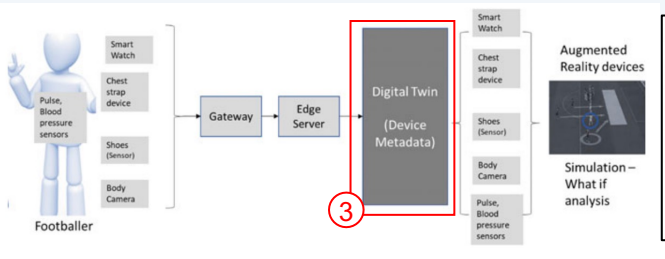


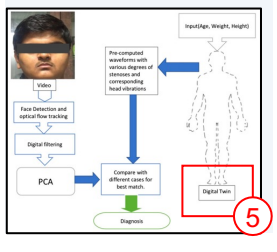


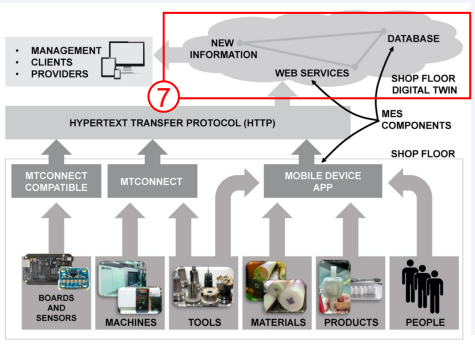


Passive









Design Time → Runtime

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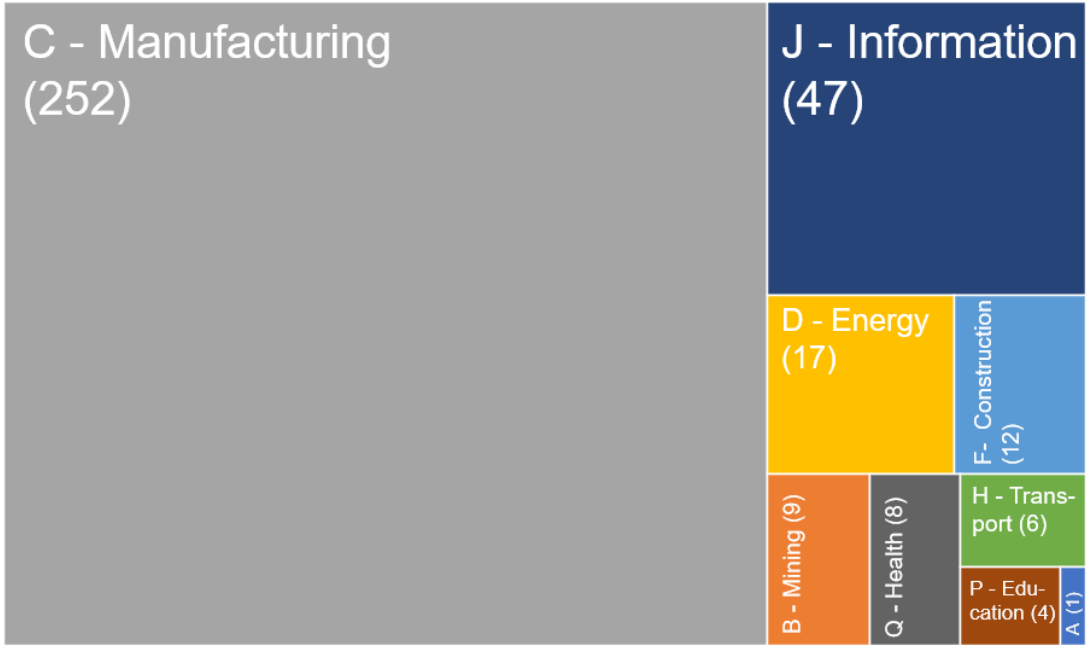
Who uses Digital Twins?

Mostly manufacturing

- According to the Level 1 classes of the Statistical Classification of Economic Activities in the European Community
- Manufacturing >> rest
- Information includes domain-independent approaches (cf. Azure, AWS, …)
- „A“… Agriculture, Forestry and Fishing



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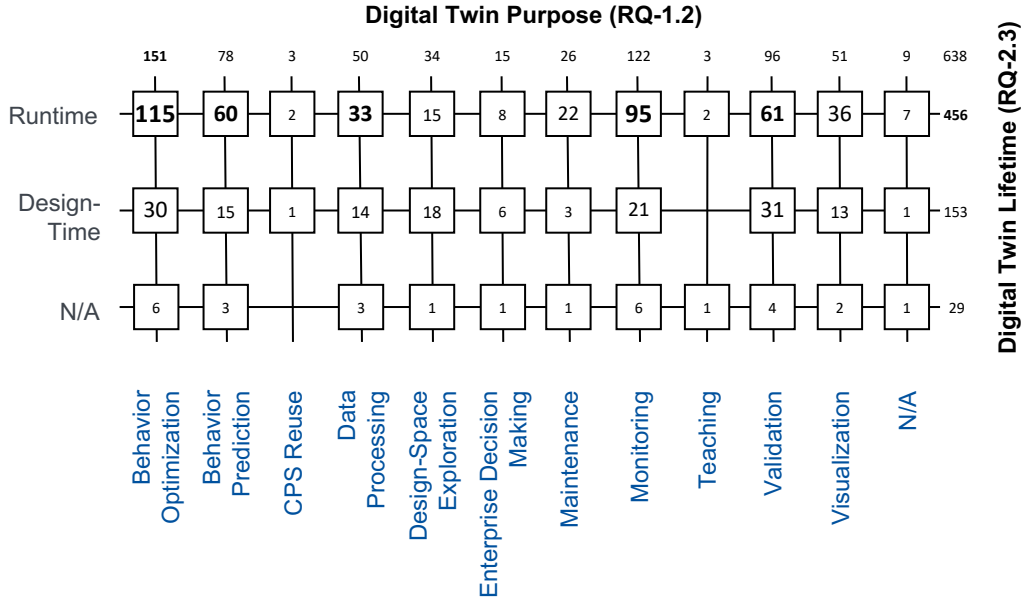
What are Digital Twins used for?

Many purposes are behavioral

- 356 papers, some w. multiple purposes
- Strong focus on using digital twins at runtime of the twinned system
- Main purposes behavioral
  - Monitor
  - Predict
  - Optimize
  - Validate
- Some counterintuitive findings
  - Design-space exploration at runtime



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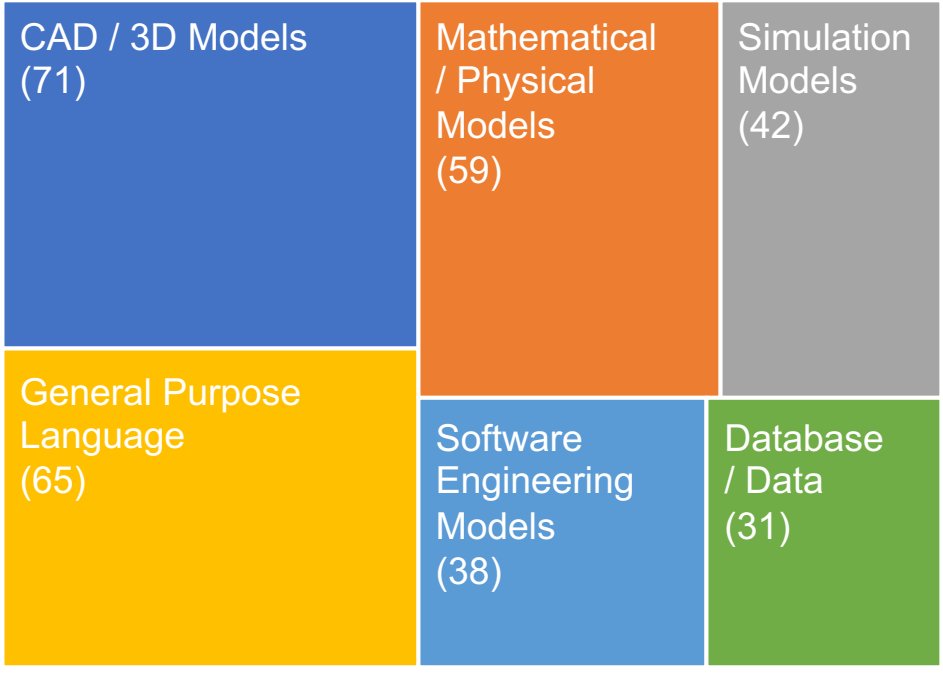
Digital Twins are Mostly Build with CAD models and GPL Code

Software engineering models used less prominently

- Most prominent CAD > GPL > Math/Phys > Simulation > SE > …
- CAD often used at design-time and/or for visualization of the twinned system
- GPL used for data transfer, analyses
- Mathematical/physical models for static analysis
- Simulation models for dynamic analysis
- Some digital twins don't use models at all



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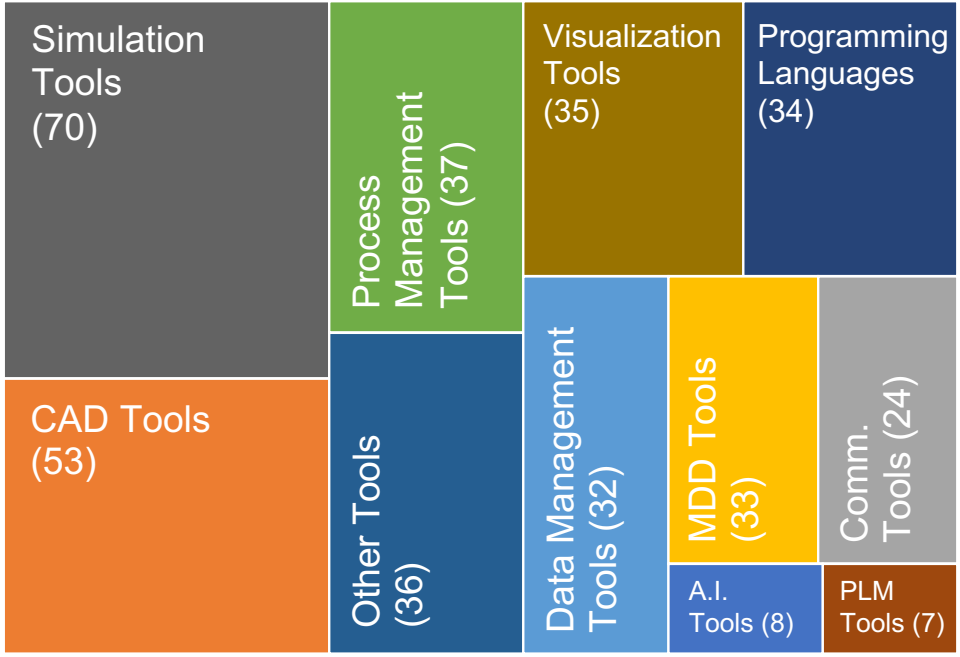
Digital Twins Mostly use Simulation and CAD Tools

Which might hint at using them before the original system

- Most prominent tools to engineer digital twins are simulation tools and CAD tools
  - Aim for precise replica of system
  - Used to systems for a physical-geometrical perspective
  - Used at design time
- Many process / data management tools
  - Better understanding of twinned system
- Only little use of AI with digital twins



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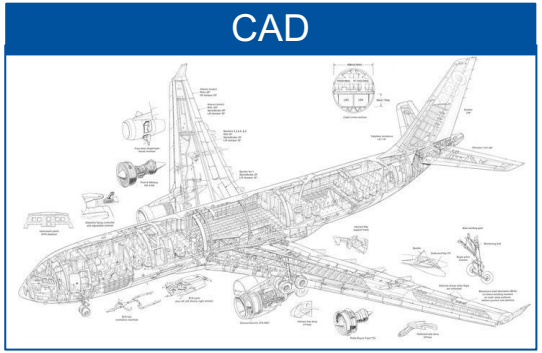
Take-away message

A digital twin is a simulation model of an existing system

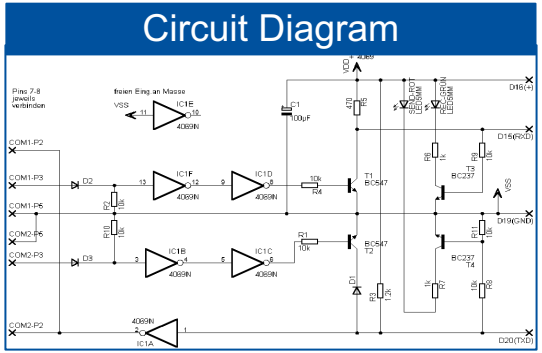
Then all of these Models are Digital Twins Obviously

As all of these models can be used to simulate an existing system

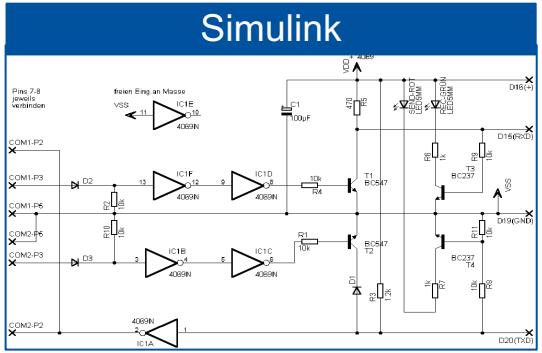
CAD



Circuit Diagram



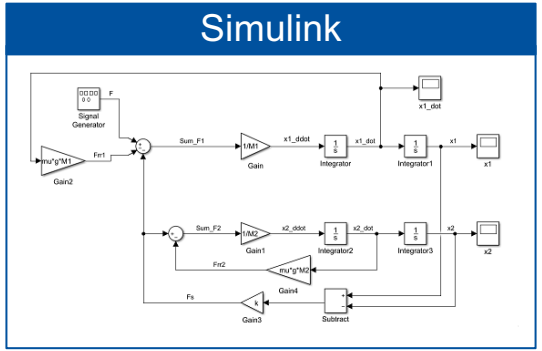
Simulink



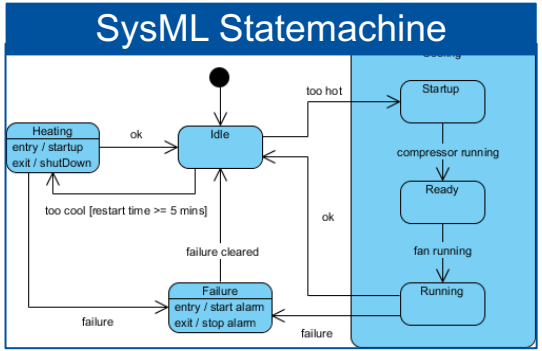
Math

$$s[m] = v\left[\frac{m}{s}\right] * t[s]$$

Simulink



SysML Statemachine



Take-away mess

A digital t… simulation model of an exis…ystem

How Research Describes Digital Twins

And why this is problematic

Ambiguous Descriptions

Refer to other, undefined, terms

- “digital avatar” [74]
- “replica of a business process” [337]
- “mimic of a real-world asset” [386]
- “digital equivalent to a physical product” [523]
- “digital duplicate” [1389]

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Narrow Descriptions

Focus on a specific kind of system or implementation tech.

- “digital model of the real network environment” [379]
- “a virtual representation of a specific product” [388]
- “virtual representation based on AR-technology” [827]

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- "virtual representation based on AR-technology" [827]

Unfeasible Descriptions

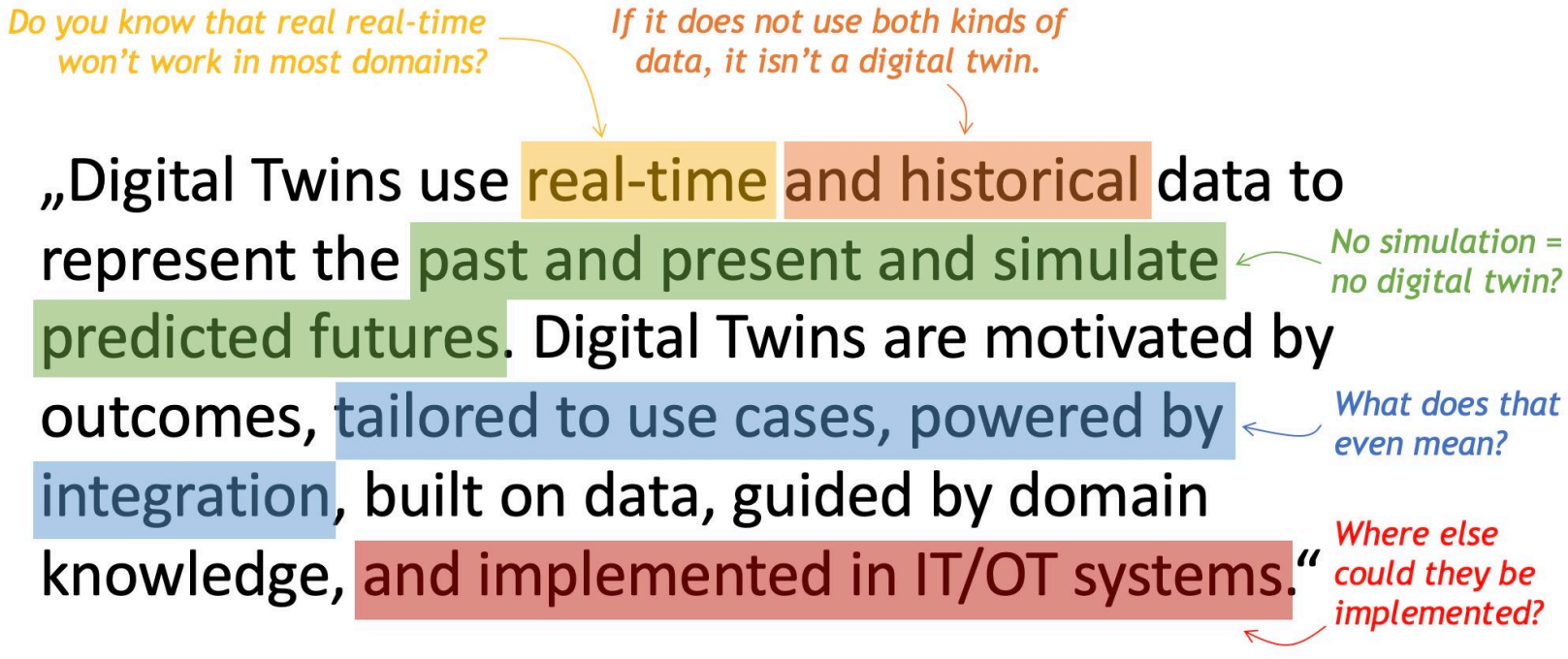
Theoretically nice, practically unfeasible

- "integrated virtual model of a real-world system containing all of its physical information" [393]
- "a complete virtual representation of a physical part or process" [1079]

M. Dalibor, N. Jansen, B. Rumpe, D. Schmalzing, L. Wachtmeister, M. Wimmer, A. Wortmann: *A Cross-Domain Systematic Mapping Study on Software Engineering for Digital Twins.* Journal of Systems and Software, 111361, 2022.

Digital Twin Consortium

“A digital twin is a virtual representation of real-world entities and processes, synchronized at a specified frequency and fidelity.”



https://www.digitaltwinconsortium.org/glossary/glossary/#digital-twin

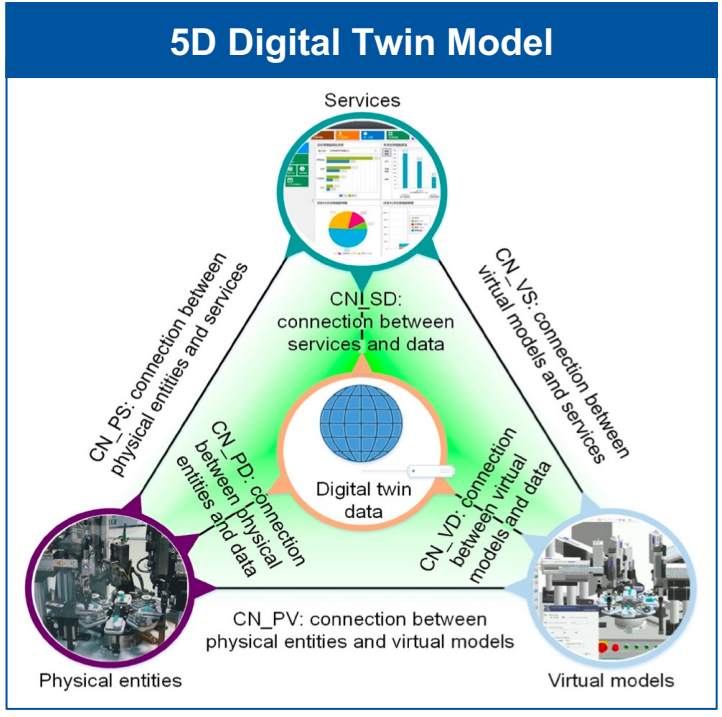
Take-away message

Most definitions of the term "digital twin" cannot distinguish them, are hardly generalizable, or not pragmatic.

A Digital Twin Definition based on their Constituents

In the 5D digital twin model, a digital twin comprises…

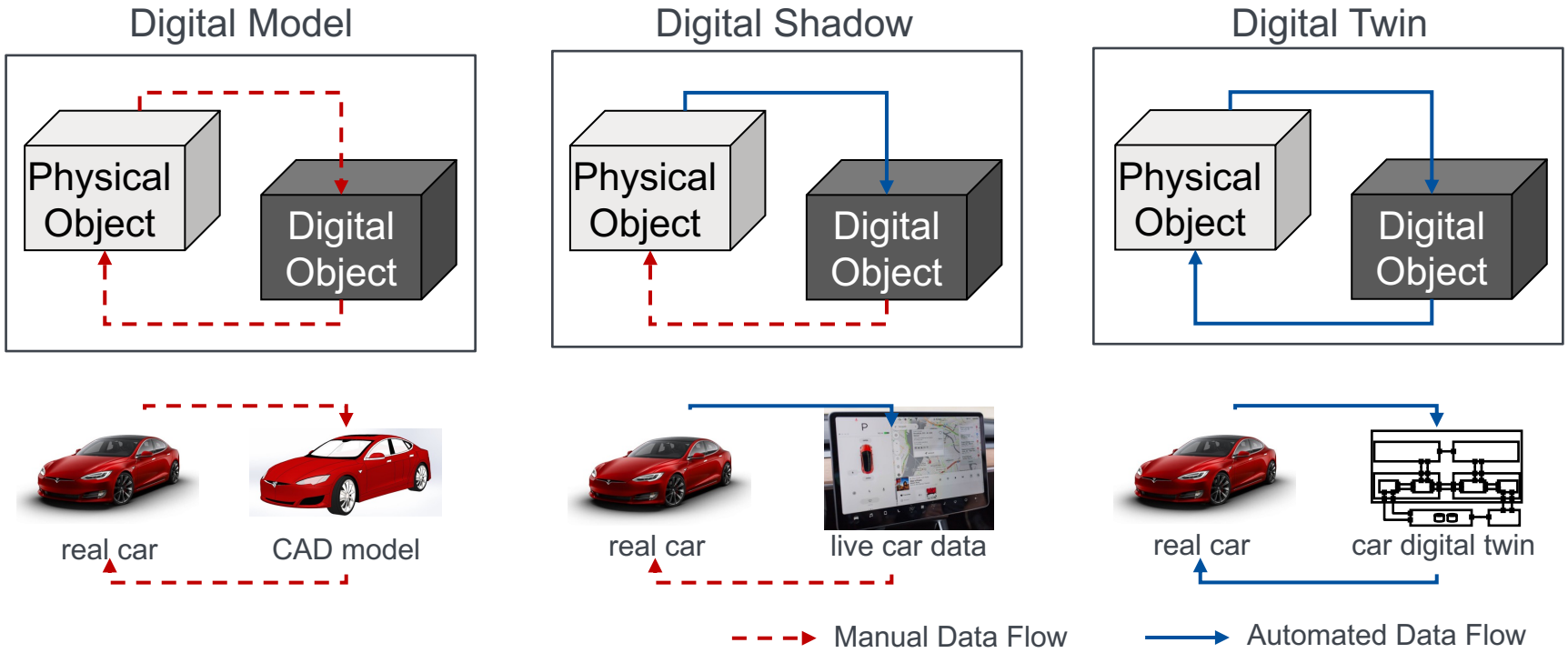
1. Physical object: Beings, cyber-physical systems, …
2. Digital object: Models, software infrastructures, VR, …
3. Services: Monitoring, optimization, prediction, …
4. Digital data: Sensor readings, manufacturing orders, …
5. Connections: WiFi, ethernet, fieldbus, …



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

A Characterization based on Data Flows

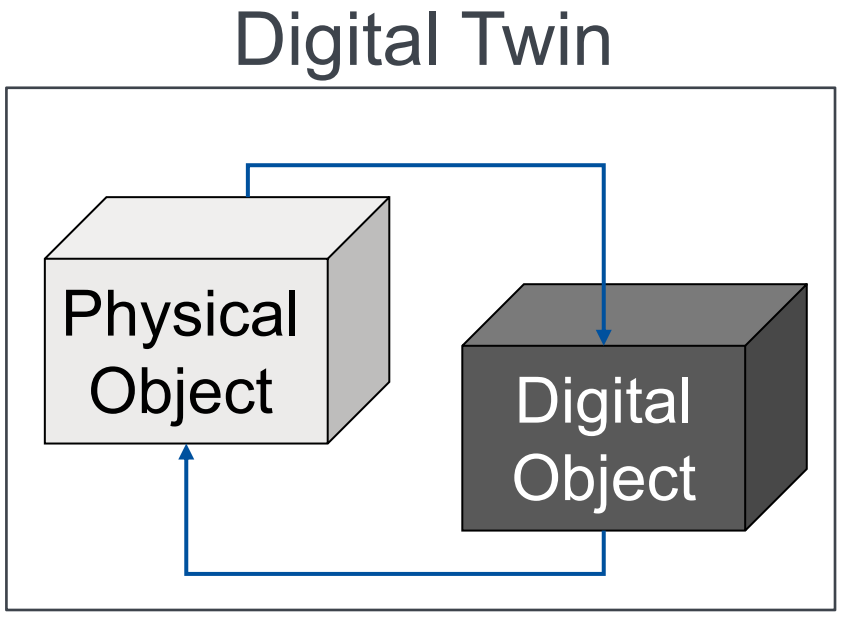
If the data flows between system and twin are of a specific form, then it is a …



Kritzinger, W., Karner, M., Traar, G., Henjes, J., & Sihn, W: *Digital Twin in manufacturing: A categorical literature review and classification*. IFAC-PapersOnLine, 2018.

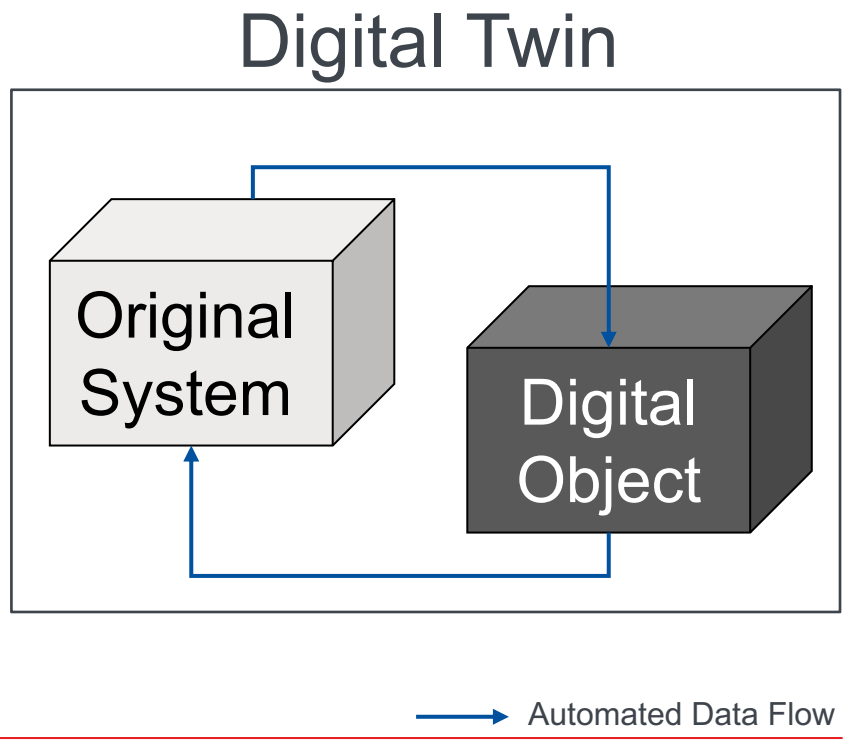
Zooming in this Definition Reveals some Issues

- Being a purely physical object is not enough
  - How would you get data from/to a tree?
  - The original system needs to be a CPS



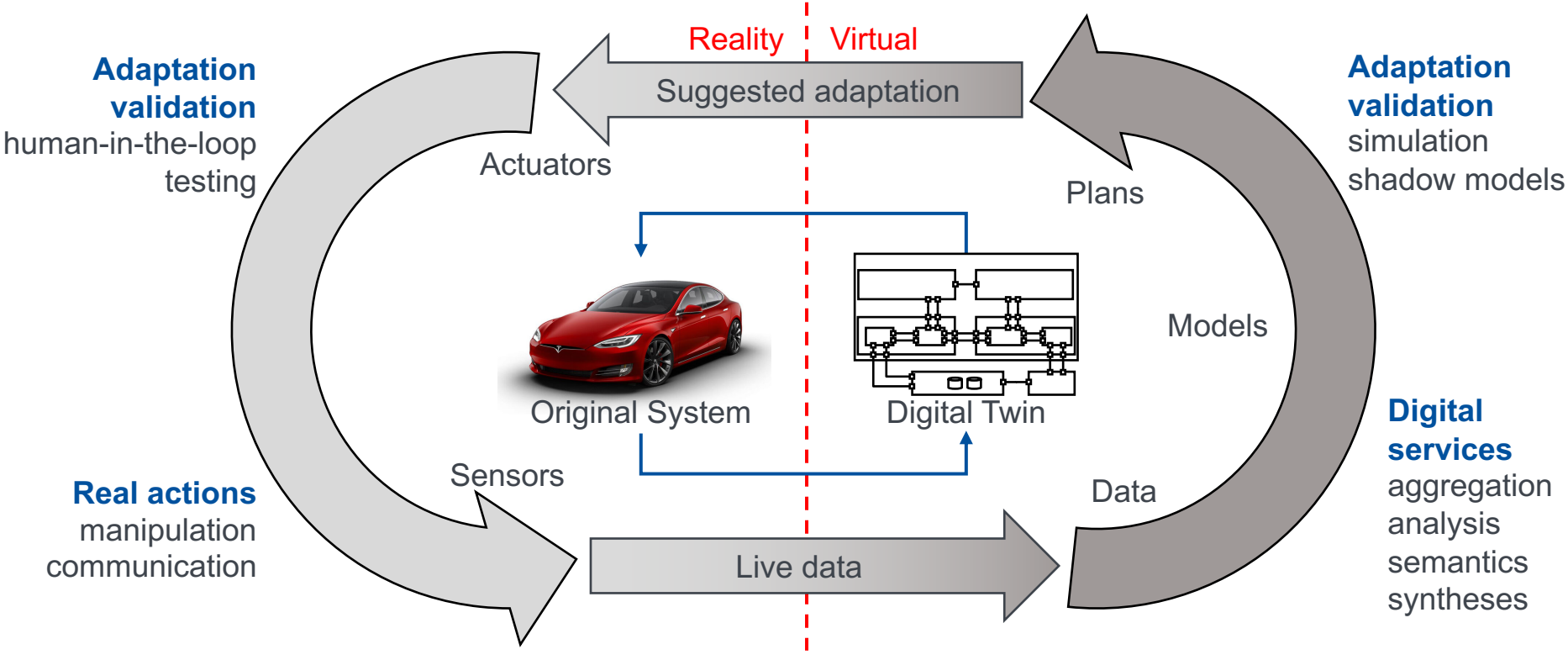
Zooming in this Definition Reveals some Issues

- Being a purely physical object is not enough
  - How would you get data from/to a tree?
  - The original system needs to be a CPS
- The digital twin might come to conclusions undesired for the original system
  - Control needs limitations (possibly HiL)
- This prevents digital twins of processes
  - Unless being a (single) digital twin of a system-of-systems



A Pattern for Digital Twins

Understood as adaptive systems interacting with their original systems

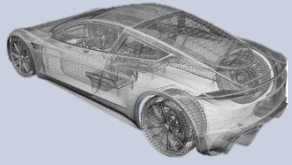
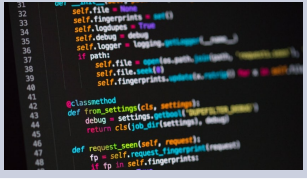


Take-away

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

Distinguishing Model-Driven Digital Twin Entities

Enforcing honesty: what do we mean when saying “digital twin”?

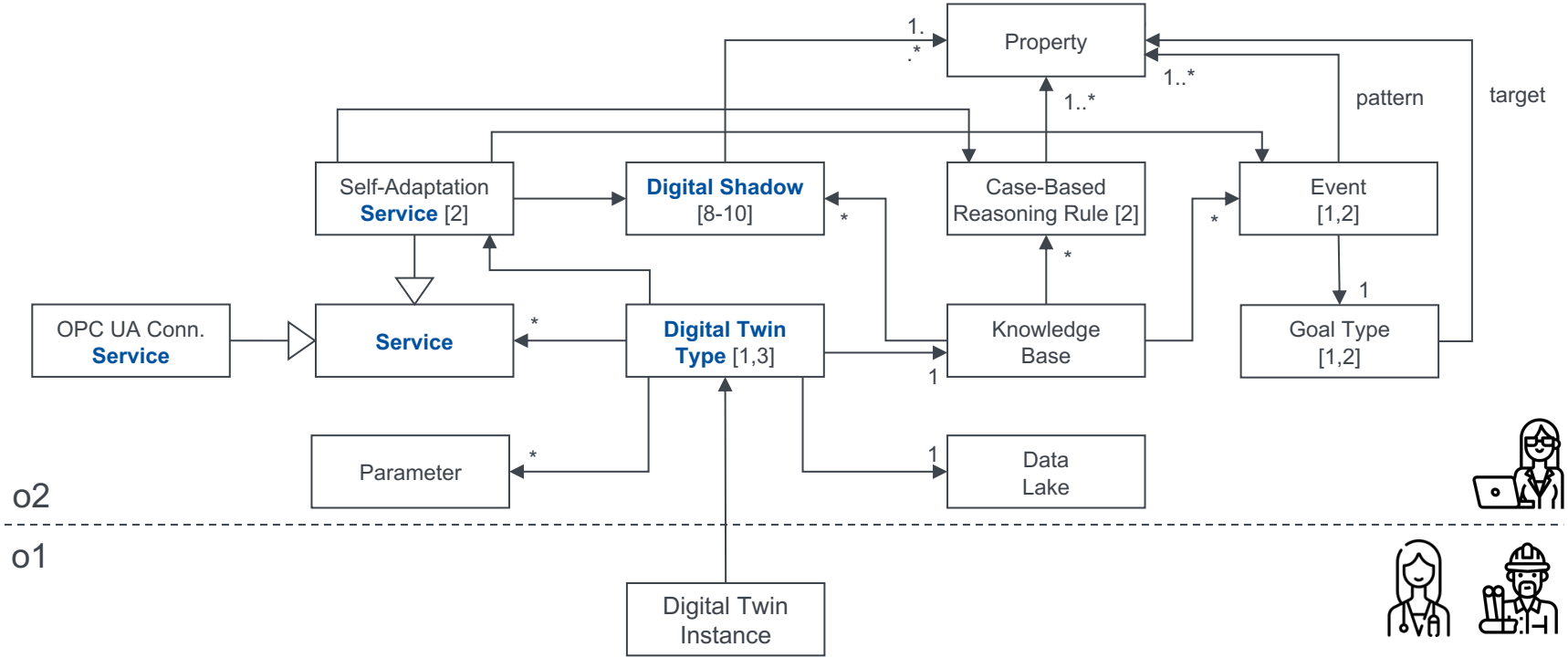
Entity	Entity Purpose	Ontological Metalevel[3]	Analogy
Digital twin **type**	Defines a **set of digital twin instances** with properties holding for all instances of this set (e.g., Tesla Roadster Twin)	o2	
Digital twin **instance**	Describes the **properties of a specific digital twin implementation** (e.g., model of the “Starman” Tesla Roadster)	o1	
Digital twin **implementation**	A **software system interacting with a CPS** to present, predict, and prescribe its behavior	o0	

[3] C. Atkinson & T. Kuhne: *Model-driven development: a metamodeling foundation*. In: IEEE Software, 20(5), 36-41. 2003.

A Specific Model-Driven Method for Engineering Digital Twins

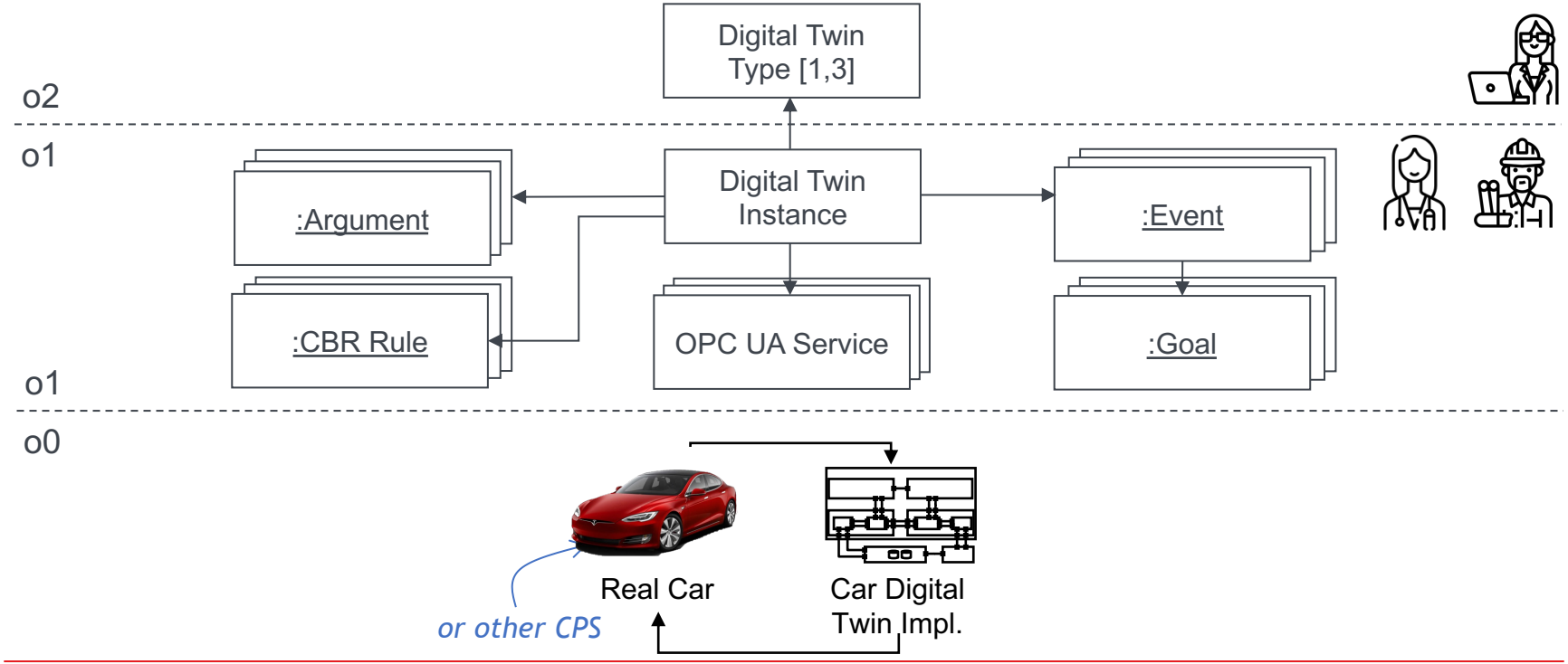
A Digital Twin Type

A self-adaptive system representing a CPS pushing data to a data lake



A Digital Twin Instance

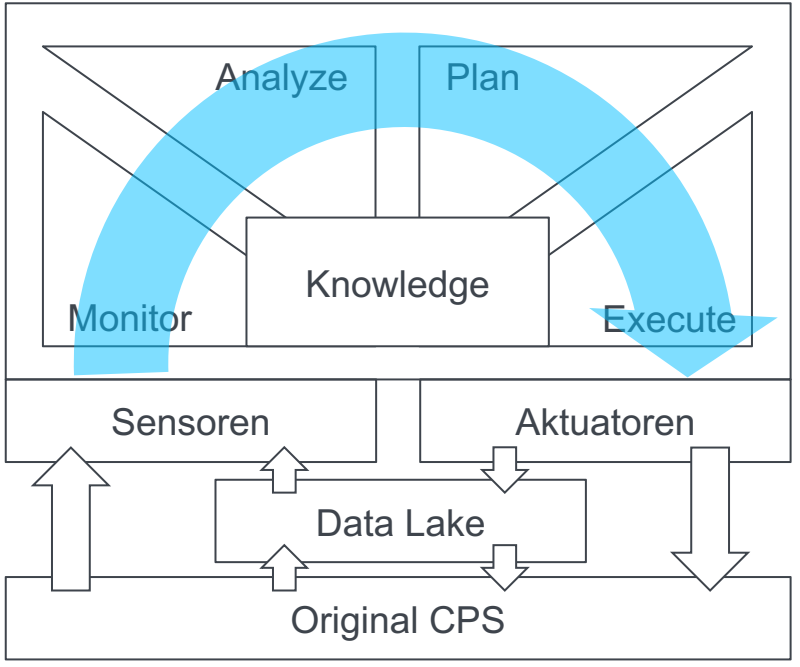
A configured instance of a specific digital twin type



Generation Target: Self-Adaptive Digital Twins

Realize MAPE-K control loop variant

- Monitor (Present)
  - Observe changes in original system & data lake
  - Emit corresponding digital shadows if necessary
- Analyze (Predict)
  - Check Event-Condition-Goal (ECG) rules against digital shadows
- Plan (Prescribe)
  - Case-Based Reasoning (CBR), AI planning, code
- Execute (Present, Prescribe)
  - Effect original system (OS) and data lake
- Knowledge
  - Events, case rules

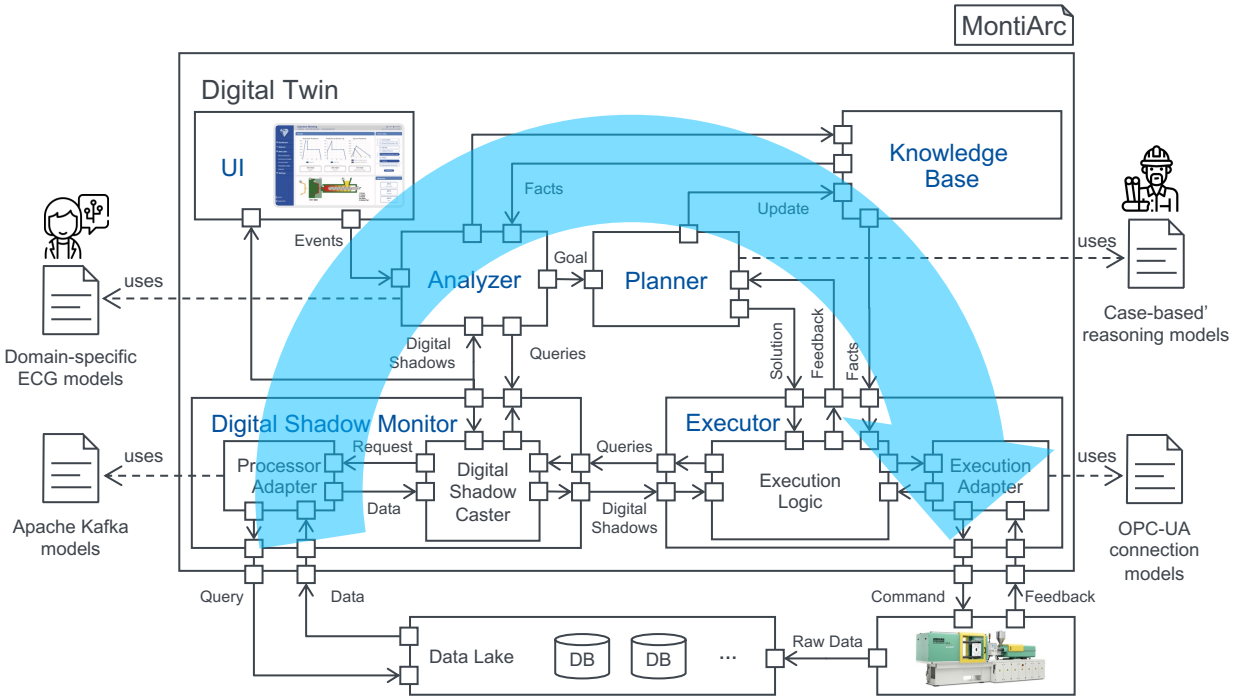


T. Bolender, G. Bürvenich, M. Dalibor, B. Rumpe, A. Wortmann: *Self-Adaptive Manufacturing with Digital Twins*. In: 2021 International Symposium on Software Engineering for Adaptive and Self-Managing Systems (SEAMS), pp. 156-166, IEEE Computer Society, 2021.

Active Digital Twins Enable Self-Adaptive Operations

Realize MAPE-K control loop

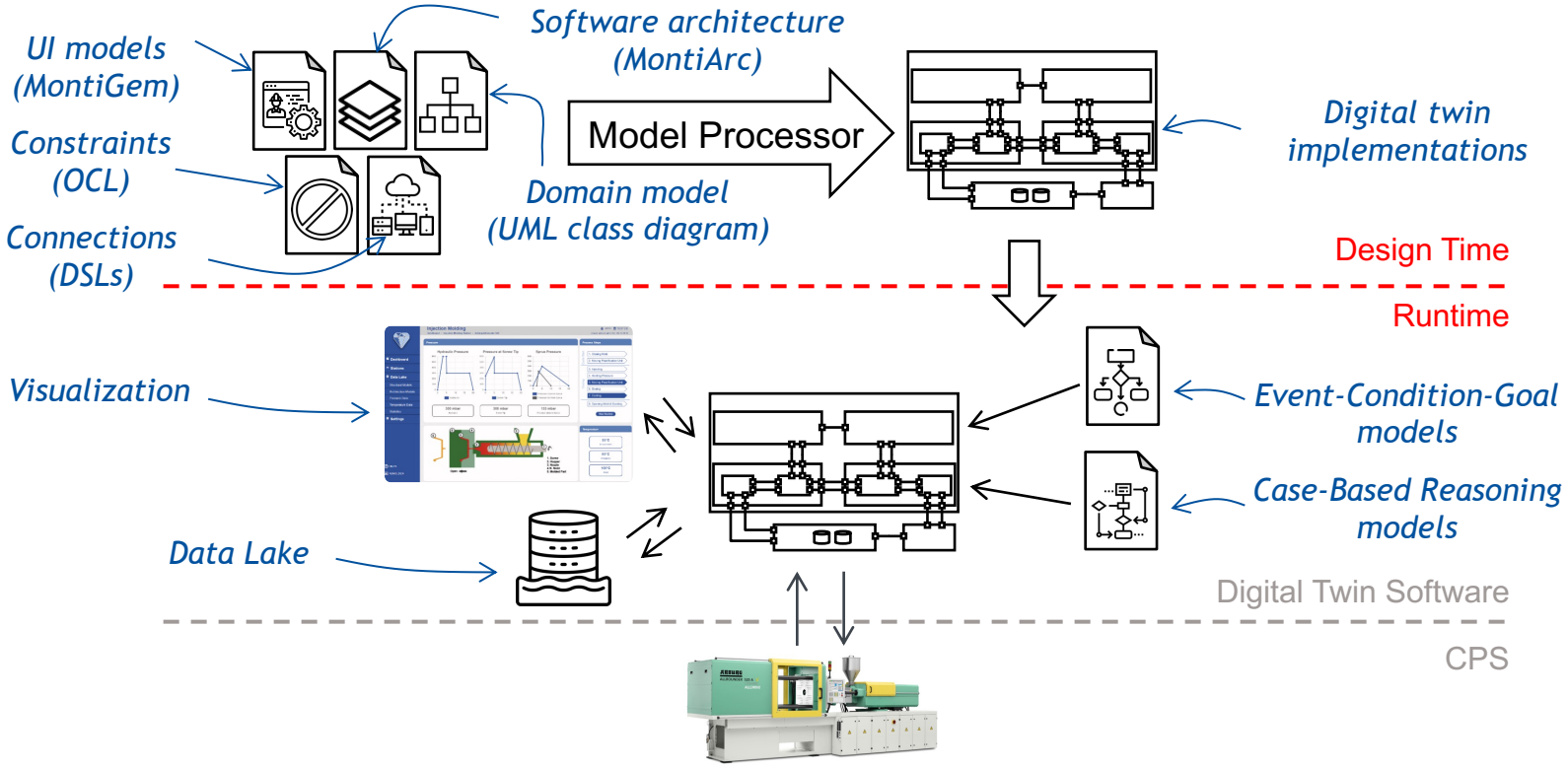
- Monitor (Present)
  - Observe changes
  - Emit digital shadows
- Analyze (Predict)
  - Check ECA rules against digital shadows
- Plan (Prescribe)
  - CBR, AI planning, code
- Execute (Present, Prescribe)
  - Effect OS and data lake
- Knowledge
  - Events, case rules



P. Bibow, M. Dalibor, C. Hopmann, B. Mainz, B. Rumpe, D. Schmalzing, M. Schmitz, A. Wortmann: *Model-Driven Development of a Digital Twin for Injection Molding*. In: S. Dustdar, E. Yu, C. Salinesi, D. Rieu, V. Pant, editors, International Conference on Advanced Information Systems Engineering (CAiSE'20), pp. 85-100, Grenoble, Springer, 2020.

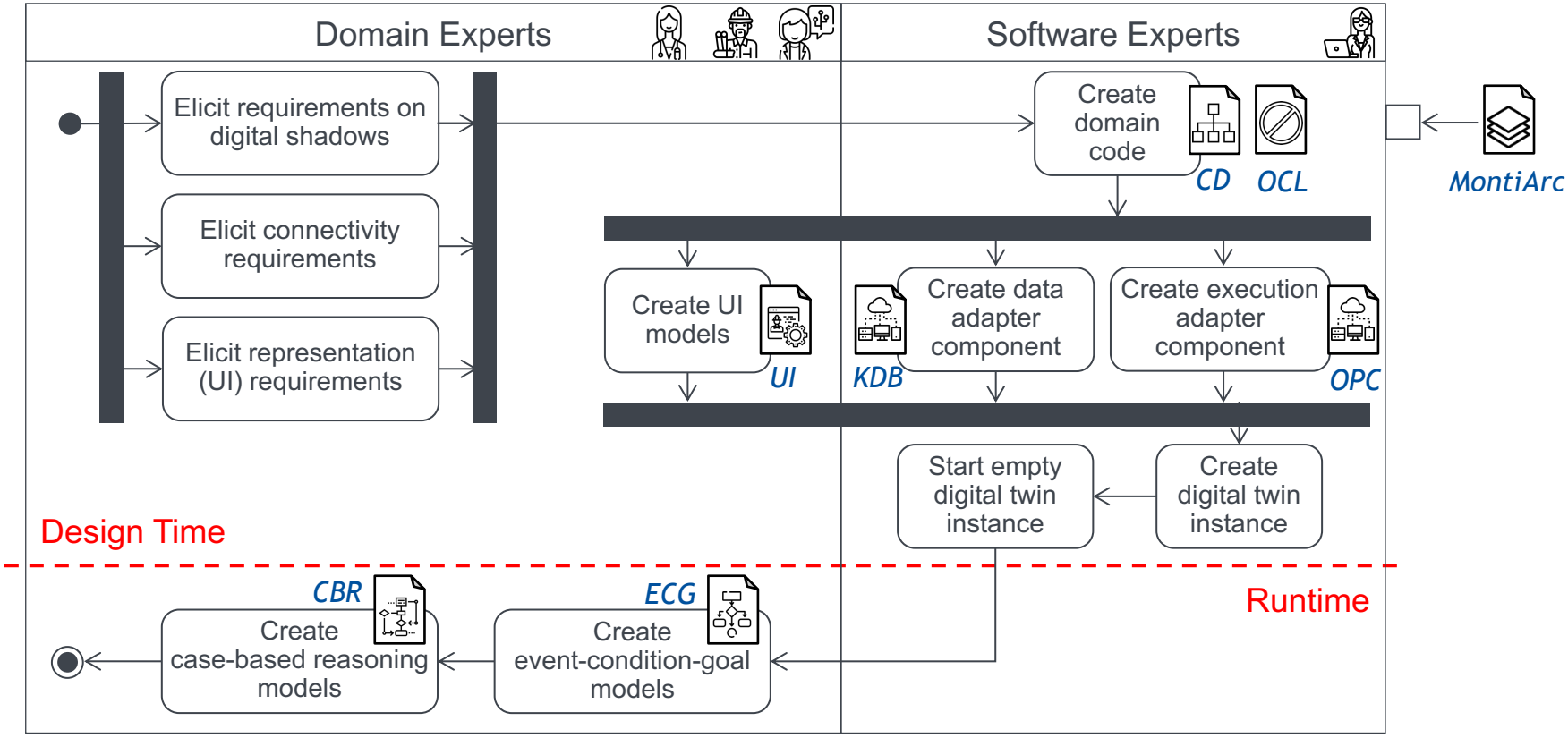
Schema: Model-Driven Development of Digital Twins

Generate at design-time and interpret at runtime



Model-Driven Development of Digital Twins

Separation of concerns between domain experts and software experts



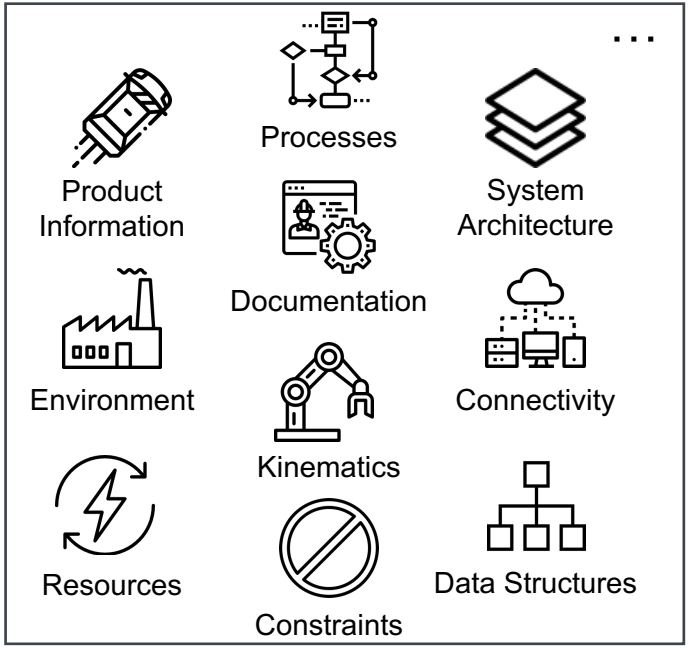
Take-away

Our digital twins are self-adaptive software systems connected to a CPS that implement a MAPE-K feedback loop to represent and manipulate that CPS.

Outlook

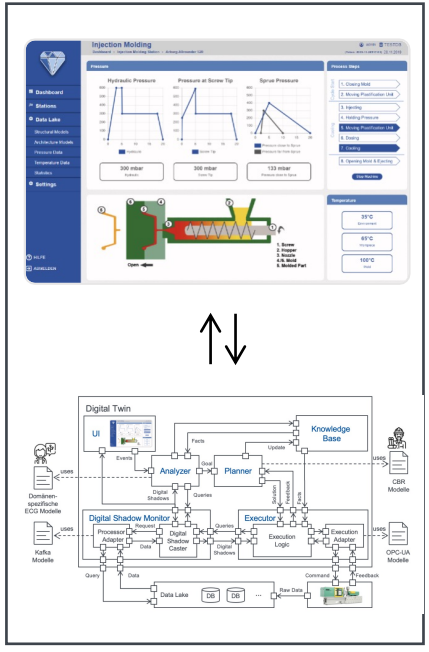
Automated Synthesis of Digital Twin Architectures

From development, simulation and software models



Development, simulation and software models

Transformationen

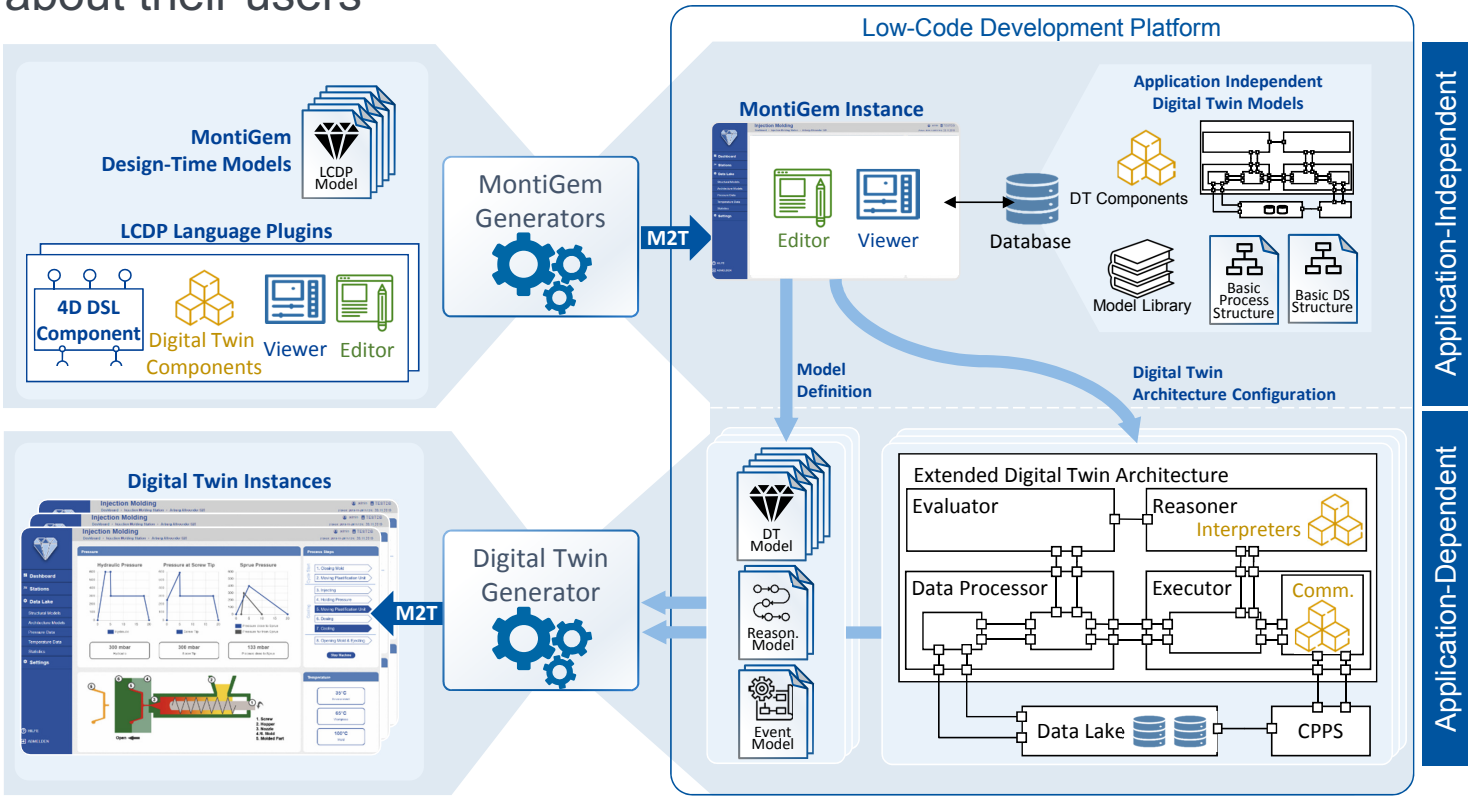


Implementation of the digital twin

- Software architecture
- Data management, UI, ...
- Efficient data acquisition and analysis
- Self-adaptive behavior optimization
- Predictive maintenance
- DevOps
- Learning
- ...

Genereating Low-Code Platforms for Digital Twins

Think about their users



M. Dalibor, M. Heithoff, J. Michael, L. Netz, J. Pfeiffer, B. Rumpe, S. Varga, A. Wortmann: *Generating Customized Low-Code Development Platforms for Digital Twins*. Journal of Computer Languages, 70, 101117, 2022.

Many Open Questions

Pertaining a definition of digital twins

1. Can there be more than one digital twin for a system?
2. What are the system boundaries of the digital twin?
3. Can the twinned system be a physical being? (how does its automated actuation work then?)
4. Can the digital twin exist without the original (i.e., before/after) ?
5. How can we migrate from digital twins as-designed to as-operated systematically (automatically)?
6. How to measure fidelity of a digital twin w.r.t to the original system? When does loss of fidelity stop the digital twin from being a digital twin?
7. How to compose complex digital twins (e.g., car DT) from others (e.g., motor DT + chassis DT)
8. Are there different kinds of digital twins?
9. How to ease operation of digital twins by domain experts?

[1] J. Michael, J. Pfeiffer, B. Rumpe, A. Wortmann: Integration Challenges for Digital Twin Systems-of-Systems. In: 10th IEEE/ACM International Workshop on Software Engineering for Systems-of-Systems and Software Ecosystems.

Should we Employ a Turing Test Variant to Determine Digital-Twin-ness?

How could that work?

Turing Test for Digital Twins

During the Turing test for digital twins, the questioner issues a series of queries to both systems. After a specified time, the questioner tries to decide which system is the original and which the digital twin.

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