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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

- Professor for model-driven development at University of Stuttgart
- Research interests documented in 90+ publications
  - Model-driven engineering
  - Language engineering
  - Formal software architectures
  - 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

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-automobilen-IT-Dschungel/

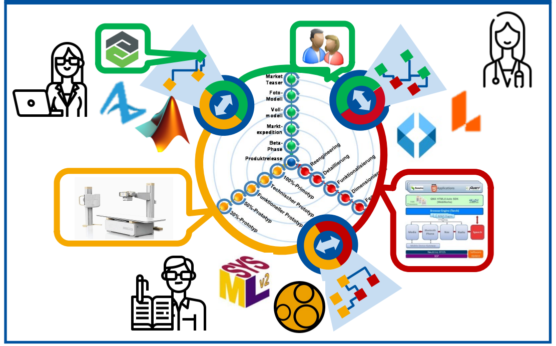
Software-Defined Manufacturing BMBF project

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

Efficiently Engineering Future's Cyber-Physical Systems

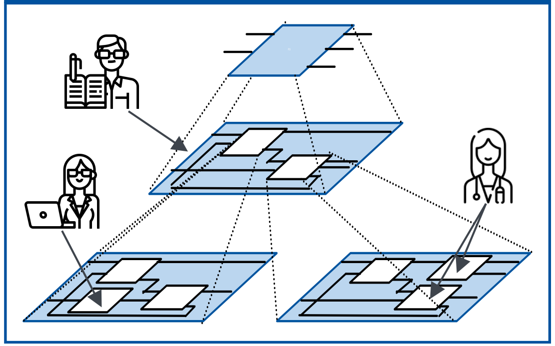
Through better languages, methods, and tools

Systematic Software Language Engineering



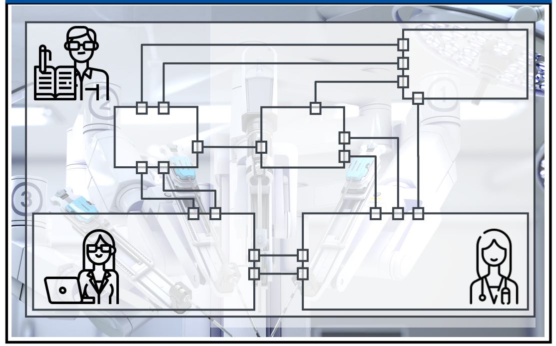
- Component-based language engineering
- Systematic reuse via language product lines
- Improves modeling precision and domain expert integration

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

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?

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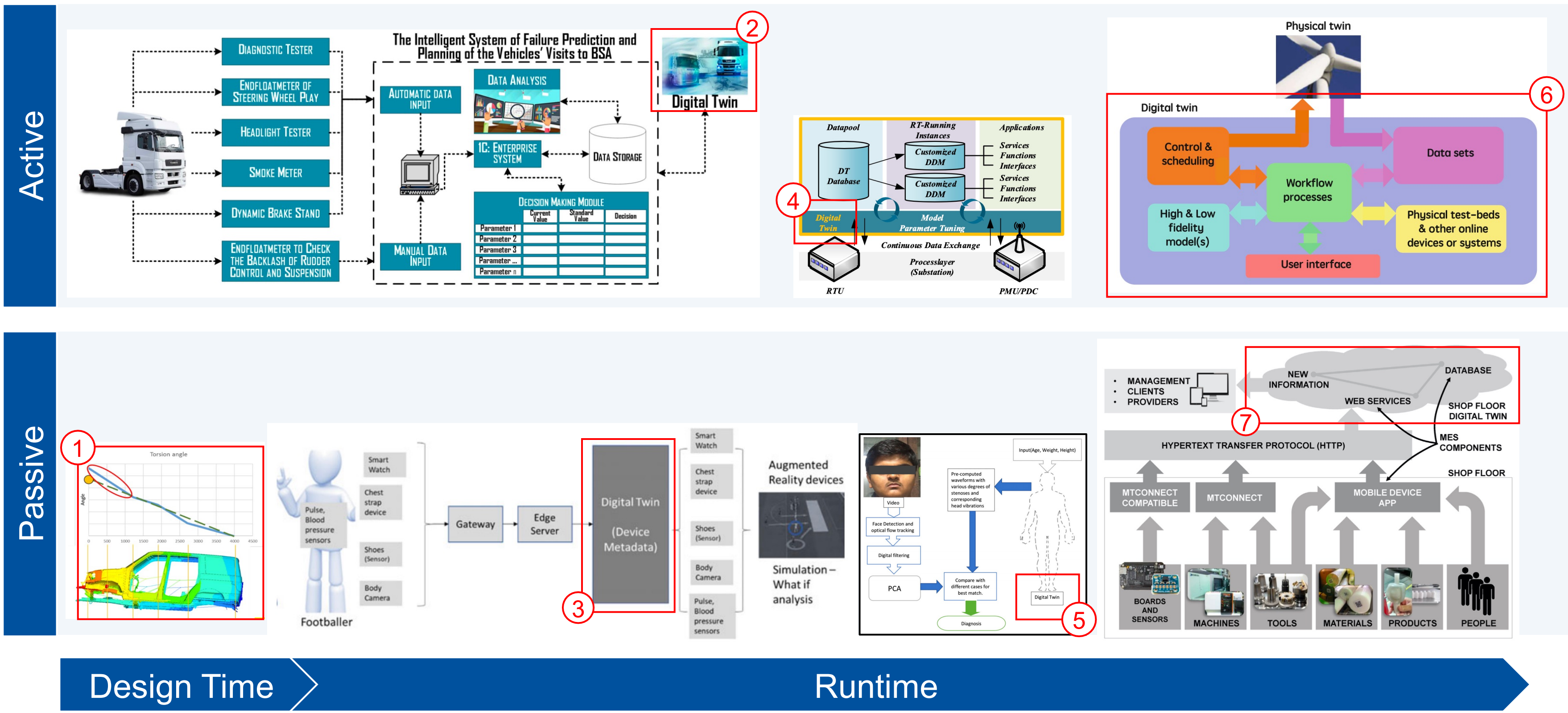
Digital Twins come in a Spectrum of various Shapes and Purposes

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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- "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 repre-sentation 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]

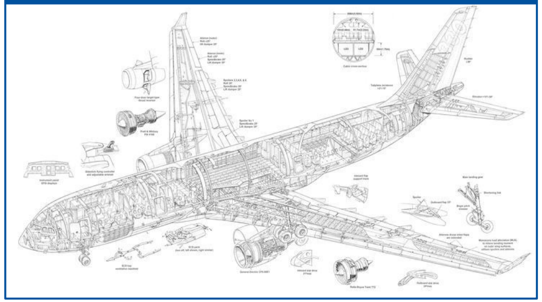
Lesson Learned

A digital twin is a simulation model of an existing system

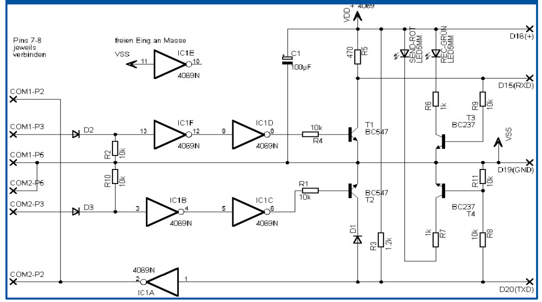
Are these Digital Twins?

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

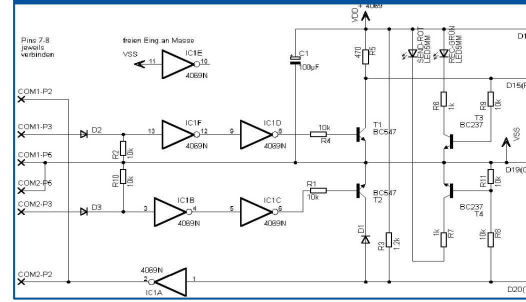
CAD



Circuit Diagram



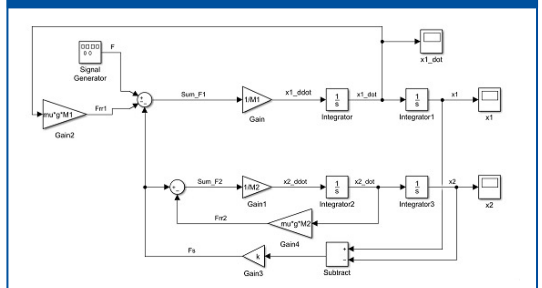
Simulink



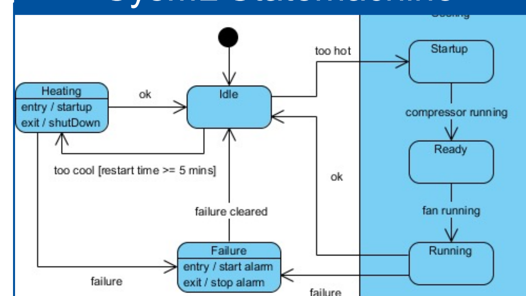
Math

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

Simulink



SysML Statemachine



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Suggestion

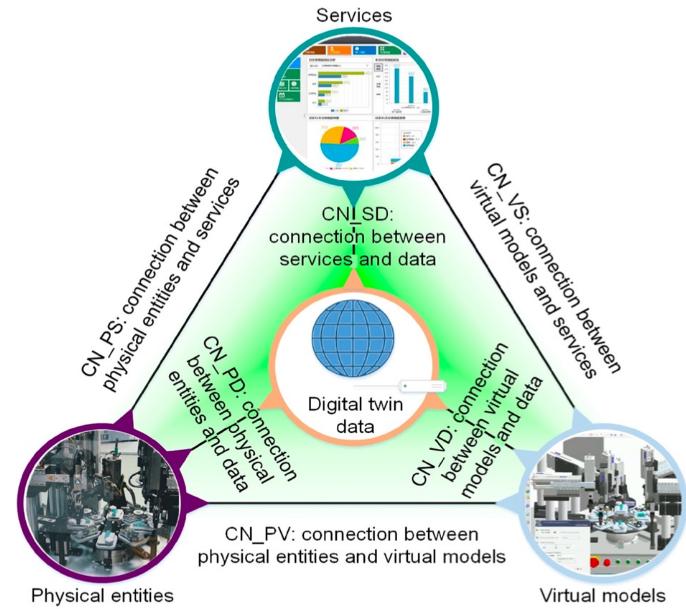
A digital twin is a software comprising models and services to use these models

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, …

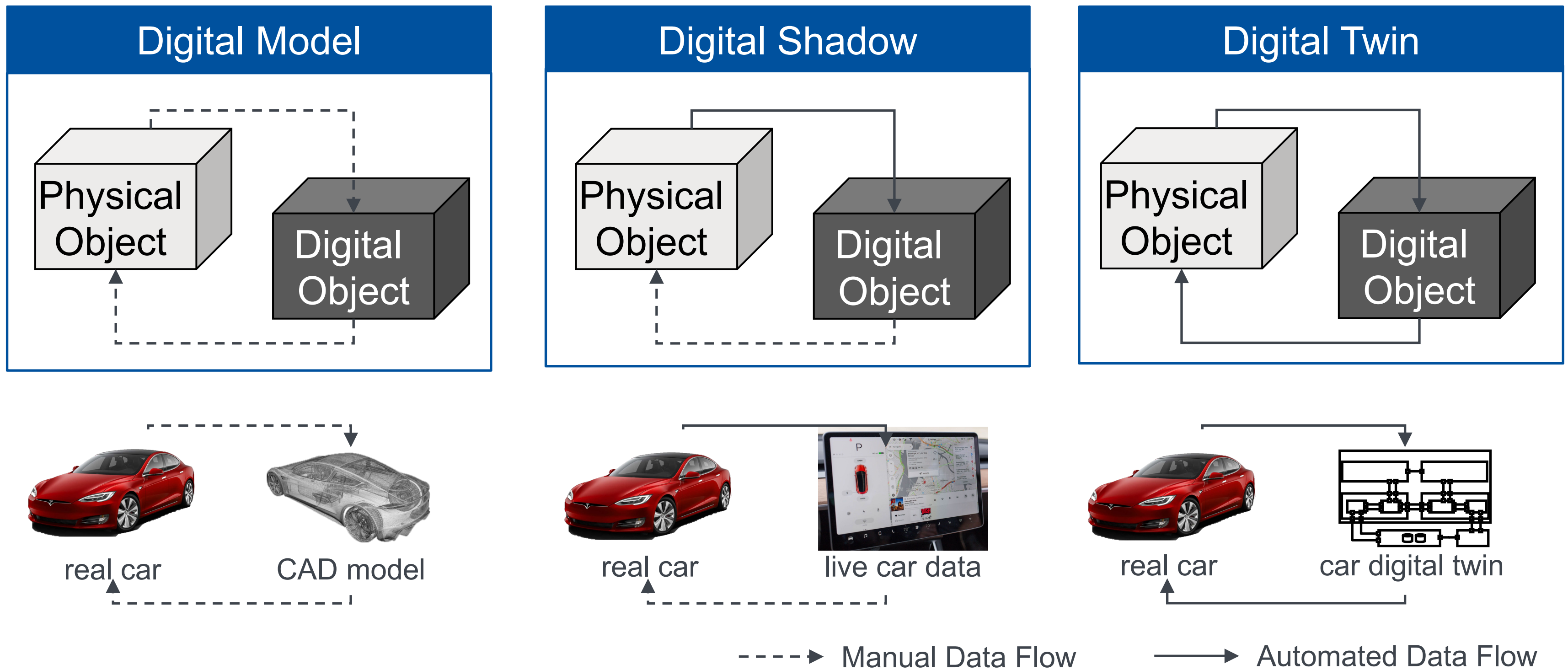
5D Digital Twin Model[1]



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

A Characterization based on Data Flows[2]

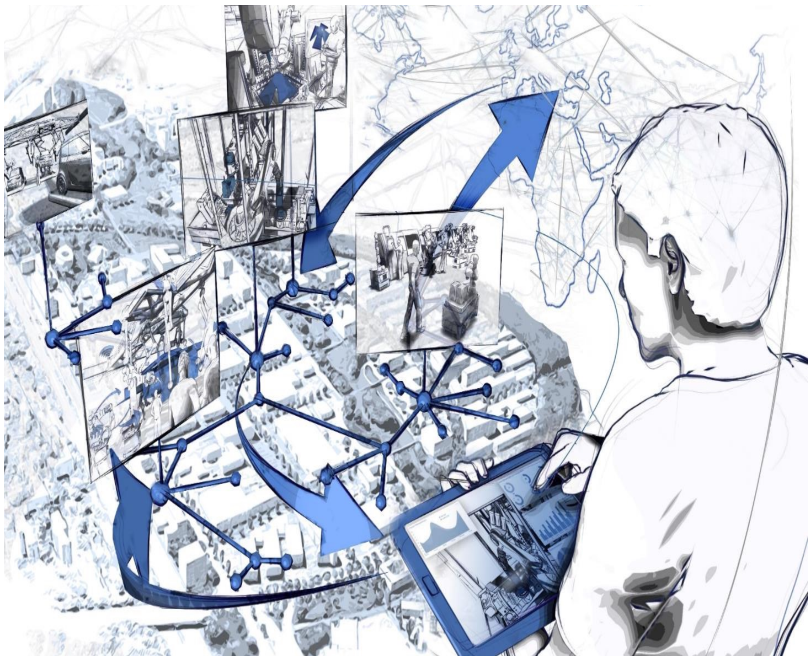
Data flows between physical and digital object(s) define what kind of system it is



[2] Kritzinger, W., Karner, M., Traar, G., Henjes, J., & Sihn, 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

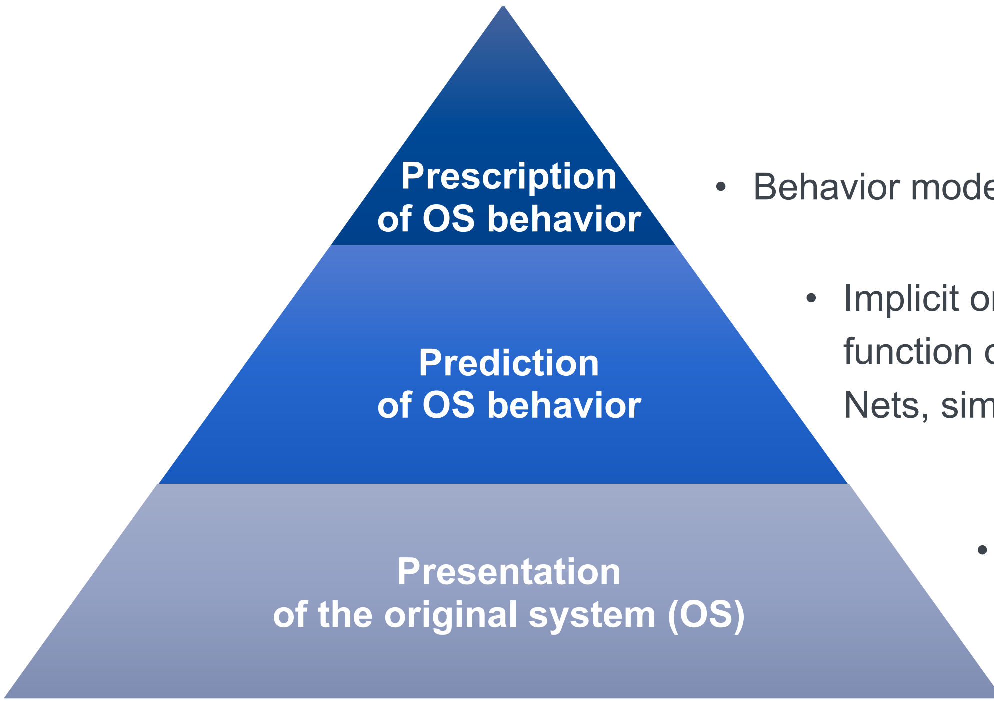


Digital Twin [1,7,8]
A digital twin of a system consists of a set of models of the system, a set of digital shadows, and provides a set of services to use the data and models purposefully with respect to the original system.

- 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

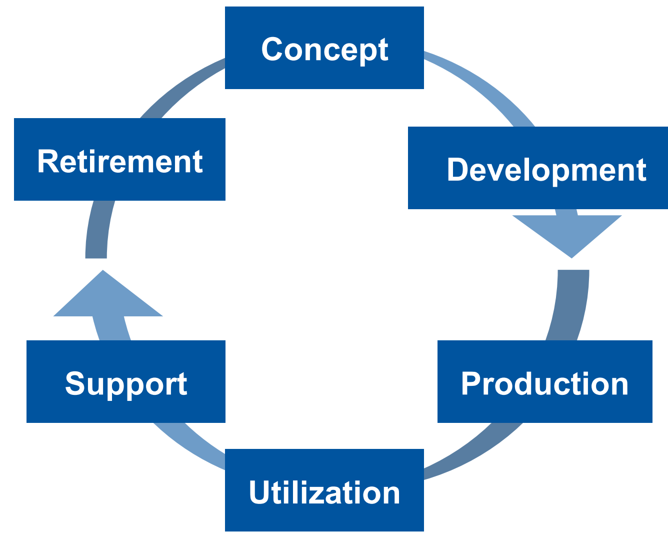


- Behavior models, process models, AI models, …..
- Implicit or explicit: Failure behavior models as function of operating conditions, fault trees, Petri Nets, simulation models, AI models, …
- Logs, data, databases, documentation, visualization, abstraction, models, digital shadows, AR, VR, ...

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)

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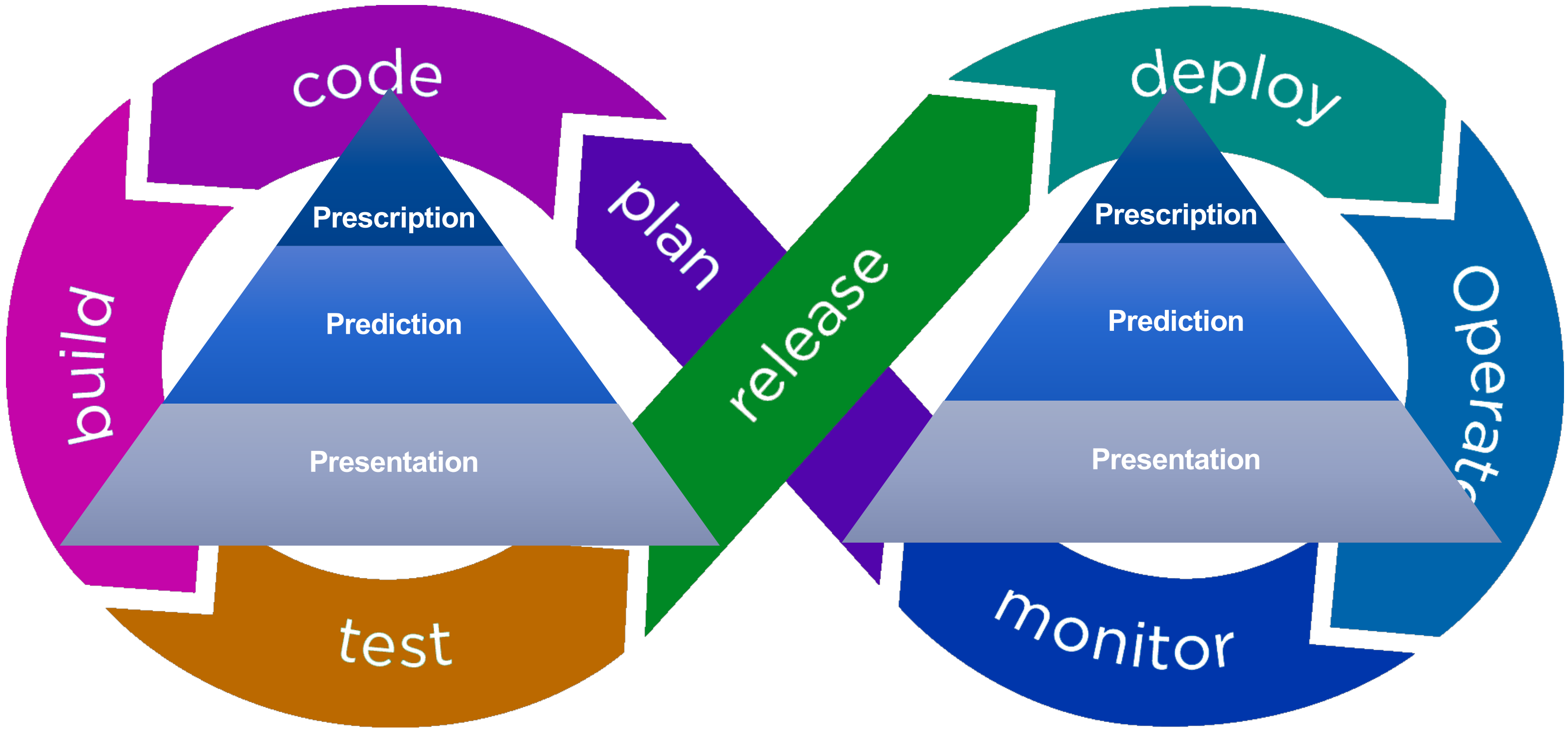
Digital Twins Could Support all Lifecycle Phases of the OS

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

Suggestion

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

Agenda

Provoking debate about digital twins

1 What is (not) a digital twin?

2 Properties of digital twins

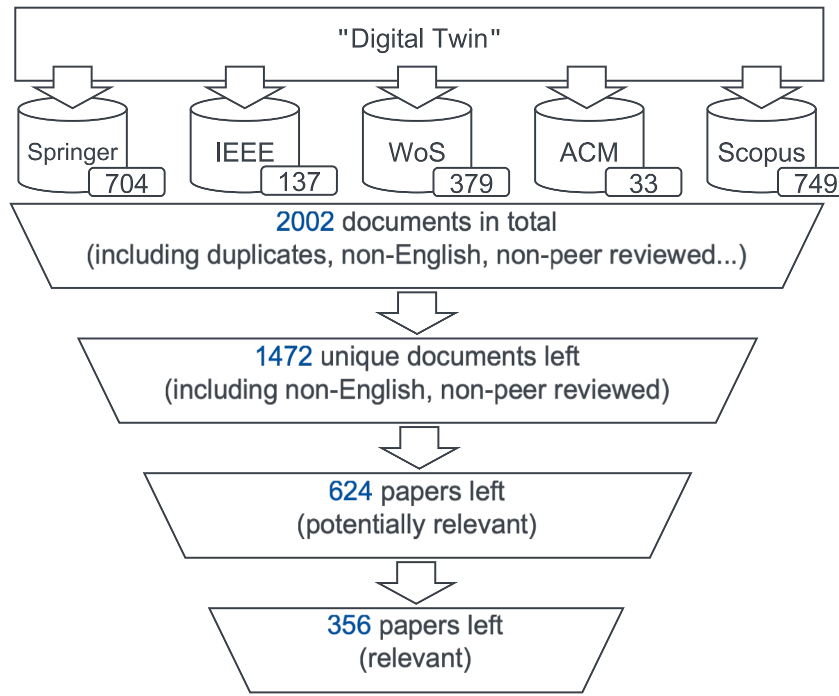
3 Model-driven engineering of digital twins

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?



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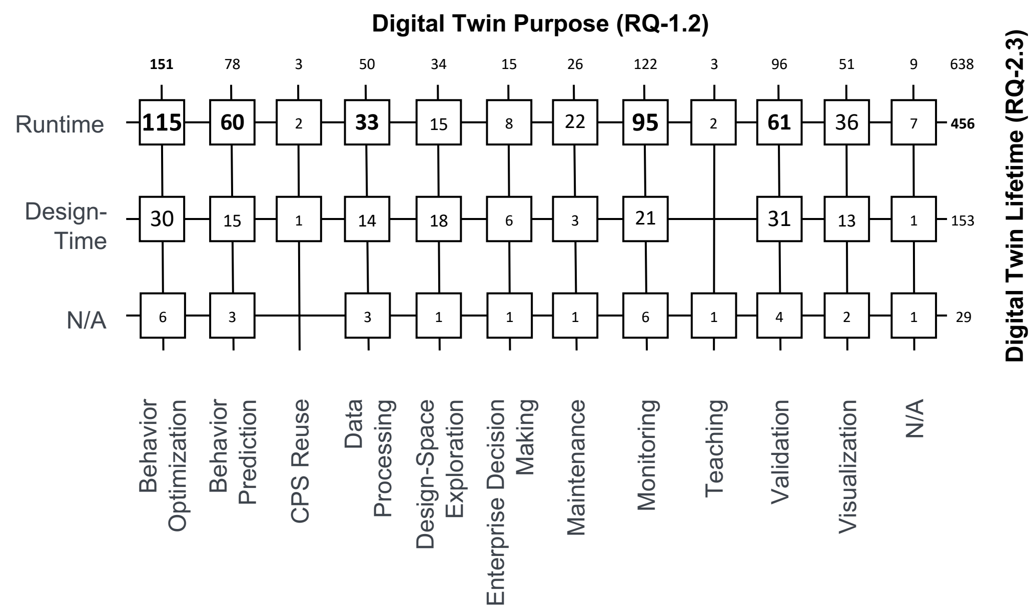
Who uses Digital Twins for which purposes?

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



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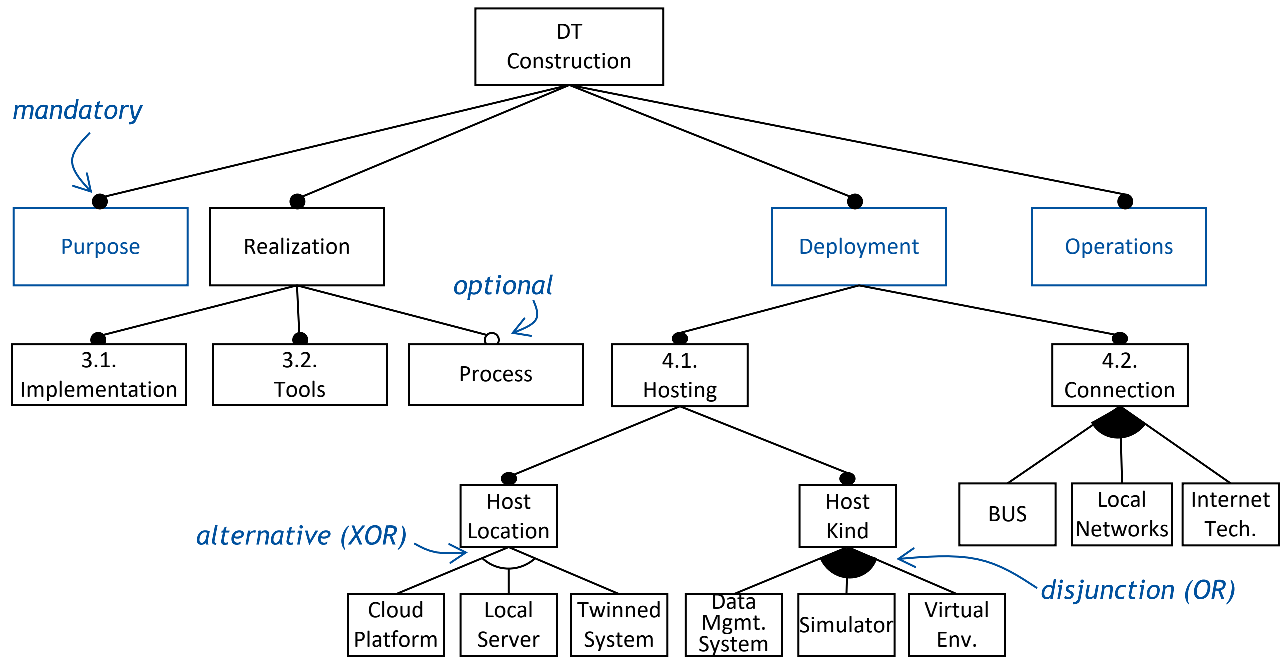
Observations on Conceptual Aspects of Digital Twins

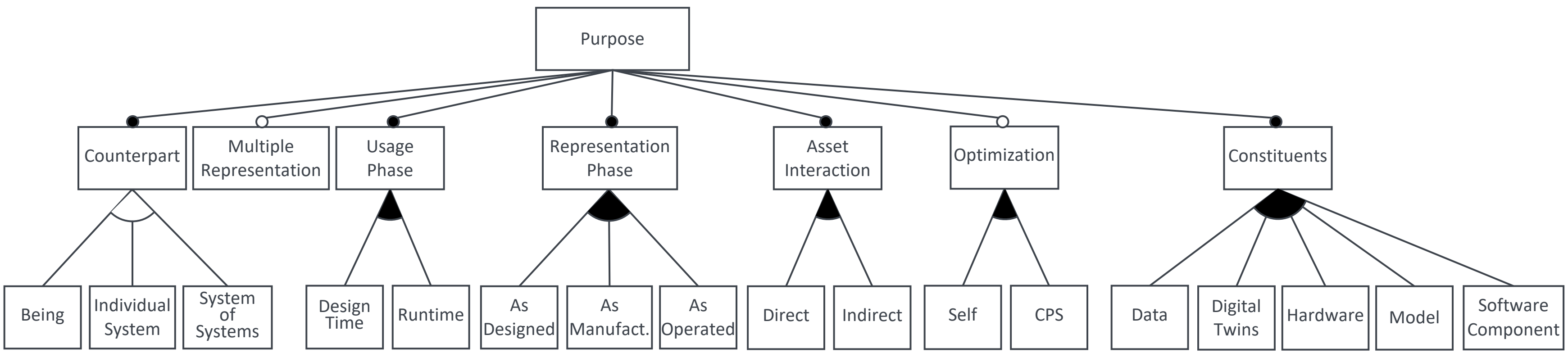
According to research literature

1. Purpose
("Why?")
2. Realization
("How?")
3. Deployment
("Where?")
4. Operations
("How?")



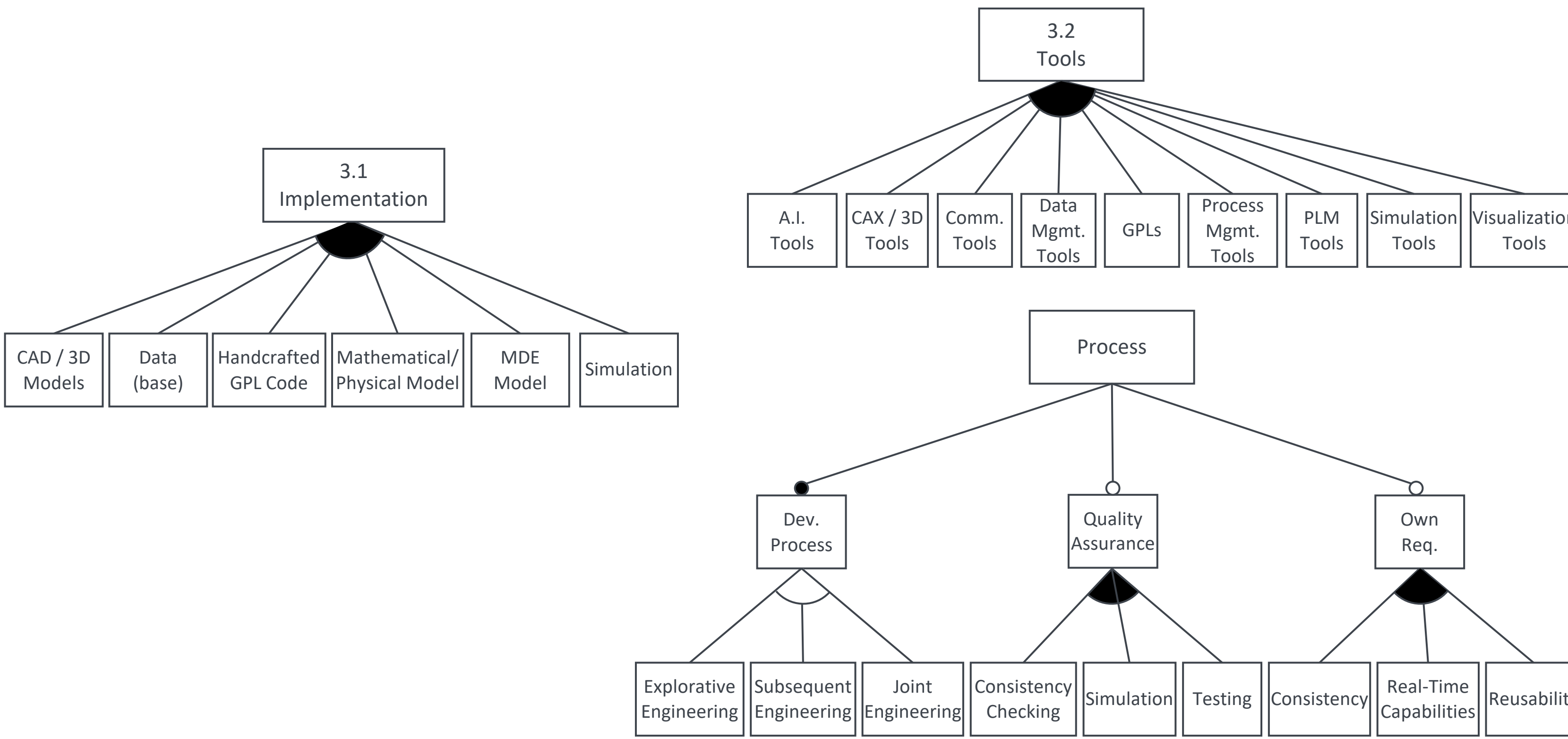
What are the Conceptual Aspects of Digital Twins?

Purpose apsects



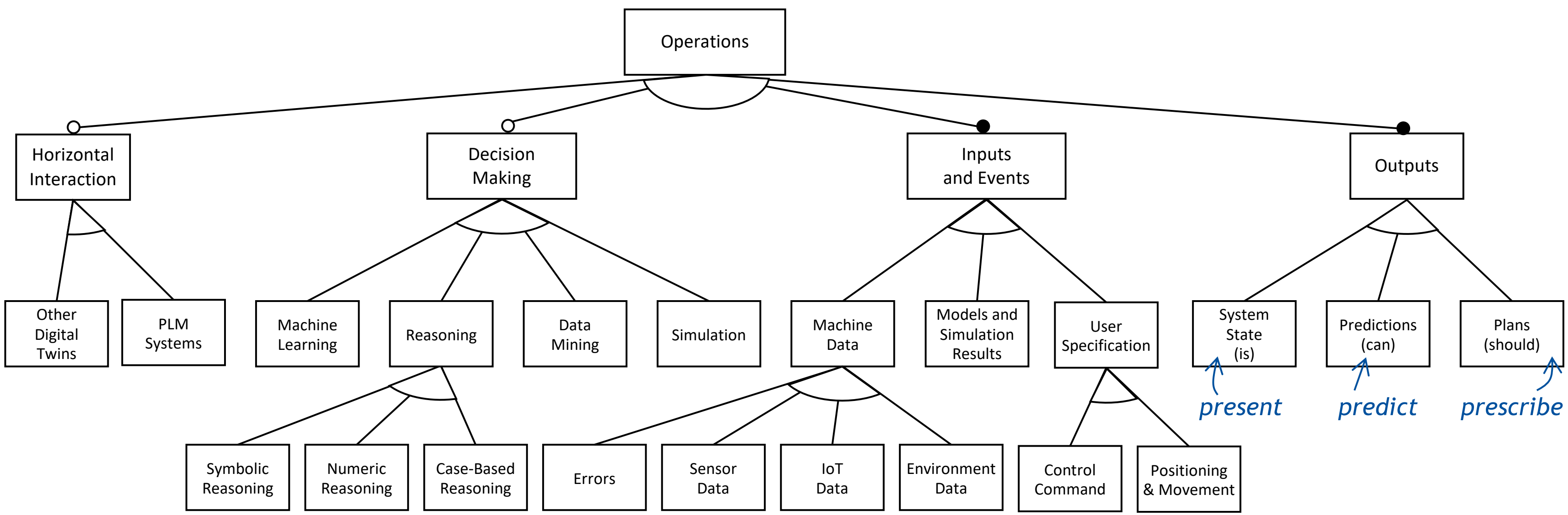
The Conceptual Aspects of Digital Twins

Realization aspects



The Conceptual Aspects of Digital Twins

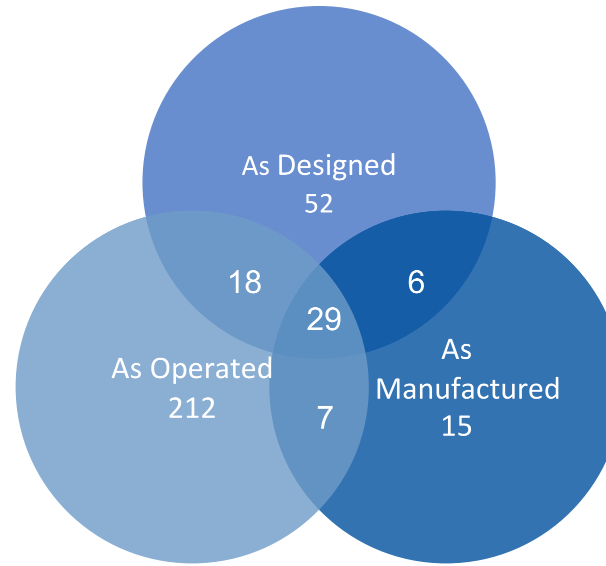
Operations aspects



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

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

Model-Based Software Engineering

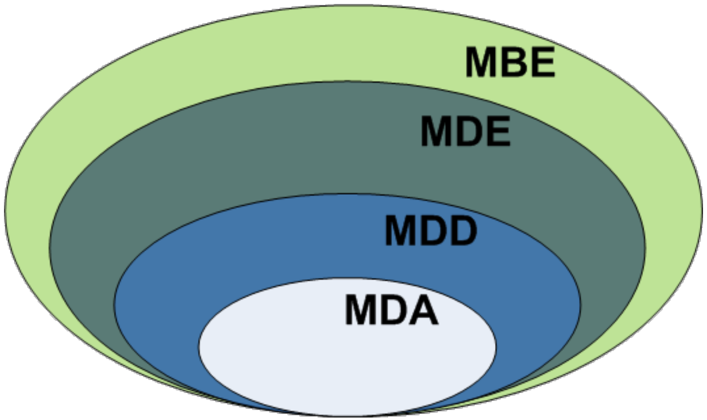
Clarifying terminology

- 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

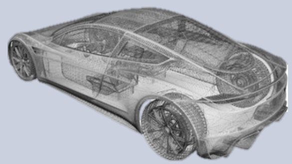
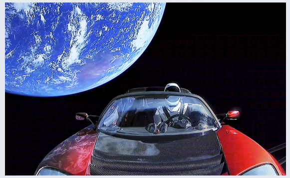
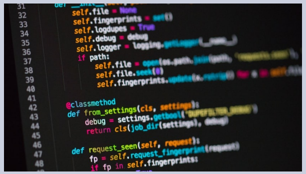
- **Model-Driven Development (MDD):**
  Models are primary artifacts for the development process

- Model-Driven Architecture (MDA):
  The Object Management Group's (OMG) vision on MDD: CIM → PIM → PSM → PSI



Distinguishing Model-Driven Digital Twin Entities

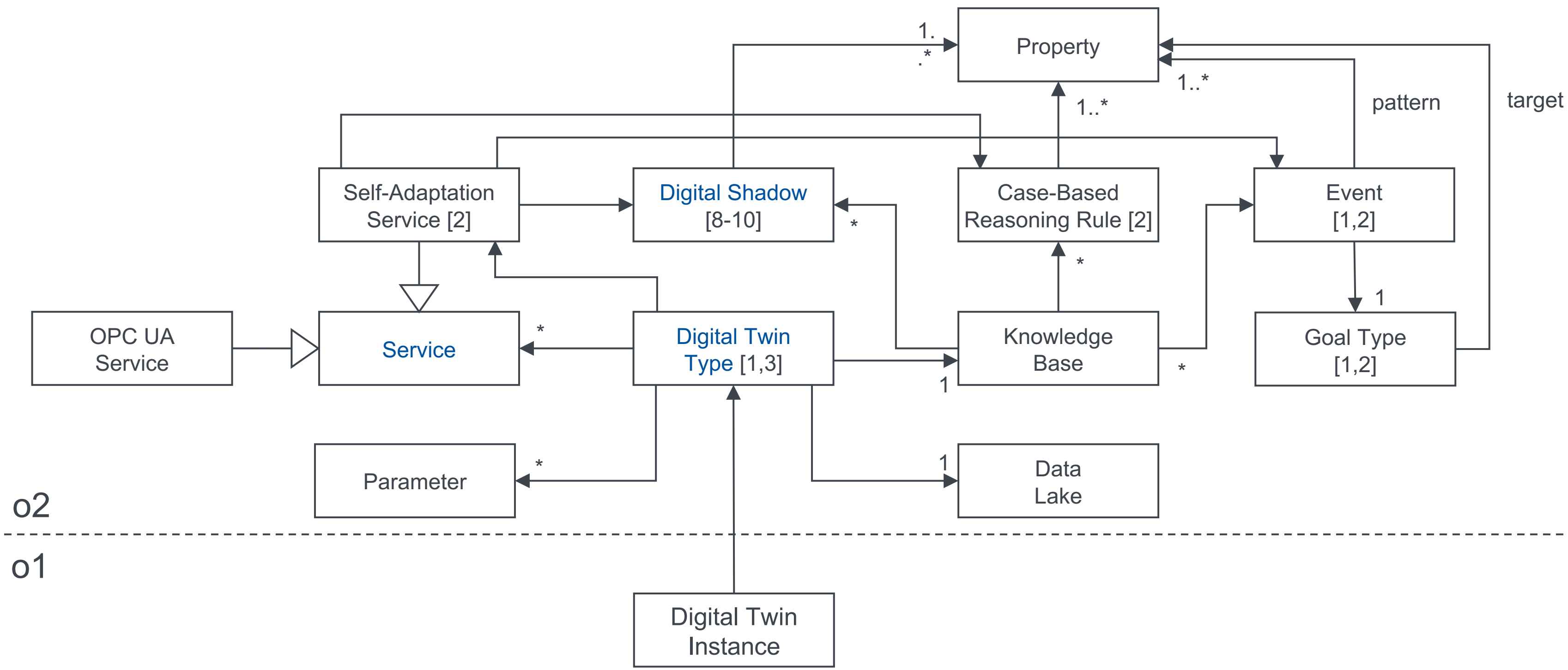
Enforcing honesty: what do we mean when saying “digital twin”?

Entity	Entity Purpose	Ontological Metalevel[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 Digital Twin Type

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



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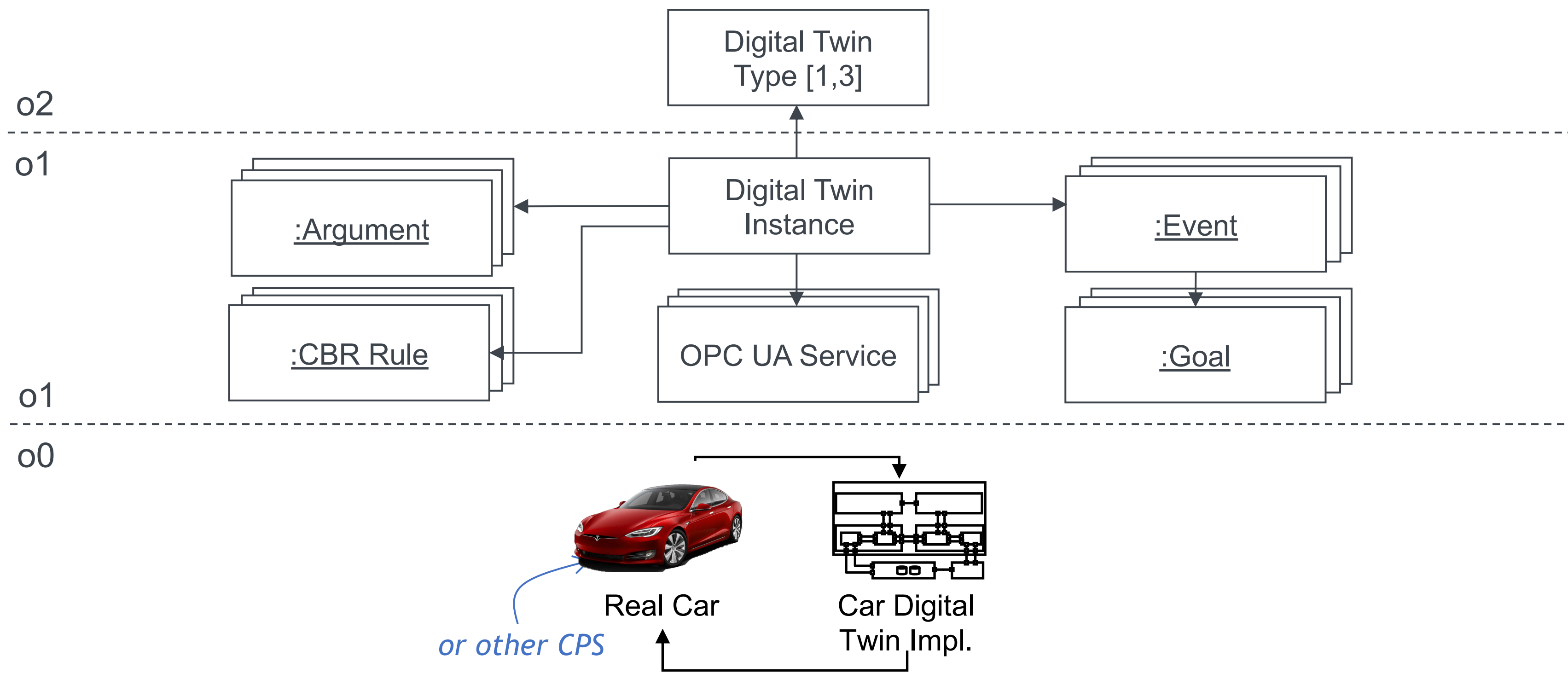
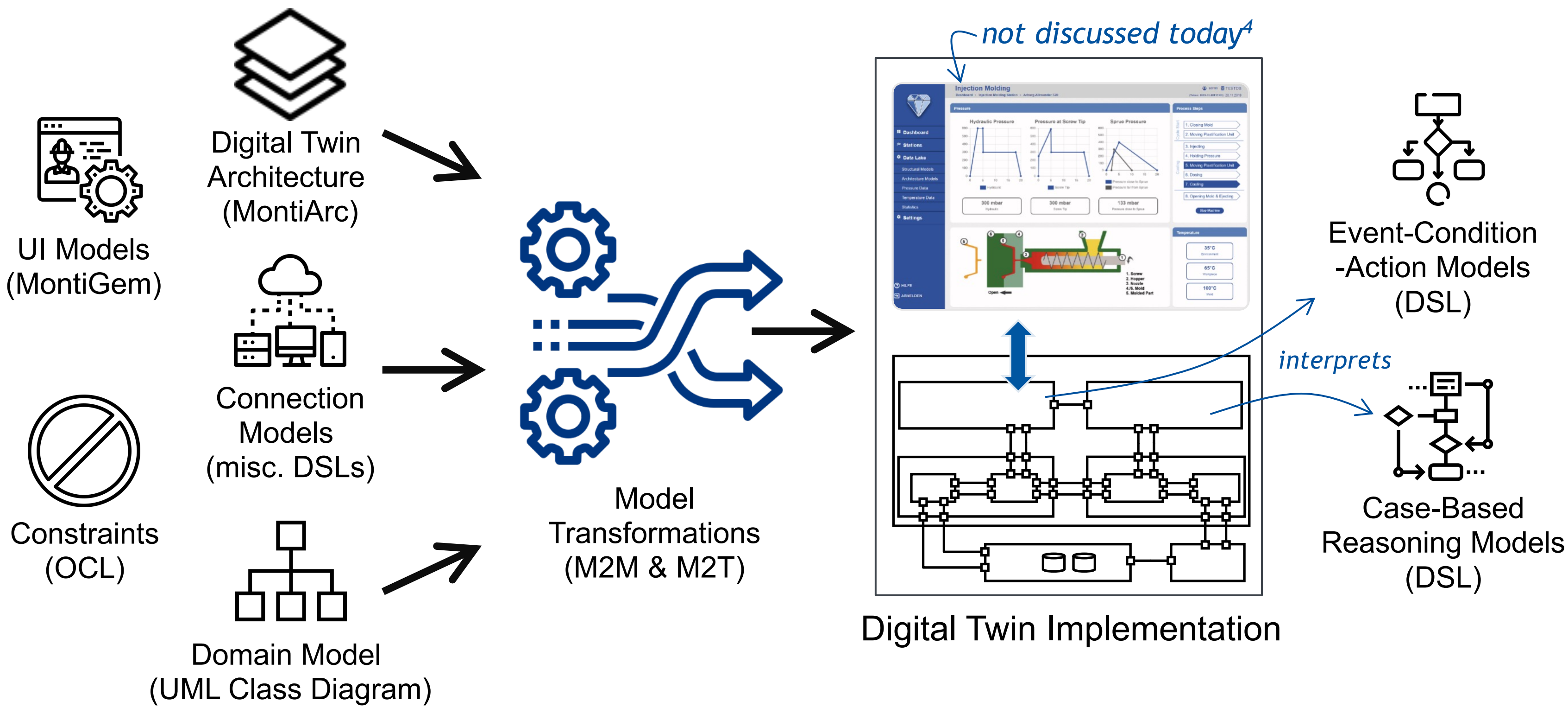
A Digital Twin Instance

A configured instance of a specific digtial twin type



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

Generating structure, interpreting behavior

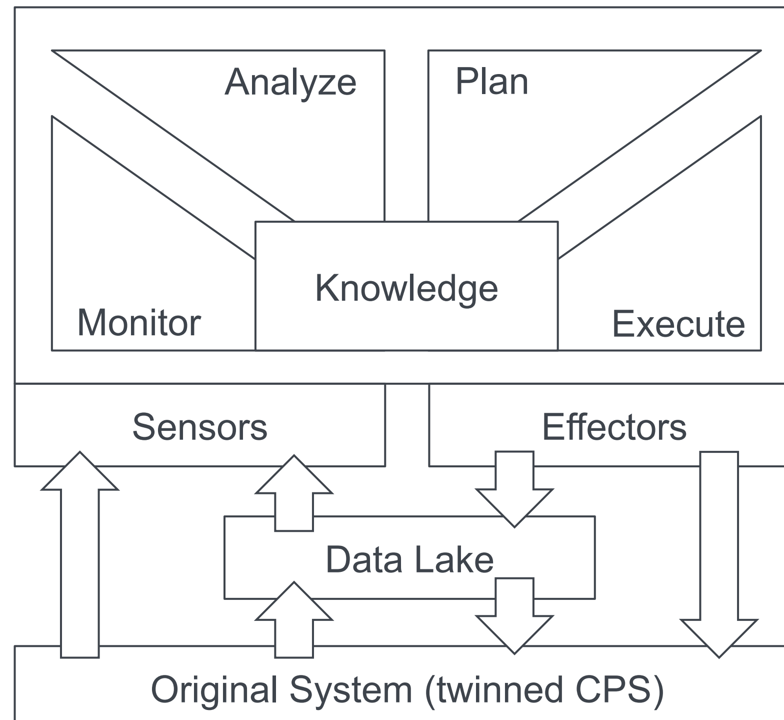


[4] Dalibor, M., Michael, J., Rumpe, B., Varga, S., & Wortmann, A. (2020,). Towards a Model-Driven Architecture for Interactive Digital Twin Cockpits. In International Conference on Conceptual Modeling (pp. 377-387). Springer, Cham.

Generation Target: Self-Adaptive Digital Twins

Realize MAPE-K control loop variant

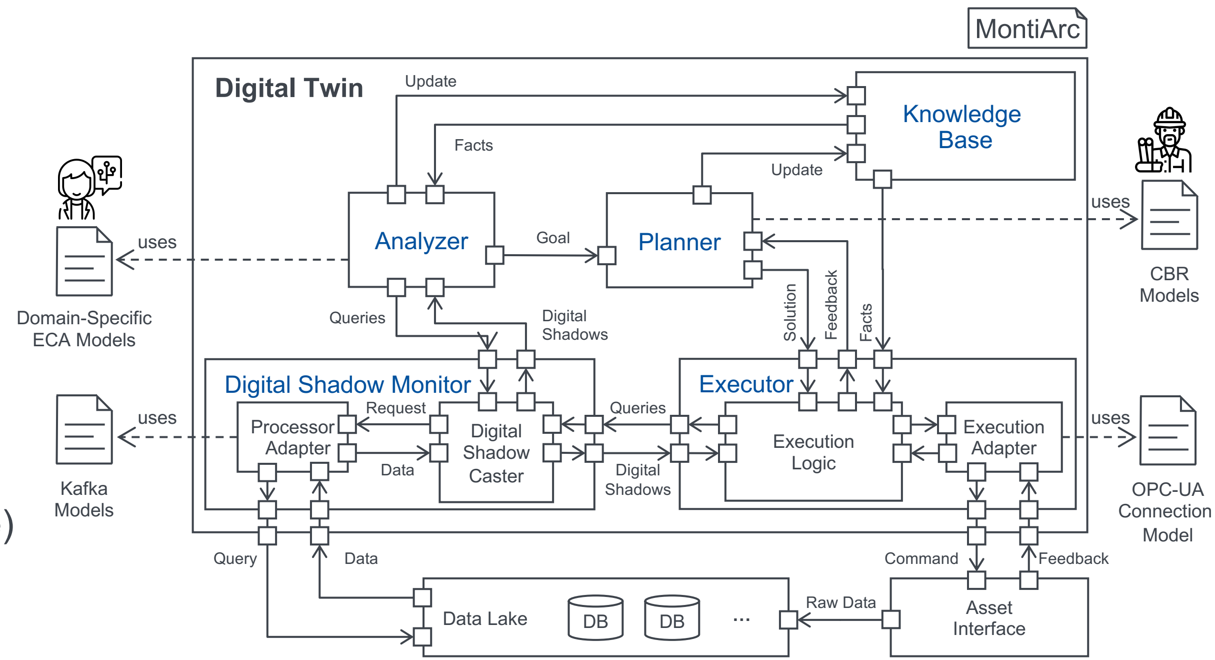
- Monitor (Present)
  - Observe changes in original system & data lake
  - Emit corresponding digital shadows if necessary
- Analyze (Predict)
  - Check Event-Condition-Action (ECA) rules against digital shadows
- Plan (Prescribe)
  - Case-Based Reasoning (CBR), AI planning, code
- Execute (Present,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

PlasticizingPhase
int machineCylcle **double** nozzleTemperature **double** dosingVolume

typed by classes and attributes defined in CD

ECA

```
behavior Phases from inj_mould_machine {
  event plasticizingEnded for PlasticizingPhase {
    trigger machineCycle
    checkTemperature(nozzleTemperature)
    && checkTemperature(nozzleTemperature@(-1))
    && dosingVolume > 60.0
  }
  goal startInjectionPhase for PlasticizingPhase {
   nozzleTemperature <= 40
  }
  plasticizingEnded => startInjectionPhase;
}
```

evaluate system when cycle counter increases

value of previous cycles

apply action if event evaluates to true

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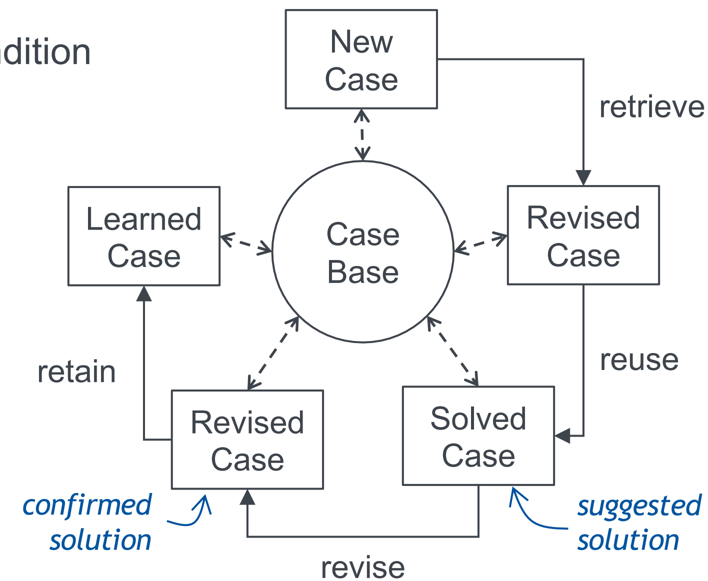
Case-Based Reasoning (CBR) Models also Reify Domain Expertise

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

```
CBR
import injectionmolding.HeatingUnit;

case Overheating(ReduceTempGoal goal) {
  if goal.currentValue > goal.targetValue;
  do HeatingUnit.reduceTemp(targetValue);
  yields
    goal.currentValue <= goal.targetValue;
}
```



Agenda

Provoking debate about digital twins

Many Open Questions

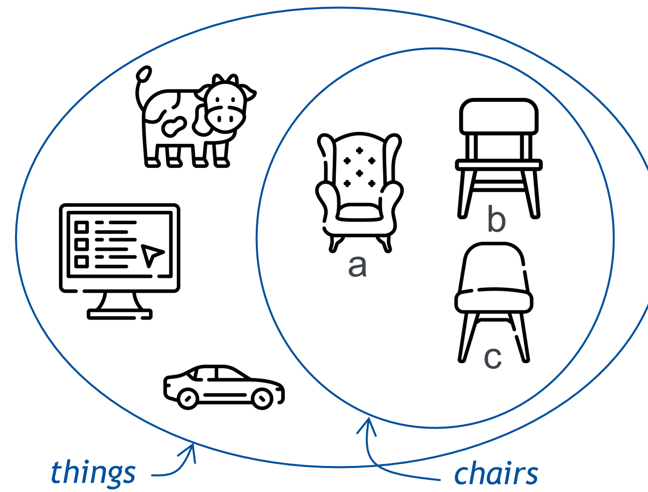
Pertaining a definition of digital twins

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
  - 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

- 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

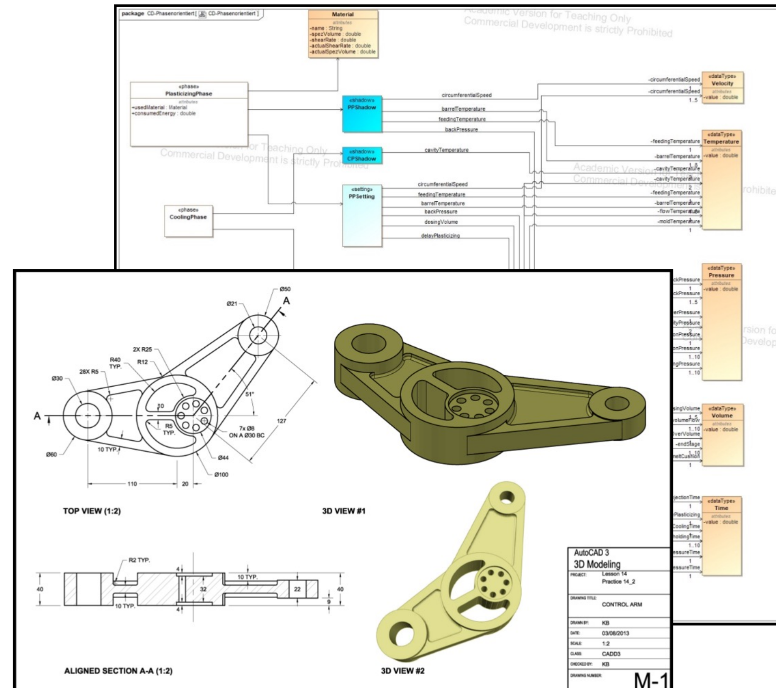
STEP (ISO 10303)

- Mathematical models: Expressions or numerical methods to convert input data into outputs to explain or prescribe system behavior

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

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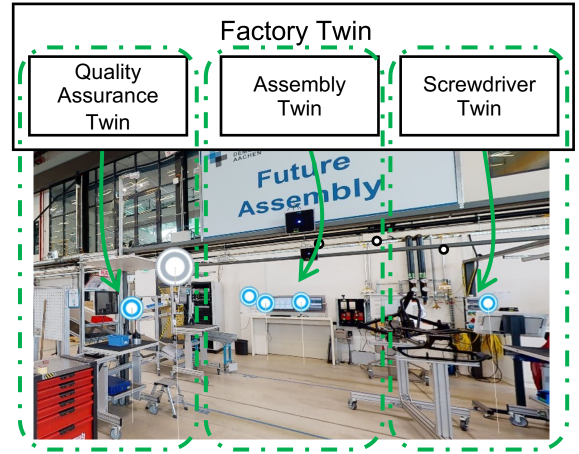
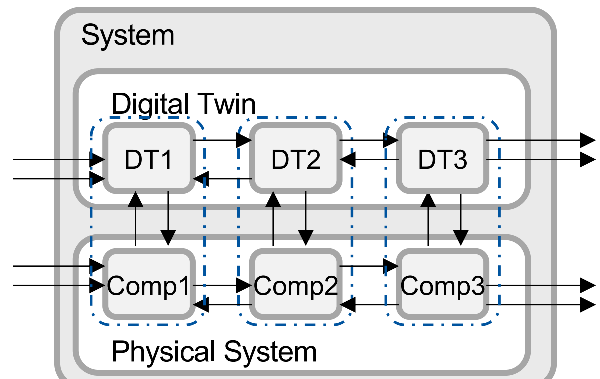
Composition of Digital Twins is Essential

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, …

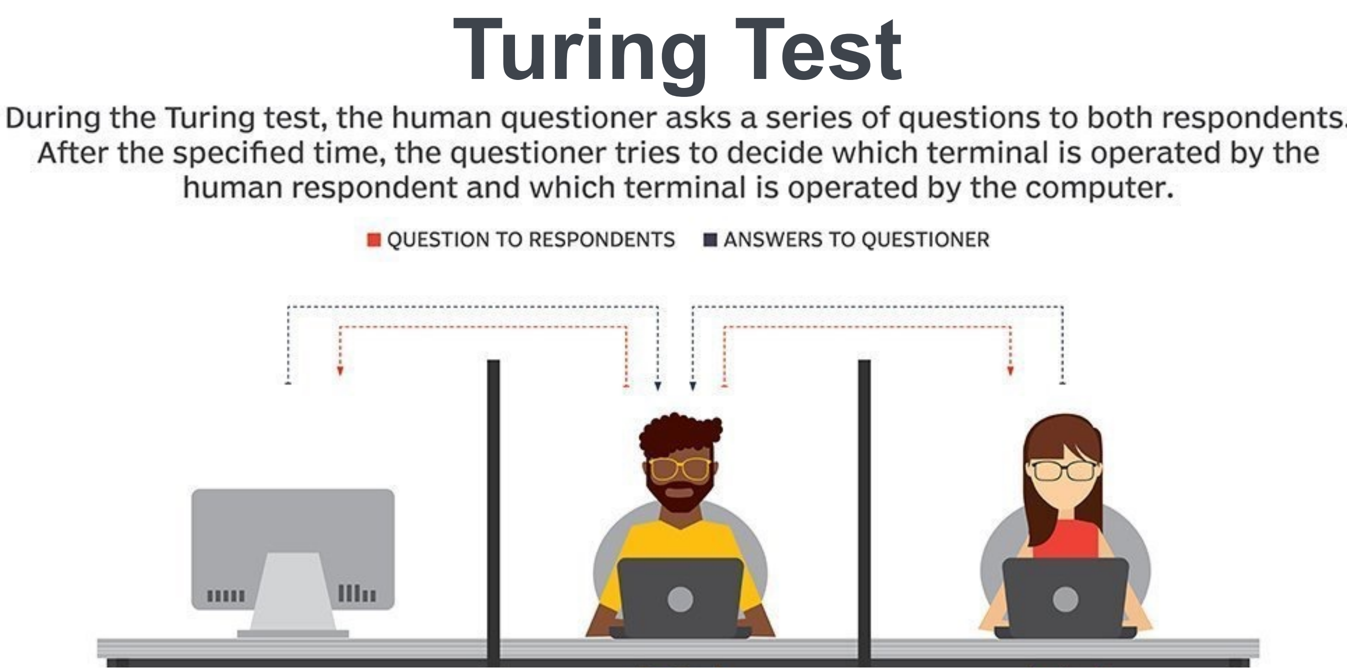




> Challenge 3: Enable the black-box composition of more complex digital twins from simpler digital twins without requiring manual interaction

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

The Turing test is a thought experiment on deciding machine intelligence



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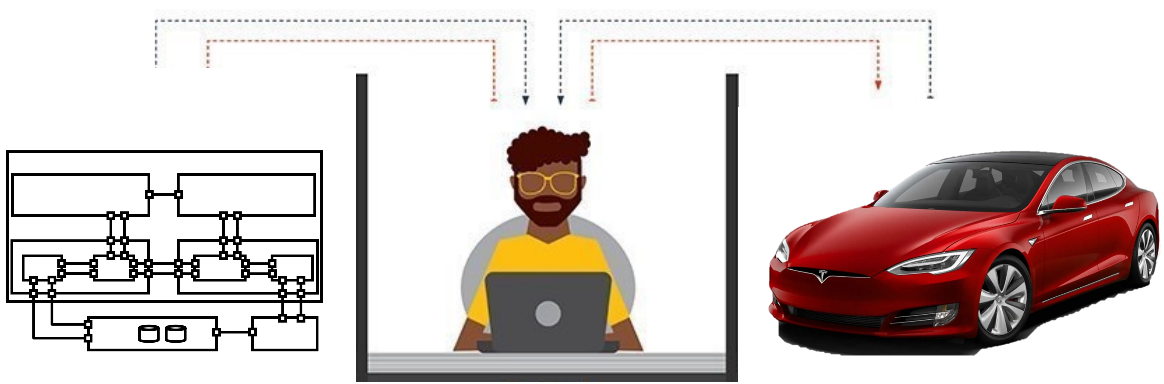
Can we Employ a Turing Test Variant to Determine Digital-Twin-ness?

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

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 Twin*s, In: 2021 International Symposium on Software Engineering for Adaptive and Self-Managing Systems (SEAMS), 2021.

[3] M. Dalibor, J. Michael, B. Rumpe, S. Varga, and A. Wortmann. Towards a Model-Driven Architecture for Interactive Digital Twin Cockpits, In: Conceptual Modeling, 2021.

[4] J. C. Kirchhof, J. Michael, B. Rumpe, S. Varga, and A. Wortmann. *Model-driven Digital Twin Construction: Synthesizing the Integration of Cyber-Physical Systems with Their Information Systems*, In: 23rd ACM/IEEE International Conference on Model Driven Engineering Languages and Systems, 2020.

[5] J. Michael, and A. Wortmann. Towards Development Platforms for Digital Twins: A Model-Driven Low-Code Approach, In: Advances in Production Management Systems. Artificial Intelligence for Sustainable and Resilient Production Systems, 2021.

In Press

[6] R. Eramo, F. Bordeleau, B. Combemale, M. van den Brand, M. Wimmer, A. Wortmann: *Conceptualizing Digital Twins* (IEEE Software), 2021.

[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.

Digital Shadows

[9] F. Becker, P. Bibow, M. Dalibor, A. Gannouni, V. Hahn, C. Hopmann, M. Jarke, I. Koren, M. Kröger, J. Lipp, J. Maibaum, J. Michael, B. Rumpe, P. Sapel, N. Schäfer, G. J. Schmitz, G. Schuh, and A. Wortmann. *A Conceptual Model for Digital Shadows in Industry and its Application*, In: Conceptual Modeling, ER 2021, pages 271-281, October, 2021, Springer.

[10] G. Schuh, C. Häfner, C. Hopmann, B. Rumpe, M. Brockmann, A. Wortmann, J. Maibaum, M. Dalibor, P. Bibow, P. Sapel, and M. Kröger. *Effizientere Produktion mit Digitalen Schatten*, ZWF Zeitschrift für wirtschaftlichen Fabrikbetrieb, 115, 2020.

MontiArc

[11] A. Haber, J. O. Ringert, B. Rumpe: *MontiArc - Architectural Modeling of Interactive Distributed and Cyber-Physical Systems*. RWTH Aachen University, Technical Report. AIB-2012-03. February 2012.

[12] J. O. Ringert, B. Rumpe, A. Wortmann: *Architecture and Behavior Modeling of Cyber-Physical Systems with MontiArcAutomaton*. In: Aachener Informatik-Berichte, Software Engineering, Band 20. 2014.

[13] A. Haber, M. Look, P. Mir Seyed Nazari, A. Navarro Perez, B. Rumpe, S. Völkel, and A. Wortmann. *Integration of Heterogeneous Modeling Languages via Extensible and Composable Language Components*, In: Model-Driven Engineering and Software Development Conference, 2015.

[14] A. Butting, O. Kautz, B. Rumpe, and A. Wortmann. *Architectural Programming with MontiArcAutomaton*, In 12th International Conference on Software Engineering Advance, 2017.

Literature

From our mapping study - 1

[24] Talkhestani, B. A., Jazdi, N., Schlögl, W., & Weyrich, M. (2018). *A concept in synchronization of virtual production system with real factory based on anchor-point method*. Procedia Cirp, 67, 13-17[74]

[74] Ciavotta, M., Alge, M., Menato, S., Rovere, D., & Pedrazzoli, P. (2017). A microservice-based middleware for the digital factory. *Procedia manufacturing*, *11*, 931-938.

[]128] Zobel-Roos, S., Schmidt, A., Mestmäcker, F., Mouellef, M., Huter, M., Uhlenbrock, L., ... & Strube, J. (2019). Accelerating biologics manufacturing by modeling or: is approval under the QbD and PAT approaches demanded by authorities acceptable without a digital-twin?. Processes, 7(2), 94.

[269] Eisenträger, M., Adler, S., Kennel, M., & Möser, S. (2018, June). Changeability in Engineering. In 2018 IEEE International Conference on Engineering, Technology and Innovation (ICE/ITMC) (pp. 1-8). IEEE.

[337] Rambow-Hoeschele, K., Nagl, A., Harrison, D. K., Wood, B. M., Bozem, K., Braun, K., & Hoch, P. (2018, June). *Creation of a digital business model builder*. In *2018 IEEE International Conference on Engineering, Technology and Innovation (ICE/ITMC)* (pp. 1-7). IEEE.[379] Deep Learning for Hybrid 5G Services in Mobile Edge Computing Systems: Learn from a Digital Twin

[386] Eyre, J. M., Dodd, T. J., Freeman, C., Lanyon-Hogg, R., Lockwood, A. J., & Scott, R. W. (2018, November). *Demonstration of an industrial framework for an implementation of a process digital twin*. In *ASME International Mechanical Engineering Congress and Exposition* (Vol. 52019, p. V002T02A070). American Society of Mechanical Engineers.

[388] Bitton, R., Gluck, T., Stan, O., Inokuchi, M., Ohta, Y., Yamada, Y., ... & Shabtai, A. (2018, September). *Deriving a cost-effective digital twin of an ICS to facilitate security evaluation*. In *European Symposium on Research in Computer Security* (pp. 533-554). Springer, Cham.

[393] Park, K. T., Nam, Y. W., Lee, H. S., Im, S. J., Noh, S. D., Son, J. Y., & Kim, H. (2019). Design and implementation of a digital twin application for a connected micro smart factory. *International Journal of Computer Integrated Manufacturing*, *32*(6), 596-614.

[497] Vijayakumar, K., Dhanasekaran, C., Pugazhenthi, R., & Sivaganesan, S. (2019). Digital Twin for factory system simulation. International Journal of Recent Technology and Engineering, 8(1), 63-68.

Literature

From our mapping study - 2

[498] Khan, A., Dahl, M., Falkman, P., & Fabian, M. (2018, August). Digital twin for legacy systems: Simulation model testing and validation. In 2018 IEEE 14th International Conference on Automation Science and Engineering (CASE) (pp. 421-426). IEEE.

[523] Anderl, Reiner, et al. "*Digital twin technology–An approach for Industrie 4.0 vertical and horizontal lifecycle integration*." *it-Information Technology* 60.3 (2018): 125-132.[827]

[827] Pargmann, H., Euhausen, D., & Faber, R. (2018, April). Intelligent big data processing for wind farm monitoring and analysis based on cloud-technologies and digital twins: A quantitative approach. In *2018 IEEE 3rd international conference on cloud computing and big data analysis (ICCCBDA)* (pp. 233-237). IEEE.

[1079] Mayes, A., Heffernan, J., Jauriqui, L., Livings, R., Biedermann, E., Aldrin, J. C., ... & Mazdiyasni, S. (2019, May). *Process compensated resonance testing (PCRT) inversion for material characterization and digital twin calibration*. In *AIP Conference Proceedings* (Vol. 2102, No. 1, p. 020019). AIP Publishing LLC.

[719] Dufour, C., Soghomonian, Z., & Li, W. (2018, June). Hardware-in-the-loop testing of modern on-board power systems using digital twins. In 2018 International Symposium on Power Electronics, Electrical Drives, Automation and Motion (SPEEDAM) (pp. 118-123). IEEE.

[1307] Glaessgen, E., & Stargel, D. (2012, April). The digital twin paradigm for future NASA and US Air Force vehicles. In 53rd AIAA/ASME/ASCE/AHS/ASC structures, structural dynamics and materials conference 20th AIAA/ASME/AHS adaptive structures conference 14th AIAA (p. 1818).

[1386] Rabah, S., Assila, A., Khouri, E., Maier, F., Ababsa, F., Maier, P., & Mérienne, F. (2018). Towards improving the future of manufacturing through digital twin and augmented reality technologies. Procedia Manufacturing, 17, 460-467.

[1389] Stojanovic, V., Trapp, M., Richter, R., Hagedorn, B., & Döllner, J. (2018). *Towards the generation of digital twins for facility management based on 3D point clouds*. *Management*, *270*, 279.

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

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

MODELS'21

Program

The workshop is schedule 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)

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