Engineering Digital Twins in the age of AI

Keynote @ AI4DT workshop, BNAIC 2026
October 21st 2026

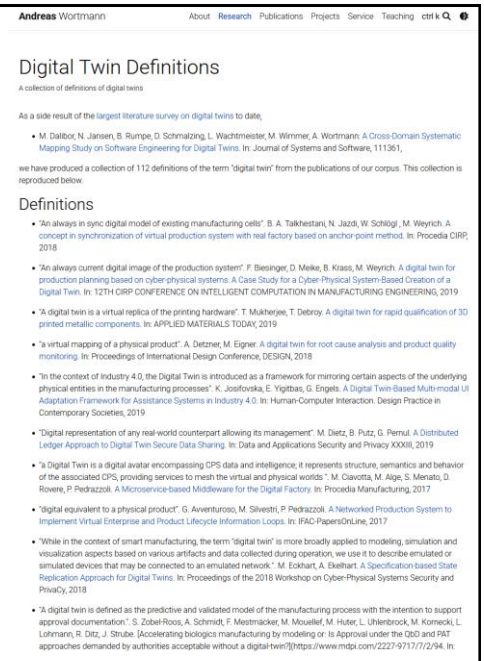
Joost Mertens
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What is a Digital Twin?

- Dalibor et al. found 112 defs



Andreas Wortmann About Research Publications Projects Service Teaching ctrl k

Digital Twin Definitions

A collection of definitions of digital twins

As a side result of the largest literature survey on digital twins to date,

- 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. In: Journal of Systems and Software, 111361,

we have produced a collection of 112 definitions of the term "digital twin" from the publications of our corpus. This collection is reproduced below.

Definitions

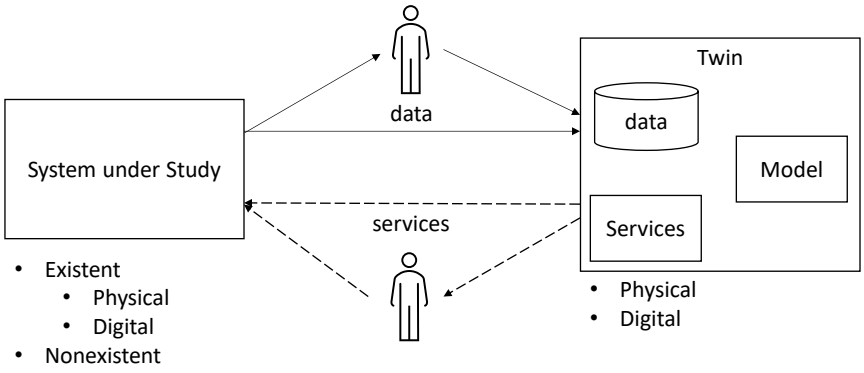
- "An always in sync digital model of existing manufacturing cells". B. A. Talkhestani, N. Jazdi, W. Schlögl , M. Weyrich. A concept in synchronization of virtual production system with real factory based on anchor-point method. In: Procedia CIRP, 2018
- "An always current digital image of the production system". F. Biesinger, D. Meike, B. Krass, M. Weyrich. A digital twin for production planning based on cyber-physical systems: A Case Study for a Cyber-Physical System-Based Creation of a Digital Twin. In: 12TH CIRP CONFERENCE ON INTELLIGENT COMPUTATION IN MANUFACTURING ENGINEERING, 2019
- "A digital twin is a virtual replica of the printing hardware". T. Mukherjee, T. Debroy. A digital twin for rapid qualification of 3D printed metallic components. In: APPLIED MATERIALS TODAY, 2019
- "a virtual mapping of a physical product". A. Detzner, M. Eigner. A digital twin for root cause analysis and product quality monitoring. In: Proceedings of International Design Conference, DESIGN, 2018
- "In the context of Industry 4.0, the Digital Twin is introduced as a framework for mirroring certain aspects of the underlying physical entities in the manufacturing processes". K. Josifovska, E. Yigitbas, G. Engels. A Digital Twin-Based Multi-modal UI Adaptation Framework for Assistance Systems in Industry 4.0. In: Human-Computer Interaction. Design Practice in Contemporary Societies, 2019
- "Digital representation of any real-world counterpart allowing its management". M. Dietz, B. Putz, G. Pernul. A Distributed Ledger Approach to Digital Twin Secure Data Sharing. In: Data and Applications Security and Privacy XXXIII, 2019
- "a Digital Twin is a digital avatar encompassing CPS data and intelligence; it represents structure, semantics and behavior of the associated CPS, providing services to mesh the virtual and physical worlds ". M. Ciavotta, M. Alge, S. Menato, D. Rovere, P. Pedrazzoli. A Microservice-based Middleware for the Digital Factory. In: Procedia Manufacturing, 2017
- "digital equivalent to a physical product". G. Aventuroso, M. Silvestri, P. Pedrazzoli. A Networked Production System to Implement Virtual Enterprise and Product Lifecycle Information Loops. In: IFAC-PapersOnLine, 2017
- "While in the context of smart manufacturing, the term "digital twin" is more broadly applied to modeling, simulation and visualization aspects based on various artifacts and data collected during operation, we use it to describe emulated or simulated devices that may be connected to an emulated network.". M. Eckhart, A. Ekelhart. A Specification-based State Replication Approach for Digital Twins. In: Proceedings of the 2018 Workshop on Cyber-Physical Systems Security and PrivaCy, 2018
- "A digital twin is defined as the predictive and validated model of the manufacturing process with the intention to support approval documentation.". S. Zobel-Roos, A. Schmidt, F. Mestmäcker, M. Mouellef, M. Huter, L. Uhlenbrock, M. Kornecki, L. Lohmann, R. Ditz, J. Strube. [Accelerating biologics manufacturing by modeling or: Is Approval under the QbD and PAT approaches demanded by authorities acceptable without a digital-twin?](https://www.mdpi.com/2227-9717/7/2/94. In:

https://awortmann.github.io/research/digital-twin-definitions/

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Twinning paradigm – Twinning System



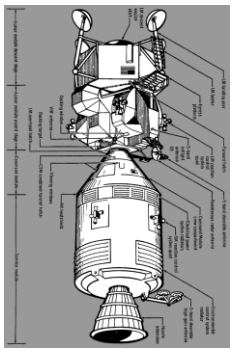
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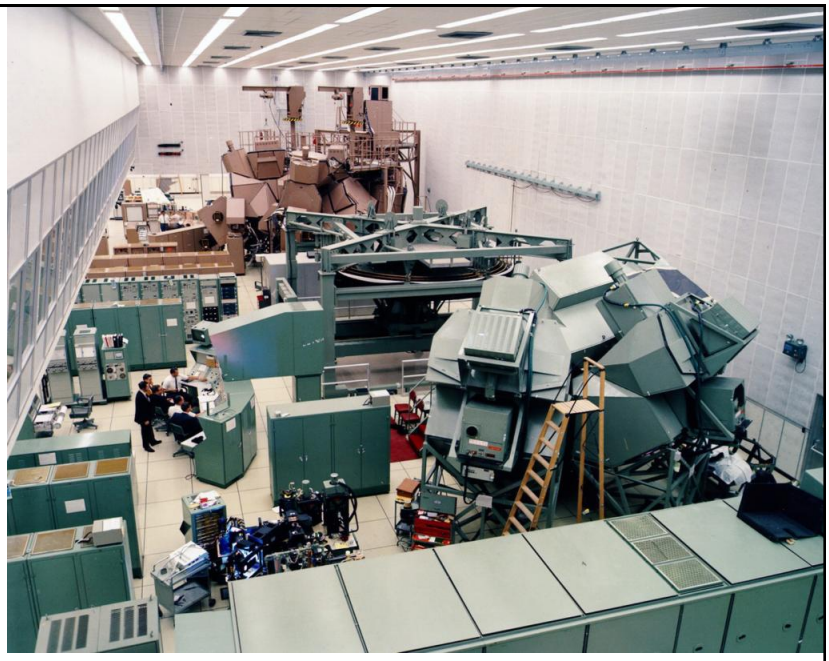


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Apollo

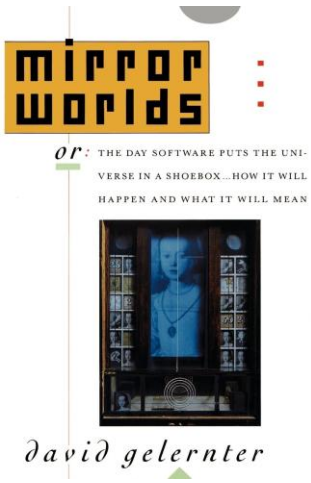
- 15 sims
- Apollo 13



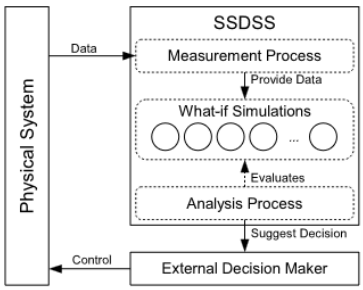


https://blogs.sw.siemens.com/simcenter/apollo-13-the-first-digital-twin/

History leading up to Digital Twin



Symbiotic Simulation Systems



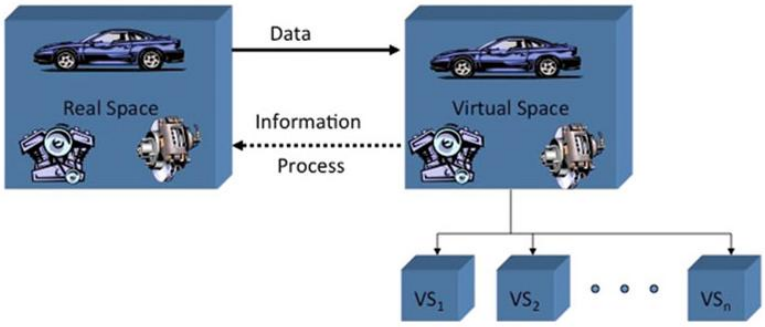
Aydt et al., Symbiotic Simulation Systems: An Extended Definition Motivated by Symbiosis in Biology, PADS2008

Digital Twin

Conceptual ideal for PLM

Michael Grieves







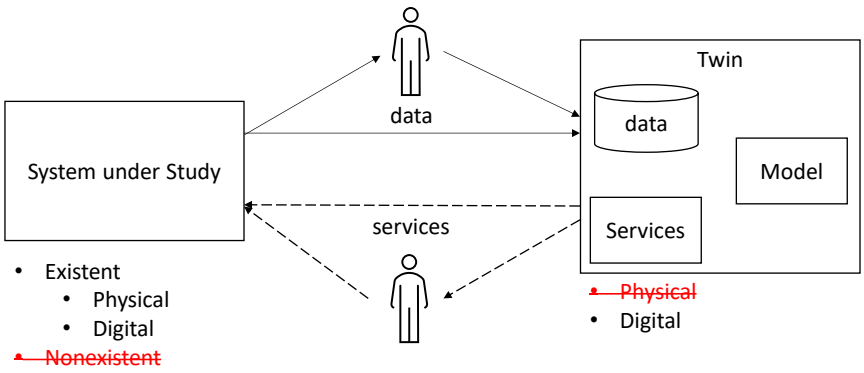
John Vickers

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Twinning paradigm – Twinning System



- Existent
  - Physical
  - Digital
- ~~Nonexistent~~

- ~~Physical~~
- Digital

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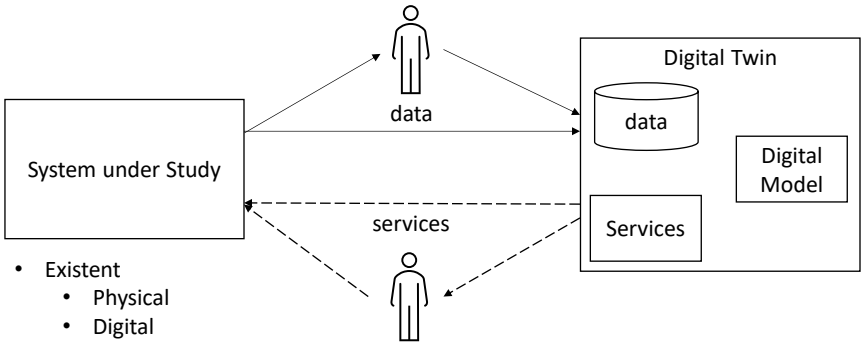
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Lugaresi and Vangheluwe, *From Digital Twins to Twinning Systems*, WSC2025

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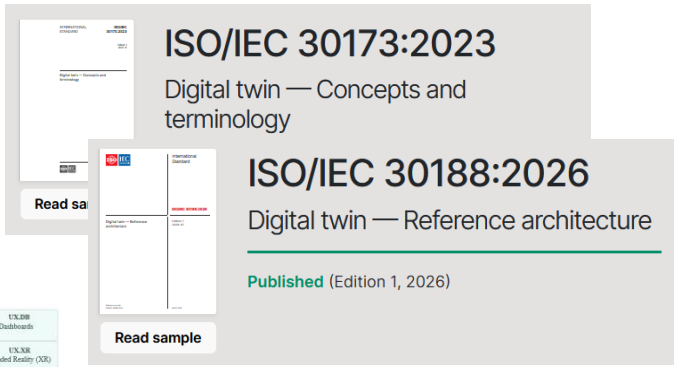
Twinning paradigm – Twinning System



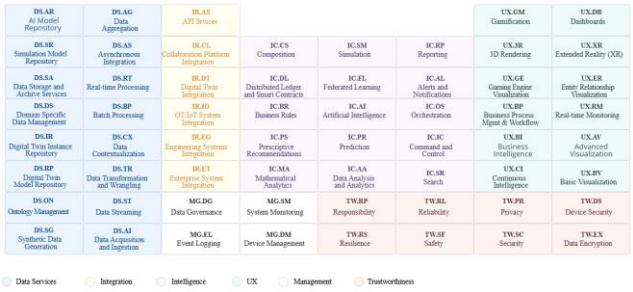
- Existent
  - Physical
  - Digital

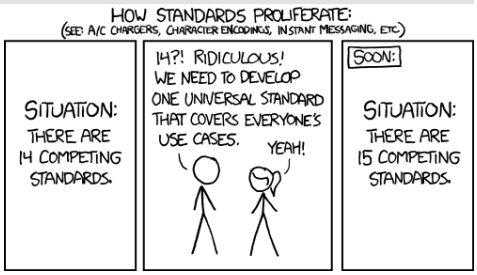
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Standardization



digital twin CONSORTIUM
An EDM Association Community





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When is a digital twin interesting?



unreachable



expensive interventions



too complex/large for local decisions



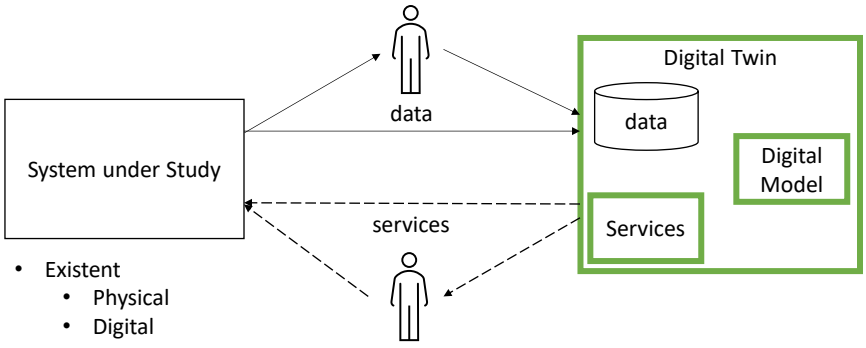
system changes over time



many future states

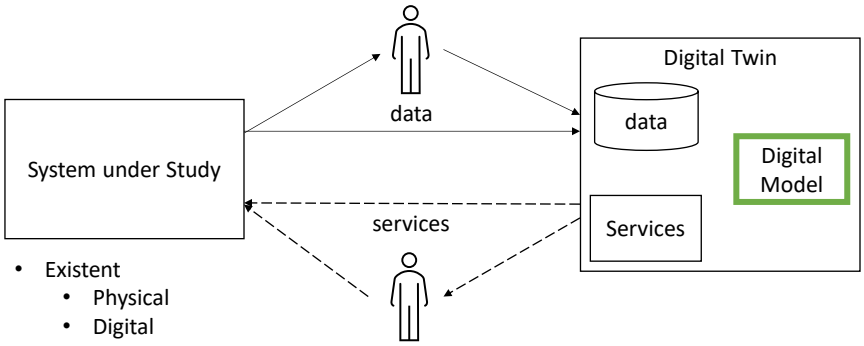
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Where does AI fit in the Digital Twin?



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AI as the digital model



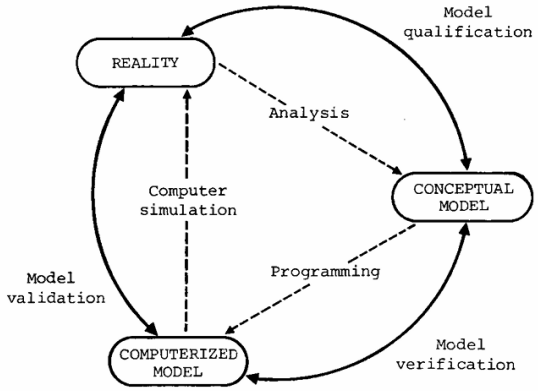
What is the model?

- Abstraction of reality, represents **properties** and/or **behaviors** of **aspects** of the system under study
  - Aspects: part of the system in which you're interested
    - Geometry
    - Kinematics
    - Electrical power draw
    - Analog or digital communication
    - Throughput (factory/production line)
- Tied closely to the **services** the digital twin provides
  - Must be a **valid** model

Model Validity

"Substantiation that a computerized model within its domain of applicability possesses a satisfactory range of accuracy consistent with ***the intended application*** *of the model*

Schlesinger et al., *Terminology for model credibility,*
SCS Technical Committee report 1979



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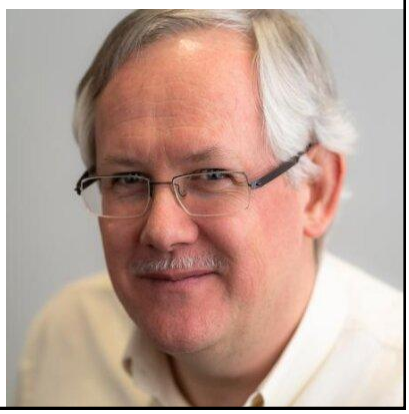
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Modeling formalisms

"Model everything at the most appropriate level(s) of detail/abstraction using the <u>most appropriate formalism(s)</u>"

Subjective:
- Intended application
- Modeler's background
- Tool availability

Artificial Intelligence?

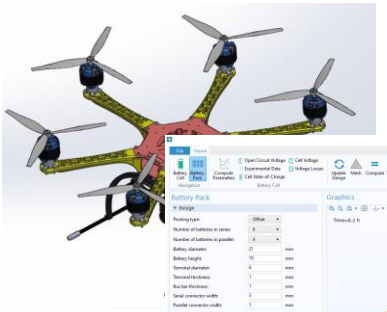


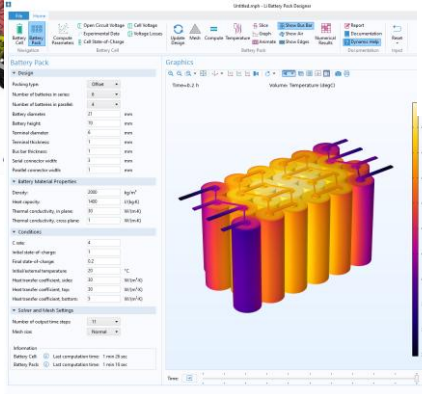
Hans Vangheluwe

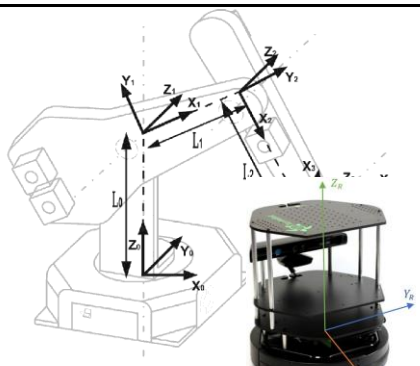
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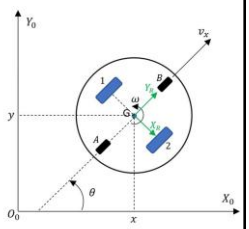
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Traditional Models











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Design time vs DT model use

Design Time

Unlimited time

Unlimited resources

Parallel to system under study

Timeliness

More limited resources

…most appropriate formalism?

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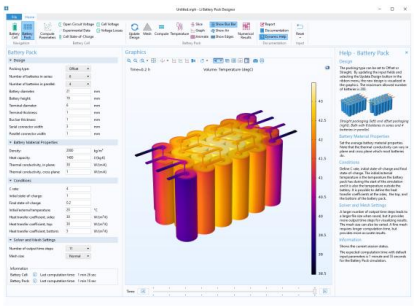
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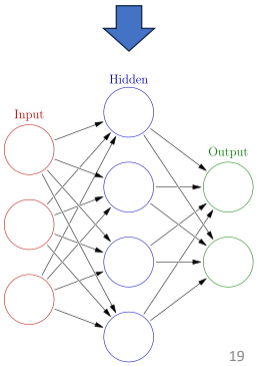
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Surrogate models

- Heavy simulation > lightweight surrogate
- Surrogate mimics simulation
- Data-driven approach
  - Sample selection (minimal heavy simulations)
  - Surrogate construction
  - Surrogate accuracy assessment
- Machine Learning:
  - SVR, ANN, Random forest





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Hybrid-physics-AI models

- Faithful representation vs compute time
  - Atmosphere
  - Oceans
  - Land
- General Circulation Model, Earth System Model
  - Grid
- GCM, ESM predict coarse resolution, large scale dynamics
- Unresolved small scale processes: parametrizations
  - AI surrogates replace the parametrizations
- Also: Physics-informed Neural Networks

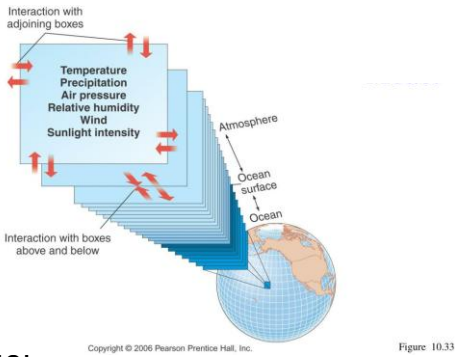
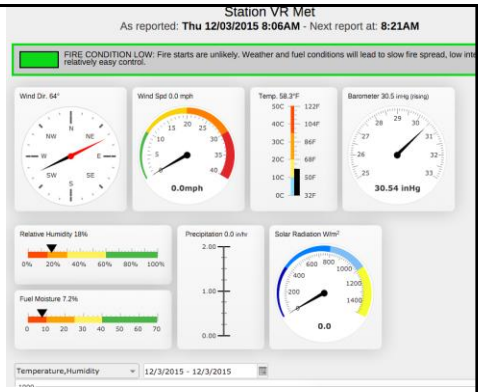


Figure 10.33

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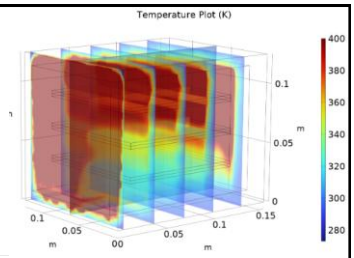
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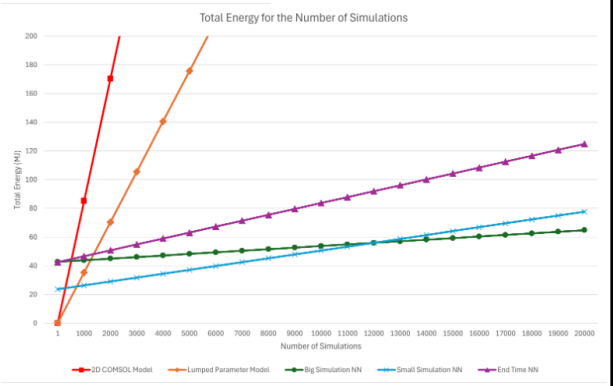
Data driven models



- System already exists
  - But no model exists
- Generate data through instrumentation
- Learn the digital twin models from the data
- Big data and deep learning but also simpler AI models

Trade-offs, considerations





- Out-of-distribution behavior
- Energy/resource utilization

$$E_{total} = E_{design} + S * E_{local}$$

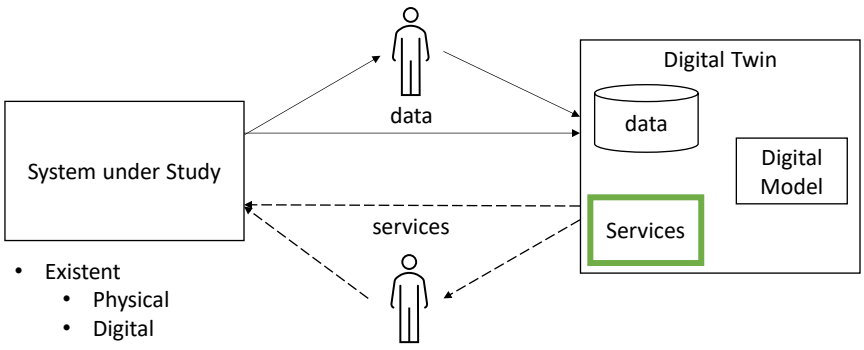
- Explainability

S. Bellis, J. Mertens and J. Denil, "Energy and Accuracy Trade-Offs in Digital Twin Modeling: A Comparative Study of an Autoclave System," *2025 Winter Simulation Conference (WSC)*

Summary

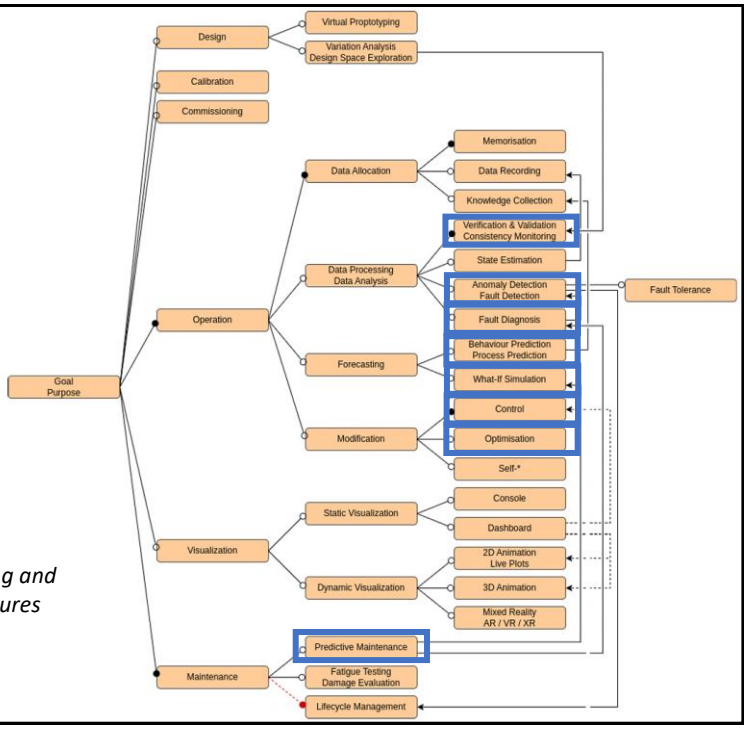
- AI offers additional modeling formalisms
  - Might be more appropriate!
  - Lightweight, faster surrogates
  - Hybrid physics-AI or physics inspired models
  - Fully data driven models
- Trade-offs must be considered
  - Out-of-distribution behavior
  - Explainability

AI in the Digital Twin's Services



DT Purpose/Goal

- Purpose/goal results in one or more services



Paredis R., Gomes C. and Vangheluwe H., *Modelling and Simulation-Based Evaluation of Twinning Architectures and Their Deployment*, IN4PL 2021

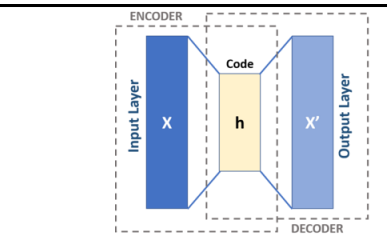
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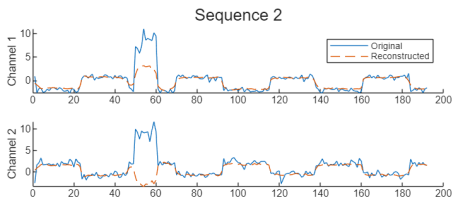
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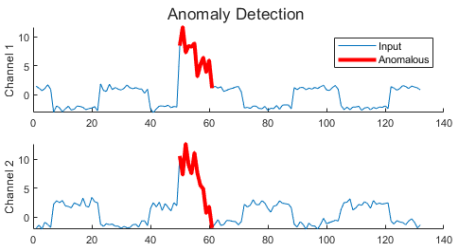
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Anomaly Detection

- Detecting when anomalies occur in time series data.
- DT is data provider:
  - Real-measurements
  - Simulation data (fault-injection possible)
- E.g. with autoencoder
  - Train on normal samples
  - Compare in- and output with error threshold
- also: isolation forest, SVM, LSTM error…





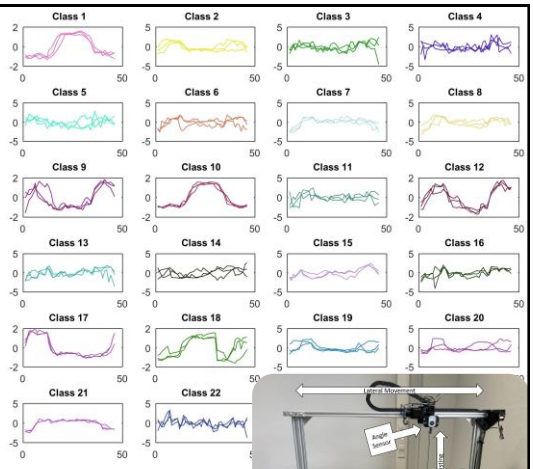


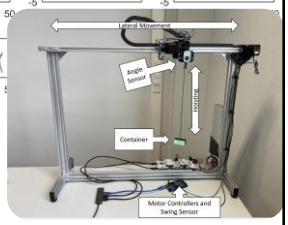
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Fault Diagnosis





- Typically after anomaly detection
- DT is again data provider
  - Real-measurements
  - Fault-injected simulation data
- E.g. Supervised time-series classification
  - Train classifier like ROCKET to map window to a fault label (others: HIVE-COTE, InceptionTime, ResNet,…)
  - DT model can help provide samples of fault classes
- Domain gap, unforeseen faults?

Mertens, J. and Denil, J., *Localizing faults in digital twin models by using time series classification techniques,* WSC2024

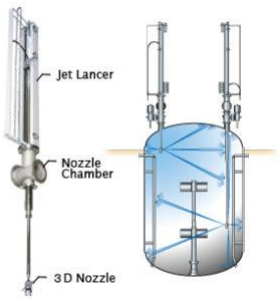
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Validation and Consistency Monitoring





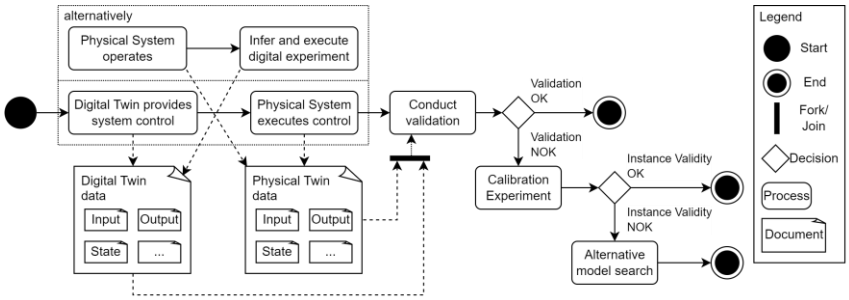
- Service quality linked to model quality
- Systems evolve over long/short time
- Model should remain consistent
- Typical DT issue:
  - When to synchronize model
- Continual validation
  - Validation techniques applied at operation time
  - Anomaly detection techniques

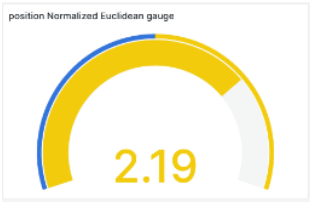
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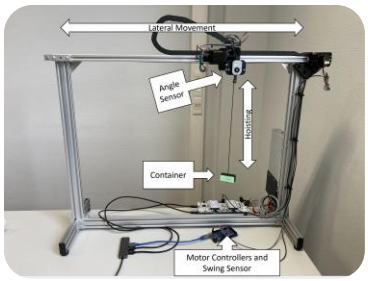
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Validation and Consistency Monitoring







Mertens, J. and Denil, J. *Reusing model validation methods for the continuous validation of digital twins of cyber-physical systems, SOSYM2024*

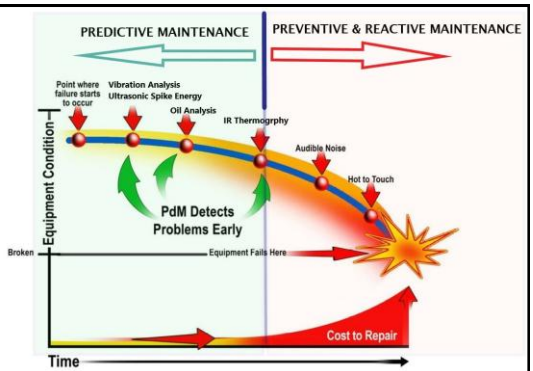
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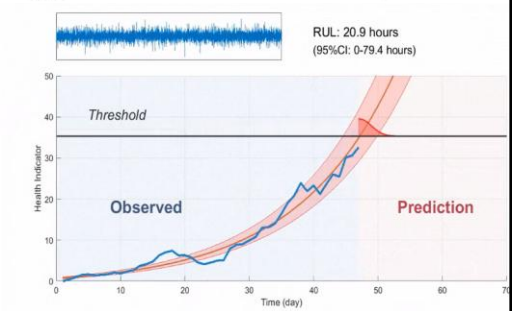
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Predictive Maintenance

- Predict RUL, take action before costs ramp up
- Lifetime data, Run-to-failure data, threshold data
- Traditional ML, deep learning
- DT again data provider:
  - Historical data, fault injected data
  - Degradation models e.g. Paris' law (fatigue cracks), battery degradation -> PINN



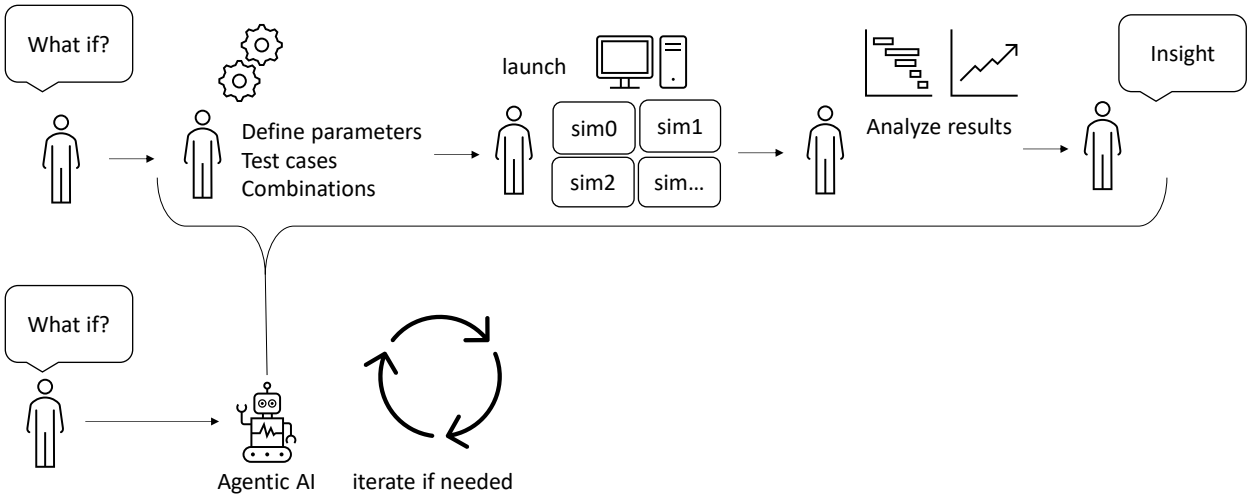


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FLANDERS MAKE

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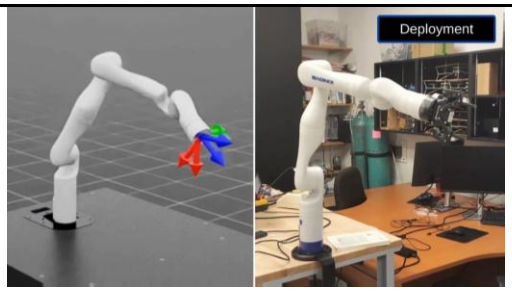
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Forecasting/Prediction, What-if Simulation



Control

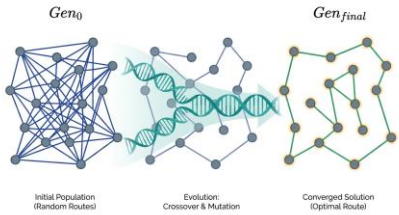
- RL for robots
- Data Center Cooling with deep learning (Google Deepmind)
- DT potential:
  - Data kickstart/augmentation
  - Instance model vs generic model
  - Historical data



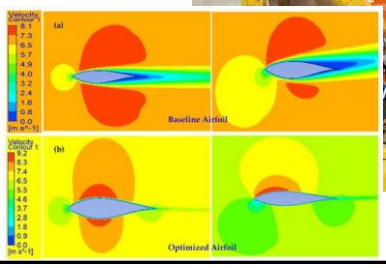


Optimization

- Scheduling problems (smart factory)
  - Schedule candidates
- Future designs
  - Search large design space
- Genetic algorithm, RL
- Also non-AI: MILP, MPC



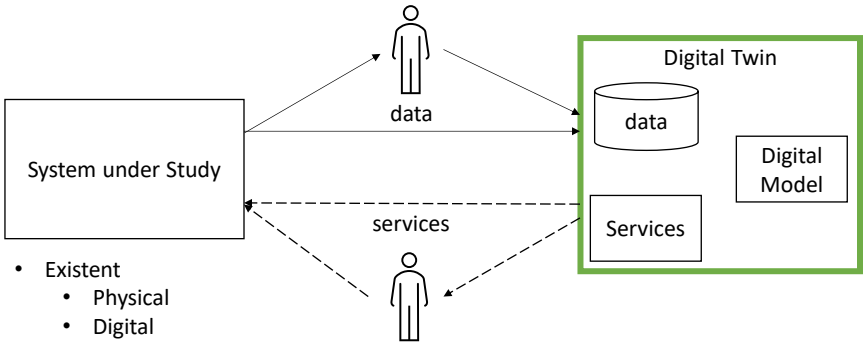




Summary

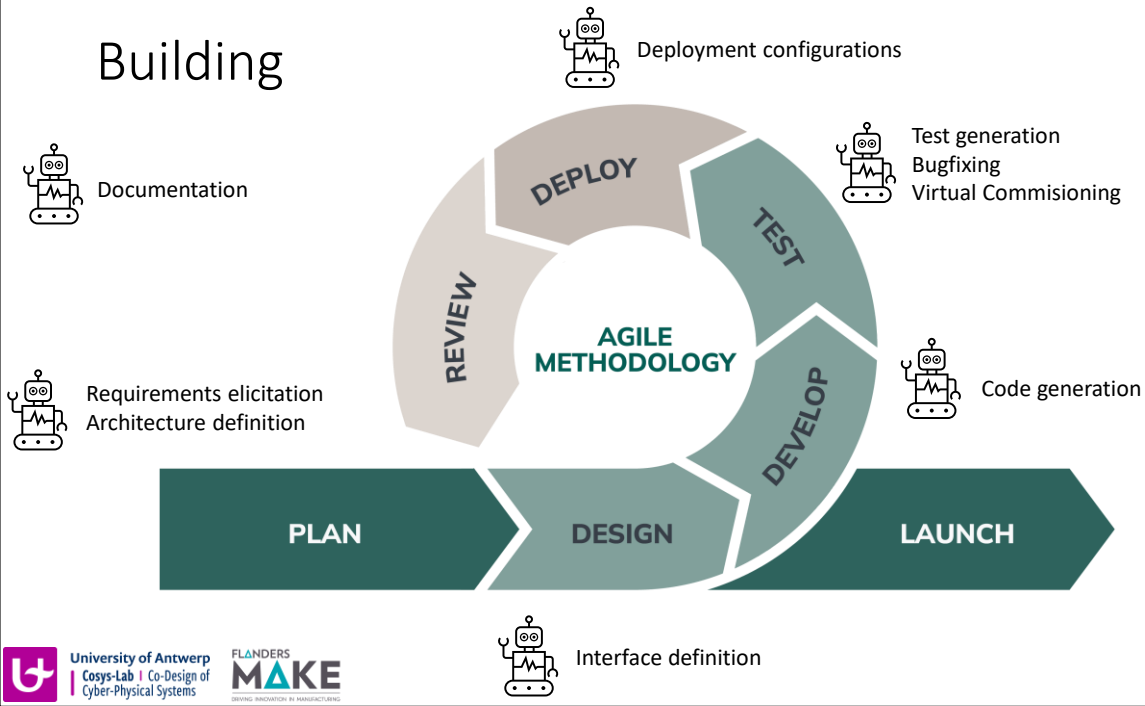
- There is close interplay between the model and the service using the model
  - Model can generate (fault-injected) data to augment measurements and train classifiers or predictors for various purposes
    - Anomaly detection
    - Fault detection and diagnosis
    - Predictive maintenance
  - BUT: Sim to real gap is real!
  - Model can make predictions for scenario exploration
    - What if analysis, set up aided by agentic AI
    - Used for training of control schemes like Reinforcement Learning
    - Used in optimizations such as genetic algorithm

AI for Building and Maintaining a Twin



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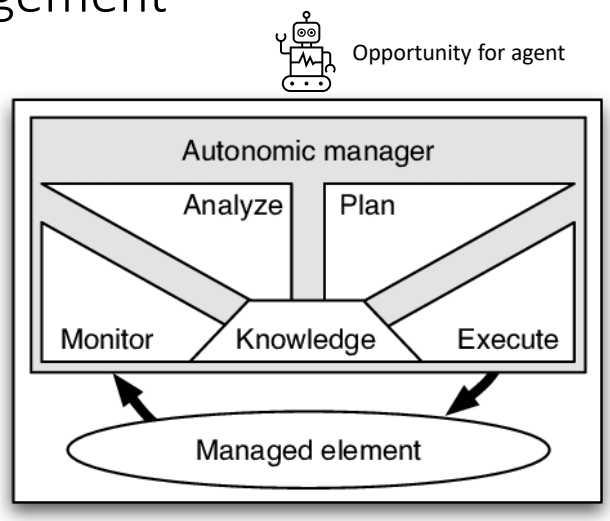
Building



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Operating – self-management

- Lifecycle management
- Runtime monitoring and drift detection
  - Identify model discrepancies
  - Flag out-of-range conditions.
- Retrain models
- Update system, manage deployment



Summarizing

- DT is software system
  - Agentic AI applicable in many phases
- DT in operation needs management
  - Agentic AI offers opportunity for autonomous management

Challenges and concerns, Future Directions

- Models & Services
  - Sim-to-real-gap
  - Out-of-distribution behavior
  - Validation, maintaining consistency
  - Trust, explainability
  - Safety

Challenges and concerns, Future Directions

- Engineering
  - General agentic AI in SW engineering
  - Self-management of lifecycle
- Philosophical take
  - What happens once everything is automated?
  - What happens on the way there (human bore out?)

Conclusion

- Three main ways AI finds its way into digital twins
- Models: enables fast surrogates, hybrid models, and data-driven representations.
- Services: more diverse and better services, richer diagnosis, prediction, optimization, and natural-language interaction
- Engineering: assistance in engineering and lifecycle management.
- Future: Evolve from systems informing human decisions to systems autonomously handle the decisions. Open challenges remain