

**University of Stuttgart**

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



# Ceci n'est pas un jumeau numérique

And other food for thought

**Andreas  
Wortmann**

# A decade of research in model-driven engineering

More at [www.wortmann.ac](http://www.wortmann.ac)

- Professor for model-driven development at University of Stuttgart
- **Research interests** documented in **90+ publications**
  - Model-driven engineering
  - Formal software architectures
  - Language engineering
  - Cyber-physical systems
- Board member of the European Association for Programming Languages & Systems (EAPLS)
- Co-organizer of 20+ international conferences and workshops
  - CoMoDiTy@ER
  - ModDiT@MODELS
- Various projects on digital twins



# Research Projects on Digital Twins

Ranging from foundations to applications

## Internet of Production DFG Excellence Cluster

- Mission: Manufacturing of the future based on **digital shadows**
- 34 institutes of RWTH Aachen University
- Results: architectures for digital twins [1-5], metamodels for digital shadows [7-10]
- More: [www.iop.rwth-aachen.de](http://www.iop.rwth-aachen.de)

## Model-Updating Digital Twins

- Mission: close the gap between **models of digital twins** as-designed and as-operated
- Results: extensions of digital twin architecture

## Software-Defined Car BMBF project

- Mission: Conceive **digital twin of the vehicle** for analysis and development purposes
- 12 partners from automotive domain
- More: <https://www.uni-stuttgart.de/universitaet/aktuelles/meldungen/Pionierarbeit-im-automobilien-IT-Dschungel/>

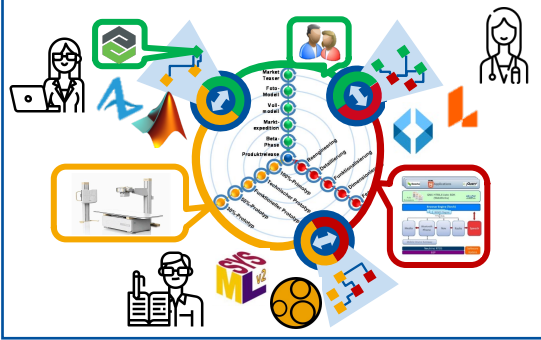
## Software-Defined Manufacturing BMBF project

- Mission: Flexible **manufacturing w. digital twins**
- 32 partners from manufacturing research
- More: <https://www.sdm4fzi.de/en/>

# Efficiently Engineering Future's Cyber-Physical Systems

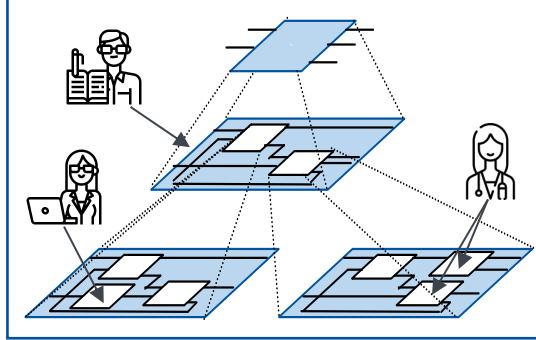
Through better languages, methods, and tools

## Systematic Software Language Engineering



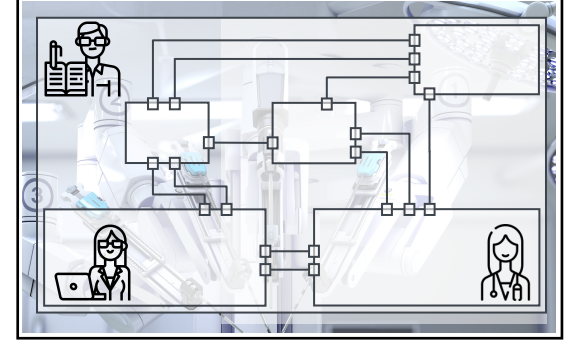
- Component-based language engineering
- Systematic reuse via language product lines
- Improves modeling precision and domain expert integration

## 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

# Agenda

## Provoking debate about digital twins

- 1 What is (not) a digital twin?
- 2 Properties of digital twins
- 3 Model-driven engineering of digital twins
- 4 Selected challenges

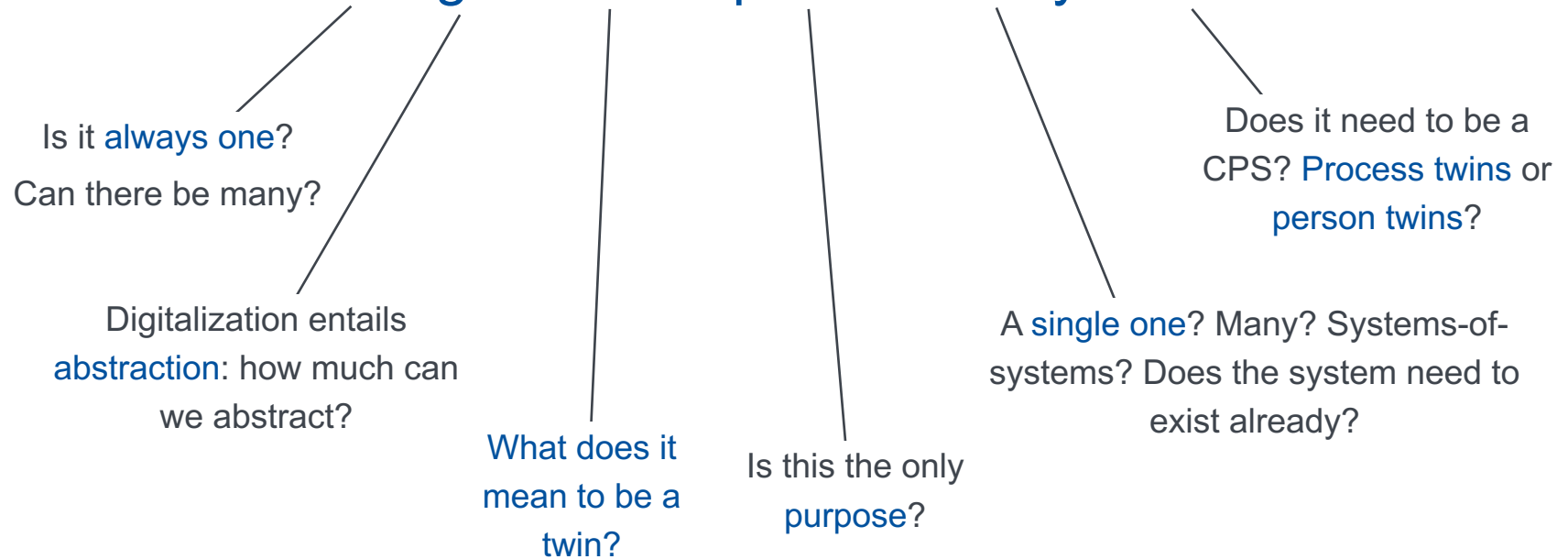
# A Simple Truth about Digital Twins

A digital twin represents a system

# A Simple Truth about Digital Twins

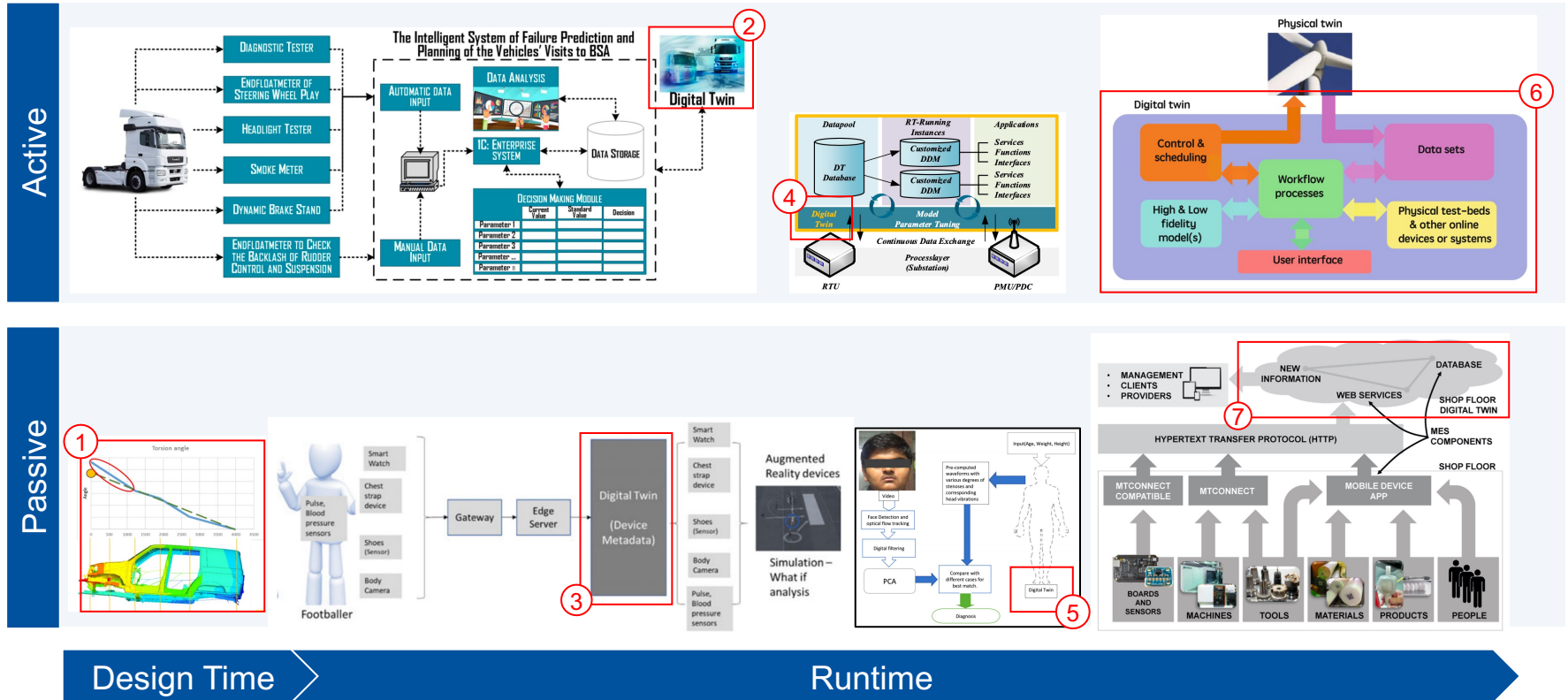
Is it?

## A digital twin represents a system



# Digital Twins come in a Spectrum of various Shapes and Purposes

And are used at different times throughout systems engineering



# 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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## 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]

# How Research Describes Digital Twins

## A new hope

### As a Model

- “defined as the **predictive and validated** model” [128]
- “a **software model** which is composed of 3D physical, mechanical, and electrical data” [497]
- “**multi-faceted dynamic set of smart digital models** of a system” [719]

### Focusing on Simulation

- “a [...] simulation model” [498]
- “integrated multiphysics, multiscale, probabilistic simulation of an **as-built vehicle or system**” [1307]
- “Digital Twin [...] describes the use of **holistic simulations** to virtually mirror a physical system.” [1386]

### Requiring an Existing System

- “always in sync digital model of **existing manufacturing cells**” [24]
- “a digital model of a **real object** containing [...] data, which are synchronized in real-time” [269]

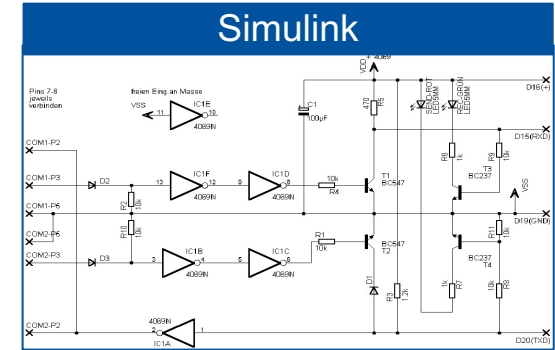
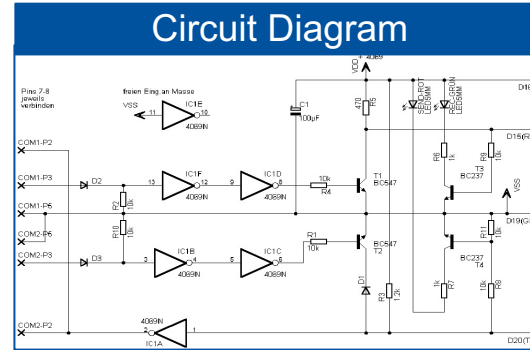
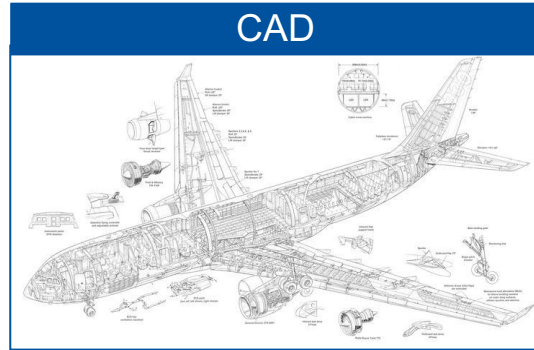
Lesson Learned

**A digital twin is not a simulation model  
of an existing system**



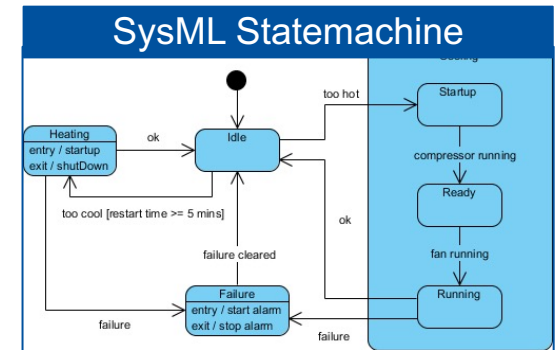
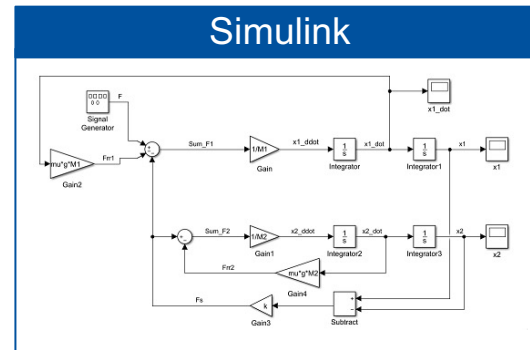
# Are these Digital Twins?

All of these models can be used to simulate an existing system



### Math

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



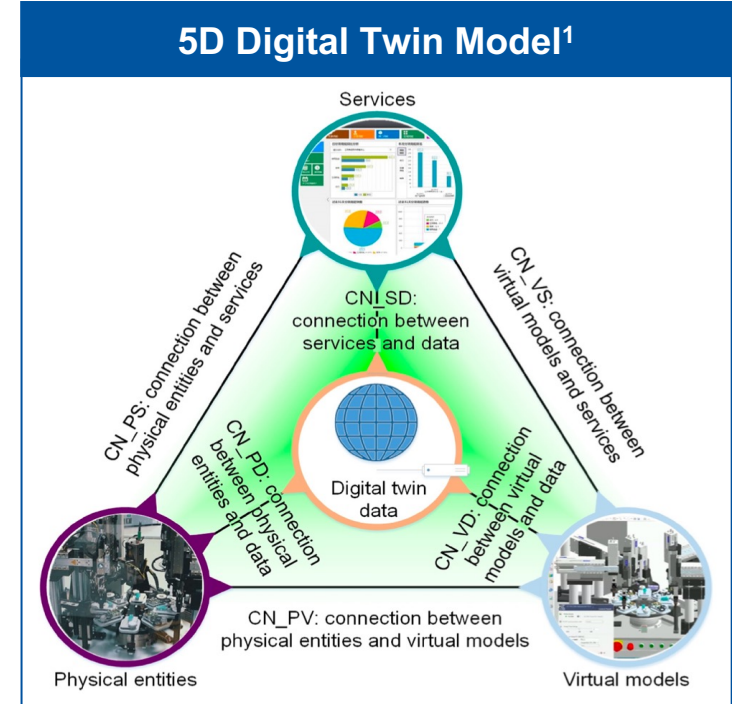
Suggestion

**A digital twin is a software  
comprising models and services  
to use these models**

# A Digital Twin Definition based on Constituents

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

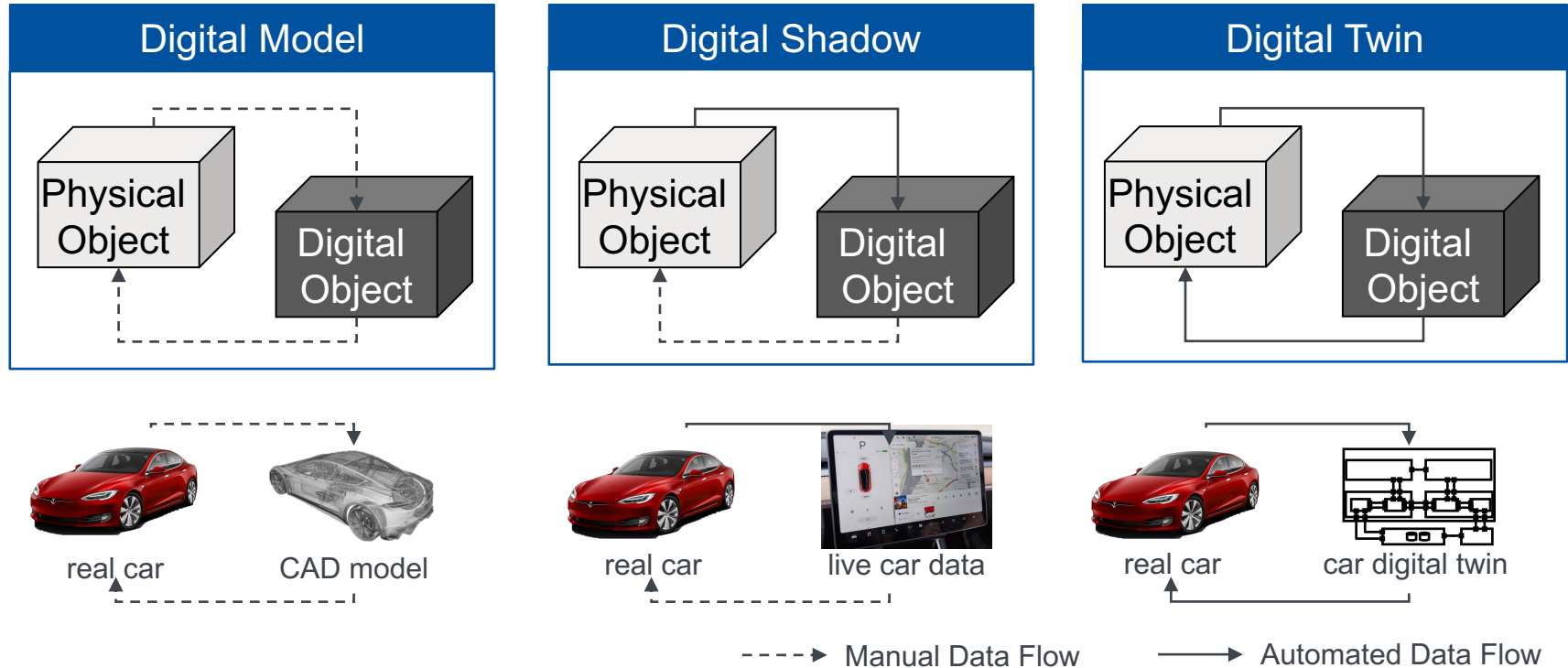
1. **Physical object:** Beings, cyber-physical systems, ...
2. **Digital object:** Models, software infrastructures, VR, ...
3. **Services:** Monitoring, optimization, prediction, ...
4. **Digital data:** Sensor readings, manufacturing orders, ...
5. **Connections:** WiFi, ethernet, fieldbus, ...



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

# A Characterization based on Data Flows<sup>2</sup>

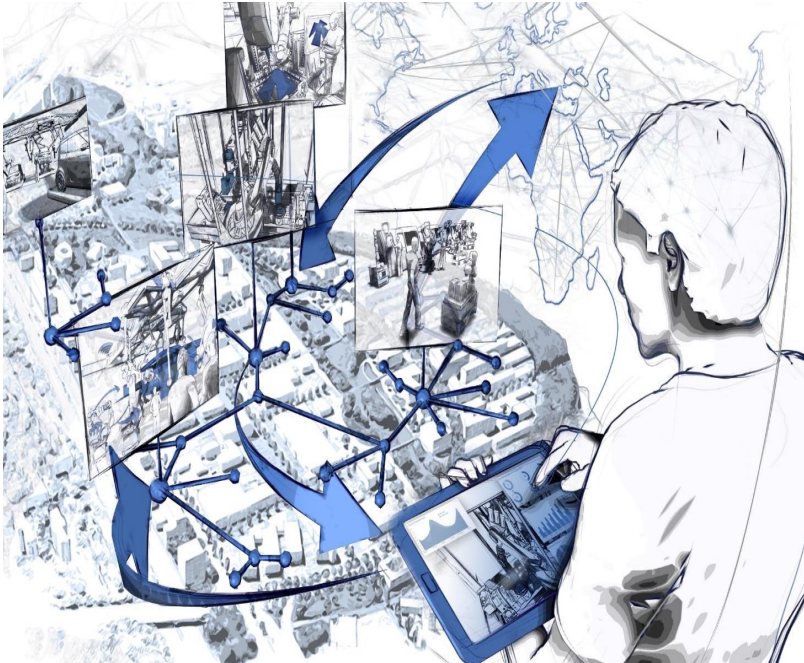
Data flows between physical and digital object(s) define what kind of system it is



<sup>2</sup> Kritzinger, W., Karner, M., Traar, G., Henjes, J., & Sih, W: Digital Twin in manufacturing: A categorical literature review and classification. IFAC-PapersOnLine, 2018.

# Proliferation of Crude Definitions Hampers Digital Twin Research

Results from the “Internet of Production” DFG excellence cluster



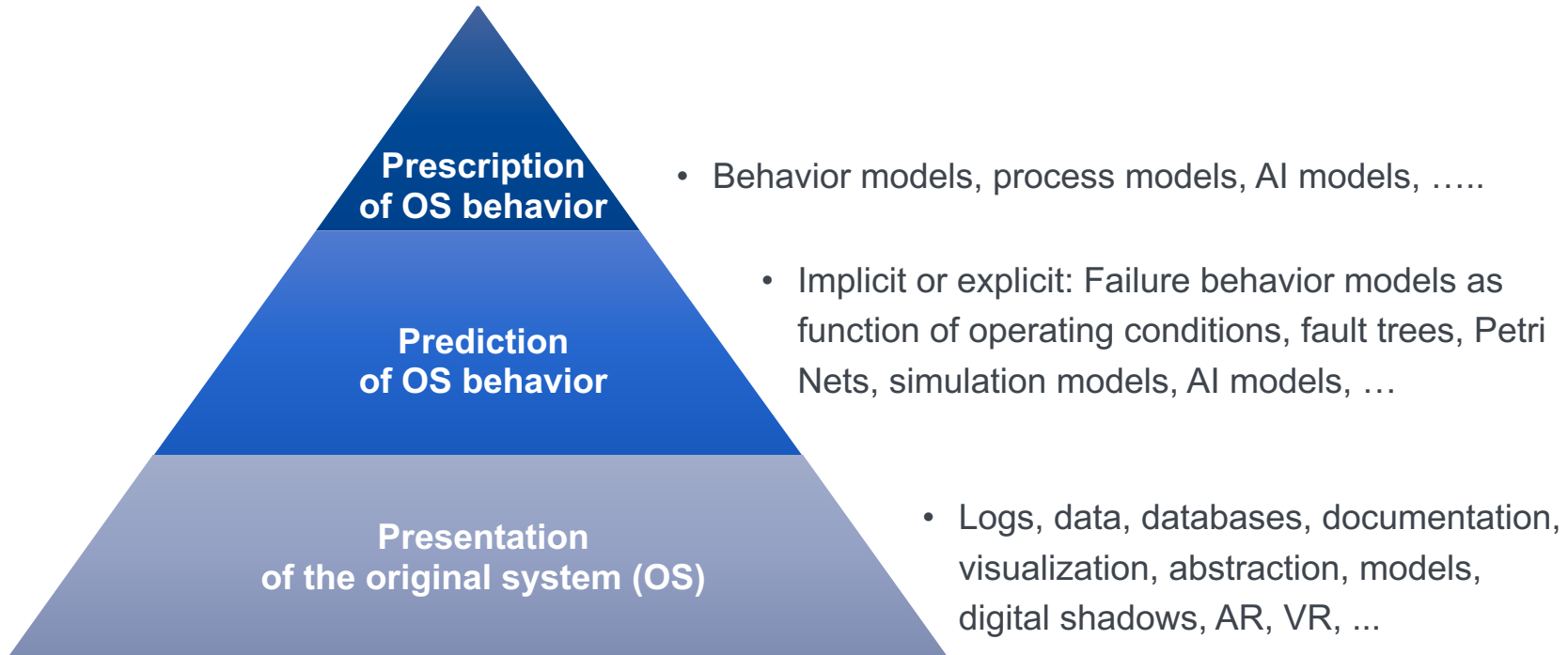
## Digital Twin [1,7,8]

A digital twin of a system consists of a set of **models** of the system, a set of **digital shadows**, and provides a set of **services** to use the data and models **purposefully** with respect to the original system.

- Relies on **better understood foundations**
  - Models (Stachowiak)
  - Digital shadows [9,10]
  - Services
- Neither prescribes purposes, nor implementation
- Captures most of the **143 definitions** encountered in a mapping study

# A Three-Layer Model of Digital Twin Purposes

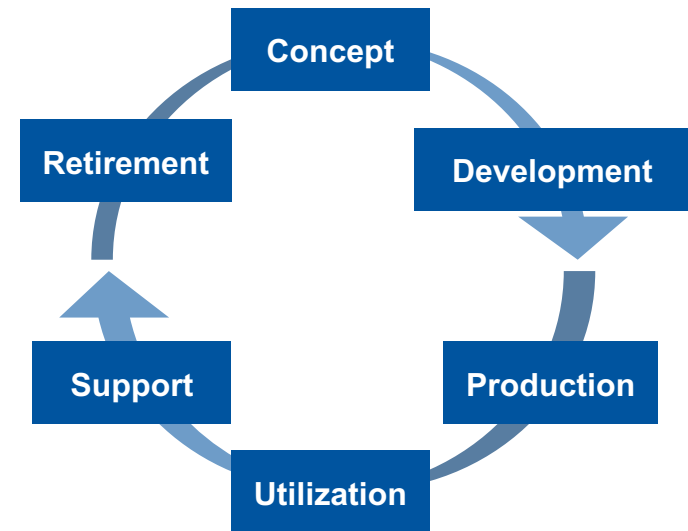
Essential digital twin functions: present, predict, prescribe twinned system



# Digital Twins Could Support all Lifecycle Phases of the OS

With different services to control/adapt/represent the CPS

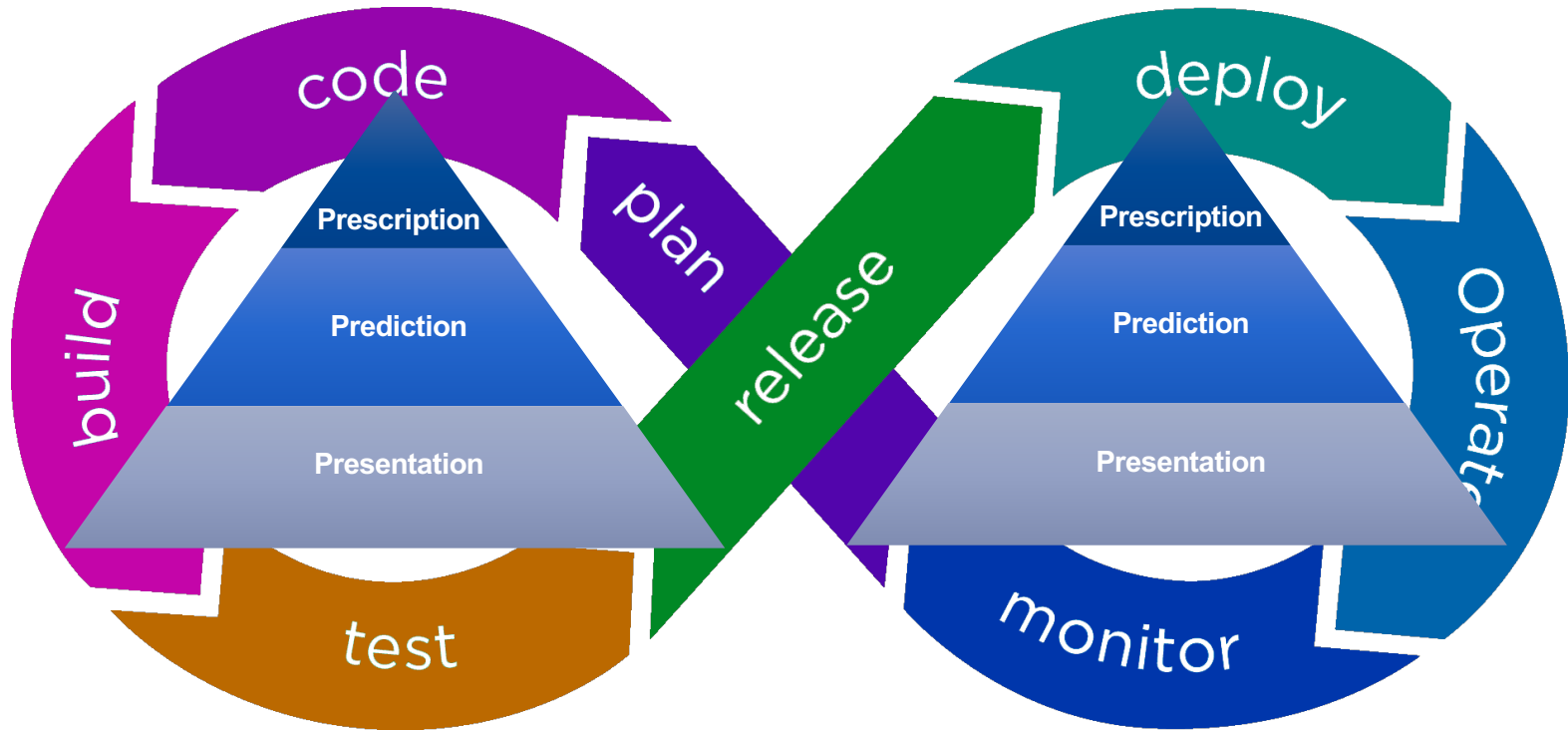
- **Concept & Development**
  - Communication support
  - Simulate behavior of system-under-development
  - Evaluate product variants to support design decisions
- **Production**
  - Supervise production, e.g., individual system deviations
  - Trace the applied materials, components, processing steps
- **Utilization & Support**
  - Provides information on system state, history and usage
  - Facilitates the improvement of future products
  - Enables predictive maintenance
- **Retirement**
  - Knowledge transfer to next generation of system



System Lifecycle from ISO/IEC 15288  
(Systems Engineering standard)

# Digital Twins Could Support all Lifecycle Phases of the OS

As the basis of a model-driven DevOps for continuous systems engineering



Suggestion

**A digital twin is a software comprising models and services to purposefully represent and manipulate its original system across its complete lifecycle**

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# Agenda

## Provoking debate about digital twins

1 What is (not) a digital twin?

2 Properties of digital twins

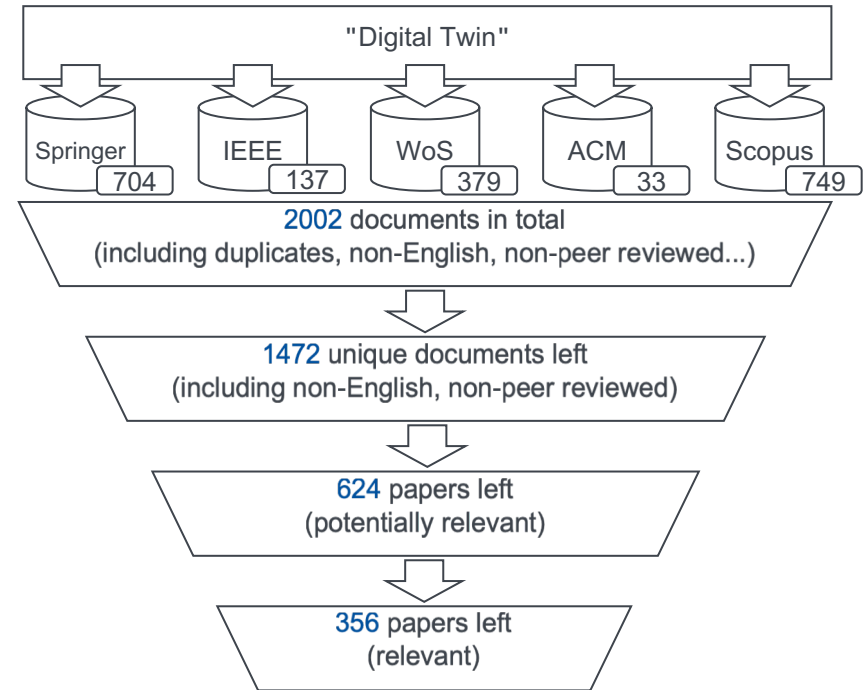
3 Model-driven engineering of digital twins

4 Selected challenges

# A Systematic Cross-Domain Mapping Study for Digital Twins

## Research questions and overview

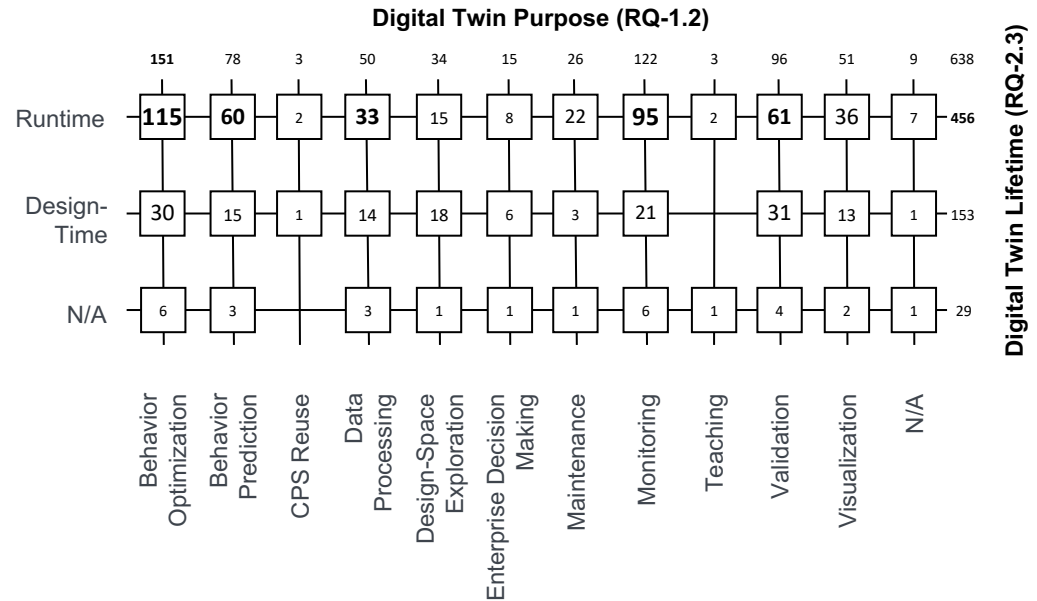
1. Who uses Digital Twins for which purposes?
2. What are the conceptual properties of Digital Twins?
3. How are Digital Twins engineered?
4. How are Digital Twins deployed?
5. How do Digital Twins operate?
6. How are Digital Twins evaluated?



# Who uses Digital Twins for which purposes?

Agriculture, Automotive, Avionics, Education, Medicine, Production, ....

- Included 356 papers, each could address **multiple purposes**
- Strong focus on using digital twins at **runtime** of the twinned system
- Main purposes behavioral
  - **Monitor (Present)**
  - **Predict**
  - **Optimize (Prescribe)**
  - **Validate**
- Some counterintuitive findings
  - Design-space exploration at runtime



# Observations on Conceptual Aspects of Digital Twins

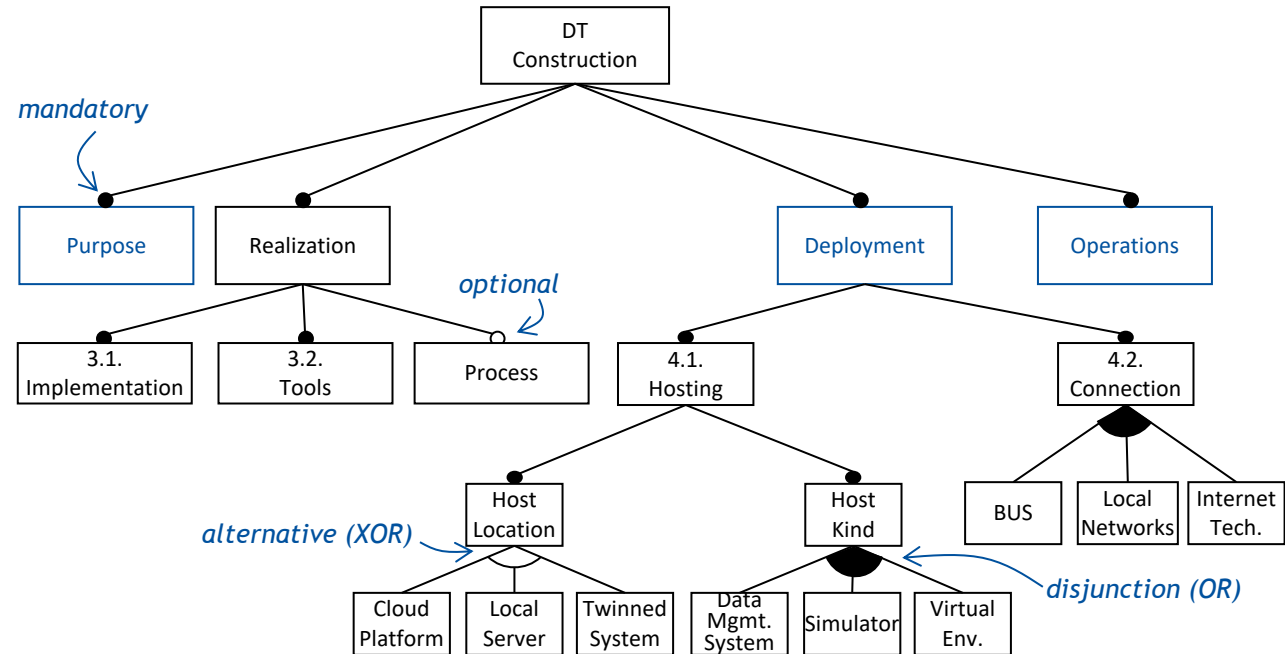
According to research literature

1. Purpose  
("Why?")

2. Realization  
("How?")

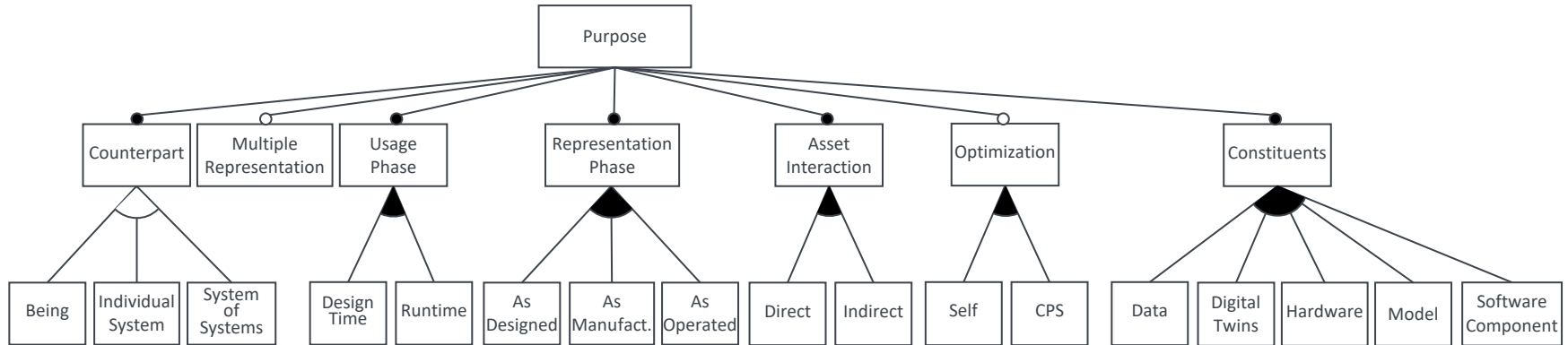
3. Deployment  
("Where?")

4. Operations  
("How?")



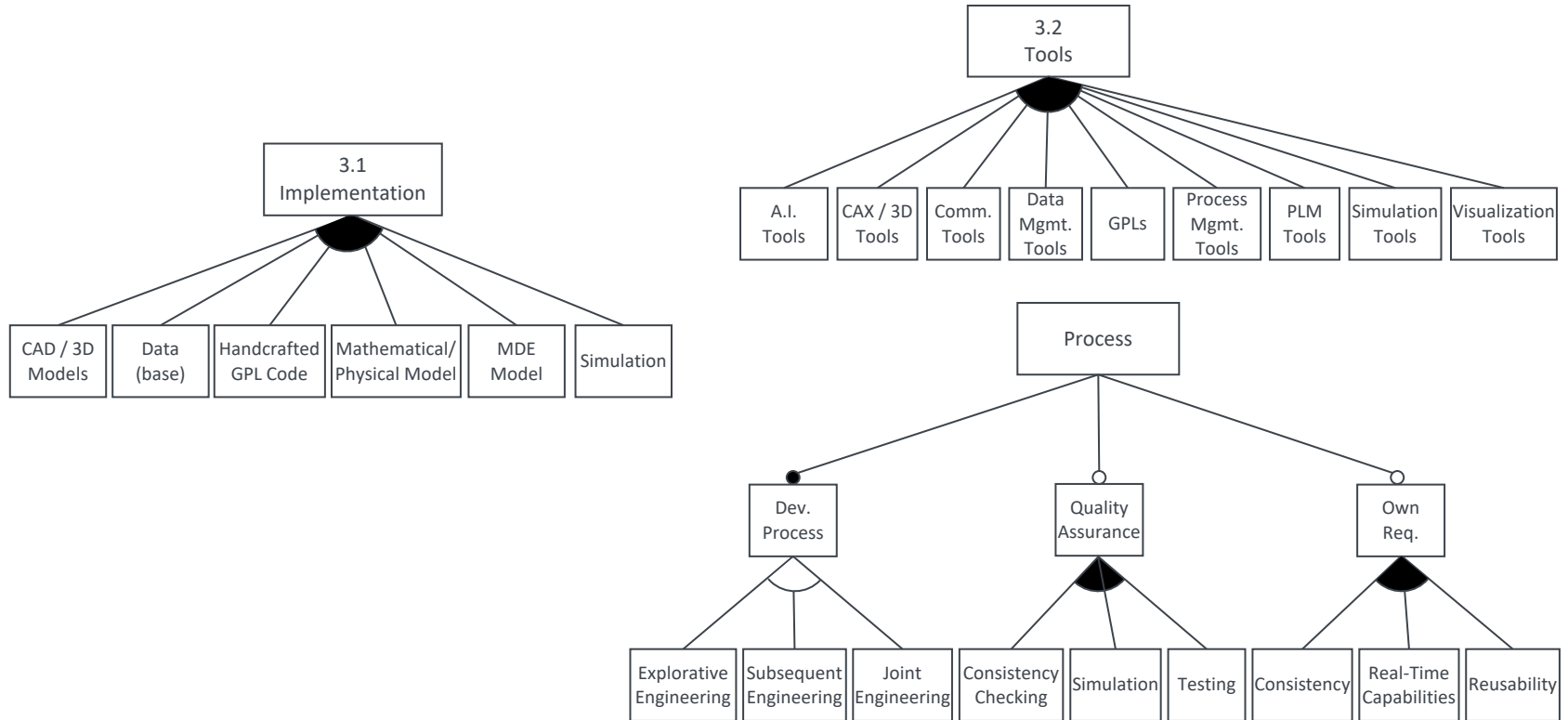
# What are the Conceptual Aspects of Digital Twins?

## Purpose aspects



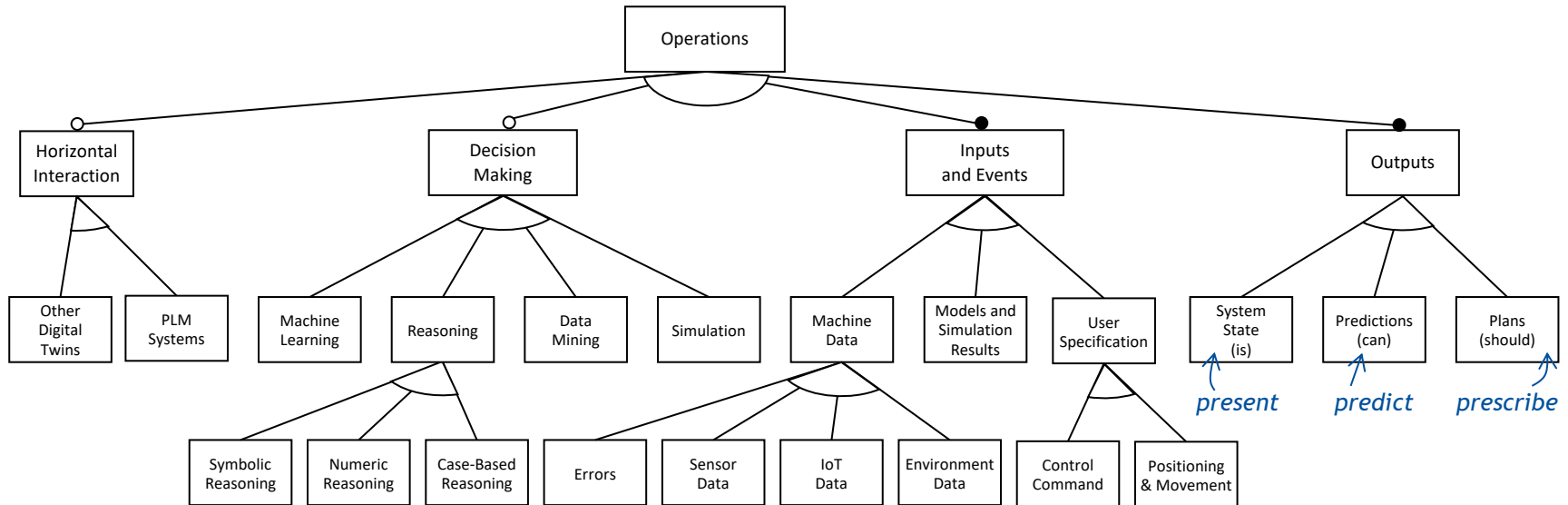
# The Conceptual Aspects of Digital Twins

## Realization aspects



# The Conceptual Aspects of Digital Twins

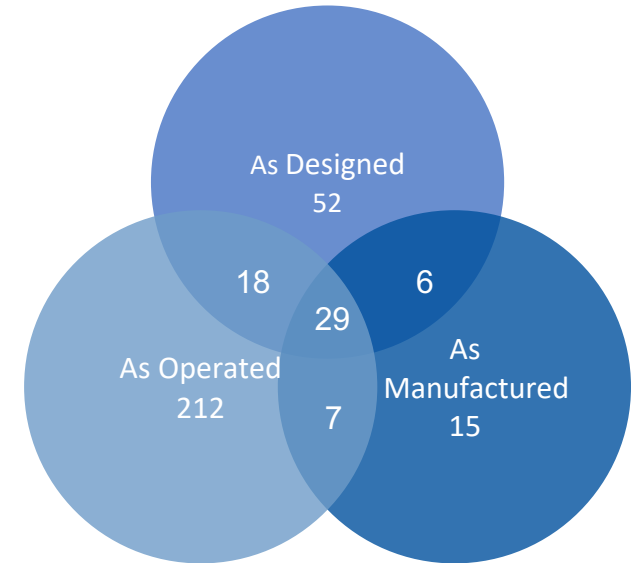
## Operations aspects



# How do Digital Twins operate?

What lifecycle stage of the CPS do they represent

- **As-Designed**
  - Represent twinned system as it was designed
  - Often a **type model** representing all instances of that system
  - Used for optimizing production process of twinned system
- **As-Manufactured**
  - Integrates data related to production of the twinned system
  - May include production tolerances, differences, etc.
  - Now an **instance model** for the specific system
- **As-Operated**
  - Represents the **twinned system in operation & changes over time**
  - Includes environmental influences, wear & tear, reconfiguration
  - For supervising and optimizing or for predicting future behavior



Observation

**Engineering digital twins demands  
making unique design decisions**

# Agenda

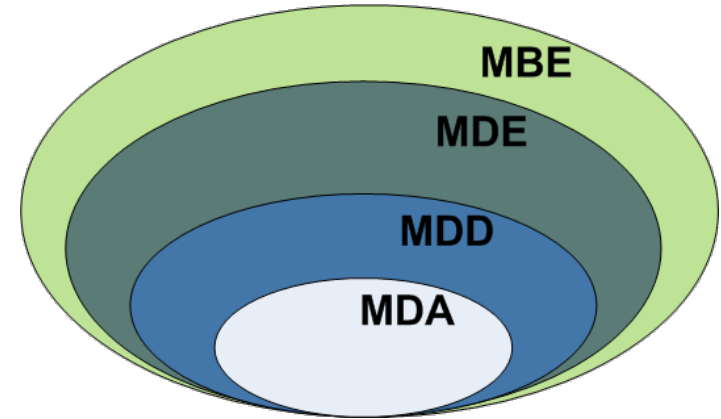
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# Model-Based Software Engineering

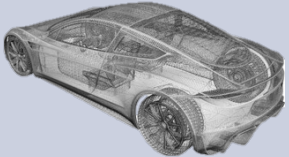

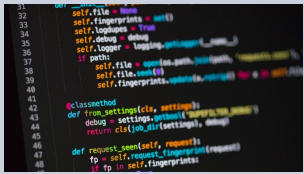
## Clarifying terminology

- **Model-Based Engineering (MBE):**  
Models are used somehow across the overall engineering process (e.g., for comm. and/or design)
- **Model-Driven Engineering (MDE):**  
Models drive parts of the overall engineering process
- **Model-Driven Development (MDD):**  
Models are primary artifacts for the development process
- **Model-Driven Architecture (MDA):**  
The Object Management Group's (OMG) vision on MDD: CIM → PIM → PSM → PSI



# Distinguishing Model-Driven Digital Twin Entities

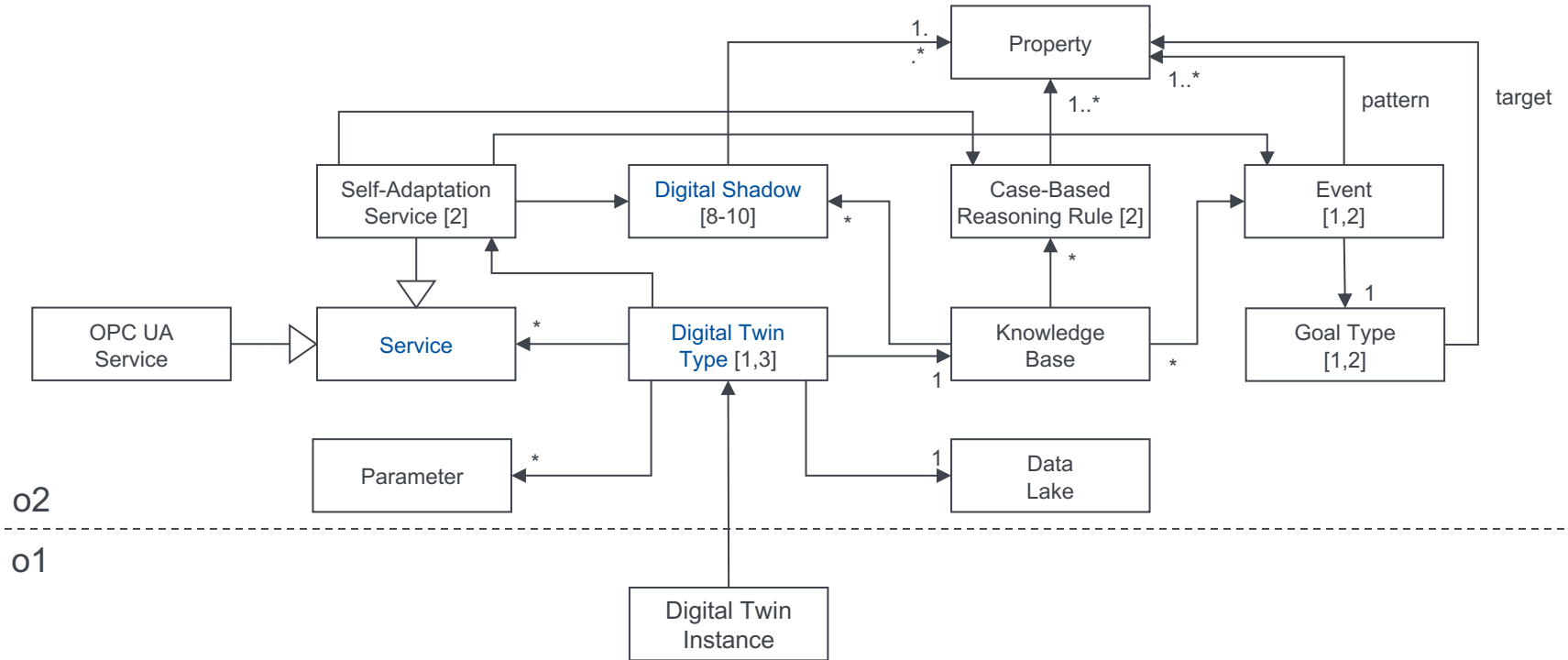
Enforcing honesty: what do we mean when saying “digital twin”?

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

<sup>3</sup> C. Atkinson & T. Kuhne: Model-driven development: a metamodeling foundation. In: IEEE Software, 20(5), 36-41. 2003.

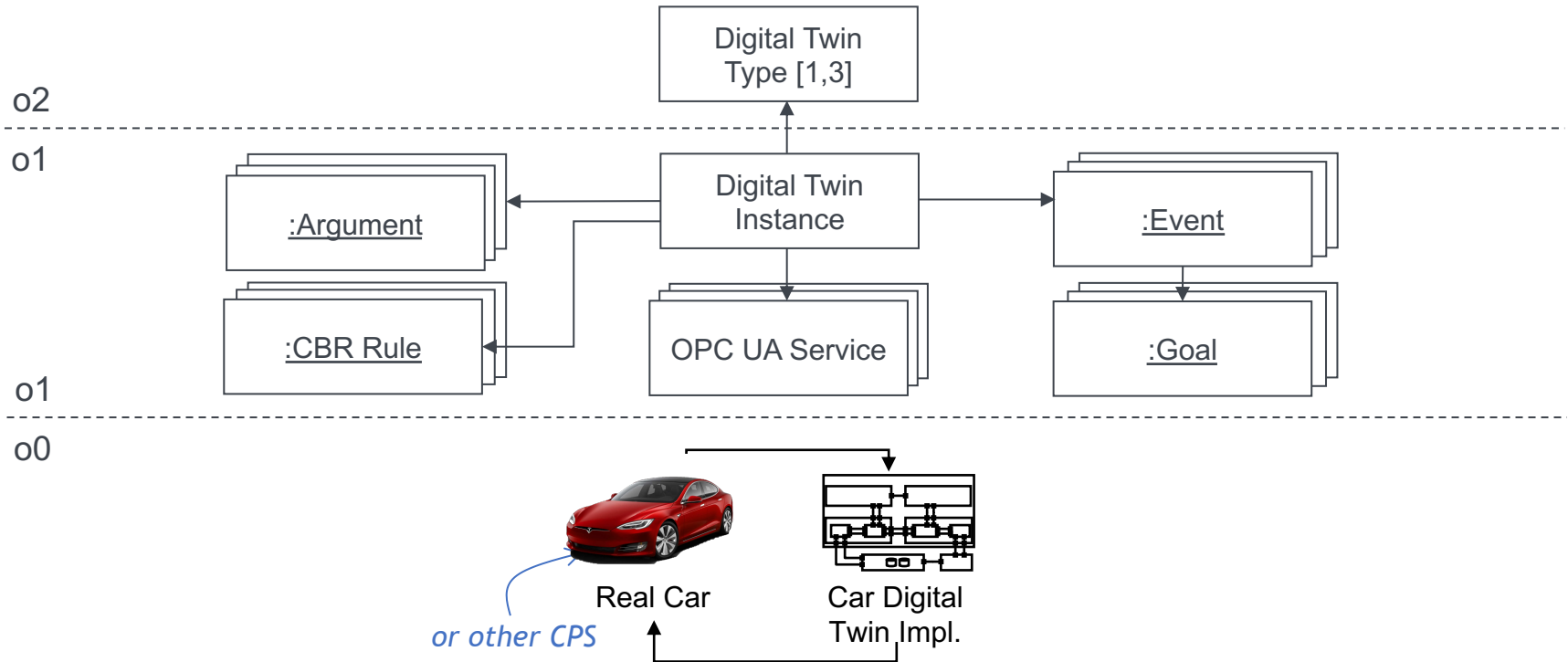
# A Digital Twin Type

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



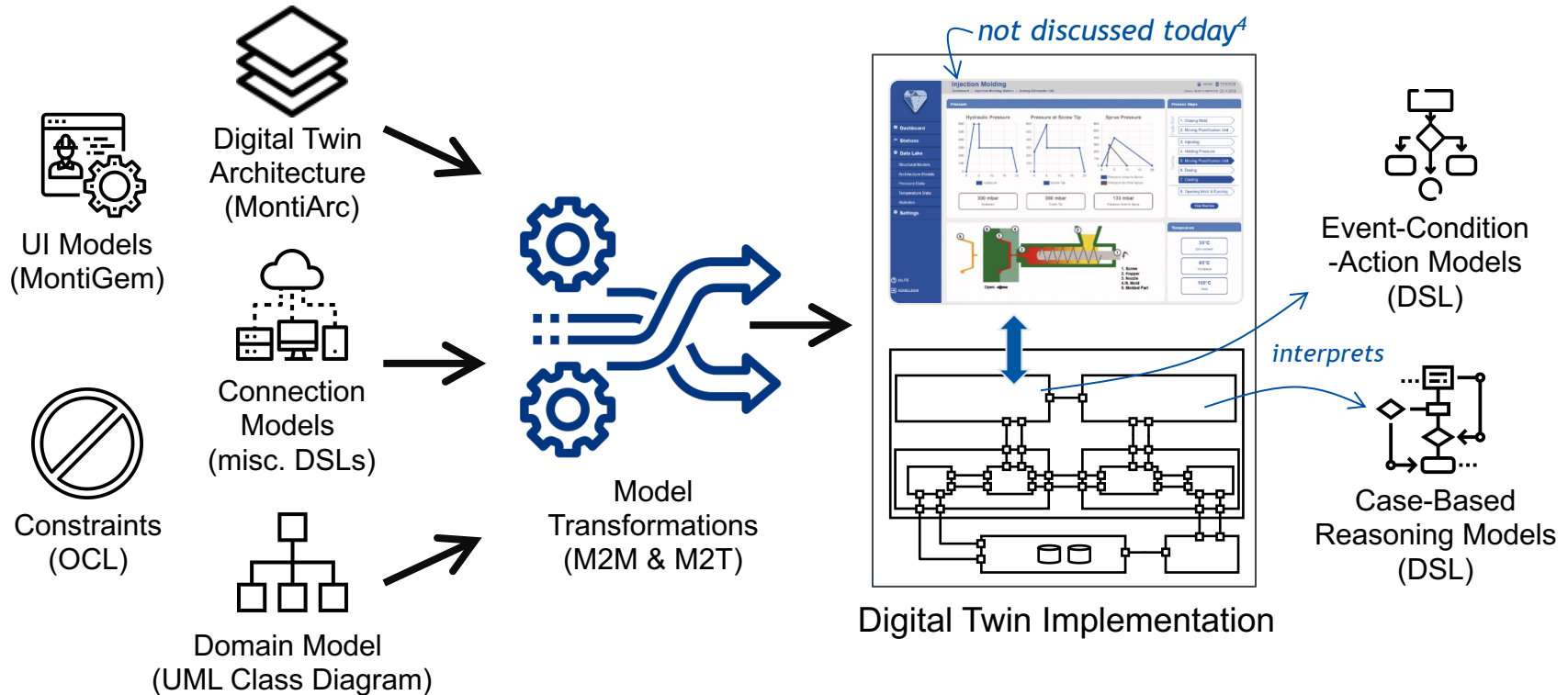
# A Digital Twin Instance

A configured instance of a specific digital twin type



# Model-Driven Engineering of 3P Digital Twins as Self-Adaptive Systems

Generating structure, interpreting behavior

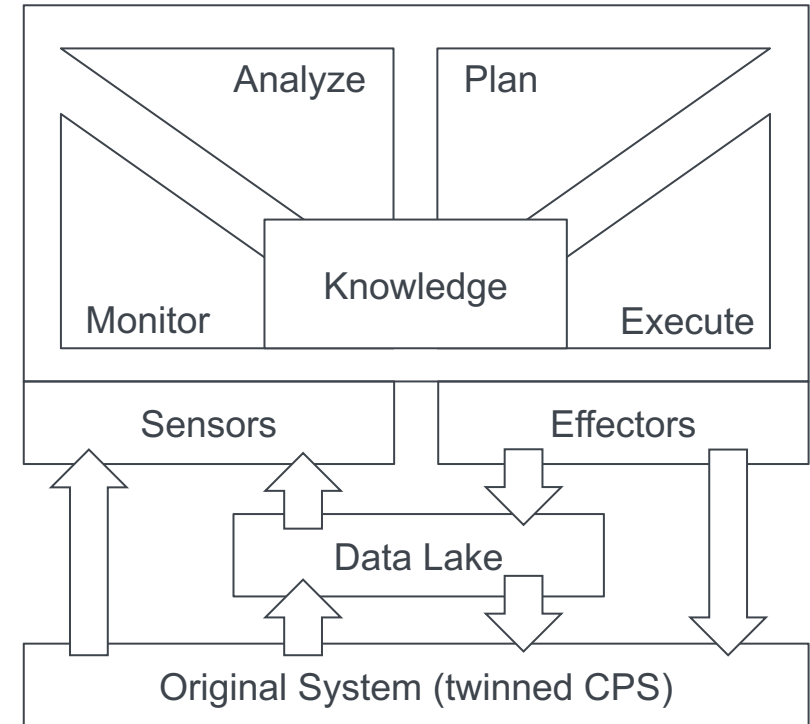


<sup>4</sup> Dalibor, M., Michael, J., Rumpe, B., Varga, S., & Wortmann, A. (2020,). Towards a Model-Driven Architecture for Interactive Digital Twin Cockpits. In International Conference on Conceptual Modeling (pp. 377-387). Springer, Cham.

# Generation Target: Self-Adaptive Digital Twins

## Realize MAPE-K control loop variant

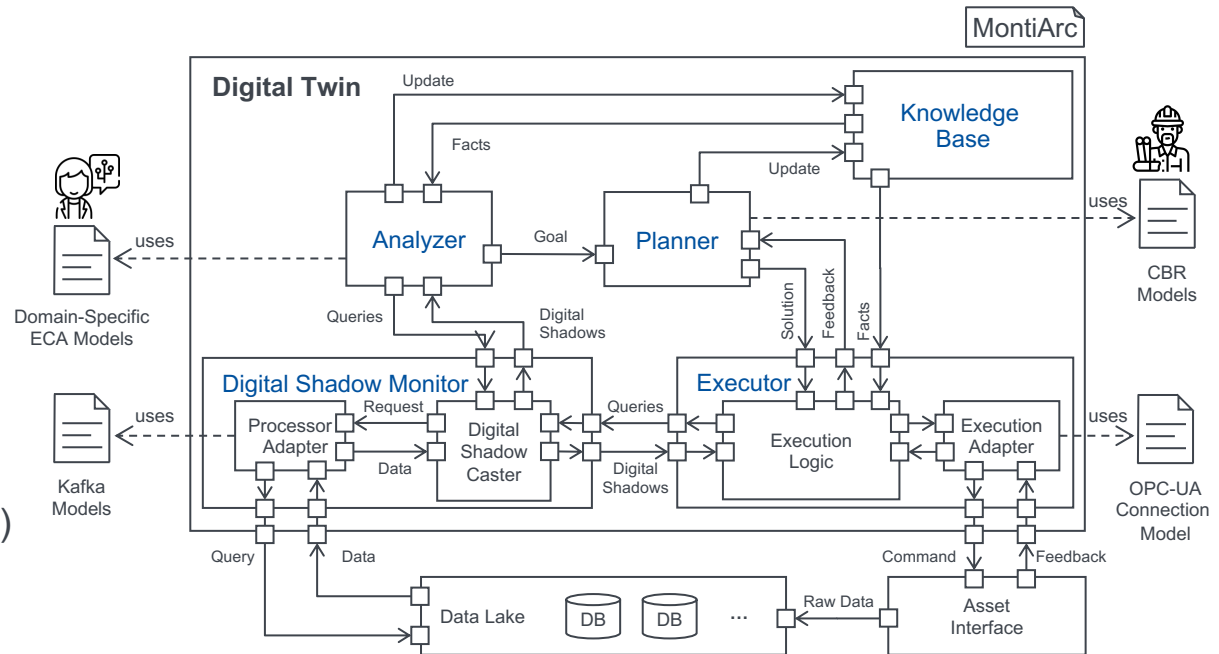
- **Monitor** (Present)
  - Observe changes in original system & data lake
  - Emit corresponding digital shadows if necessary
- **Analyze** (Predict)
  - Check Event-Condition-Action (ECA) rules against digital shadows
- **Plan** (Prescribe)
  - Case-Based Reasoning (CBR), AI planning, code
- **Execute**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



# 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



# Event-Condition-Action (ECA) Models Reify Domain Expertise

Events predict when the digital twin needs to act on the twinned CPS

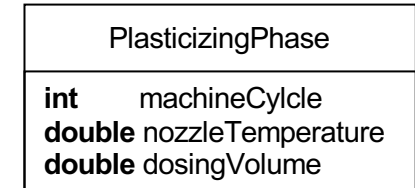
- Digital twins **observe events** of the twinned system, e.g.,

- Human interaction
- Machine wear
- Environmental conditions

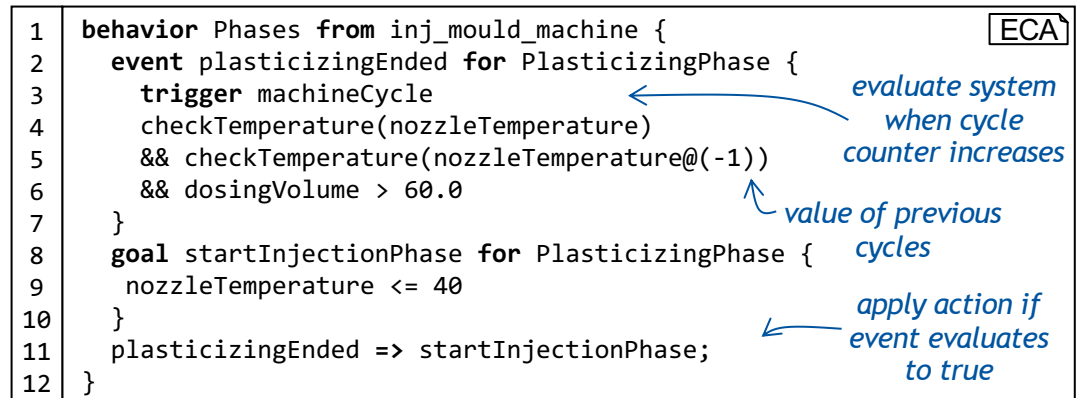
- ECA rules

- Typed based on the domain model
- Descriptive: do not prescribe how** to act upon events but what needs to be achieved
- Actions: Goals to achieve**
- Interpreted** at digital twin runtime

class diagram → 



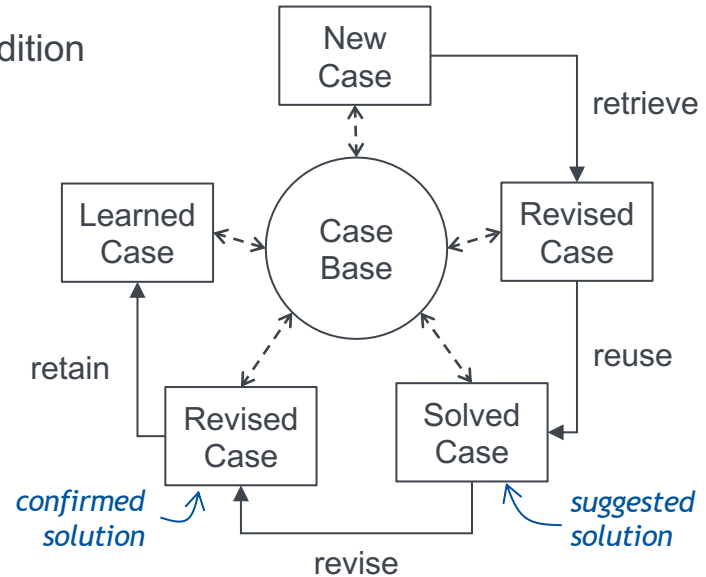
typed by classes and attributes  
defined in CD



# Case-Based Reasoning (CBR) Models also Reify Domain Expertise

Reason on and learn from observed events

- **Problem-solving paradigm** reusing solutions from encountered situations to find similar solutions
- Case comprises
  - **Application condition** (situation): Refines of event condition
  - **Actions** to be performed
  - Intended situation after action execution
- Models **interpreted** at digital twin runtime



```
1 import injectionmolding.HeatingUnit;
2
3 case Overheating(ReduceTempGoal goal) {
4   if goal.currentValue > goal.targetValue;
5   do HeatingUnit.reduceTemp(targetValue);
6   yields
7     goal.currentValue <= goal.targetValue;
8 }
```

CBR

# Agenda

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- 1 What is (not) a digital twin?
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# Many Open Questions

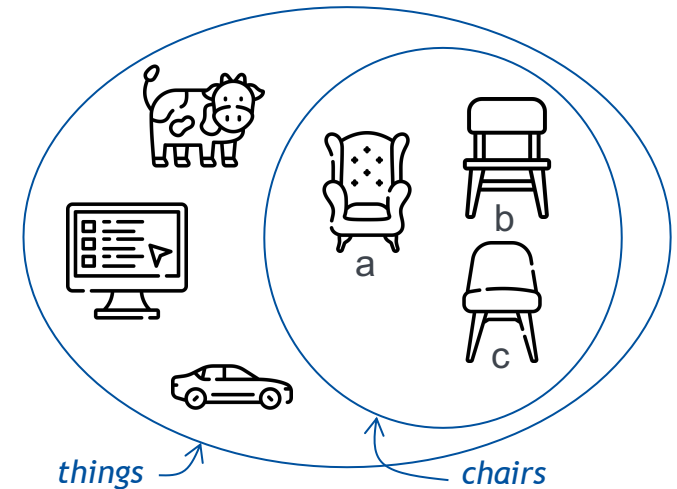
## Pertaining a definition of digital twins

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?
7. When does loss of fidelity stop the digital twin from being a digital twin?
8. Are there **different kinds** of digital twins?

# Without a Proper Definition, Digital Twins are a Piecemeal Technology

Most definitions of digital twins are either ambiguous, narrow, or impossible



- A definition **separates a set** into included things and excluded things
- **Intensional**: Characterize the nature of included things
  - Example: *A chair is a physical object that has legs, a backrest and does not move by itself*
- **Extensional**: Enumerate included things
  - $\text{Chairs} := \{a, b, c\}$
- We need a proper intensional definition of digital twins
- To communicate about them, build theories, reuse parts, ...



**Challenge 1:** Find a commonly accepted, intensional, definition of “Digital Twin” that does (a) not rely on undefined terms, (b) is independent on a domain/technology/application, (c) feasible to achieve

# Kinds of Engineering Models used in Systems Engineering

That might be useful to represent the systems with a digital twin

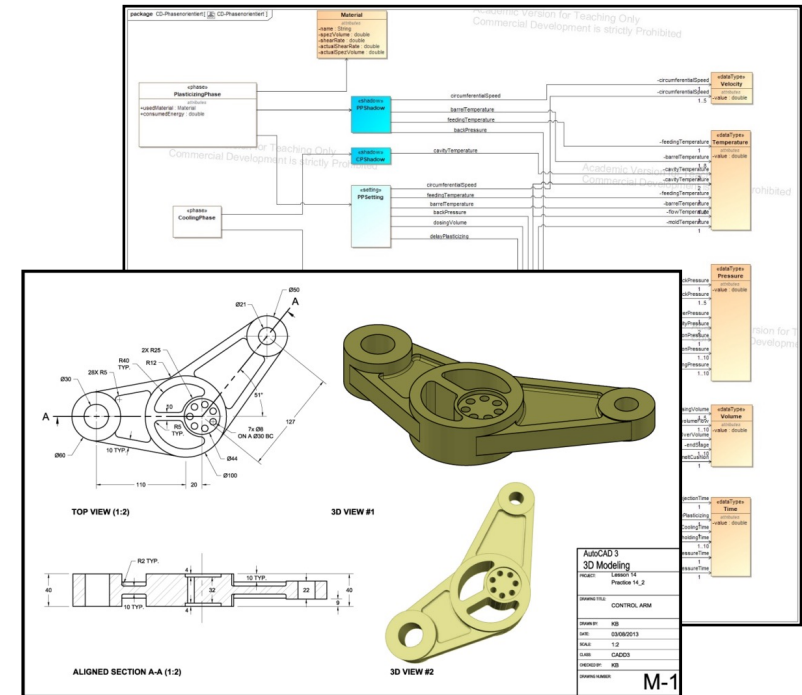
- **Structural models:** Representing relevant parts of the system-of-interest
    - System under development, its environment
    - Its environments
  - **Behavioral models:** Describe a system's (inter)actions
- UML/SysML/Ontology
- 
- UML and SysML logos. UML is a 3D logo with 'U' in red and 'ML' in yellow and blue. SysML is a 3D logo with 'SYS' in red and 'ML' in yellow and blue.
- **Physical models:** Objects that are identical in the relevant attributes of the real system or similar, e.g., test bench
  - **Geometrical models:** Mathematical description of shapes
  - **Mathematical models:** Expressions or numerical methods to convert input data into outputs to explain or prescribe system behavior
- STEP (ISO 10303)
- 
- SolidWorks logo. It features a stylized '3S' in blue and yellow, with the word 'SolidWorks' in red below it.

# Engineering Digital Twins is Challenging

Yet most are handcrafted

- Cyber-physical systems are complex
  - Many components & functionalities
- Reflected in digital twins, which provide different
  - Functions, services, views on CPS state and data
- Creating a **useful digital twins** requires
  - **Domain knowledge** about the CPS
  - Software engineering expertise
  - Tremendous effort
- Does not scale up

**Challenge 2:** Reuse engineering models that are created during system design for systematic efficient definition of larger parts of a digital twin

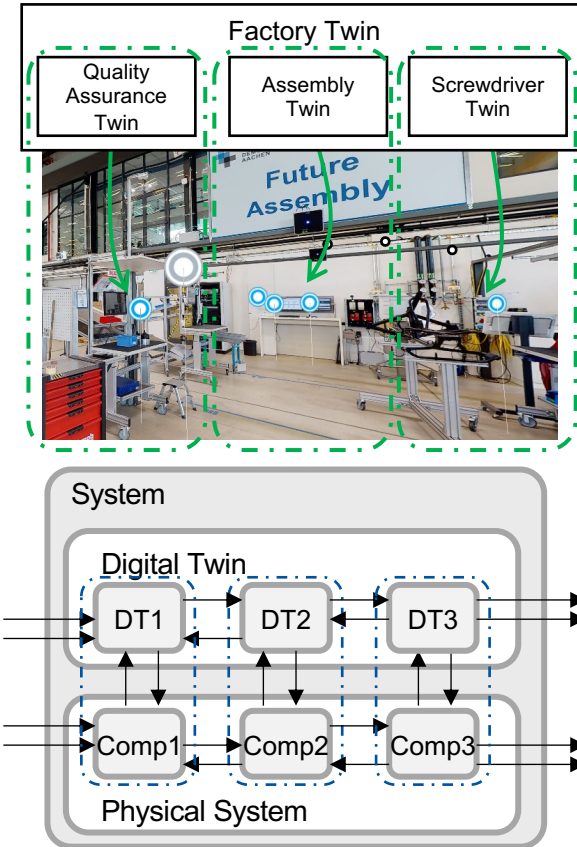


# Composition of Digital Twins is Essential

Combine simple digital twins to build more complicated digital twins

- Composition **vital** to many disciplines
- Examples: function composition (math), product composition (mechanics), software composition (CS) ...
- Software engineering **without composition unthinkable**
- **Idea:** When physical composing car chassis and motor, compose their digital twins as well
  - Many questions: (a) how to compose, (b) which parts to compose, (c) are there conflicting parts, ...

**Challenge 3:** Enable the black-box composition of more complex digital twins from simpler digital twins without requiring manual interaction



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

The Turing test is a thought experiment on deciding machine intelligence

## Turing Test

During the Turing test, the human questioner asks a series of questions to both respondents.  
After the specified time, the questioner tries to decide which terminal is operated by the human respondent and which terminal is operated by the computer.

■ QUESTION TO RESPONDENTS ■ ANSWERS TO QUESTIONER

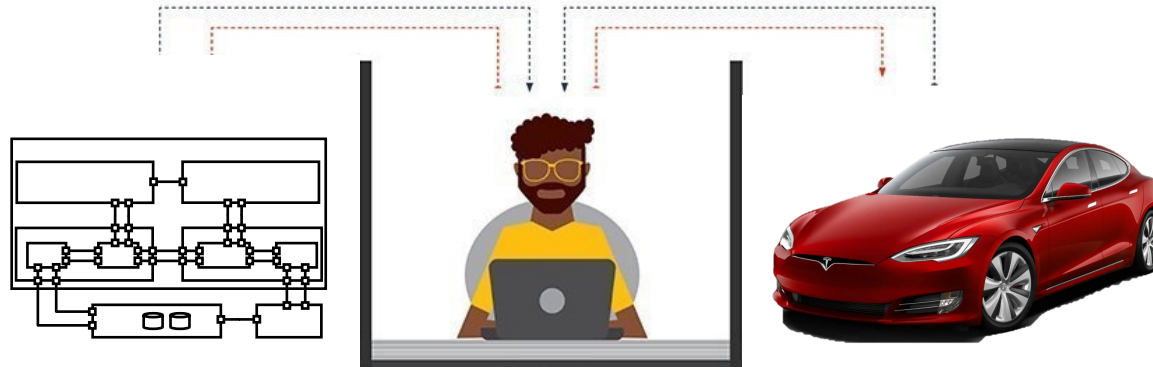


# Can we Employ a Turing Test Variant to Determine Digital-Twin-ness?

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**.

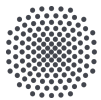


**Challenge 4:** Identify a way to discriminate digital twins from other software systems

# Summary

1. Most descriptions of digital twins in literature are **unsatisfying for scientific discourse**
2. A digital twin **is not** a (simulation) model
  - **is a software** comprising models and services to use these models w.r.t. the original system
  - has a **bidirectional information exchange** to configure/control the original system
3. Distinguish “digital twin **type**” from “digital twin **instance**” from “digital twin **implementation**”
4. Engineering digital twin types/instances/implementations requires considering **many different aspects**
5. **Gap between digital twins as-designed, as-manufactured, as-operated** needs to be closed
6. Abandoning ad-hoc digital twin engineering requires addressing **many open research questions**

Join the discussion at the **Workshop on Model-Driven Development of Digital Twins (ModDiT)**  
<https://gemoc.org/events/moddit2021> (hopefully back for MODELS'22)



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# Further Reading

## Digital Twins

- [1] P. Bibow, M. Dalibor, C. Hopmann, B. Mainz, B. Rumpe, D. Schmalzing, M. Schmitz, and A. Wortmann. *Model-Driven Development of a Digital Twin for Injection Molding*, International Conference on Advanced Information Systems Engineering (CAiSE'20), 2020.
- [2] T. Bolender, G. Bürvenich, M. Dalibor, B. Rumpe, and A. Wortmann. *Self-Adaptive Manufacturing with Digital Twins*, In: 2021 International Symposium on Software Engineering for Adaptive and Self-Managing Systems (SEAMS), 2021.
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- [7] Brauner et al.: A Computer Science Perspective on Digital Transformation in Production (ACM Transactions on Internet of Things), 2021.
- [8] C. Brecher, M. Dalibor, B. Rumpe, K. Schilling, A. Wortmann: *An Ecosystem for Digital Shadows in Manufacturing* (CIRP CMS), 2021.

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# Sources of Third-Party Image Materials

## Slide Source of Image Materials

- 15 Tesla Model S: <https://de.motor1.com/news/445337/tesla-battery-day-2020-highlights/>  
Tesla Model S CAD: <https://www.3dcadbrowser.com/3d-model/tesla-roadster-2020>  
Dashboard: Tesla CAD: <https://www.3dcadbrowser.com/3d-model/tesla-roadster-2020>
- 19 DevOps Loop: <https://geko.cloud/en/what-is-devops/>
- 31 MDE schema: <https://modeling-languages.com/clarifying-concepts-mbe-vs-mde-vs-mdd-vs-mda/>
- 34 Starman: <https://www.flickr.com/photos/peterthoeny/39417002964>  
Source Code: Photo by [Ilya Pavlov](#) on [Unsplash](#)
- 50 Turing Test: <https://www.techtarget.com/searchenterpriseai/definition/Turing-test>

# Researching Digital Twins is a Team Effort

Join the community

✓ MODELS'21

## Workshop on Model-Driven Development of Digital Twins

<https://gemoc.org/events/moddit2021>

- Workshop topics
  - Modelling concepts and languages, methods, and tools for developing digital twins
  - Quality assurance for and evaluation of digital twins
  - Deployment and operation of digital twins
  - Architectural patterns for digital twins
  - Continuous improvement and DevOps
  - Combining models and data in digital twins
- Hopefully back with MODELS'22

### Program

The workshop is scheduled on Oct. 12th (Tue). All times are in CET.

#### Session 01 (17:00 - 18:15): Opening and Keynote (chair: B. Combemale)

- Opening by the organizers
- Keynote by Prof. Bernhard Rumpe ([slide](#))

#### Session 02 (18:15 - 19:15): Engineering Digital Twins (chair: R. Eramo)

- Paula Muñoz, Javier Troya and Antonio Vallecillo. *Using UML and OCL Models to Realize High-Level Digital Twins* ([slide](#), [GitHub repo](#))
- Istvan David, Jessie Galasso and Eugene Syriani. *Inference of Simulation Models in Digital Twins by Reinforcement Learning* ([slide](#))
- Mark van den Brand, Loek Cleophas, Raghavendran Gunasekaran, Boudewijn Haverkort, David Manrique Negrin and Hossain Muhammad Muctadir. *Models Meet Data: Challenges to Create Virtual Entities for Digital Twins* ([slide](#))

#### Session 03 (19:30 - 20:30): Digital Twin Exemplars (chair: F. Bordeleau)

- Hari Govindasamy, Ramya Jayaraman, Burcu Taspinar, Daniel Lehner and Manuel Wimmer. *Air Quality Management: An Exemplar for Model-Driven Digital Twin Engineering* ([slide](#))
- David A Manrique Negrin, Loek Cleophas and Mark van den Brand. *Using Ptolemy II as a framework for virtual entity integration and orchestration in digital twins* ([slide](#))
- Matthew Bonney, Marco De Angelis, Mattia Dal Borgo and David Wagg. *Digital Twin Operational Platform for Connectivity and Accessibility using Flask Python* ([slide](#))

#### Session 04 (20:30 - 21:30): Invited Flash Talks and Demo (chair: M. v.d. Brand)

- Talk 1
- Francis Bordeleau. *Can Digital Twins be used for the continuous improvement of DevOps processes?* ([slide](#))
- Gijs Walravens. *Towards Digital Twins for soccer robots: a use case in reusing artifacts* ([slide](#))