

University of Stuttgart

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



Digital Twins

An Introduction



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A Decade of Research in Software Engineering for Cyber-Physical Systems

To improve engineering and operations of complex systems

- Akad. Oberrat & Venia Legendi at **computer science** of RWTH Aachen
- Leader **model-based systems engineering group** of GfSE (German INCOSE chp.)
- **European Association for Programming Languages and Systems** board
- Research interests
 - Model-driven engineering
 - SW language engineering
 - **Digital twins**
 - Cyber-physical systems
- 110+ publications (h: 26, i10: 65)
- **Digital twin keynotes:** Dagstuhl, EDT.Community, SECPPS
- **Digital twin workshops:** ModDiT, CoMoDiTy, MPM4DT
- **Digital twin projects:** SDM^{flex}, SofDCar, Model-Based DevOps, ...



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?

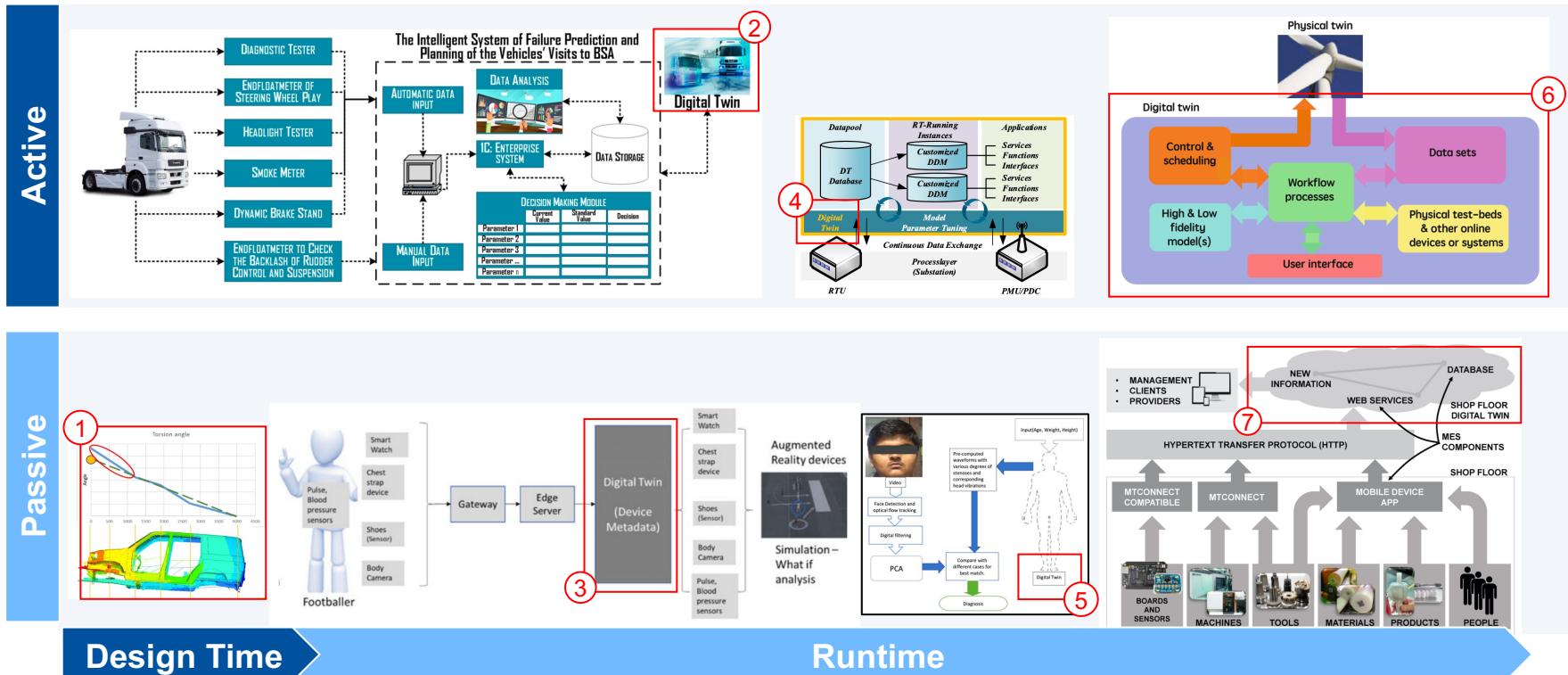
Is this the only purpose?

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

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

The Largest Systematic Cross-Domain Mapping Study for Digital Twins

Various shapes and purposes used at different lifecycle times

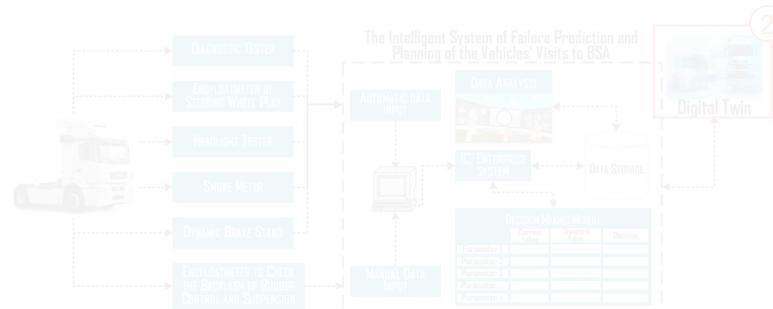


Dalibor, Jansen, Rumpe, Schmalzing, Wortmann: A Cross-Domain Systematic Mapping Study on Software Engineering for Digital Twins. In: Journal of Systems and Software, 2022.

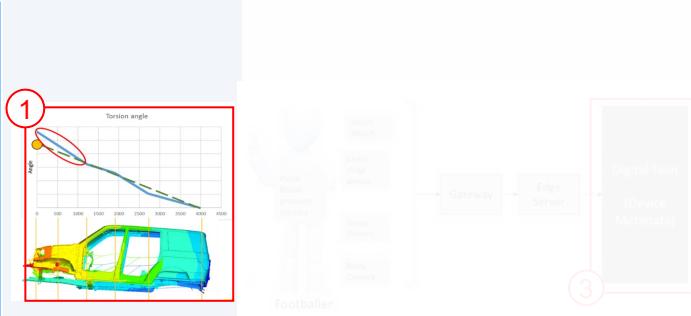
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Various shapes and purposes used at different lifecycle times

Active



Passive



Design Time

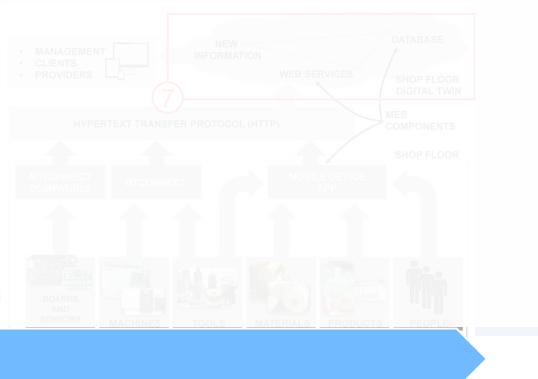
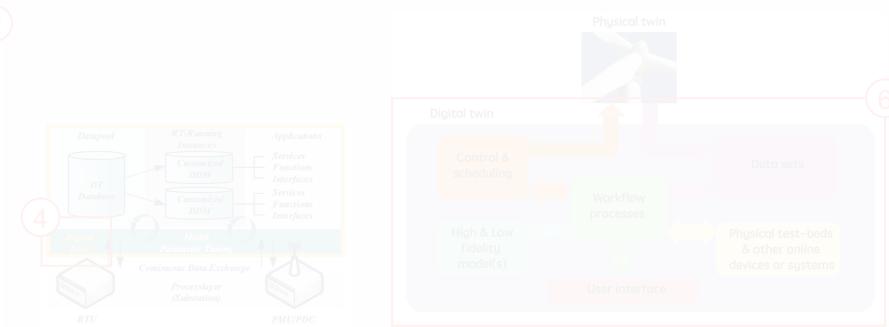
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6

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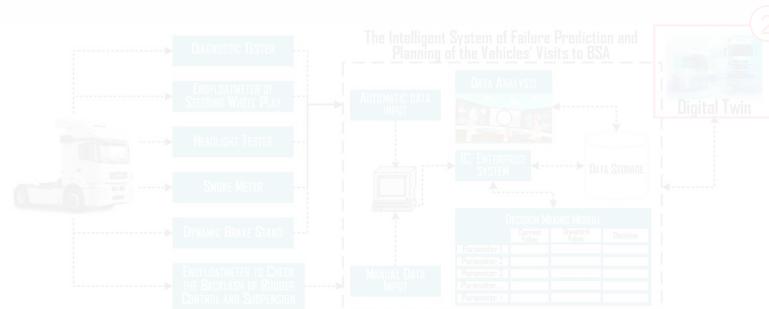
Runtime



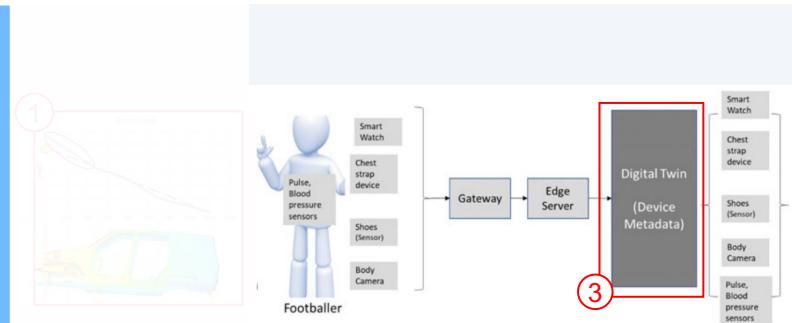
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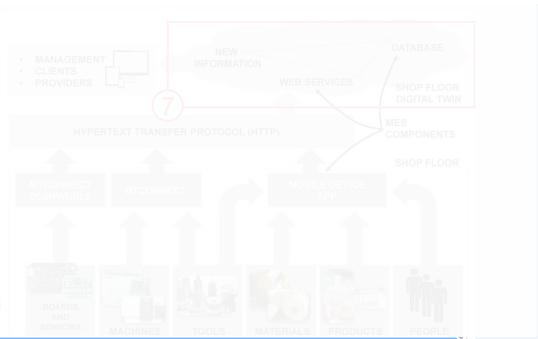
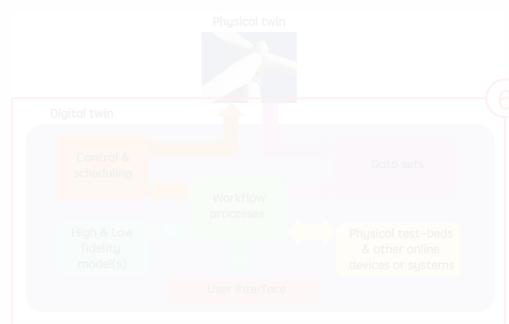


Design Time

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7



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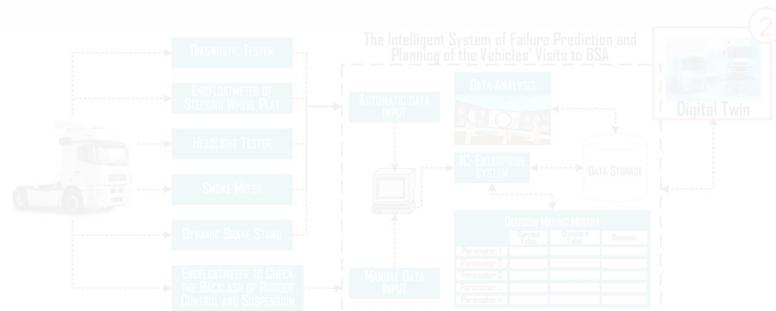


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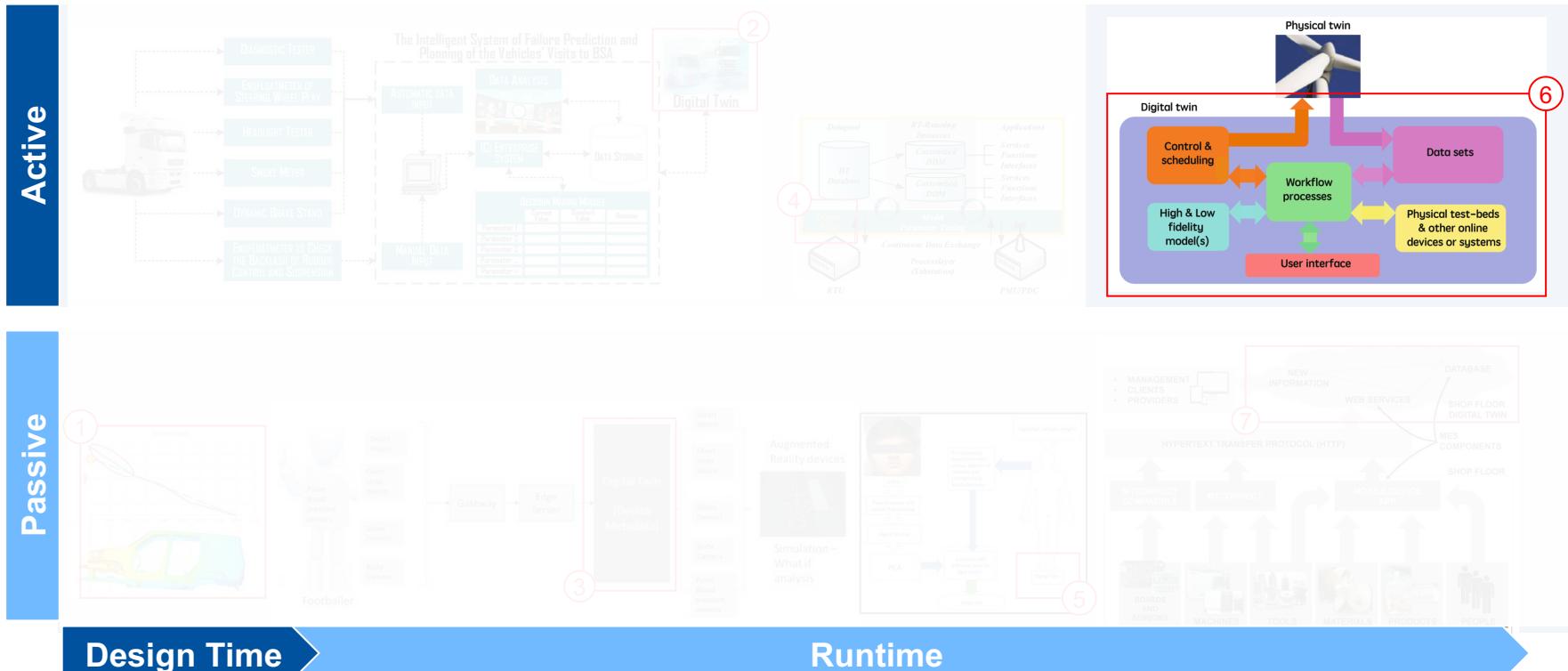
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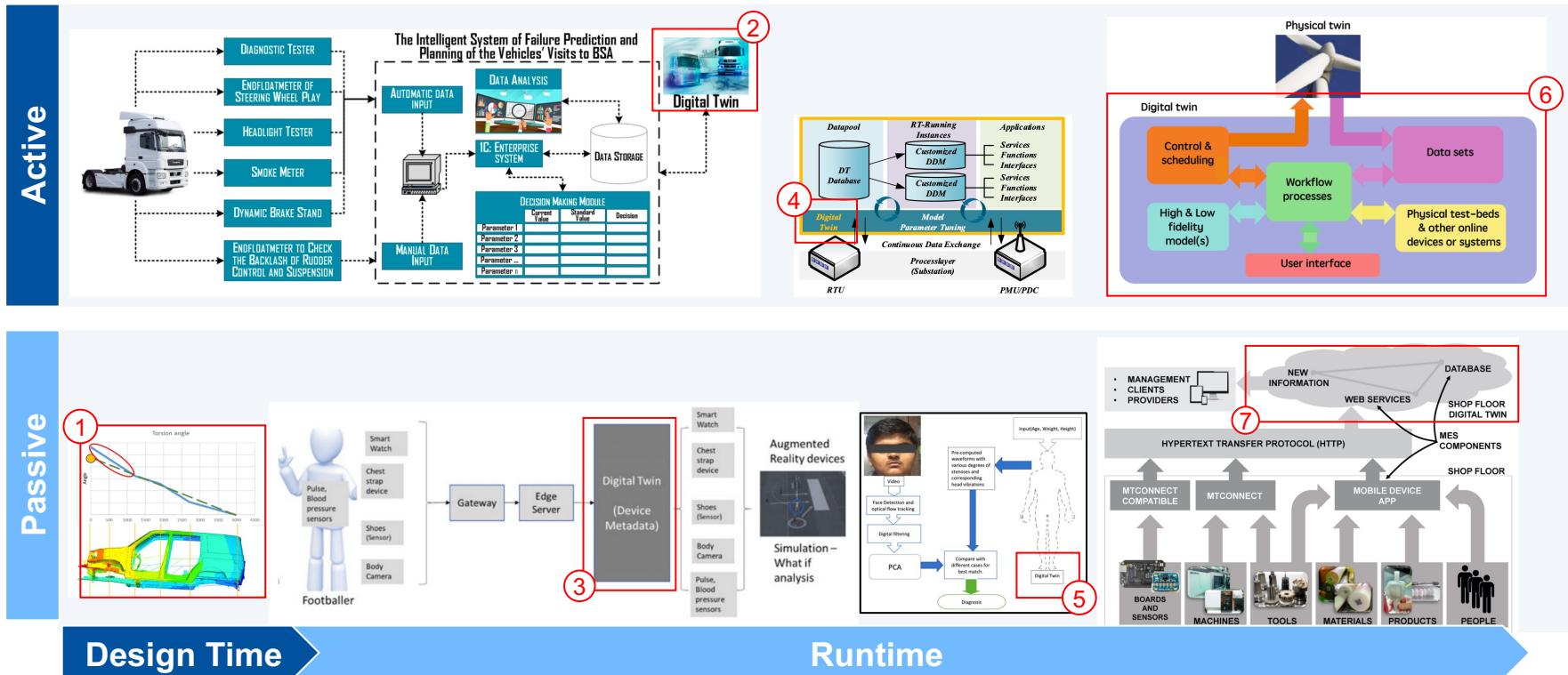
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The Largest Systematic Cross-Domain Mapping Study for Digital Twins

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Dalibor, Jansen, Rumpe, Schmalzing, Wortmann: A Cross-Domain Systematic Mapping Study on Software Engineering for Digital Twins. In: Journal of Systems and Software, 2022.

Most of the 118 Descriptions we Identified of Digital Twins are Problematic

Hampers understanding, discussion, engineering, and operating digital twins

Ambiguous	Restricted	Unrealistic
<p>Refer to undefined terms:</p> <ul style="list-style-type: none">“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]	<p>Focus specific kind of system or implementation technology:</p> <ul style="list-style-type: none">“digital model of the real network environment” [379]“a virtual representation of a specific product” [388]“virtual representation based on AR-technology” [827]	<p>Practically unfeasible:</p> <ul style="list-style-type: none">“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]

Dalibor, Jansen, Rumpe, Schmalzing, Wortmann: A Cross-Domain Systematic Mapping Study on Software Engineering for Digital Twins. In: Journal of Systems and Software, 2022.

Most Descriptions of Digital Twins are Problematic

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]

...for 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]

...of 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]

Dalibor, Jansen, Rumpe, Schmalzing, Wortmann: A Cross-Domain Systematic Mapping Study on Software Engineering for Digital Twins. In: Journal of Systems and Software, 2022.

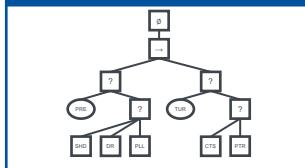
Take-away message

A digital twin **must be a simulation model of an existing system**

All of these Models can be used to Simulate (Parts of) a CPS

But are they digital twins?

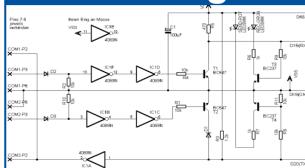
Behavior Tree



CAD



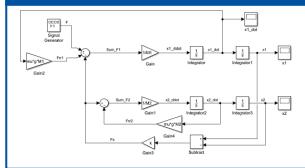
Circuit Diagram



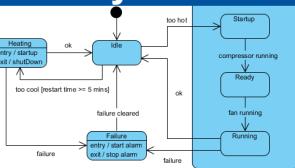
Math

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

Simulink



SysML



Typical Requirements on Digital Twins

- **uses real-time data** to update itself
- **integrates data** from the CPS to meaningful information
- **manages interaction** between itself and the real CPS
- **optimizes behavior** of the CPS
- ... yields **sufficient fidelity** to the CPS
- **communicates** to its environment

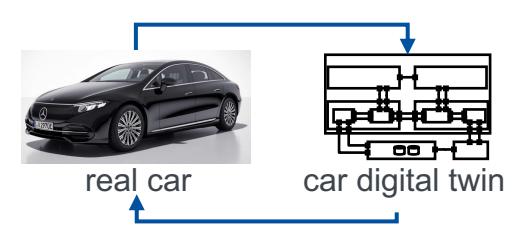
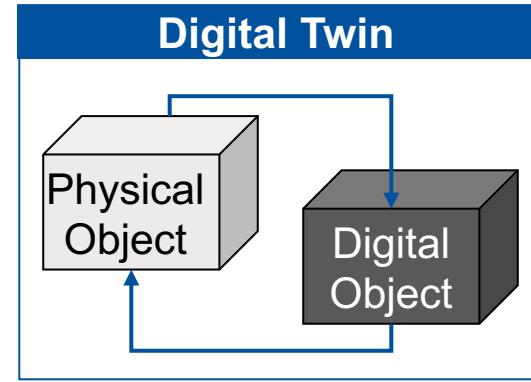
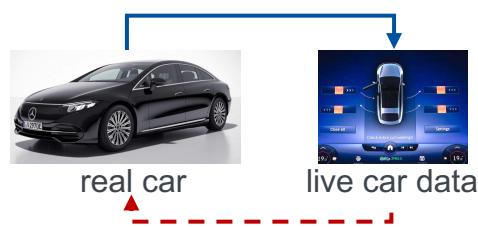
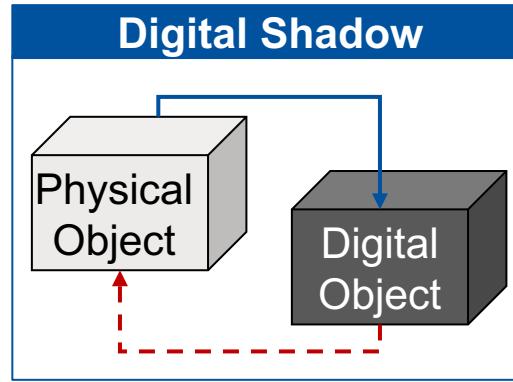
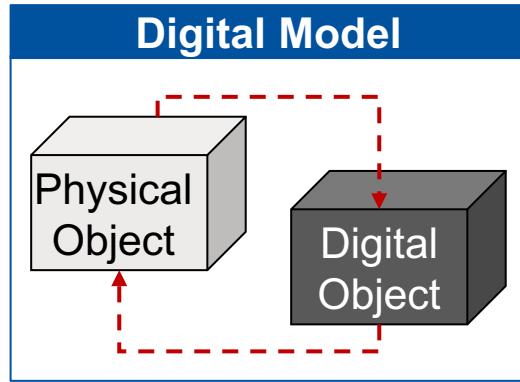
Durão, Haag, Anderl, Schützer, Zancul: *Digital Twin Requirements in the Context of Industry 4.0*. In: 15th IFIP International Conference on PLM, 2018.

Take-away message

A digital twin ~~must~~ be a simulation
model of a ~~real~~ operating system

A Characterization based on Data Flows

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



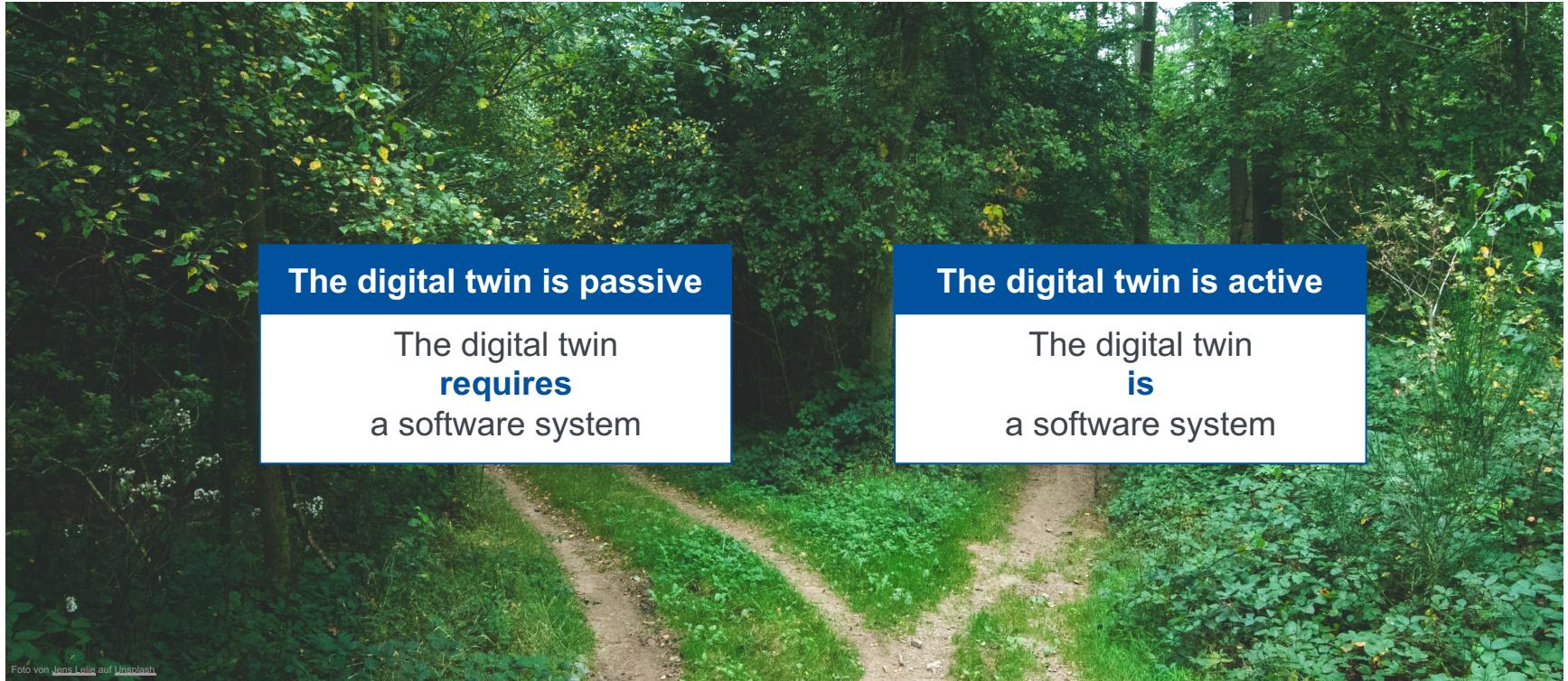
→ Manual Data Flow

→ Automated Data Flow

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

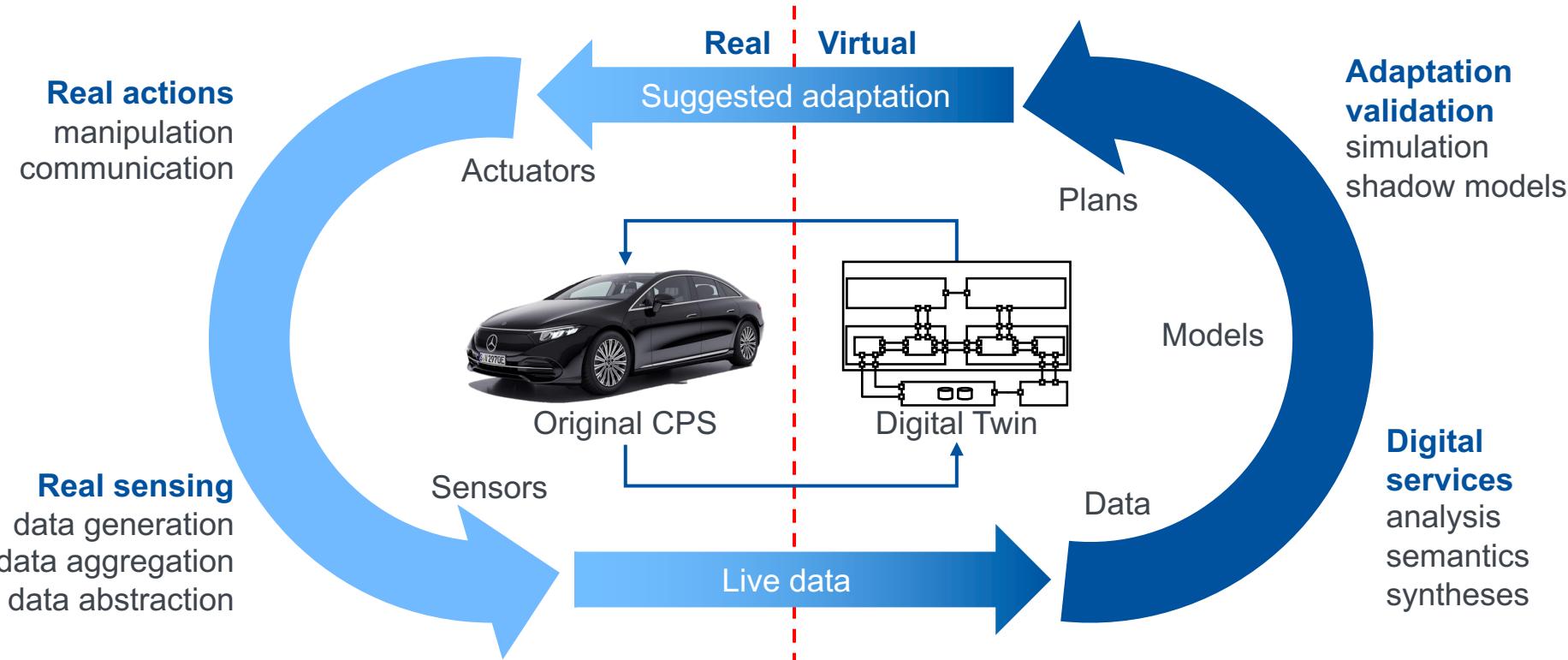
Two Essential Ways of Understanding Digital Twins

Can the digital twin act itself or does it need a support system?



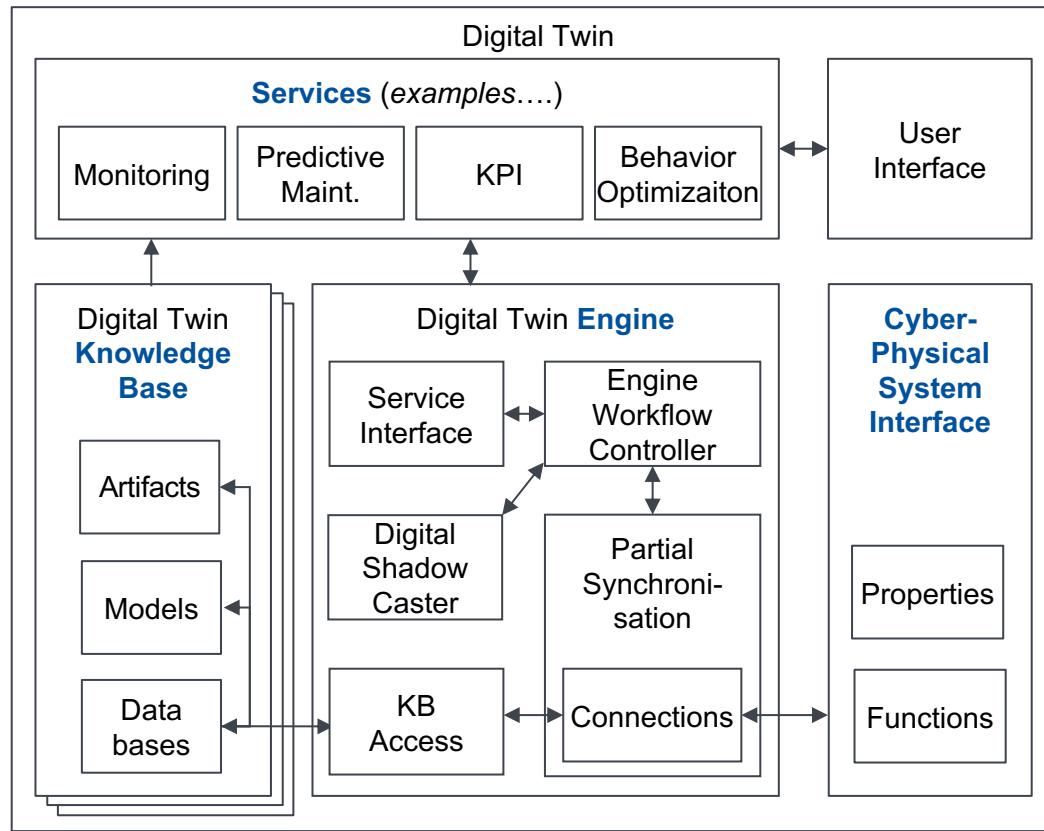
A Pattern for Active Digital Twins

Understood as software systems interacting with their original CPS



Essential Components of a Conceptual Model of Digital Twins

To interface the CPS, synchronize it with a KB and provided added-value services



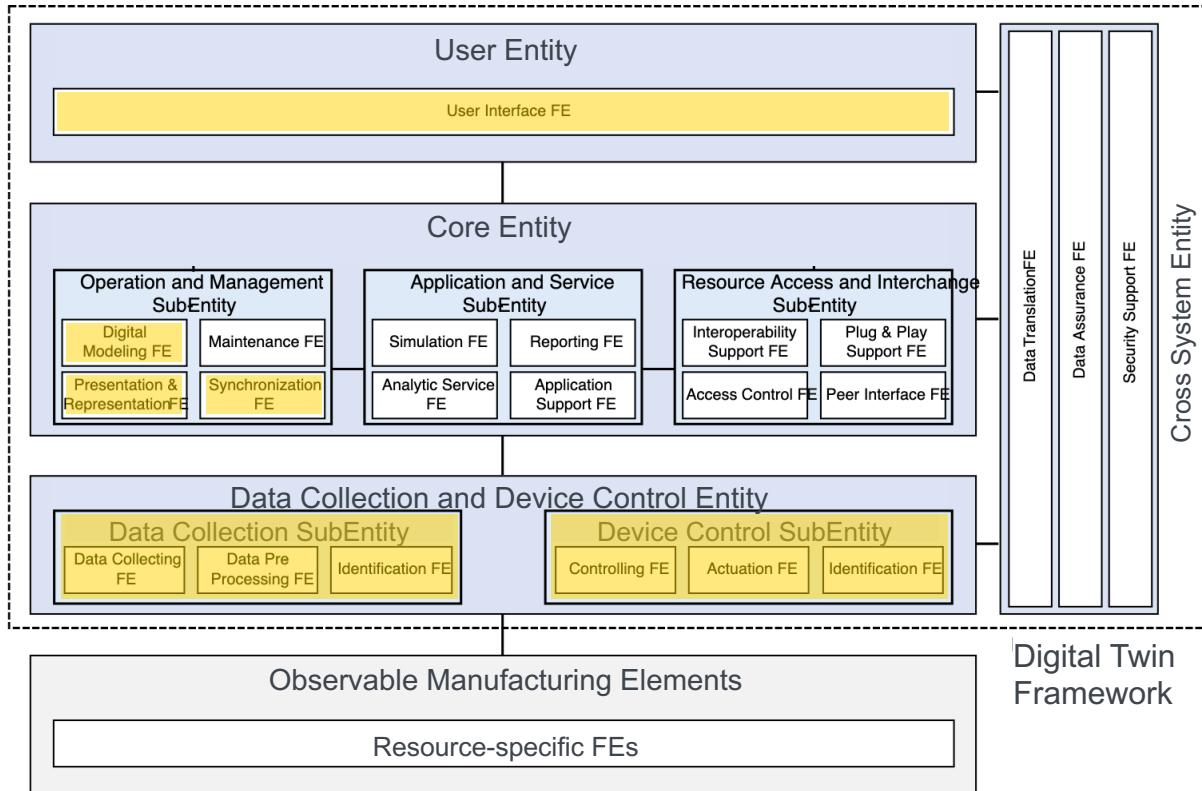
Take-away message

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)

The digital twin standard for manufacturing refines the conceptual model

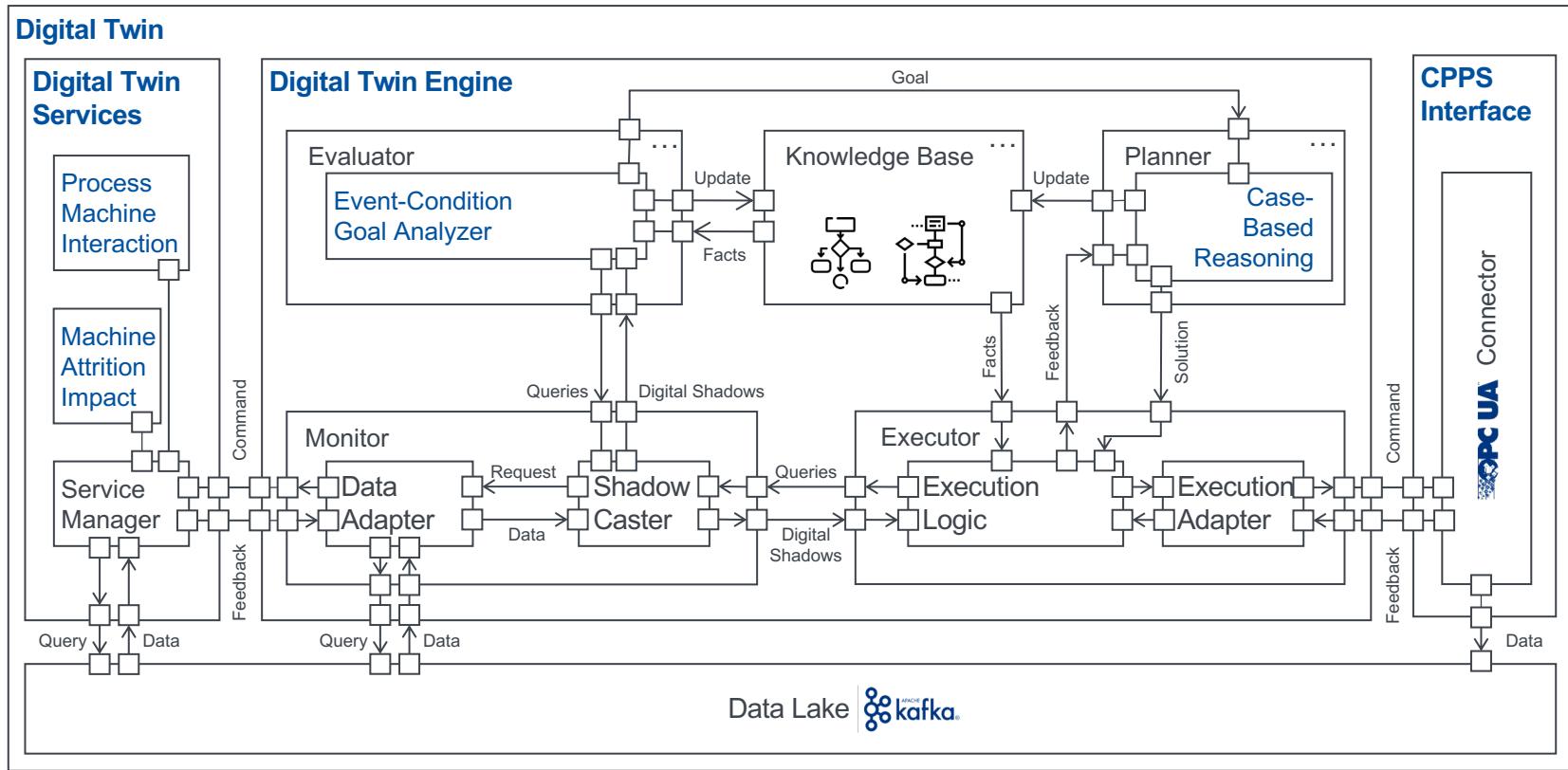
- Published in **2021**
- Part 1: **Overview** and general principles
- Part 2: Reference **architecture**
- Part 3: Digital **representation of manufacturing elements**
- Part 4: **Information exchange**



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

Flexible SDM through Quality-Aware Digital Twins (SDM^{flex})

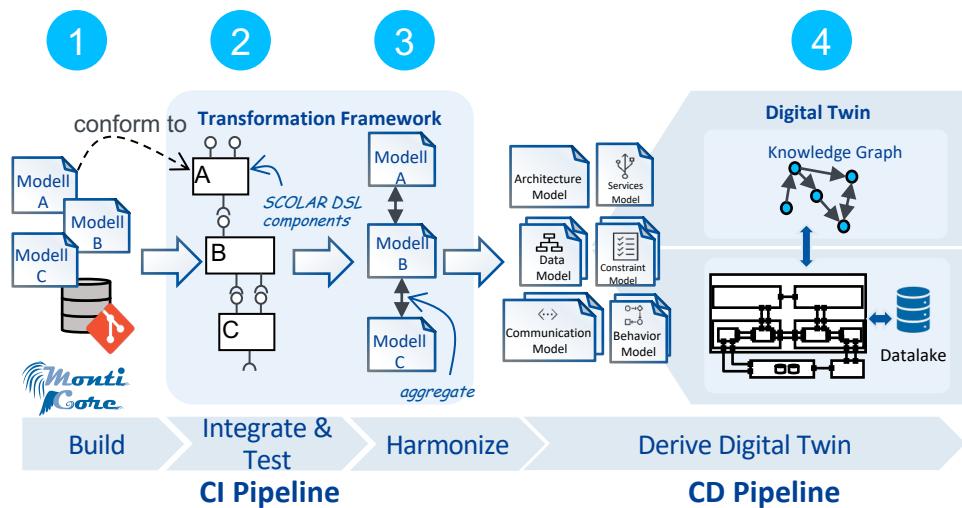
Process-specific quality predictions through learning capabilities



Software-Defined Car (SofDCar)

Synthesis of digital twins from engineering models

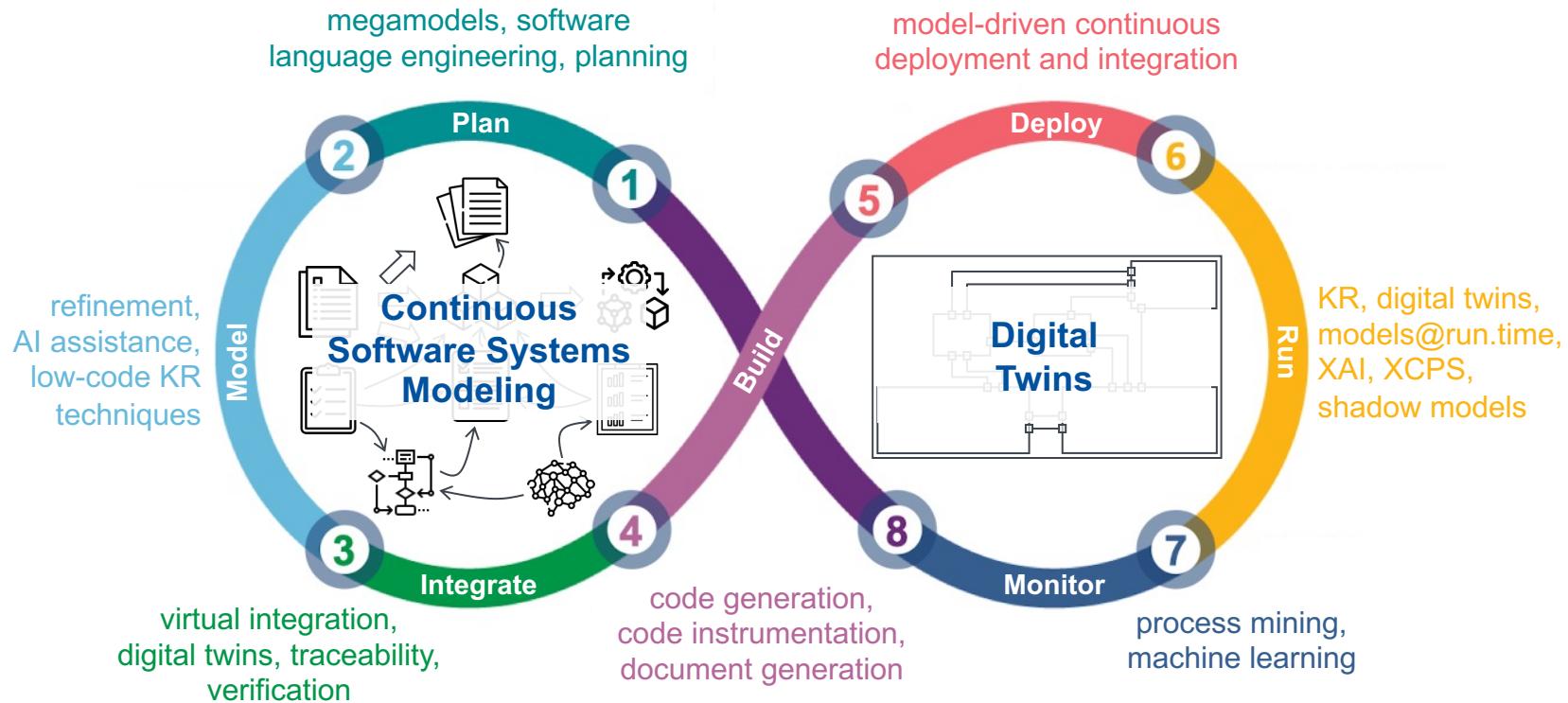
- Identification of models employed for automotive systems and their digital twins
- Creation of **SCOLAR language components**
- Harmonization of models through language component aggregation
- Basis for **change analysis, change propagation**, synthesis of digital twin parts
- Synthesis of model knowledge graph to reason over **embodied systems knowledge**



Model-Based DevOps for Cyber-Physical Systems (MBDO)

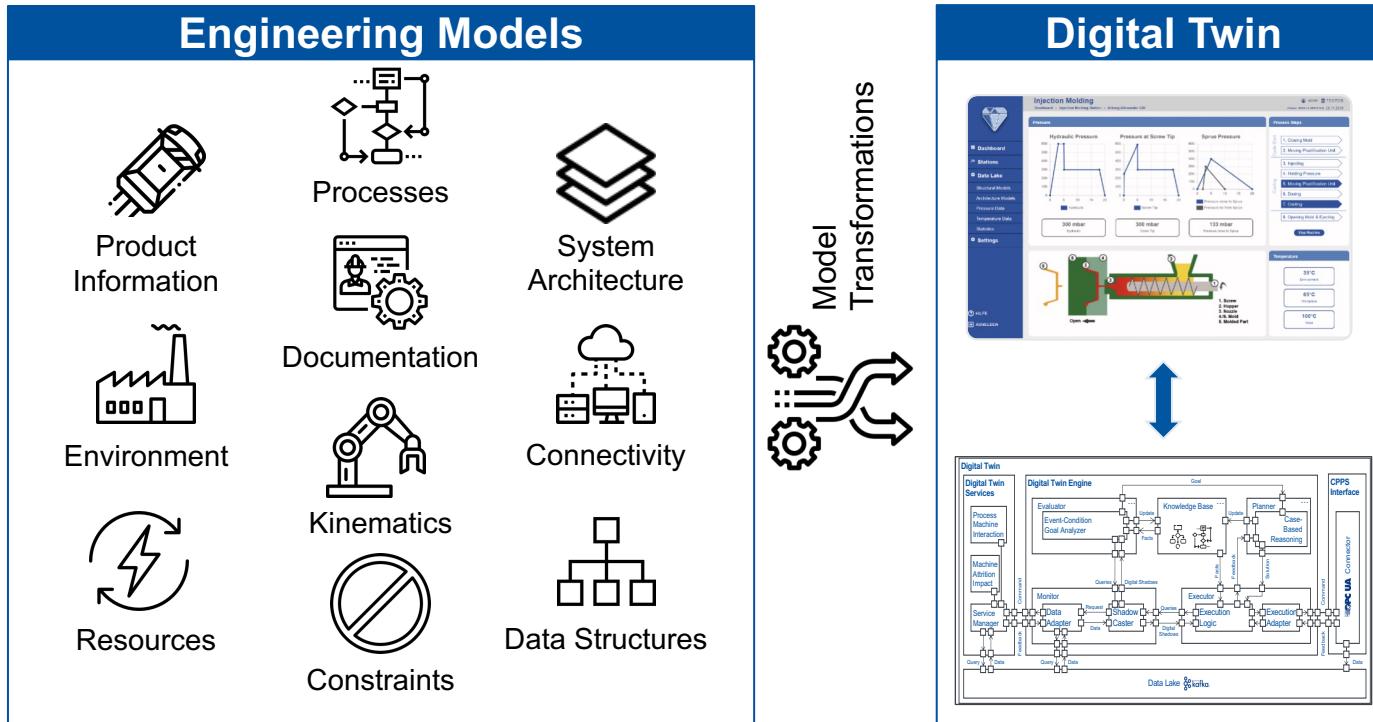


Combining top-down systems modeling with bottom-up learning



Challenge 1: Automate the Engineering of Digital Twins

Synthesize (parts of) digital twin from engineering/simulation models of CPS

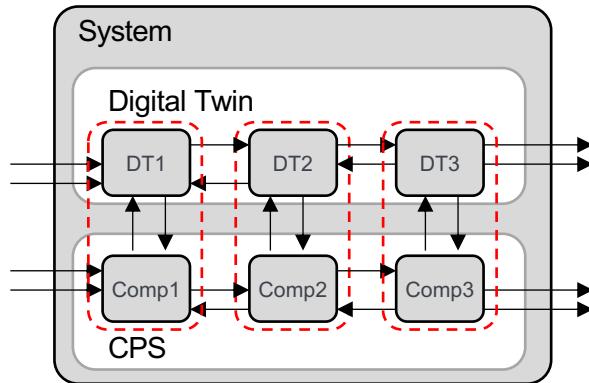
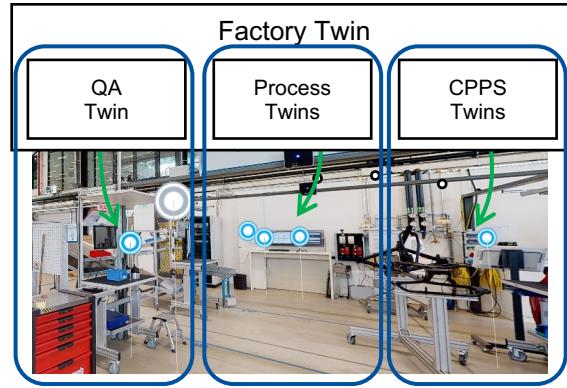
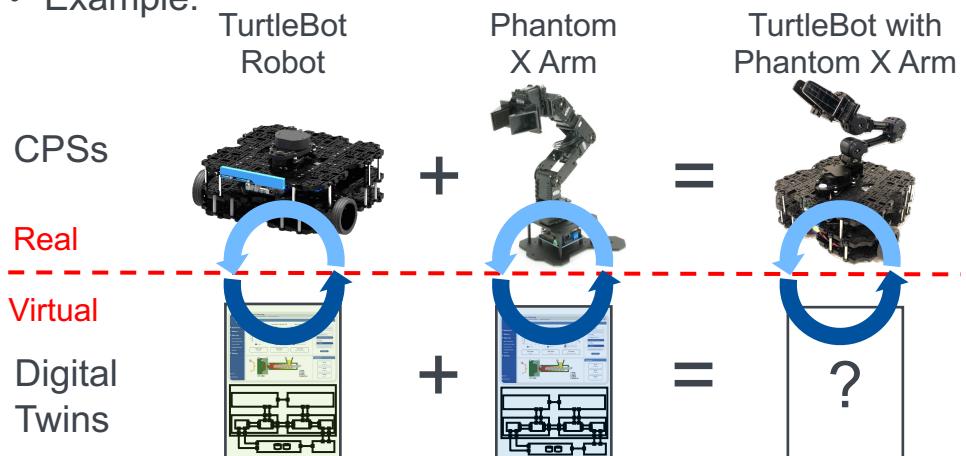


Michael, Pfeiffer, Rumpe, Wortmann: *Integration challenges for digital twin systems-of-systems*. In: Workshop on Software Engineering for Systems-of-Systems and Software, 2022.

Challenge 2: Automatically Compose Digital Twins

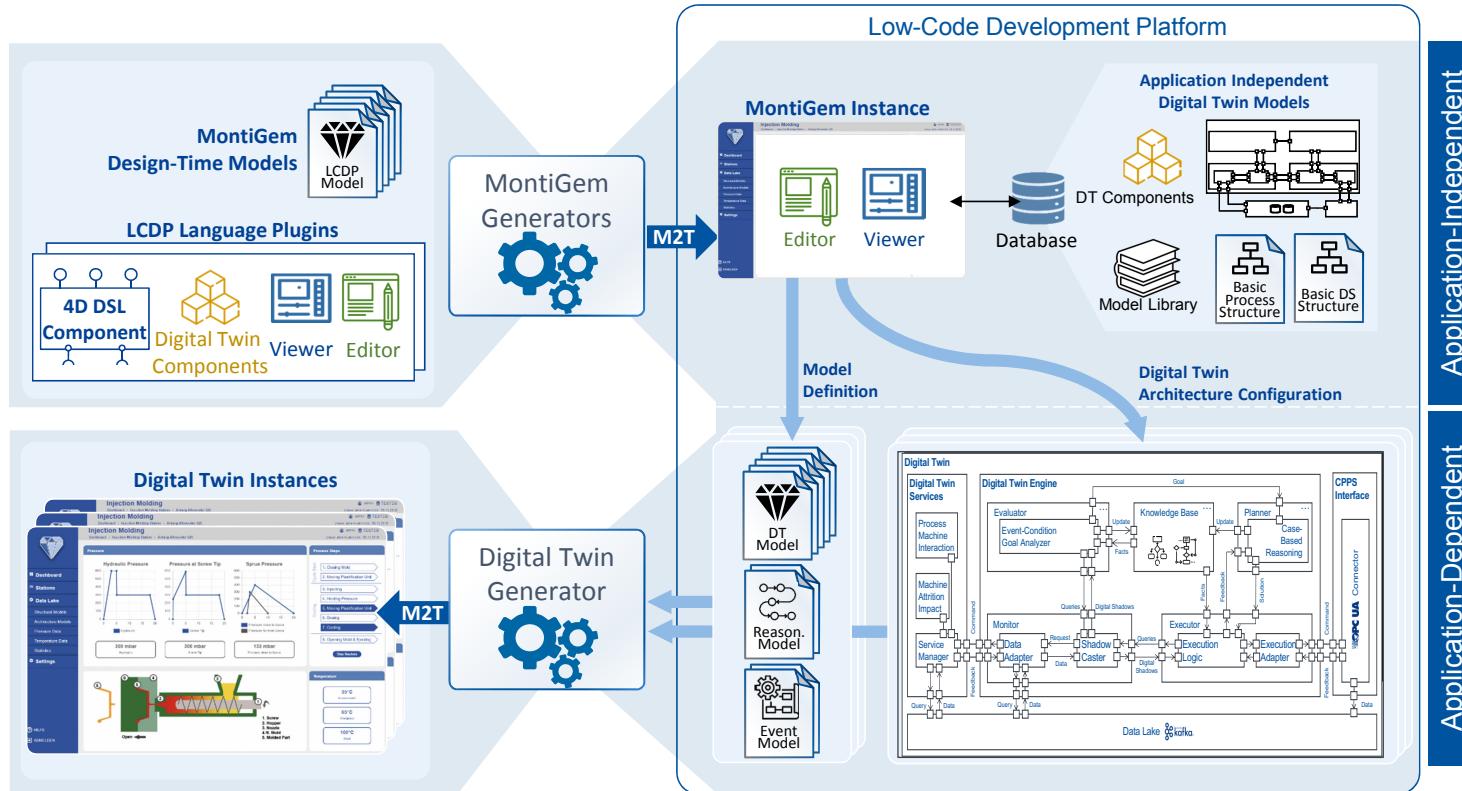
Efficiently create complex digital twins from simple ones

- **Reuse through composition is essential** to engineering
 - Functions (math)
 - Physical parts (mechanics)
 - Code modules (software engineering), ...
- Example:



Challenge 3: Think About the Operators of Digital Twins

Automatically synthesize low-code platforms for digital twins

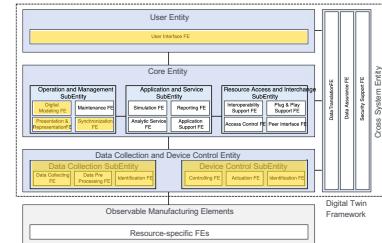
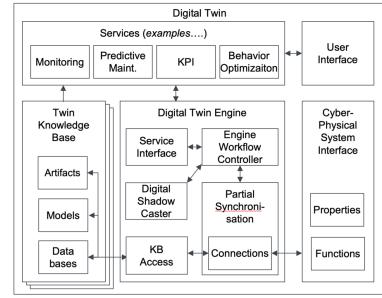


Kirchhof, Michael, Rumpe, Varga, Wortmann: *Model-Driven Digital Twin Construction*. In: MODELS'20, 2020.

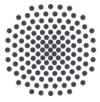
Take-Away Messages

- There still is **no common understanding** of what a digital twin is
- A digital twin needs a well-defined **purpose**
- A digital twin needs a **comprehensive software infrastructure**
- This infrastructure should be **part of the digital twin** (cf. ISO 23247)
- **Definition**

“A digital twin is a **software system** using **data, models, and services** to purposefully **represent and manipulate** a CPS.”
- **Challenges:** synthesis from engineering models, composition, low-code, ...



Michael, Pfeiffer, Rumpe, Wortmann: *Integration challenges for digital twin systems-of-systems*. In: Workshop on Software Engineering for Systems-of-Systems and Software, 2022.



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