

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

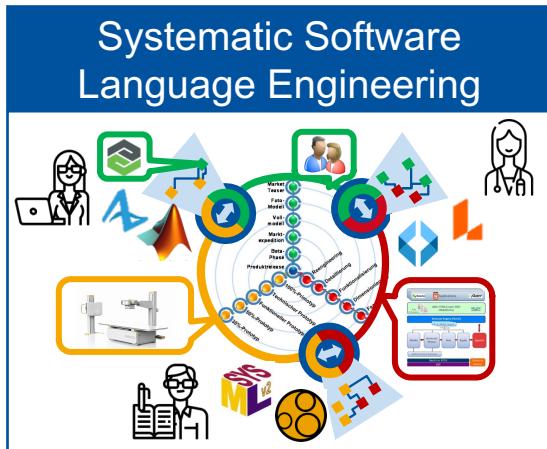
Jun.-Prof. Dr. rer. nat. habil. Andreas Wortmann

- 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

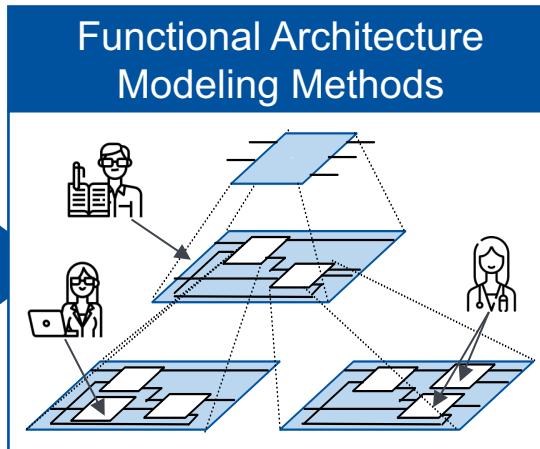


Enabling Domain Experts to Contributing Machine-Processable Solutions

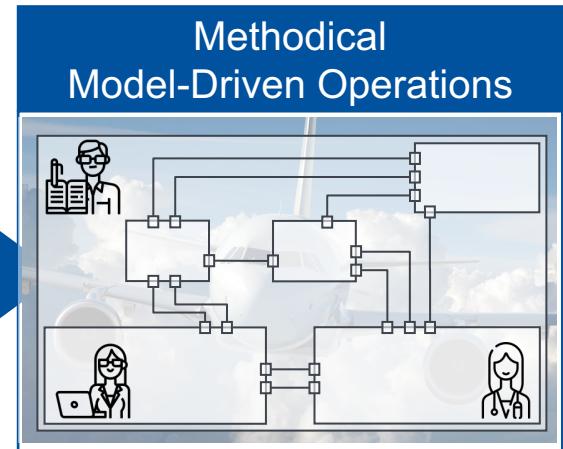
Through better abstraction and automation



- 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

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?

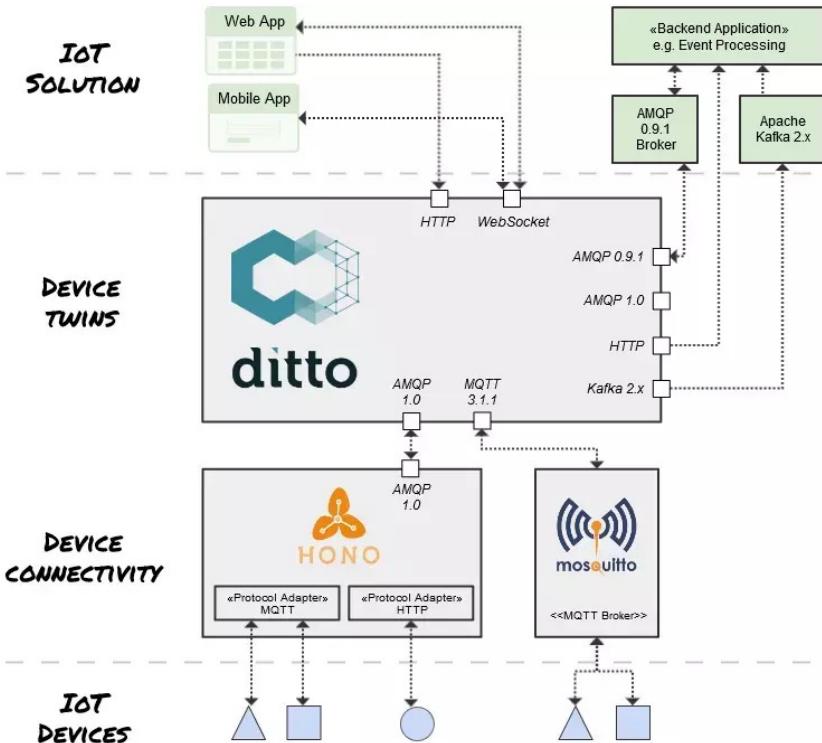
Is this the only
purpose?

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

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

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

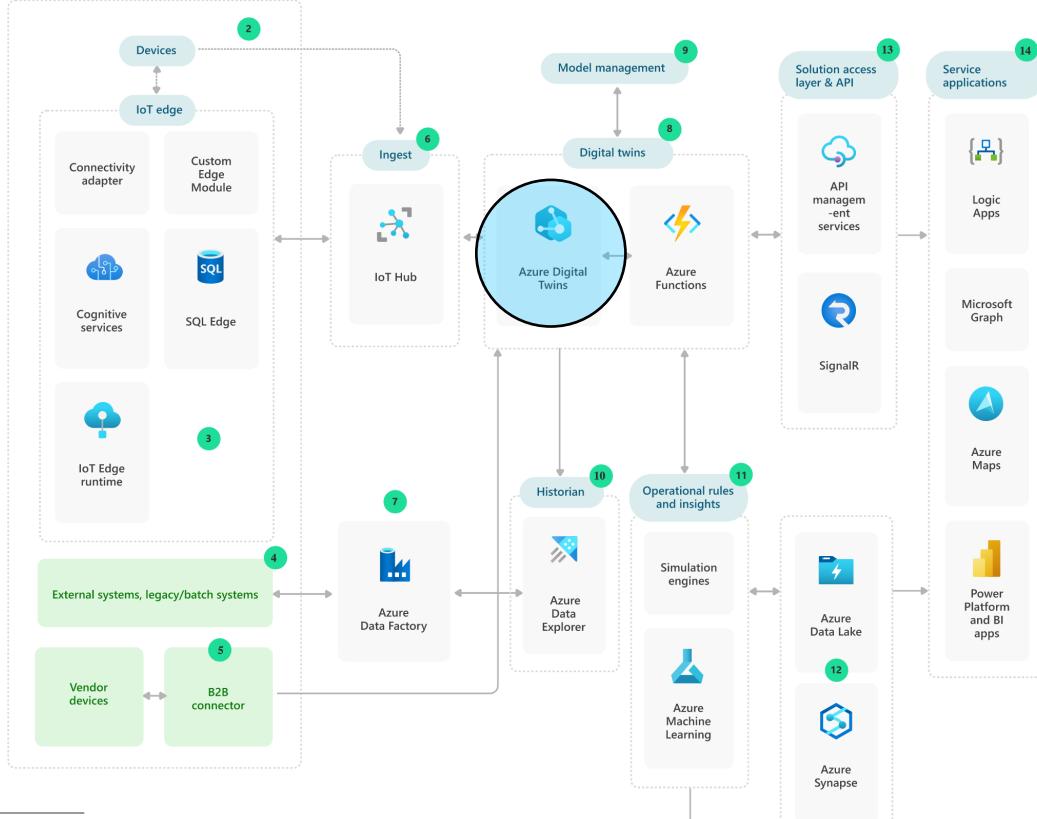
infomodel RaspberryPi{
functionblocks {

    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

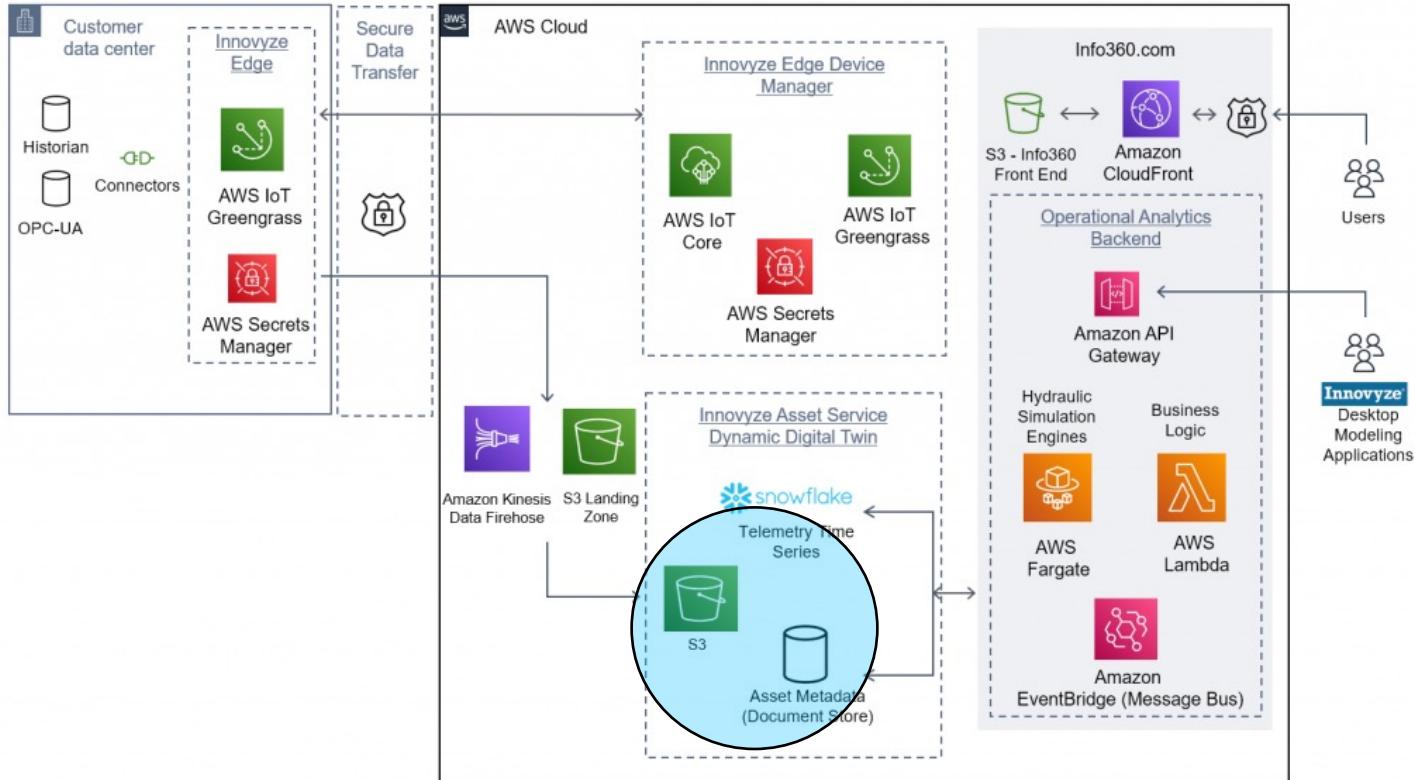
MS DTDL Example

```
{  
  "@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

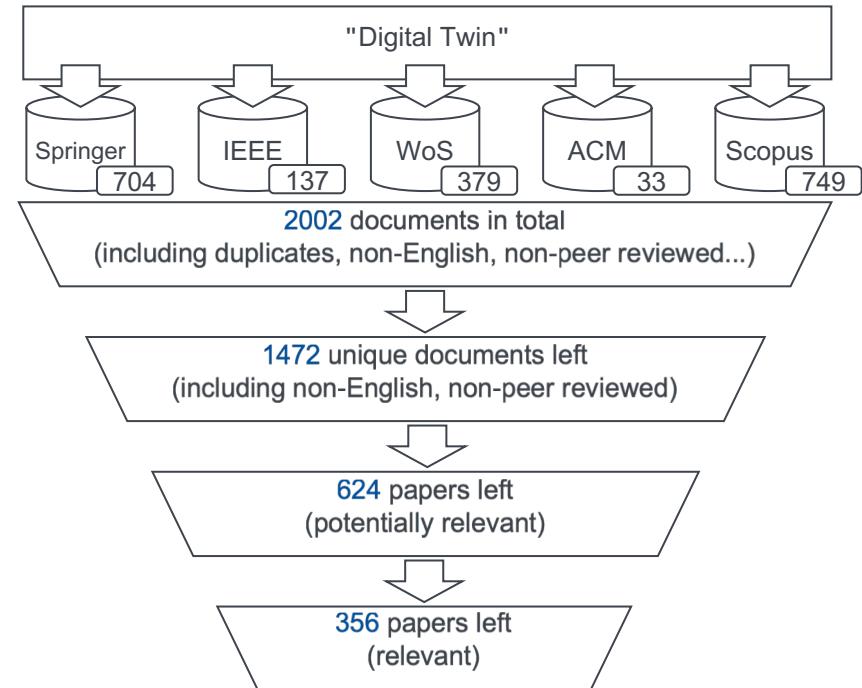


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A Systematic Cross-Domain Mapping Study for Digital Twins

Research questions and overview

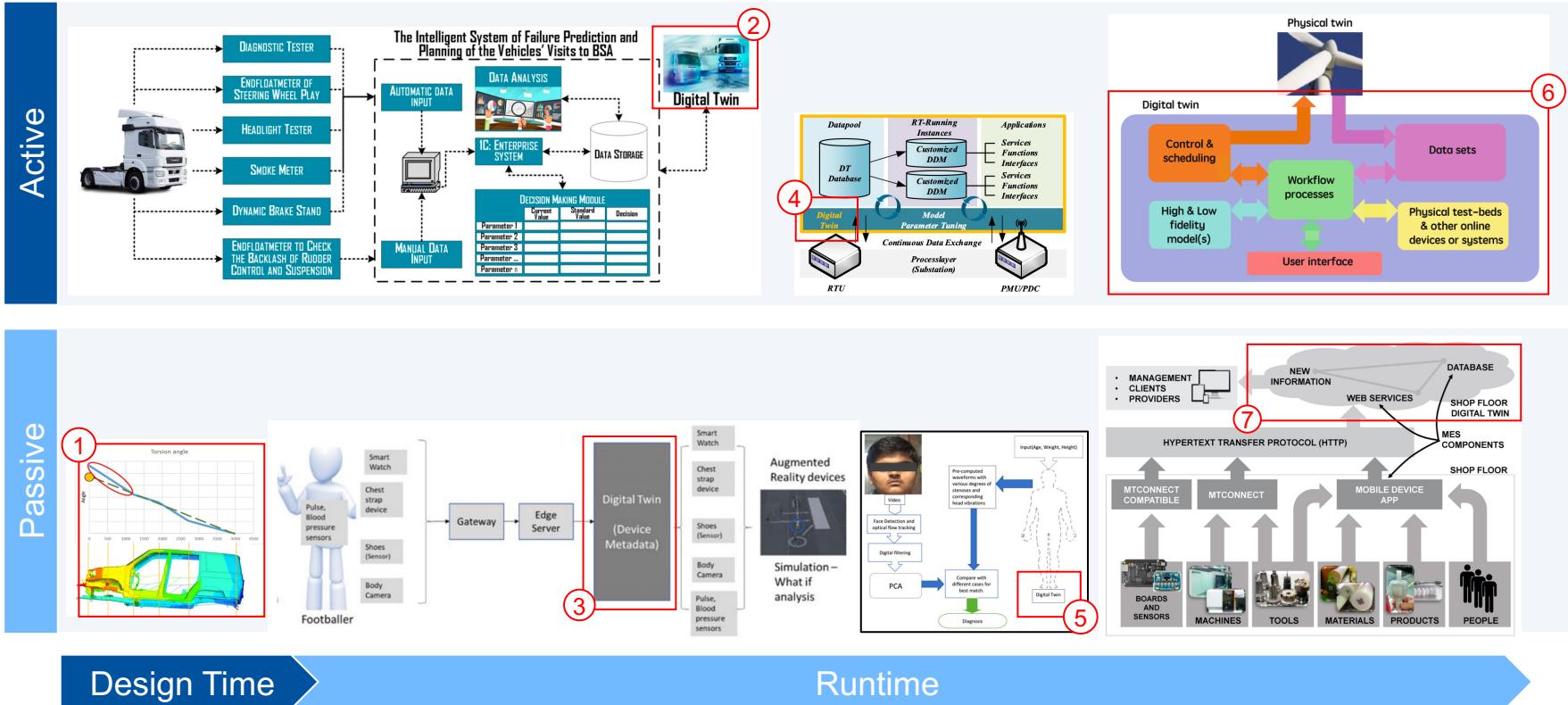
1. Who uses Digital Twins for which **purposes**?
2. What are the **conceptual** properties of Digital Twins?
3. How are Digital Twins **engineered**?
4. How are Digital Twins **deployed**?
5. How do Digital Twins **operate**?
6. How are Digital Twins **evaluated**?



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

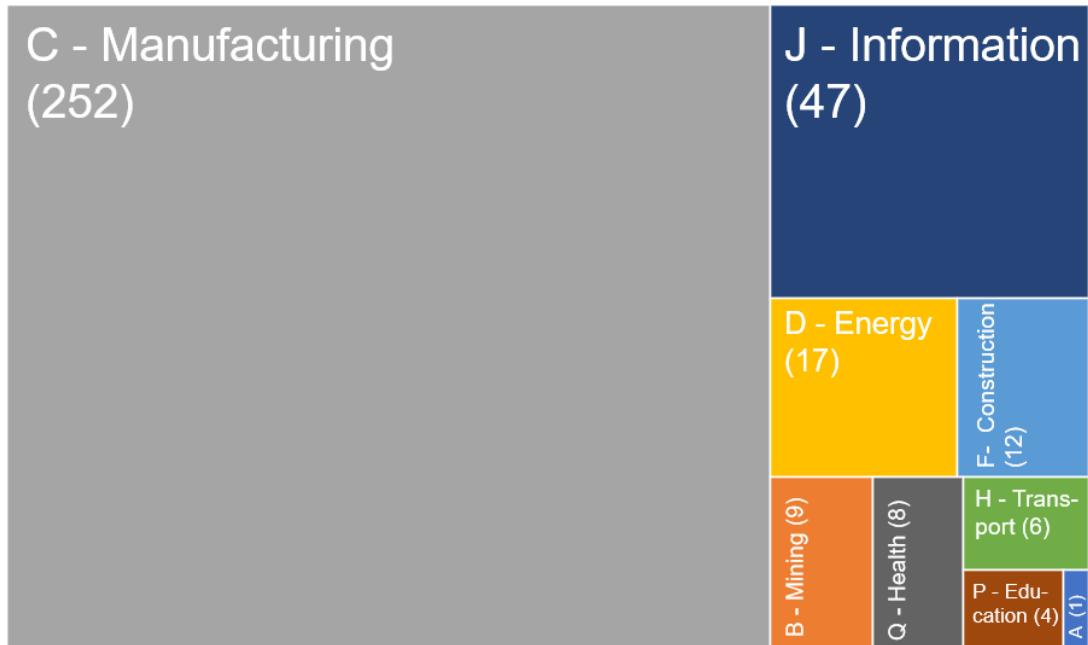
And are used at different times throughout systems engineering



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

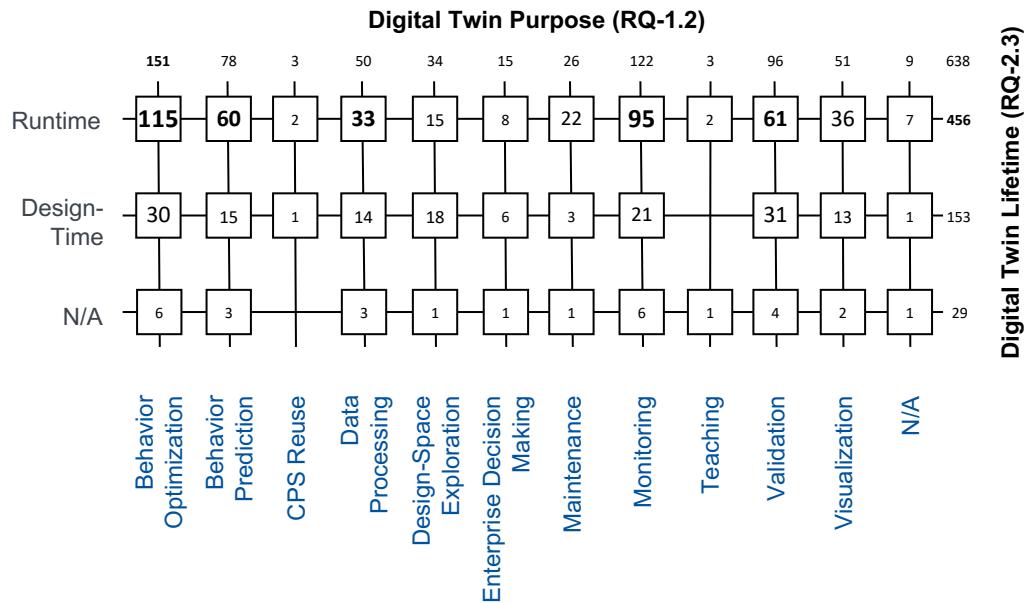


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What are Digital Twins used for?

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

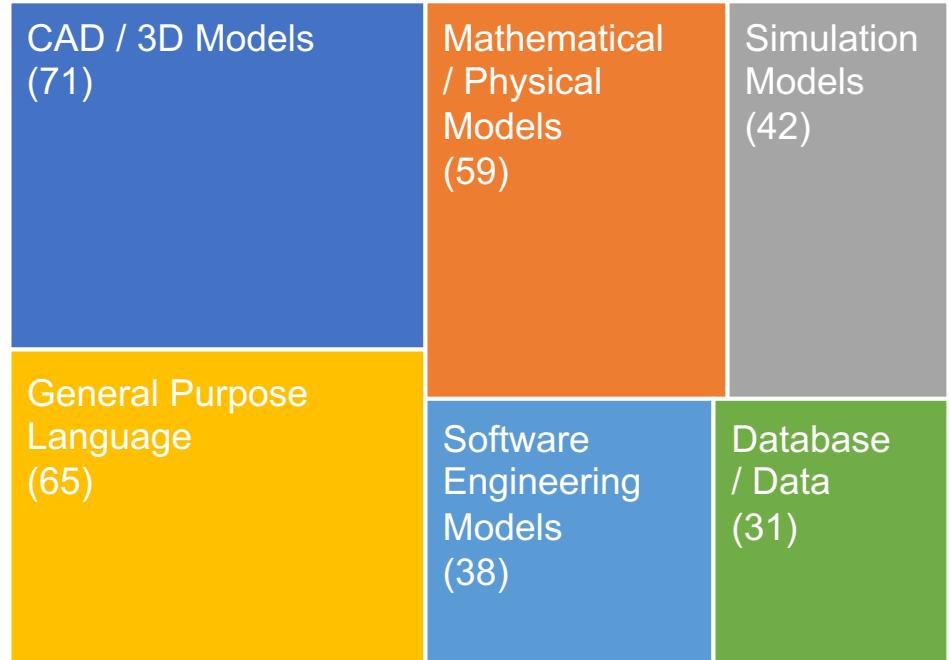


M. Dalibor, N. Jansen, B. Rumpe, D. Schmalzing, L. Wachtmeister, M. Wimmer, A. Wortmann: *A Cross-Domain Systematic Mapping Study on Software Engineering for Digital Twins*. Journal of Systems and Software, 111361, 2022. – Preprint at www.wortmann.ac/preprints

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

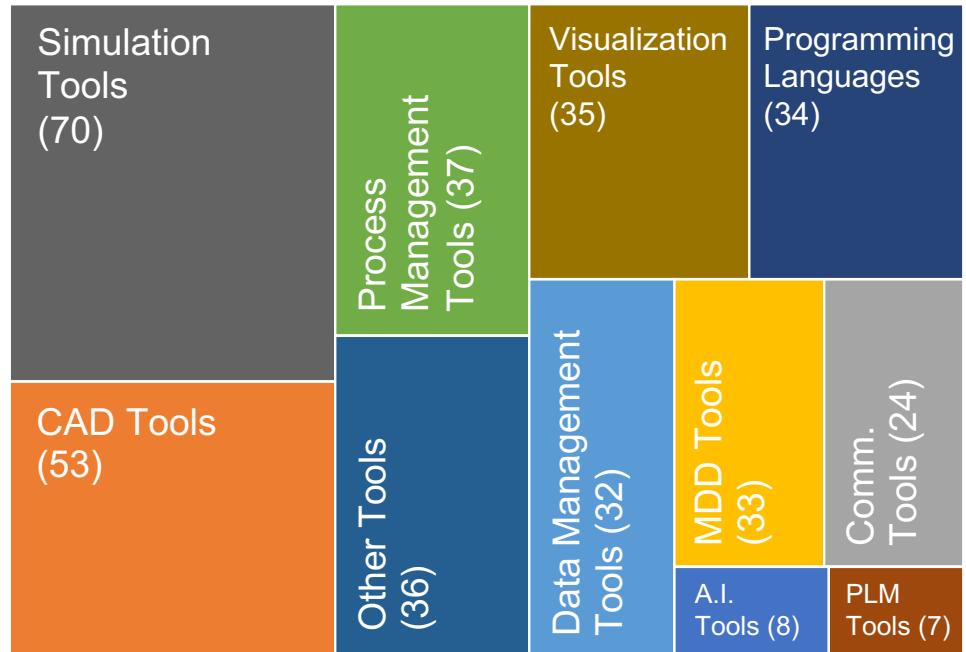


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Digital Twins Mostly use Simulation and CAD Tools

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



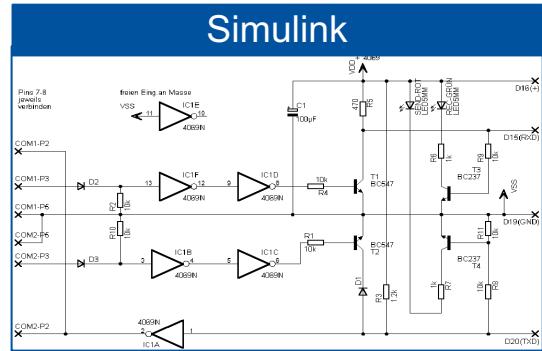
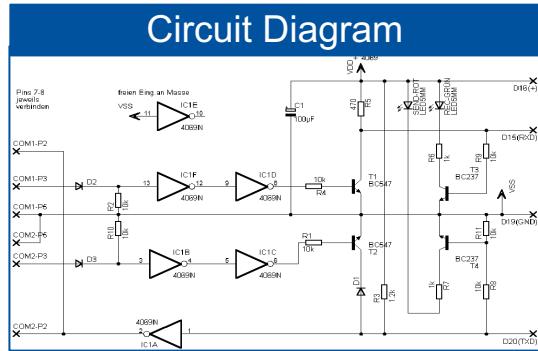
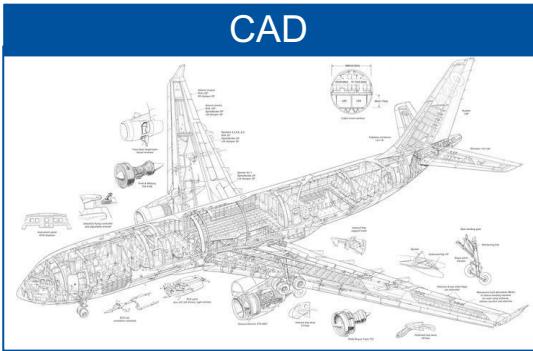
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Take-away message

**A digital twin is a simulation model
of an existing system**

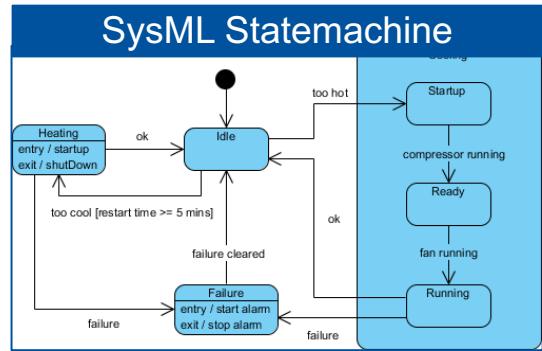
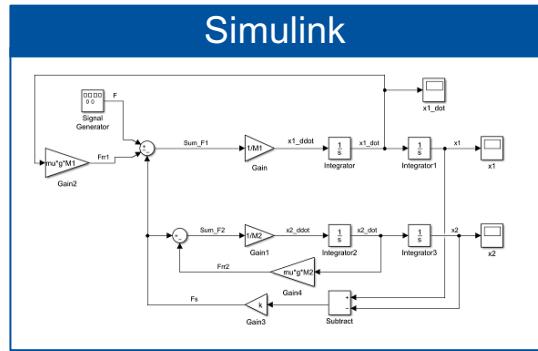
Then all of these Models are Digital Twins Obviously

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



Math

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





Take-away message

**A digital twin
of an existing
simulation model**

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]

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. – Preprint at www.wortmann.ac/preprints

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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. – Preprint at www.wortmann.ac/preprints

Digital Twin Consortium

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

Do you know that real real-time won't work in most domains?

If it does not use both kinds of data, it isn't a digital twin.

„Digital Twins use **real-time** and **historical data** to represent the **past and present** and simulate **predicted futures**. Digital Twins are motivated by **outcomes**, tailored to use **cases**, powered by **integration**, built on **data**, guided by **domain knowledge**, and implemented in **IT/OT systems**.“

No simulation = no digital twin?

What does that even mean?

Where else could they be implemented?

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

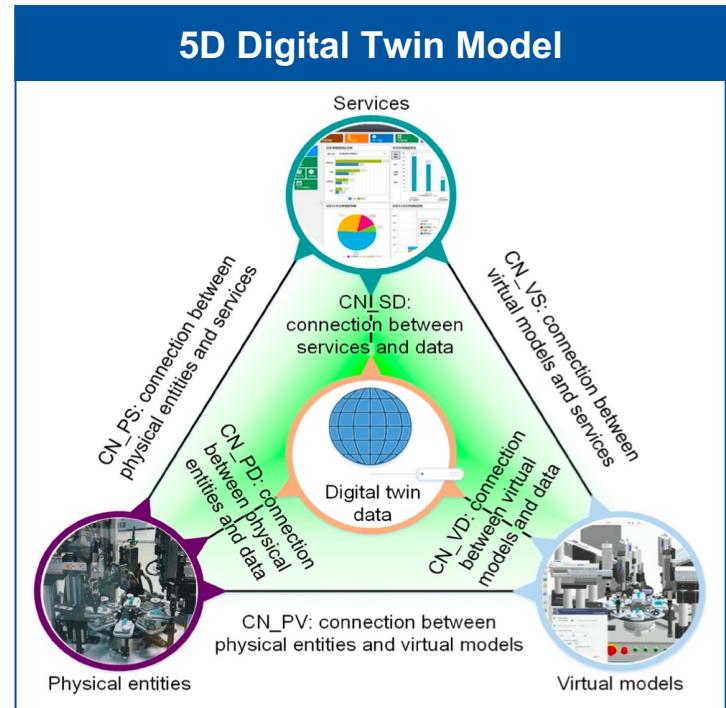
Take-away message

**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...

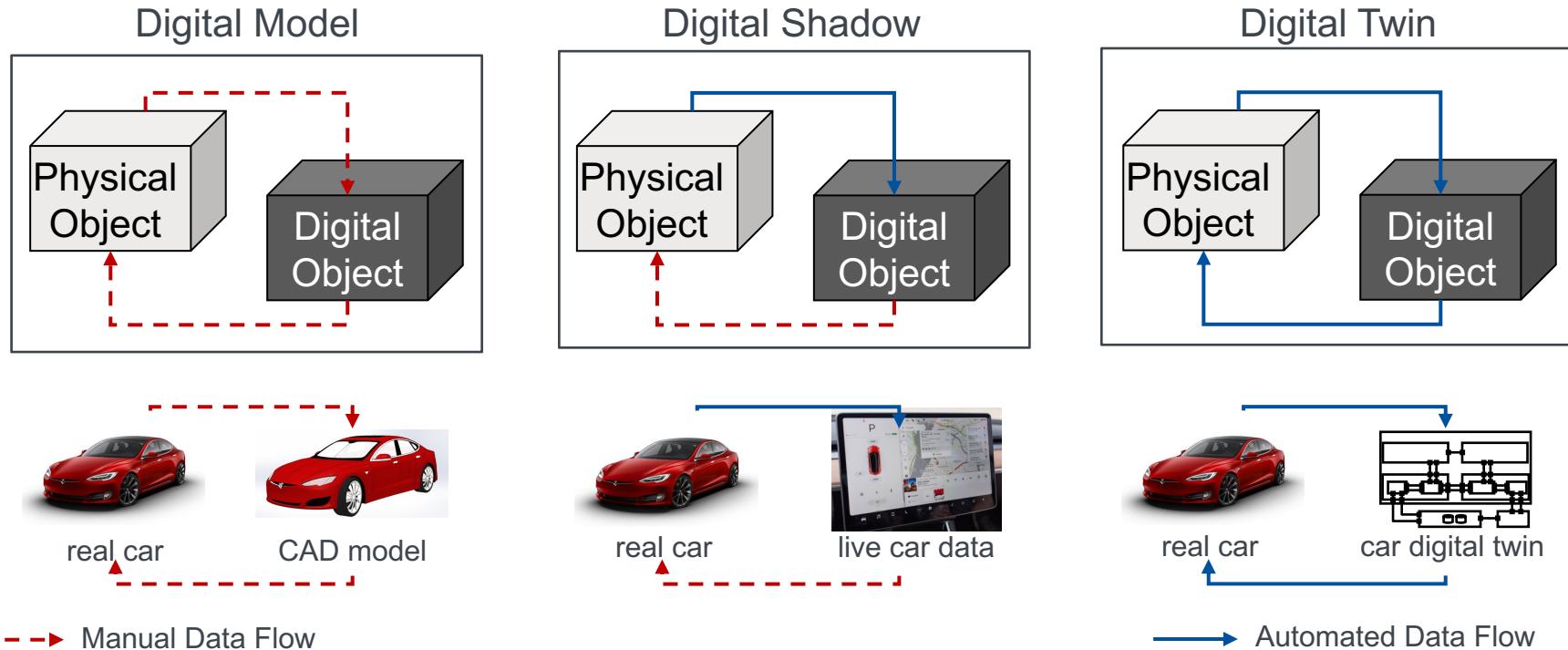
1. Physical object: Beings, cyber-physical systems, ...
2. Digital object: Models, software infrastructures, VR, ...
3. Services: Monitoring, optimization, prediction, ...
4. Digital data: Sensor readings, manufacturing orders, ...
5. Connections: WiFi, ethernet, fieldbus, ...



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

A Characterization based on Data Flows

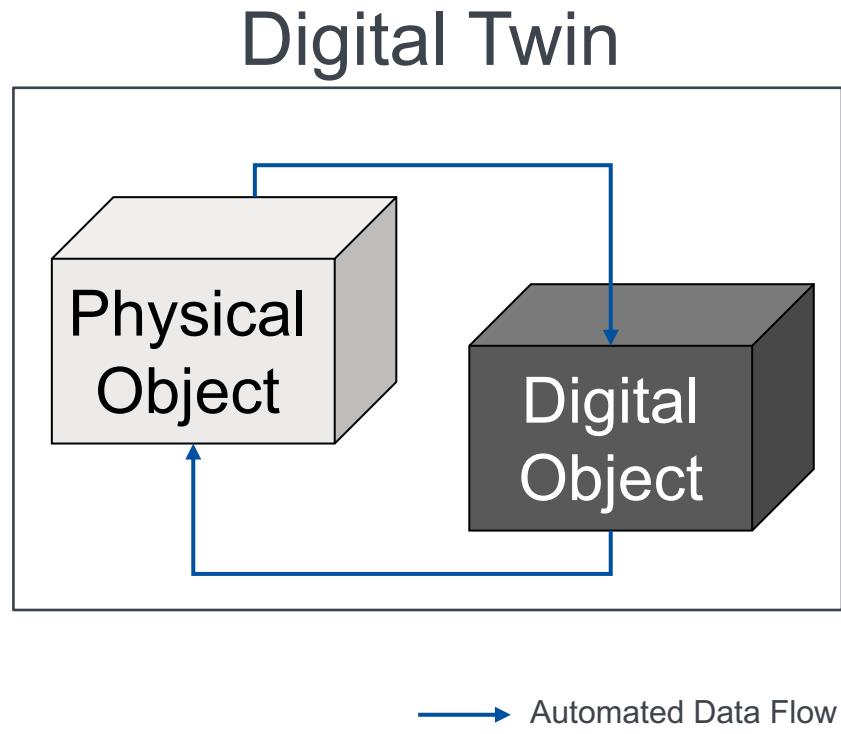
If the data flows between system and twin are of a specific form, then it is a ...



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

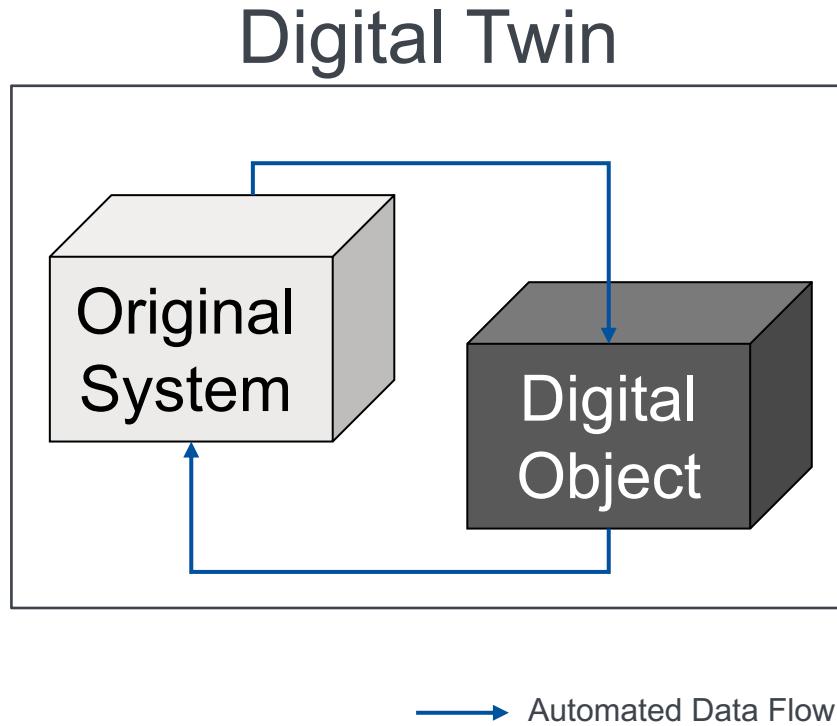
Zooming in this Definition Reveals some Issues

- 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



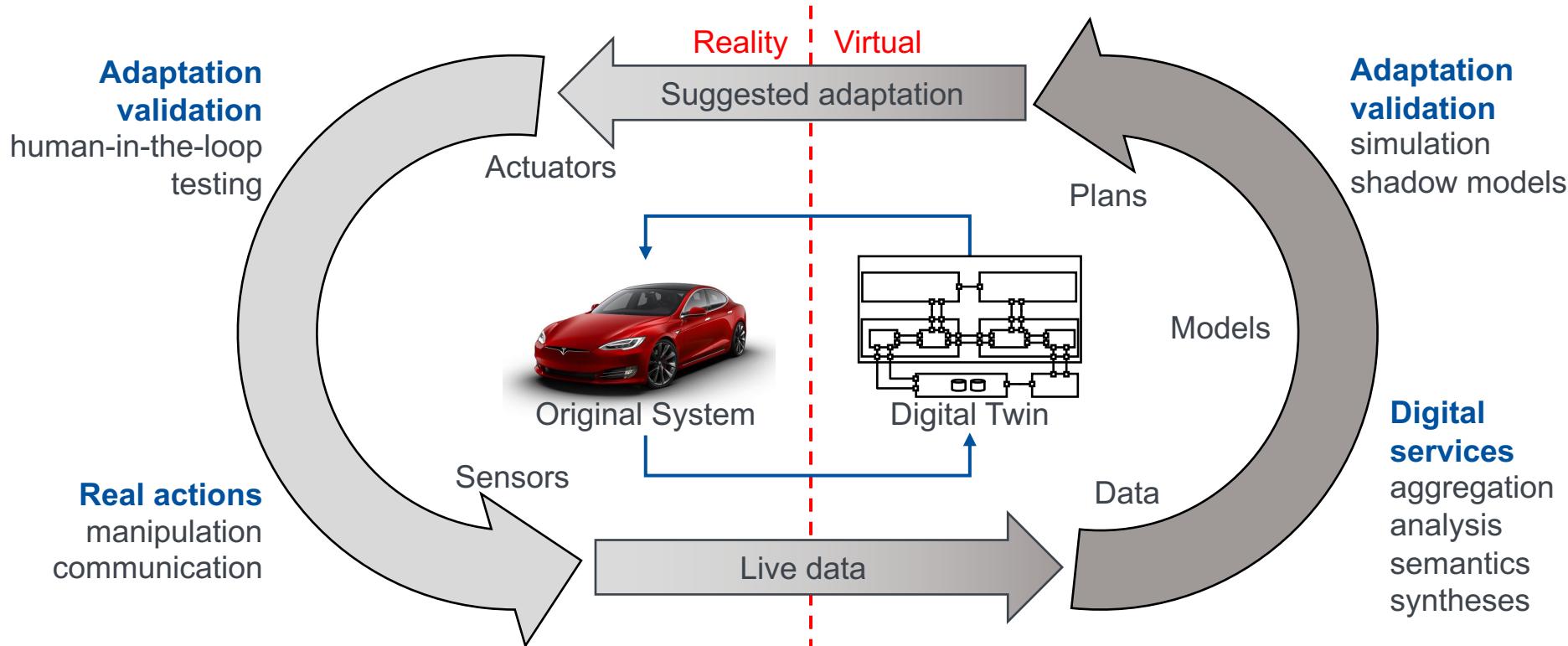
Zooming in this Definition Reveals some Issues

- 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”?

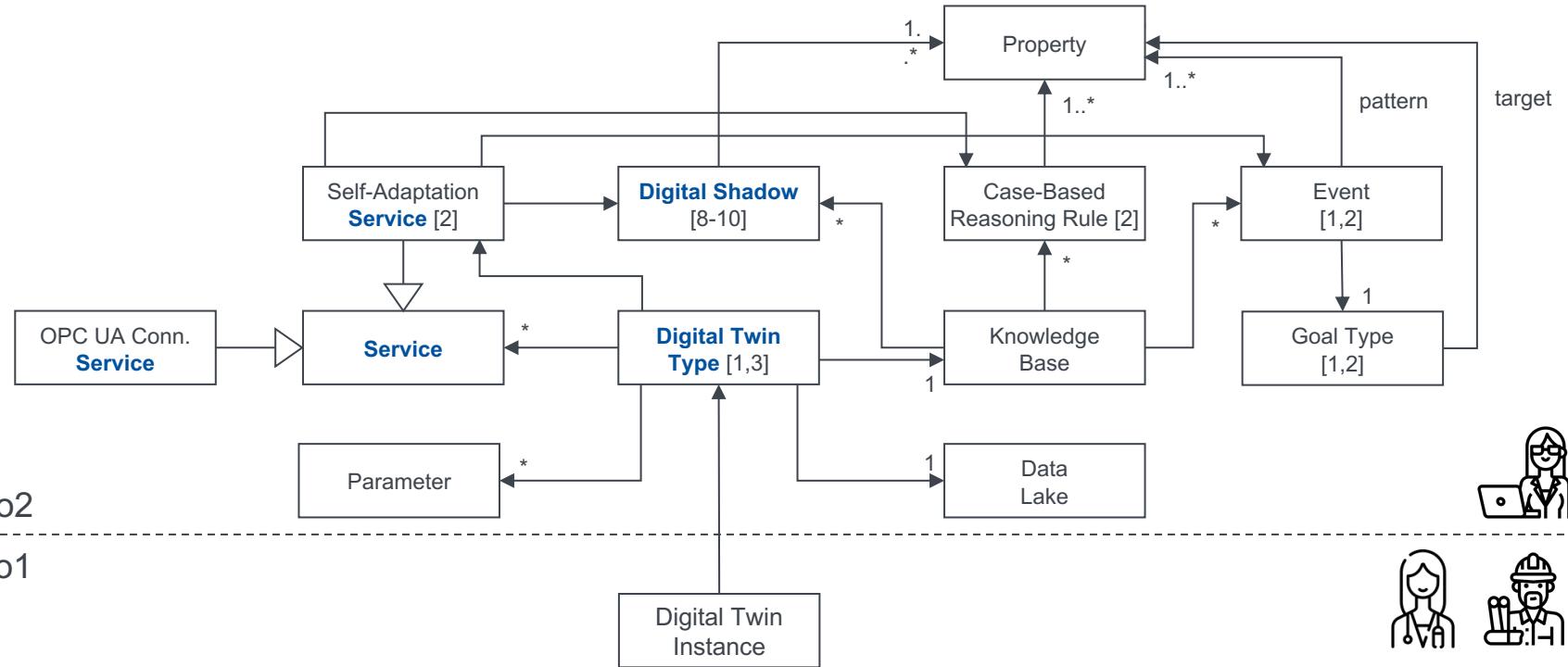
Entity	Entity Purpose	Ontological Metalevel ³	Analogy
Digital twin type	Defines a set of digital twin instances with properties holding for all instances of this set (e.g., Tesla Roadster Twin)	o2	
Digital twin instance	Describes the properties of a specific digital twin implementation (e.g., model of the “Starman” Tesla Roadster)	o1	
Digital twin implementation	A software system interacting with a CPS to present, predict, and prescribe its behavior	o0	<pre>31 self._file = None 32 self._fingerprint = {} 33 self._logger = None 34 self._debug = False 35 self._logger = logging.getLogger(__name__) 36 self._logger.setLevel(logging.INFO) 37 self._file = None 38 self._file = None 39 self._fingerprint = {} 40 41 42 @classmethod 43 def from_settings(cls, settings): 44 debug = settings.getboolean("debug", False) 45 return cls(logger=settings.logger, 46 debug=debug) 47 48 def request_secrets(self, request): 49 fp = self._file.read() 50 if fp: 51 self._fingerprint =</pre>

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

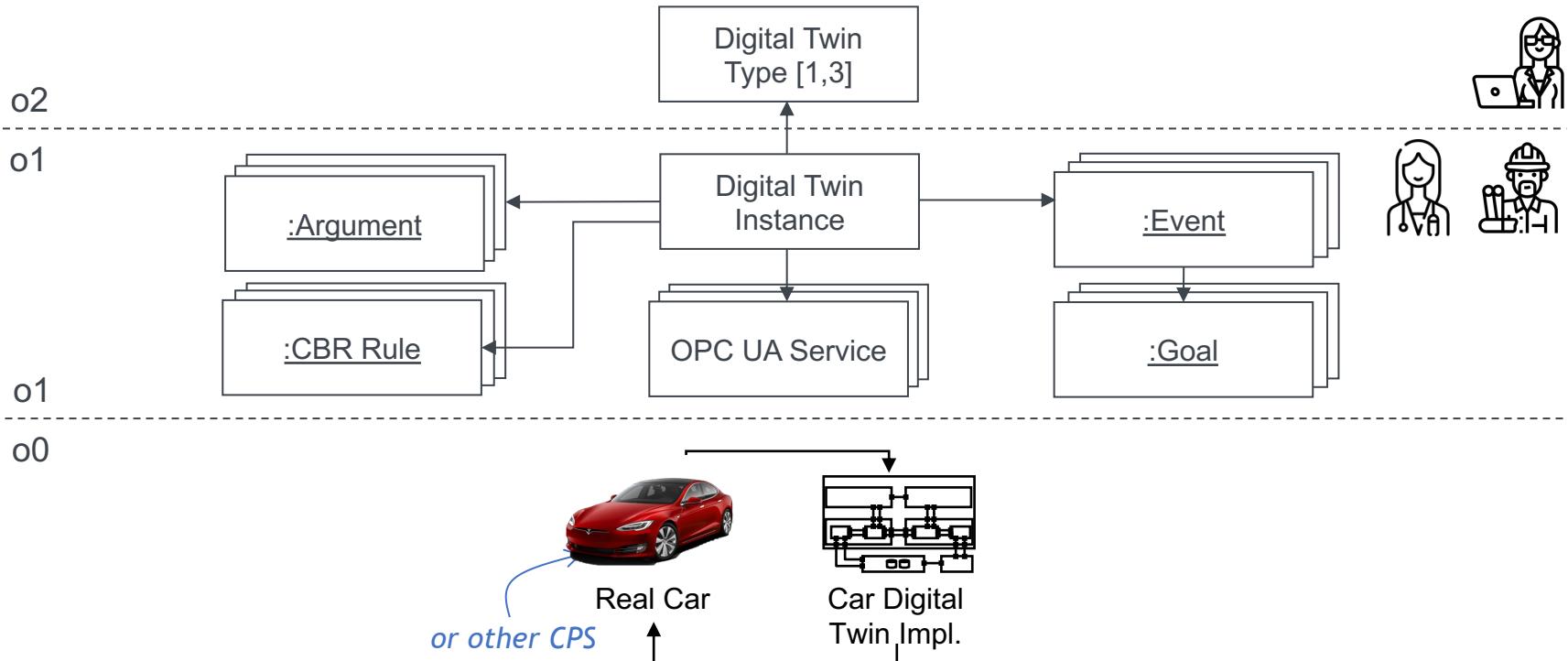
A Digital Twin Type

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



A Digital Twin Instance

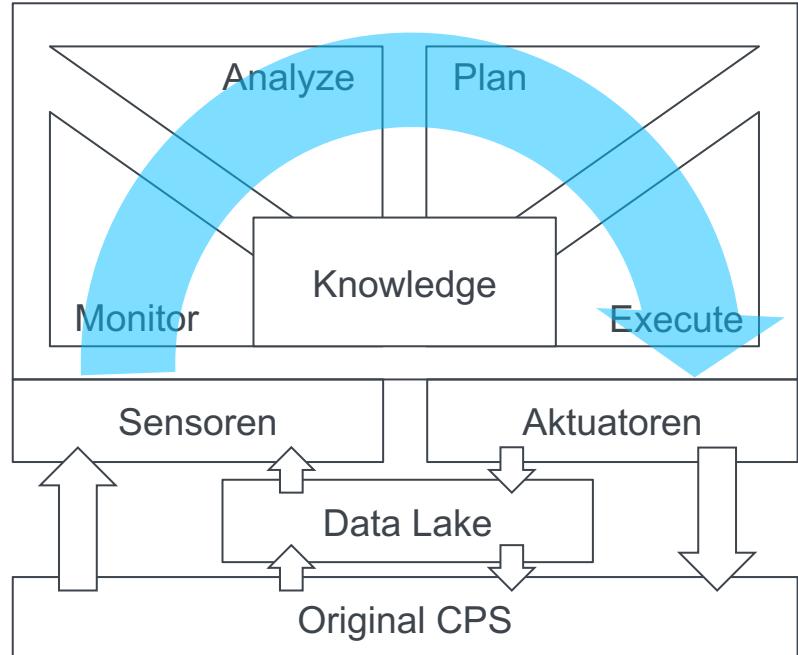
A configured instance of a specific digital twin type



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

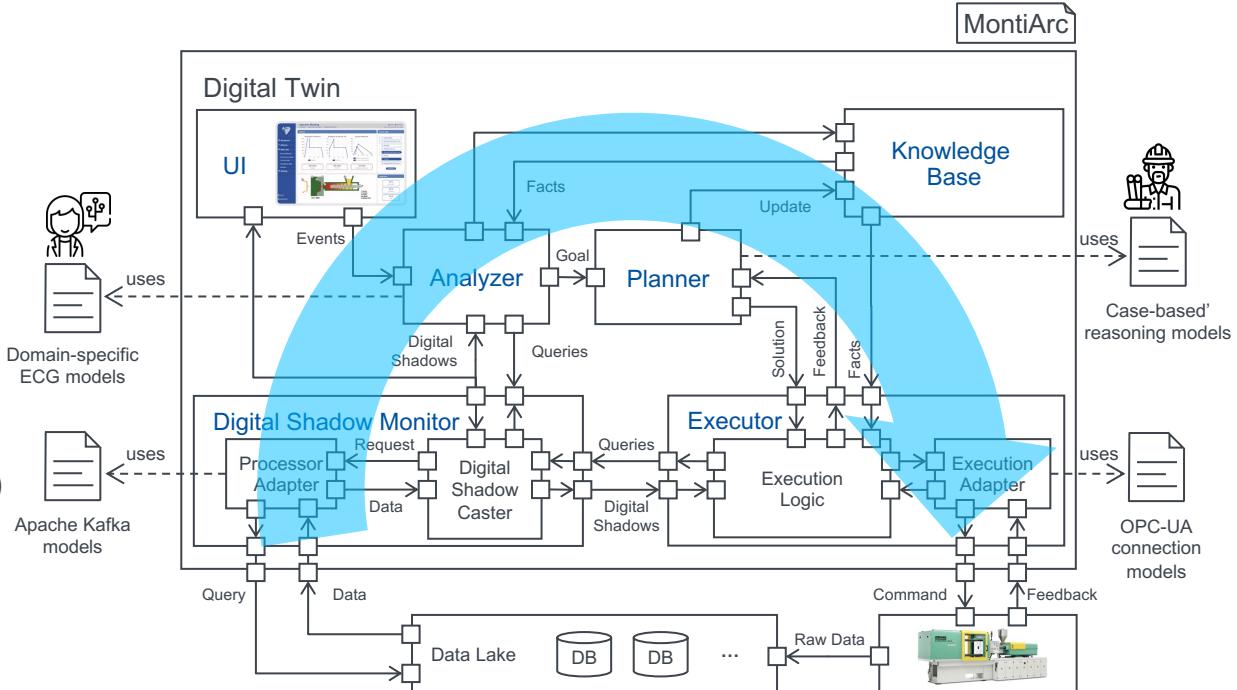


T. Bolender, G. Bürvénich, M. Dalibor, B. Rumpe, A. Wortmann: *Self-Adaptive Manufacturing with Digital Twins*. In: 2021 International Symposium on Software Engineering for Adaptive and Self-Managing Systems (SEAMS), pp. 156-166, IEEE Computer Society, 2021.

Active Digital Twins Enable Self-Adaptive Operations

Realize MAPE-K control loop

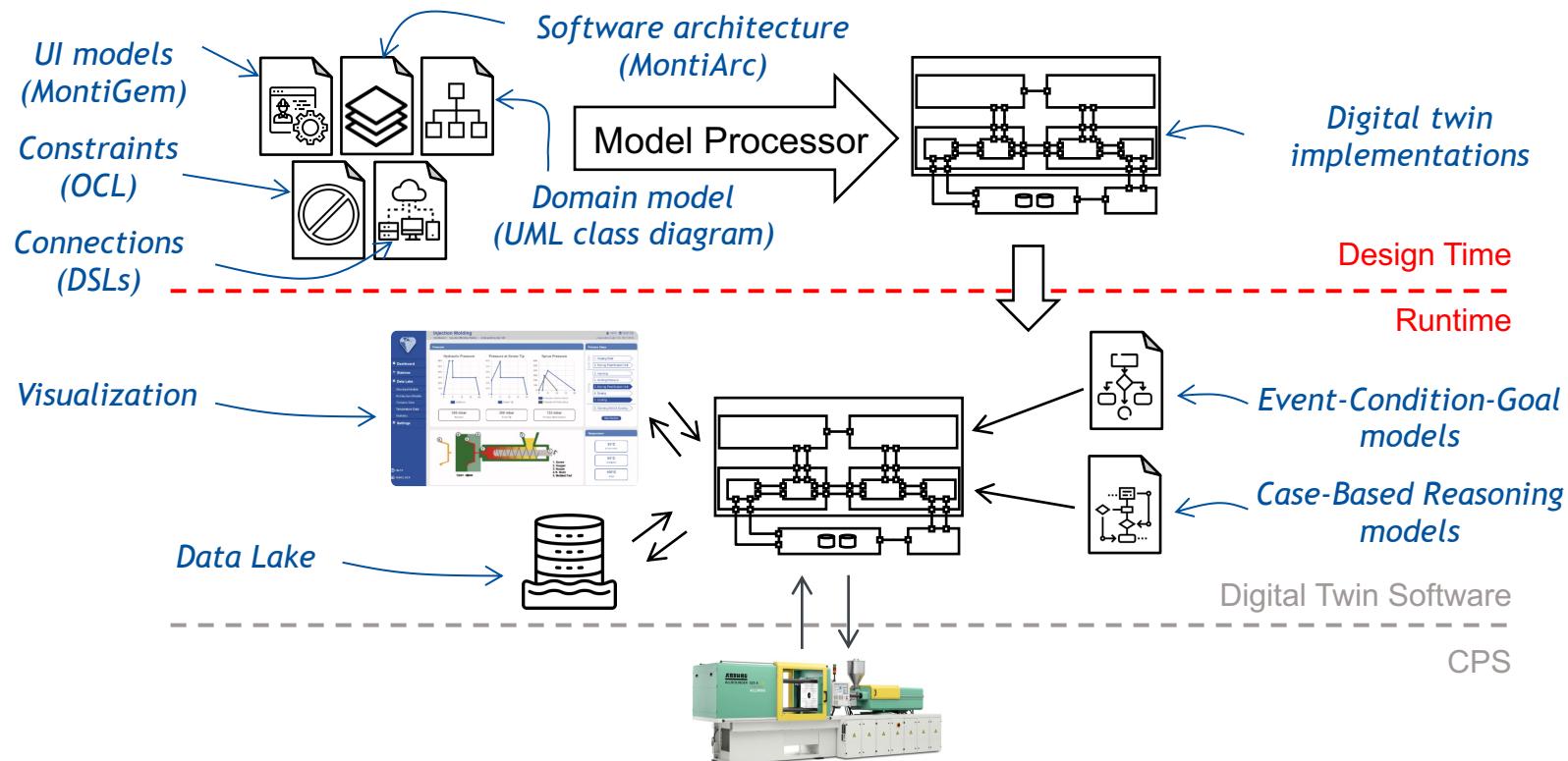
- **Monitor (Present)**
 - Observe changes
 - Emit digital shadows
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 - CBR, AI planning, code
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P. Bibow, M. Dalibor, C. Hopmann, B. Mainz, B. Rumpe, D. Schmalzing, M. Schmitz, A. Wortmann: *Model-Driven 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.

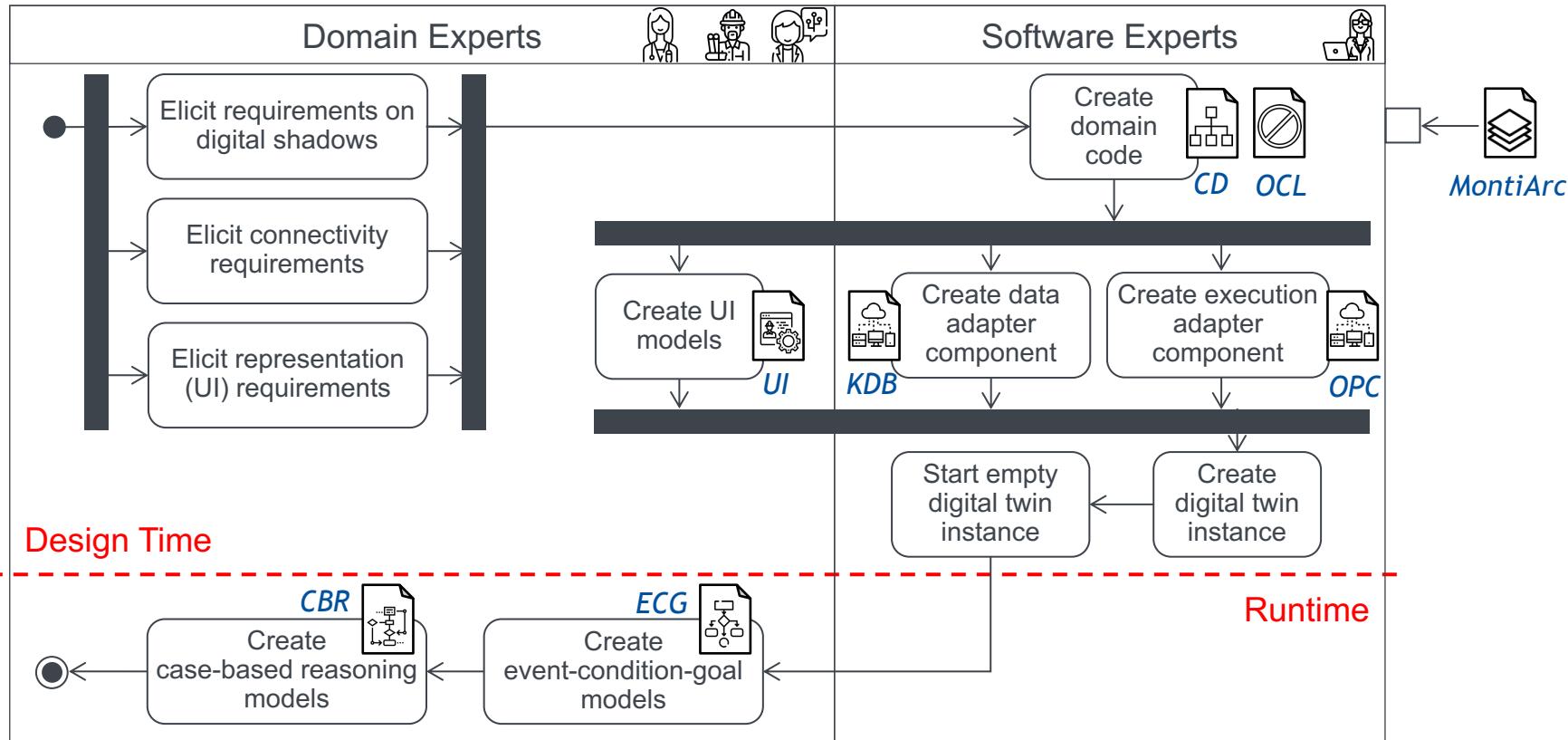
Schema: Model-Driven Development of Digital Twins

Generate at design-time and interpret at runtime



Model-Driven Development of Digital Twins

Separation of concerns between domain experts and software experts



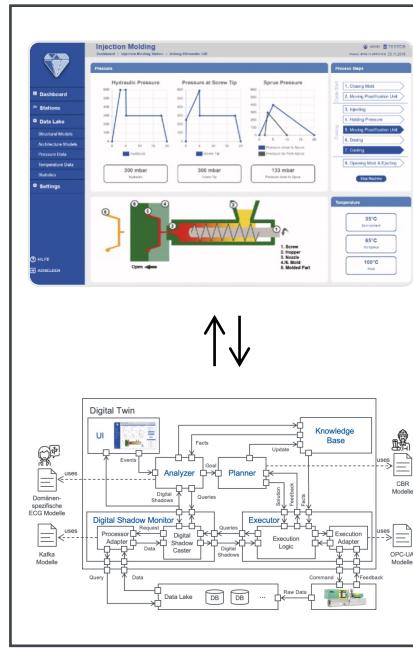
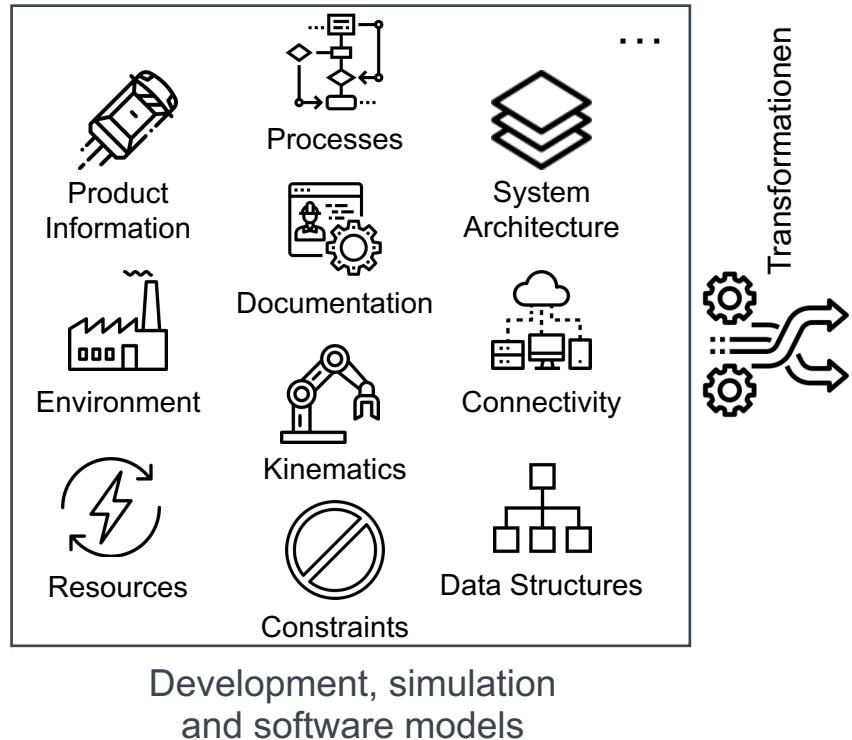
Take-away

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

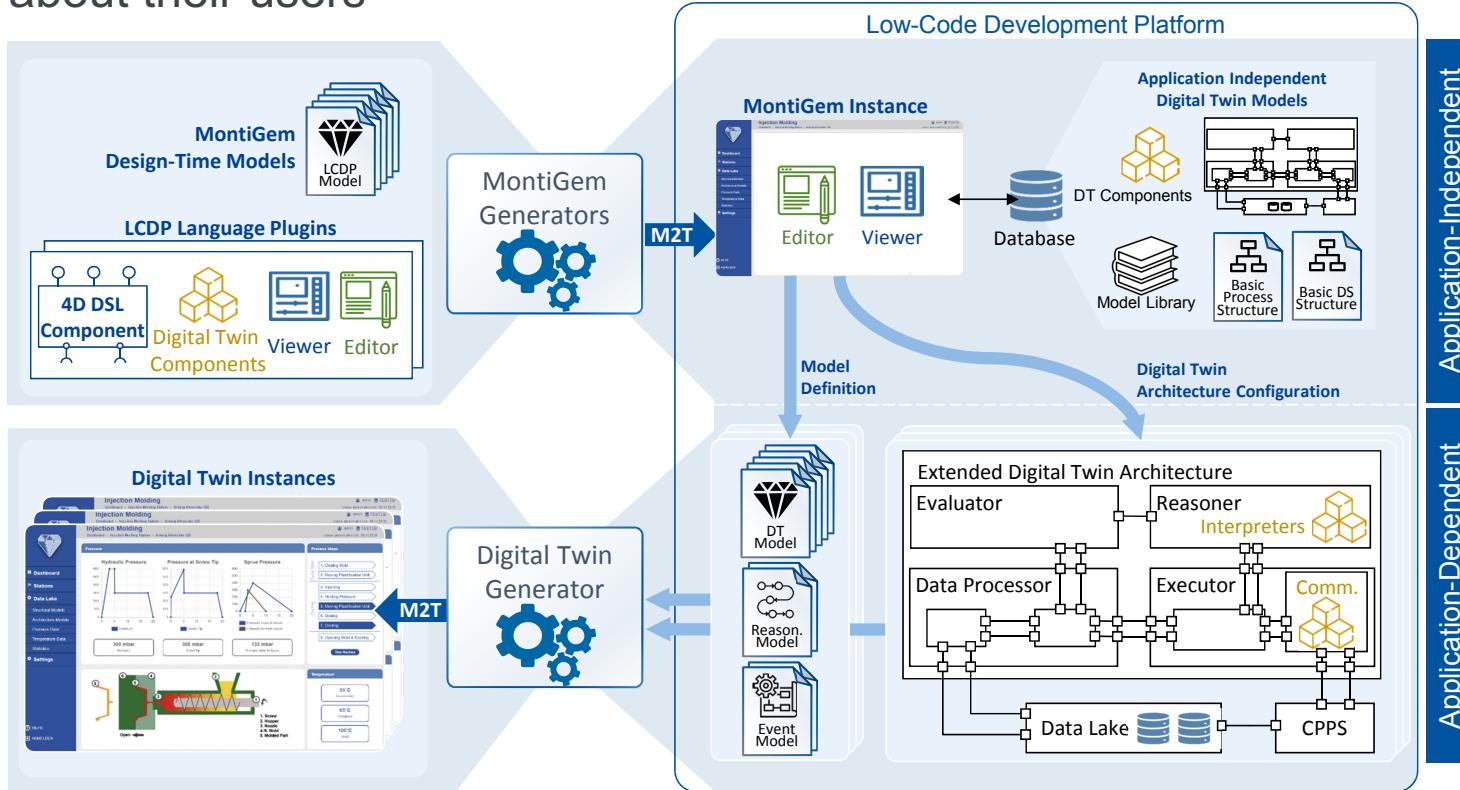


Implementation of the
digital twin

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

Generating 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.

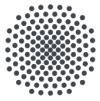
Should we Employ a Turing Test Variant to Determine Digital-Twin-ness?

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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