SIMULTECH 2026

16th International Conference on Simulation and Modeling Methodologies, Technologies and Applications

Porto, Portugal 18 - 20 July, 2026

From Digital Twins to the Twinning Paradigm

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19 July 2026 – Porto, Portugal

University of Antwerp

Ansymo
Antwerp Systems & Software Modelling
University of Antwerp

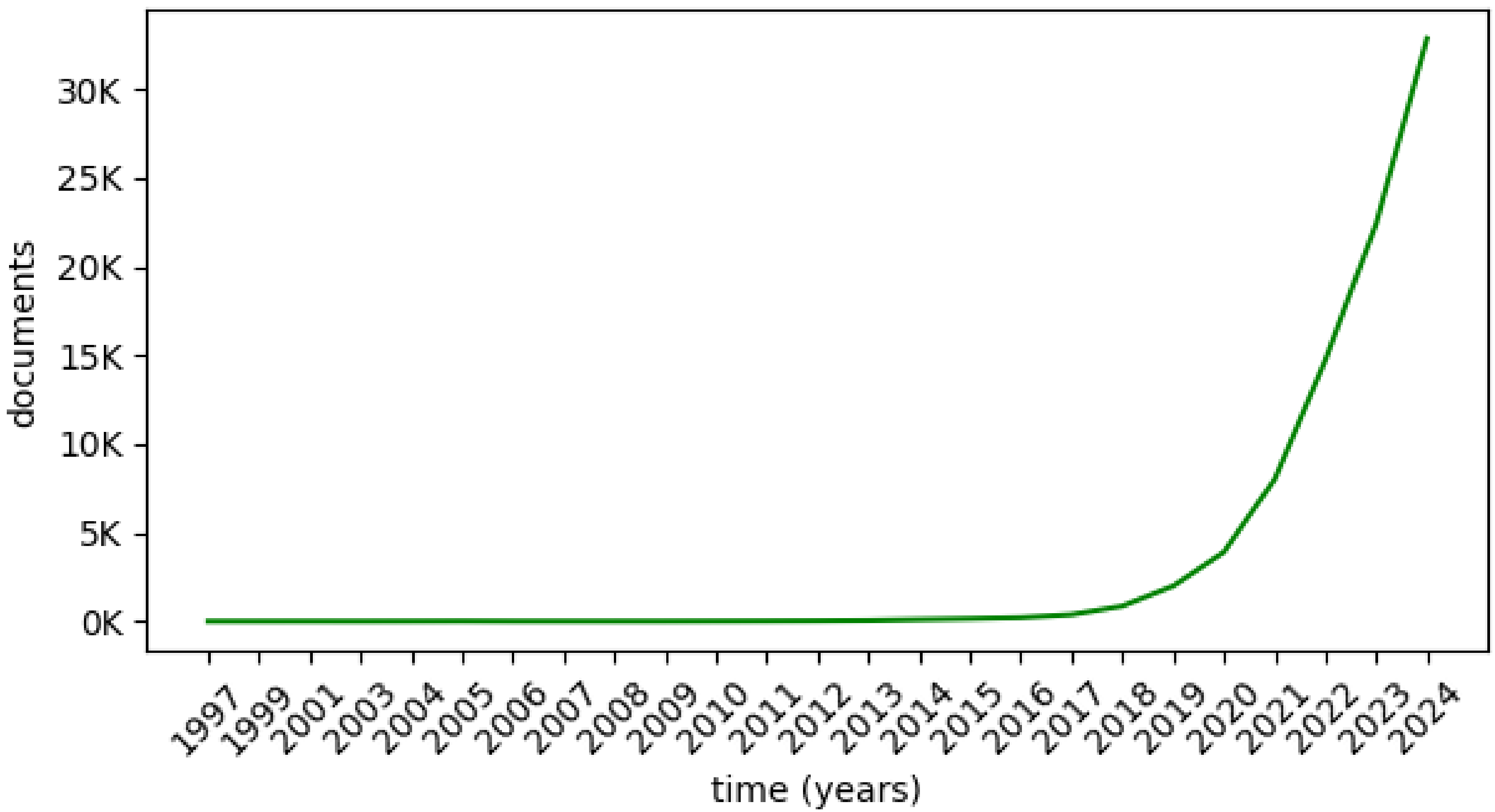
Nexor
Cyber-Physical Systems
University of Antwerp

FLANDERS MAKE

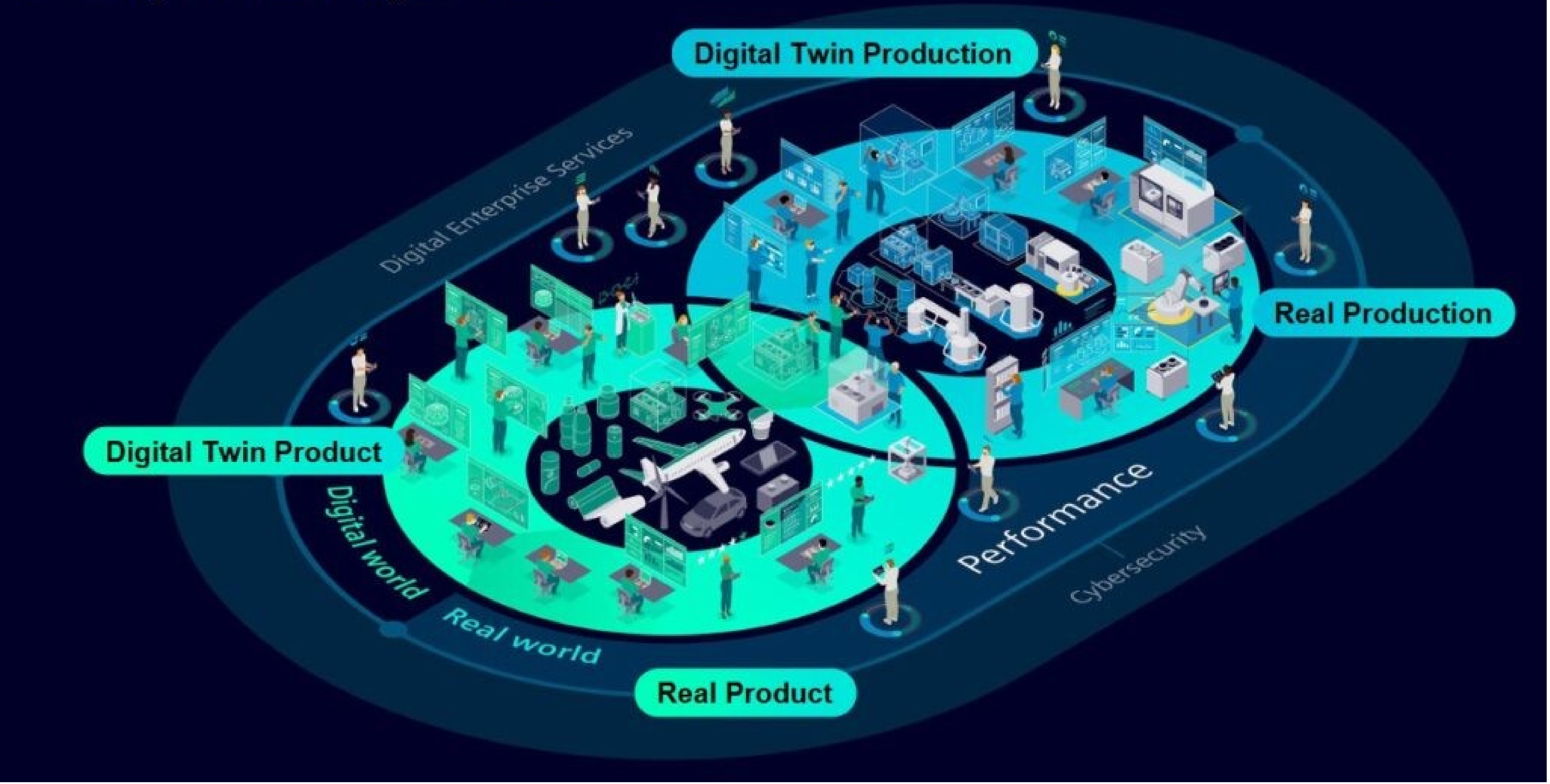
MPM4CPS

cost

Scopus document count for **"digital twin*" OR "digital shadow*"**,
Accessed: 22 February 2025

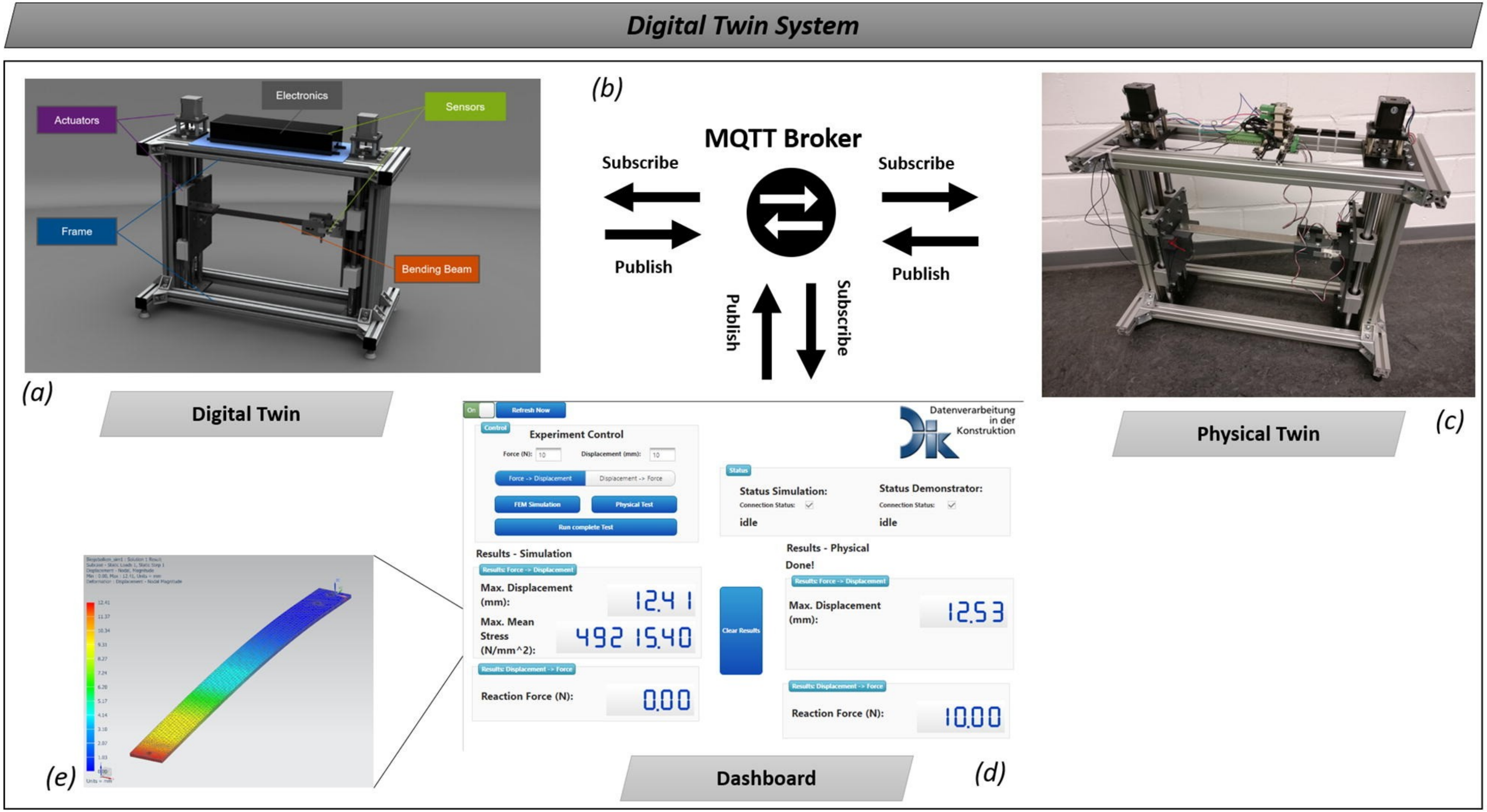


The comprehensive Digital Twin



https://blogs.sw.siemens.com/xcelerator/2025/06/03/the-comprehensive-digital-twin-explained/

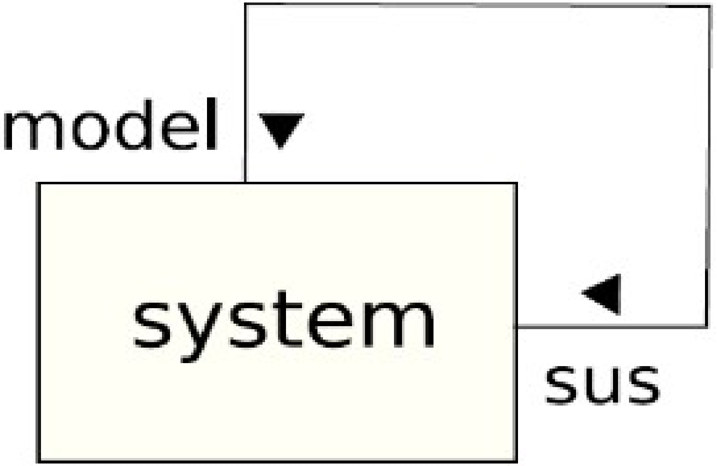
typical example of a Digital **Shadow** for **dashboarding**



Sebastian Haag, Reiner Anderl. *Digital twin – Proof of concept*. Manufacturing Letters, Volume 15, Part B, pp. 64 – 66, 2018.

Foundations: a bit about Modelling, Experimentation, and Validity

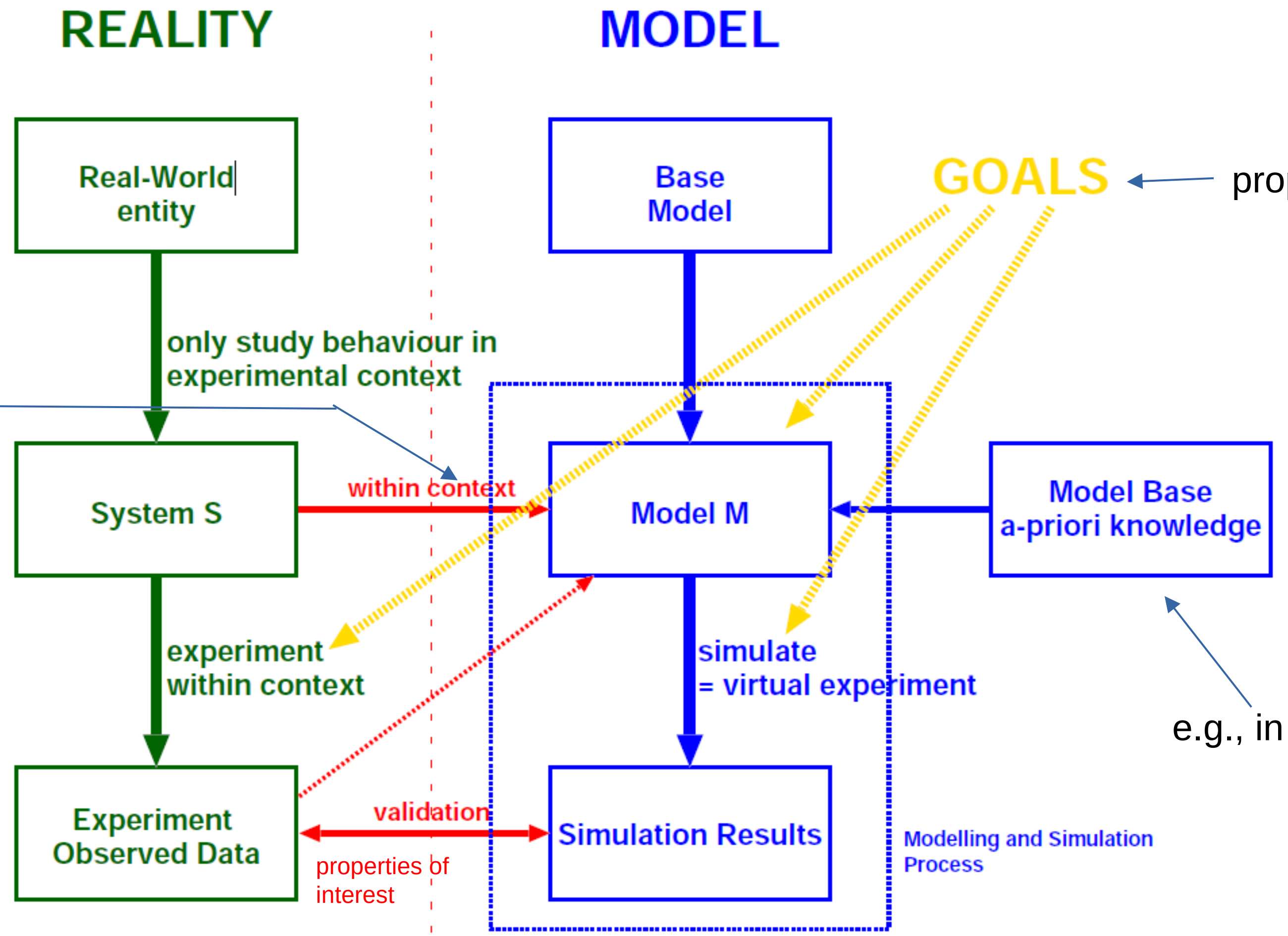
Marvin L. Minsky



To an observer B, an object A* is a model of an object A to the extent that B can use A* to answer questions that interest him about A.

Matter, Mind and Models

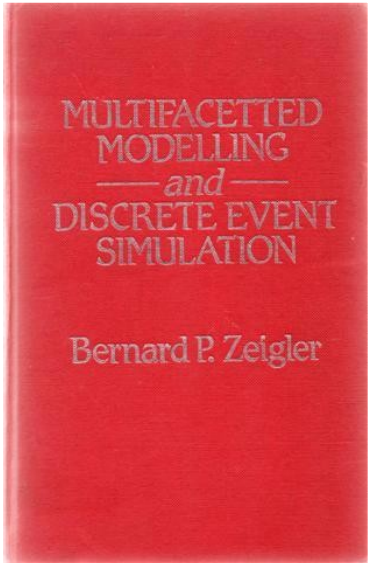
modelling for: substitutability (engineering), explainability (science)



properties of interest

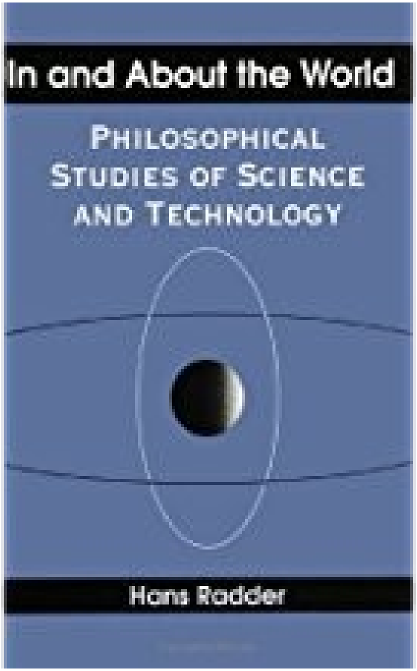
validity “frame”

e.g., in Modelica Library

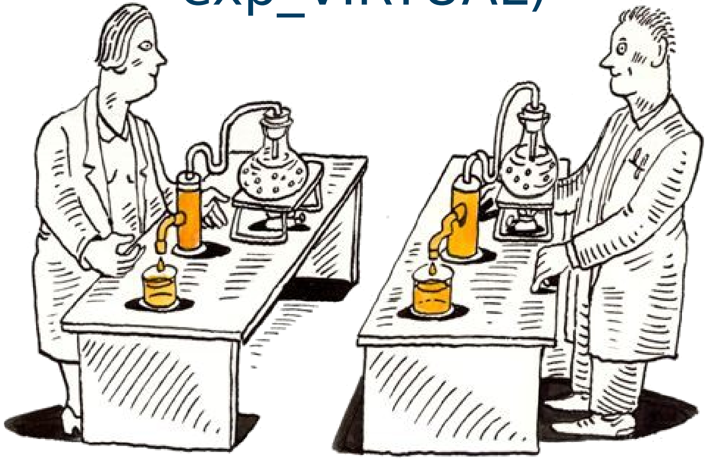


Bernard P. Zeigler. *Multi-faceted Modelling and Discrete-Event Simulation*. Academic Press, 1984.

Basis of Science: **Reproducibility** of **Experiments**



Experiment
(both exp_REAL and
exp_VIRTUAL)



Repeatable
Replicable
Reproducible

Plesser, H. E. 2018. *Reproducibility vs. Replicability: A Brief History Of A Confused Terminology.* Frontiers in neuroinformatics 11:76.

Model Validity Motivating Example: Electrical Resistor

Property of interest (PoI):

geometry

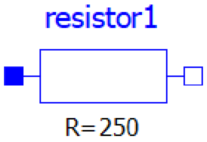
https://grabcad.com/library/resistors-0-5w-pitch-12-7mm-500mil-1

Model Validity Motivating Example: Electrical Resistor

Property of interest (PoI):

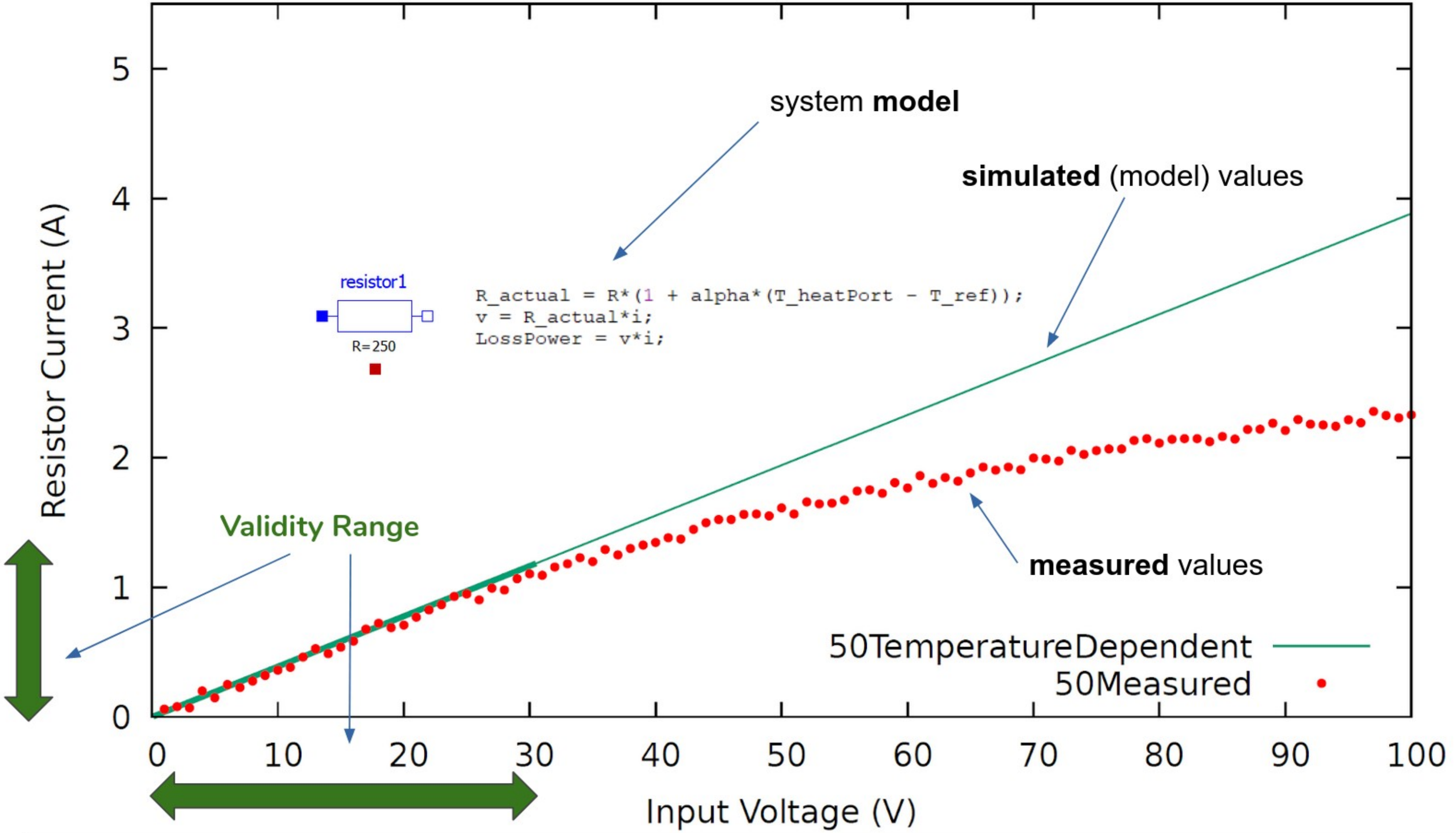
constitutive relation

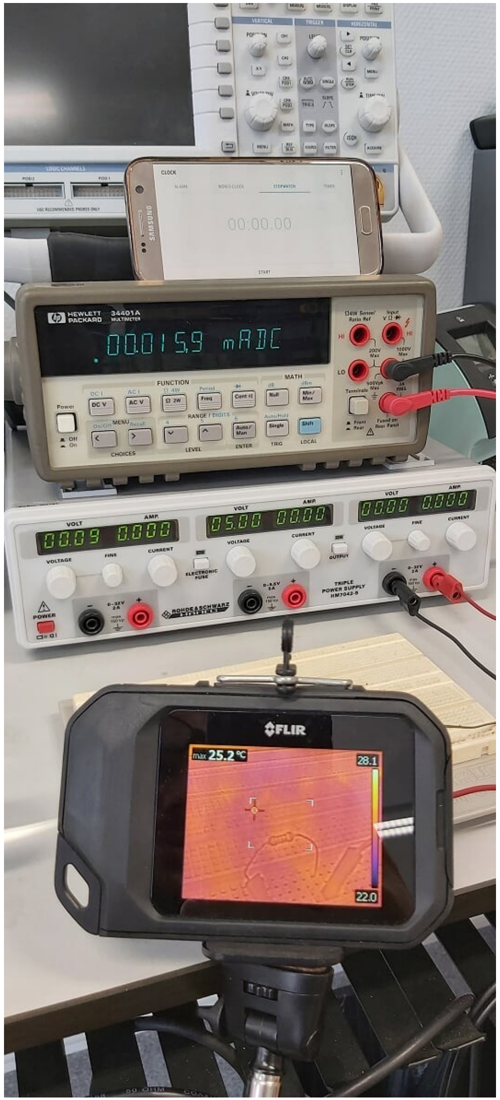
between voltage drop *V* over resistor and current *i* through resistor



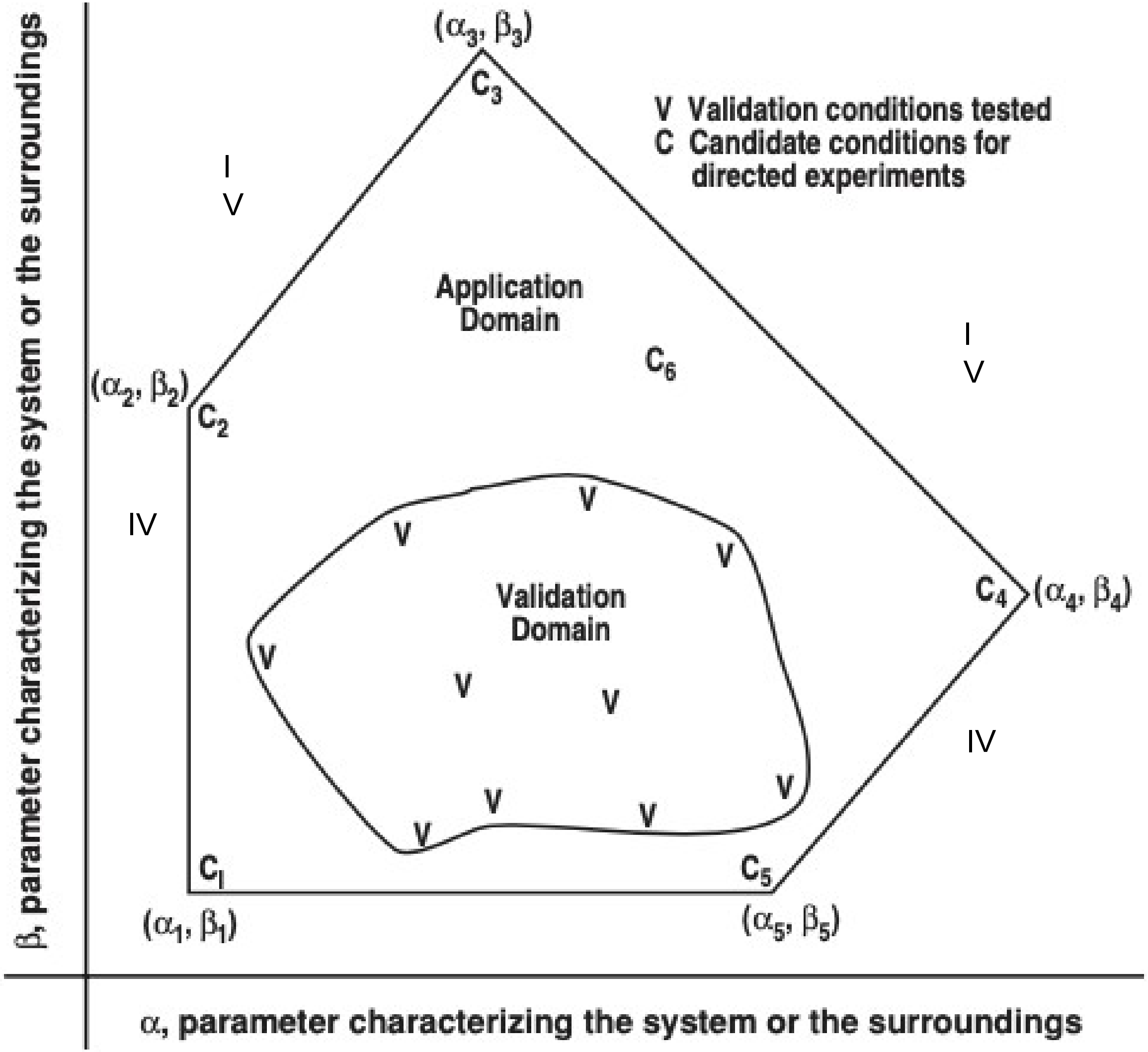

```
R*i = v
```

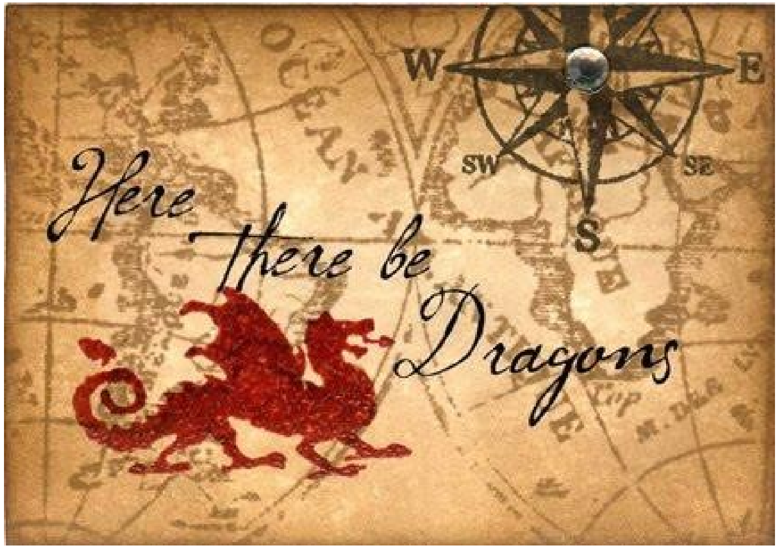
A Resistor Model’s **Validity Range**





https://msdl.uantwerpen.be/cloud/public/fcfc42

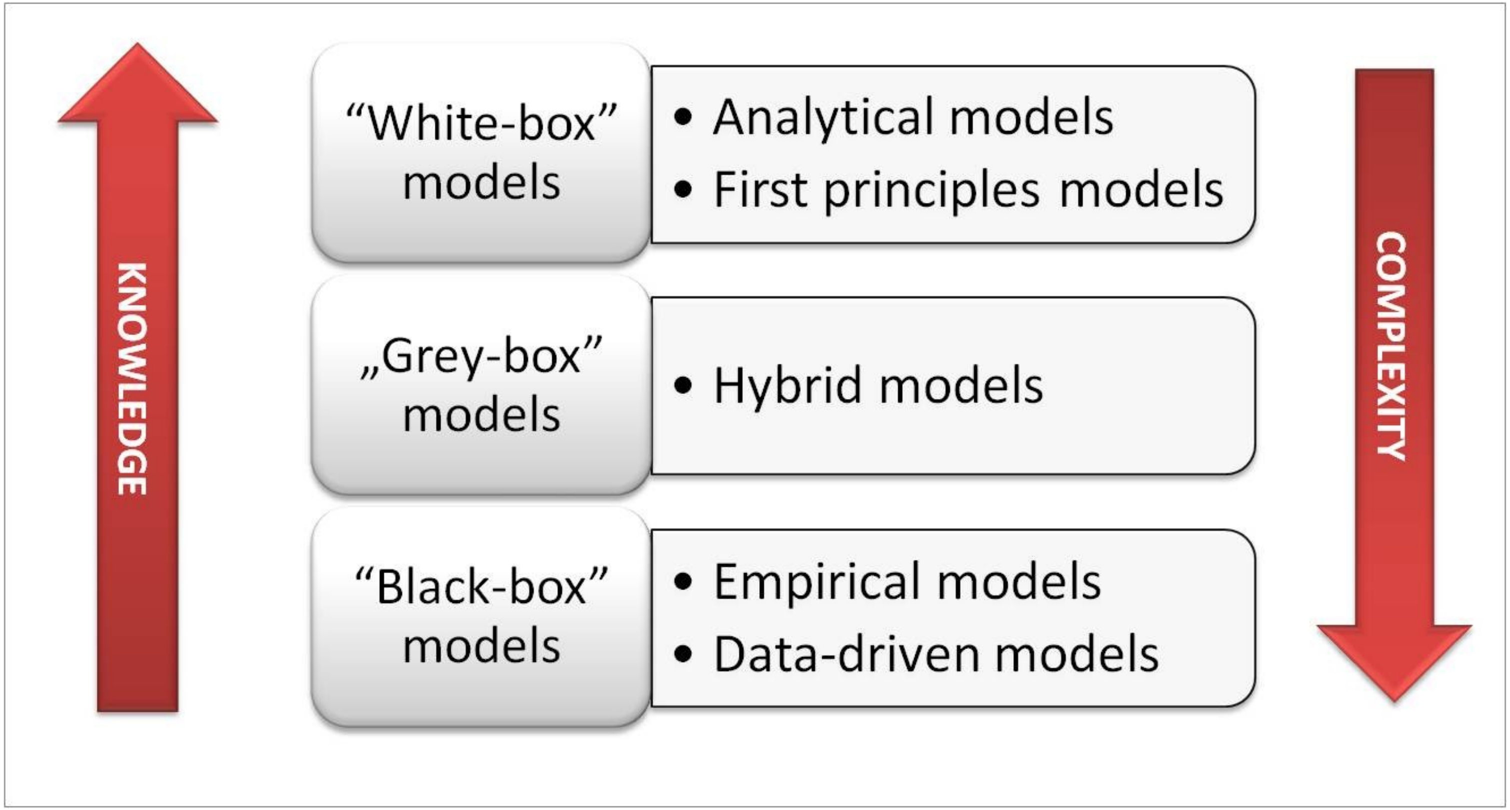




W. Oberkampf, C. Roy. *Verification and Validation in Scientific Computing.* Cambridge University Press, 2010.

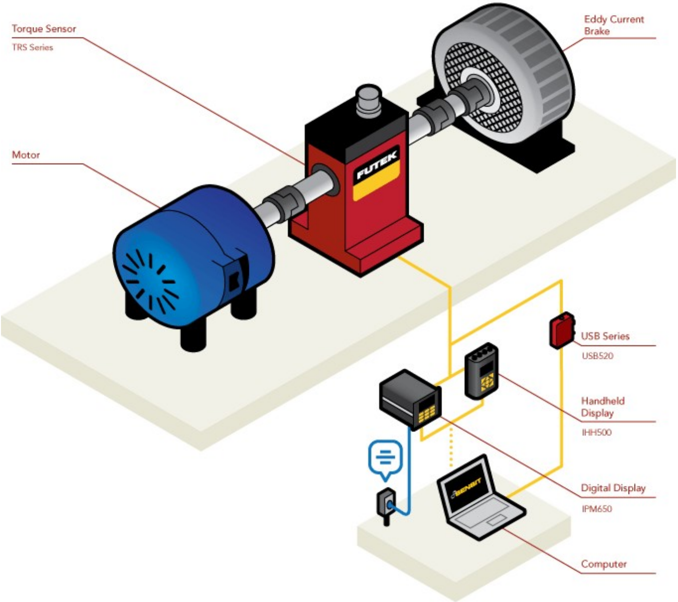
different ways of **obtaining** models
(in same or different formalisms)

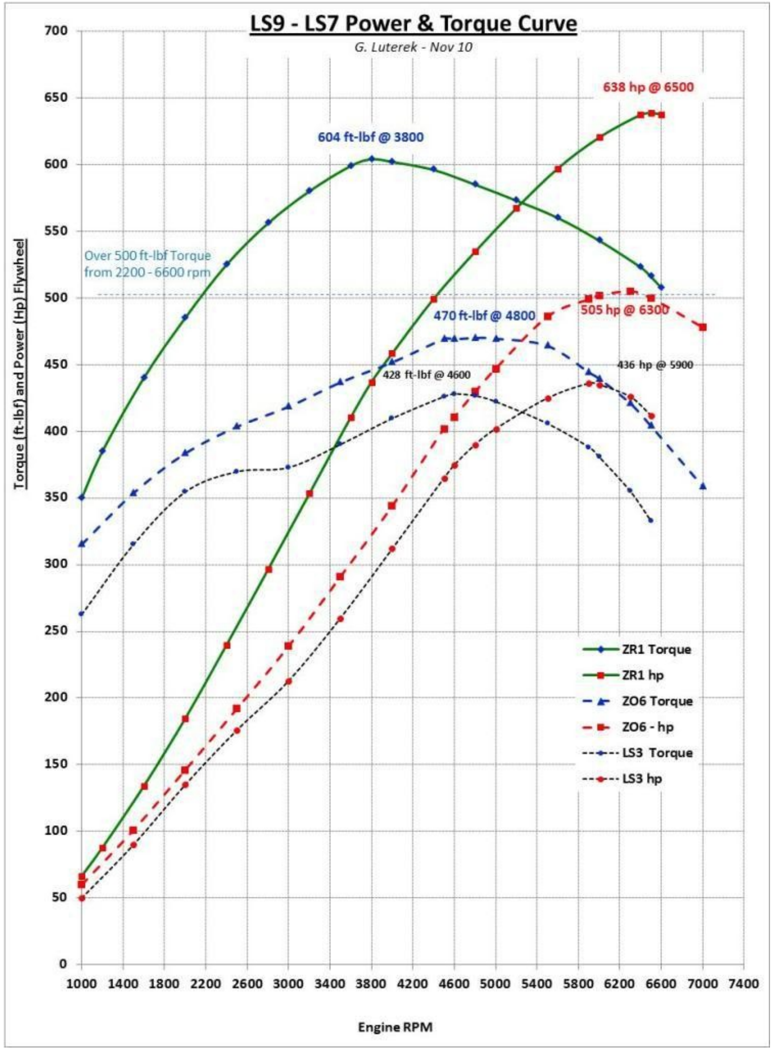
→ different DTs



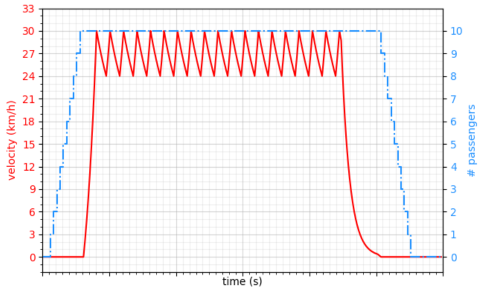
simulatelive.com

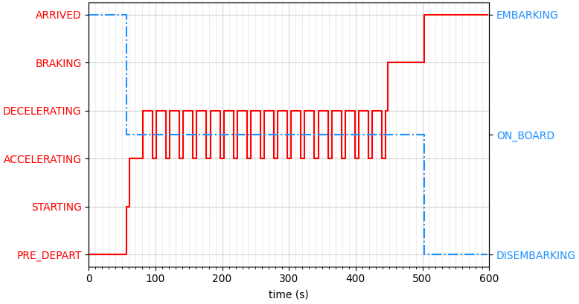
Black Box model: “Torque Curve” (measured)

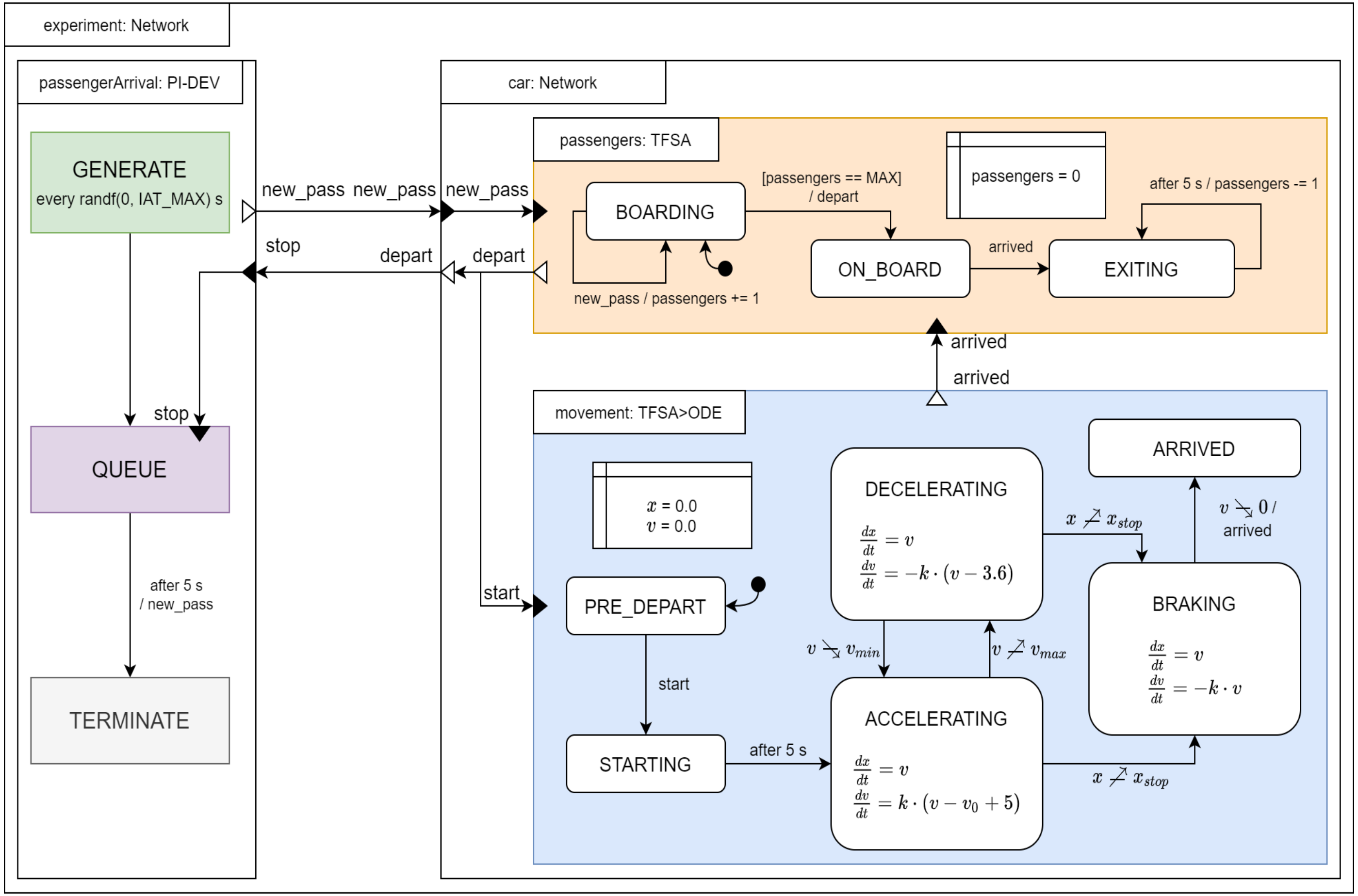




use models in **most appropriate formalism(s)**

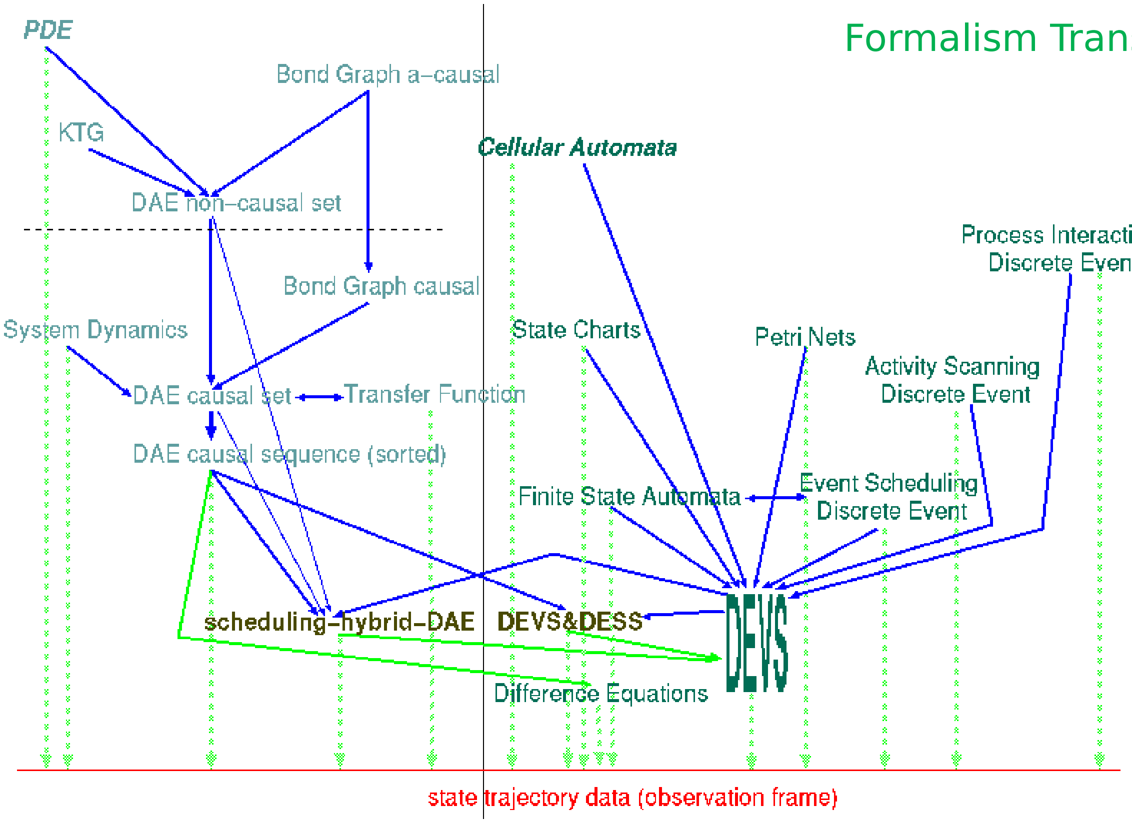




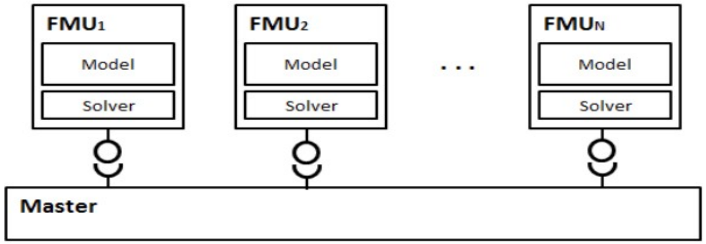


R. Paredis, J. Denil, and H.Vangheluwe. 2021.
"Specifying and Executing the Combination of Timed Finite State Automata and Causal-Block Diagrams by Mapping onto DEVS". In Proceedings of WSC 2021.

Formalism Transformation Graph (FTG)
co-simulation



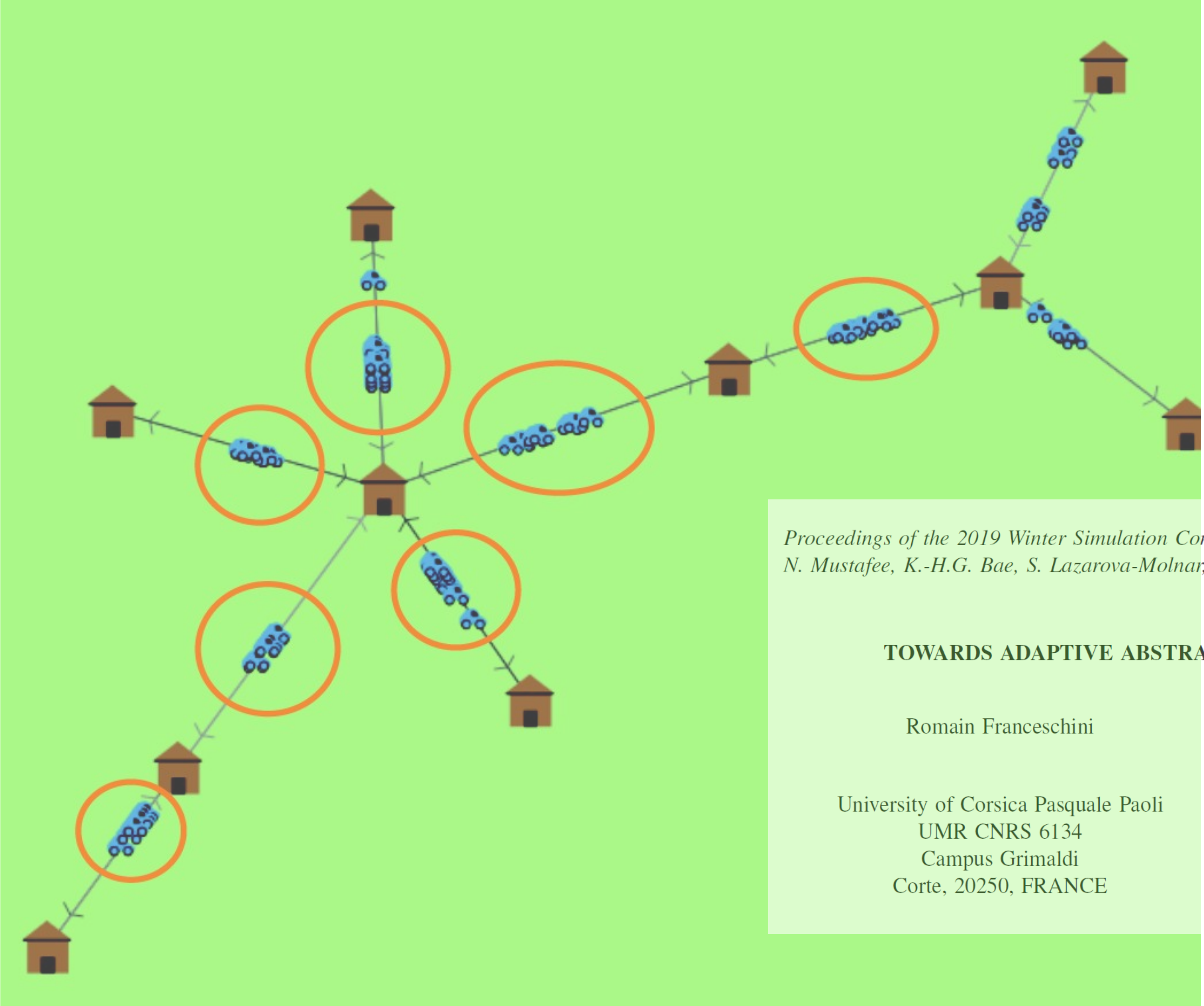
FUNCTIONAL MOCK-UP INTERFACE



Cláudio Gomes, Casper Thule, David Broman, Peter Gorm Larsen, and Hans Vangheluwe. Co-simulation: A survey. ACM Computing Surveys (CSUR) , 51(3):49:1-49:33, 2018.

Abstraction

- For performance (scale-ability)
- For **insight**



Proceedings of the 2019 Winter Simulation Conference
N. Mustafee, K.-H.G. Bae, S. Lazarova-Molnar, M. Rabe, C. Szabo, P. Haas, and Y.-J. Son, eds.

TOWARDS ADAPTIVE ABSTRACTION IN AGENT BASED SIMULATION

Romain Franceschini

University of Corsica Pasquale Paoli
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Corte, 20250, FRANCE

Simon Van Mierlo
Hans Vangheluwe

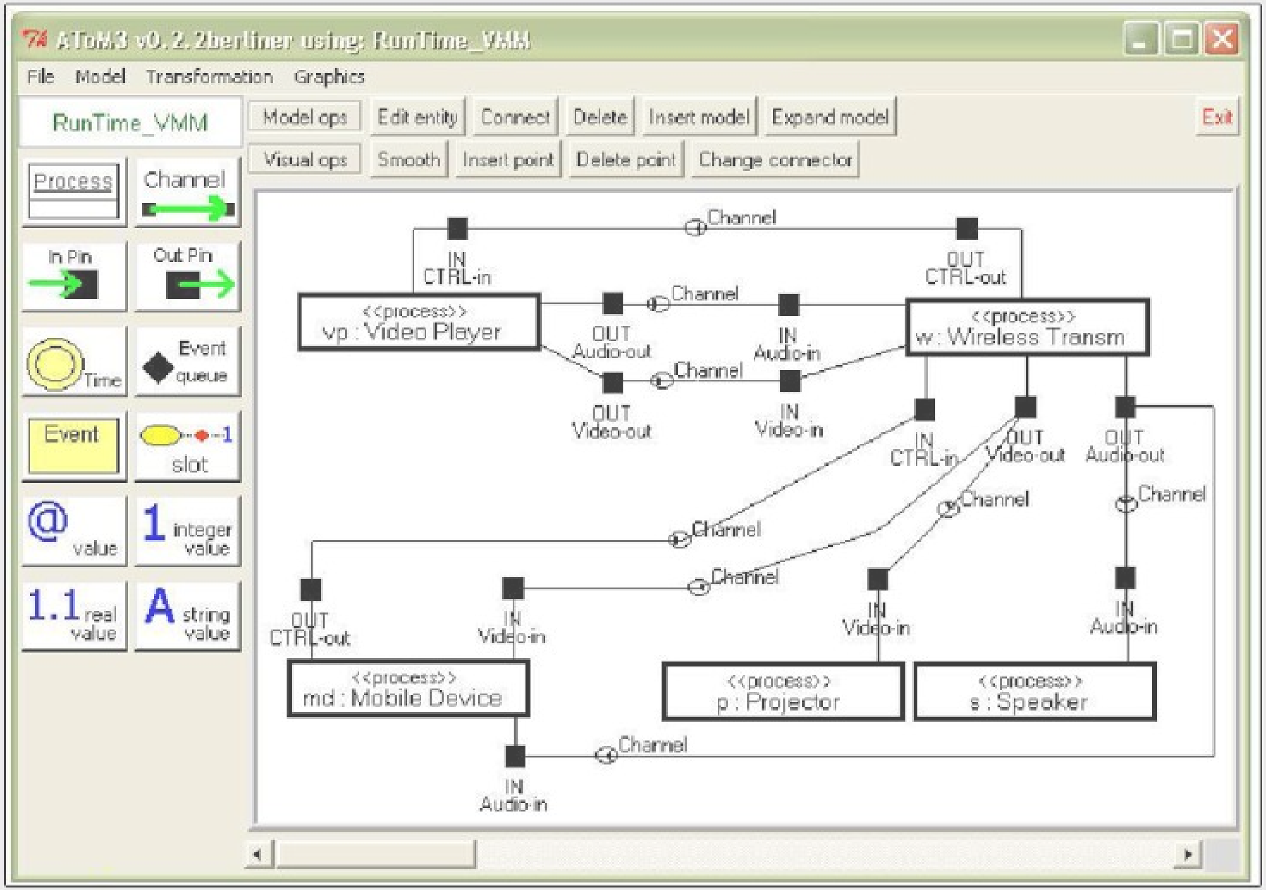
Department of Mathematics and Computer Science
University of Antwerp - Flanders Make
Middelheimlaan 1
Antwerp, 2020, BELGIUM

Divide et Impera

Views

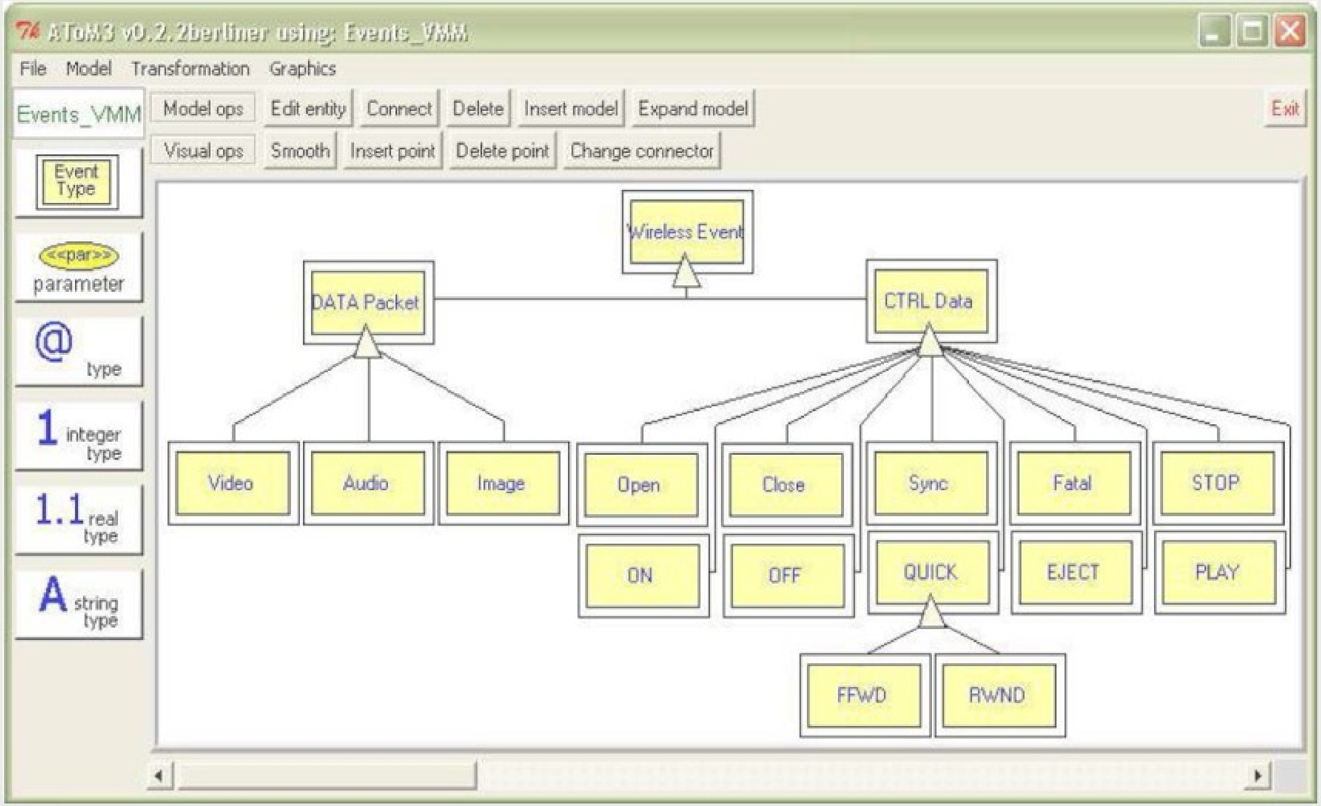
Wireless Home Entertainment System

Multiple (consistent !) Views (in $\neq$ Formalisms)

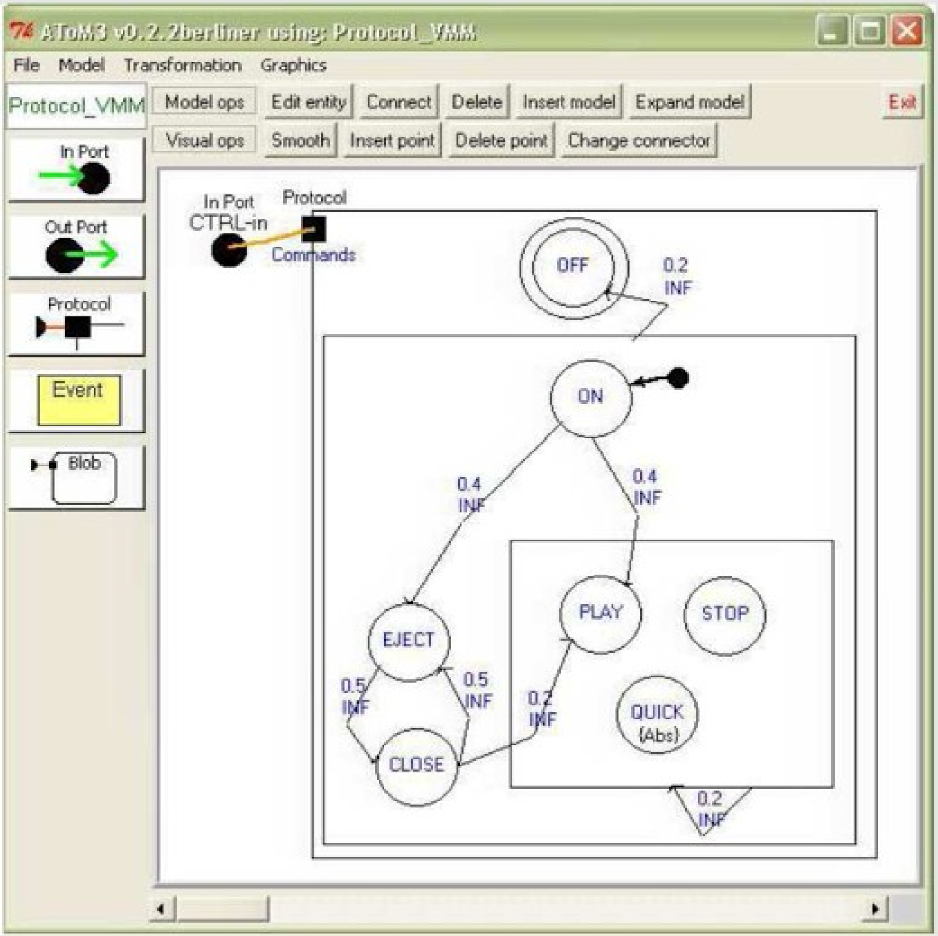


E. Guerra, P. Diaz and J. de Lara, A formal approach to the generation of visual language environments supporting multiple views. 2005 IEEE Symposium on Visual Languages and Human-Centric Computing (VL/HCC'05), Dallas, TX, USA, 2005, pp. 284-286, doi: 10.1109/VLHCC.2005.6.

View: Events Diagram



View: Protocol Statechart



Consistency!

Journal of Computer Languages 76 (2023) 101223

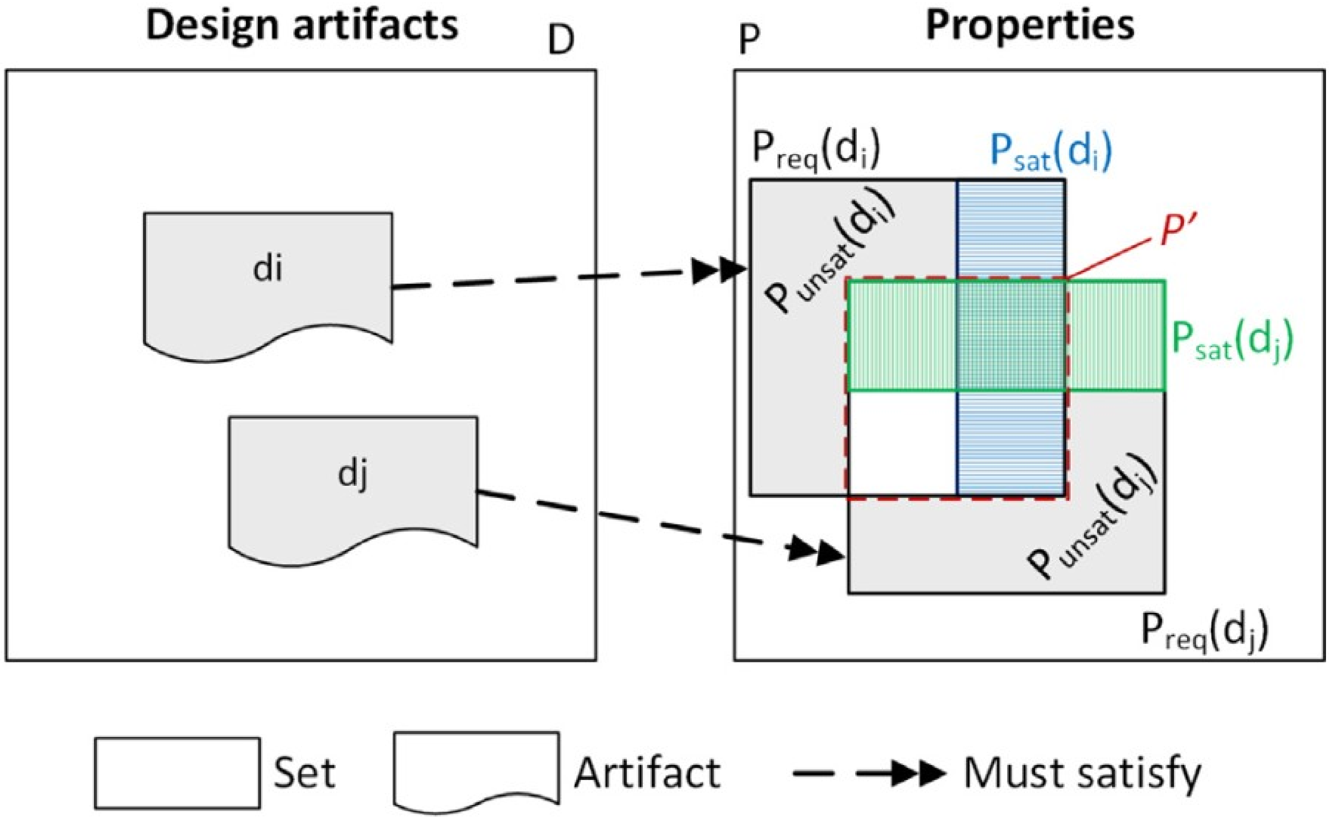
Contents lists available at ScienceDirect

Journal of Computer Languages

journal homepage: www.elsevier.com/locate/cola

Model consistency as a heuristic for eventual correctness

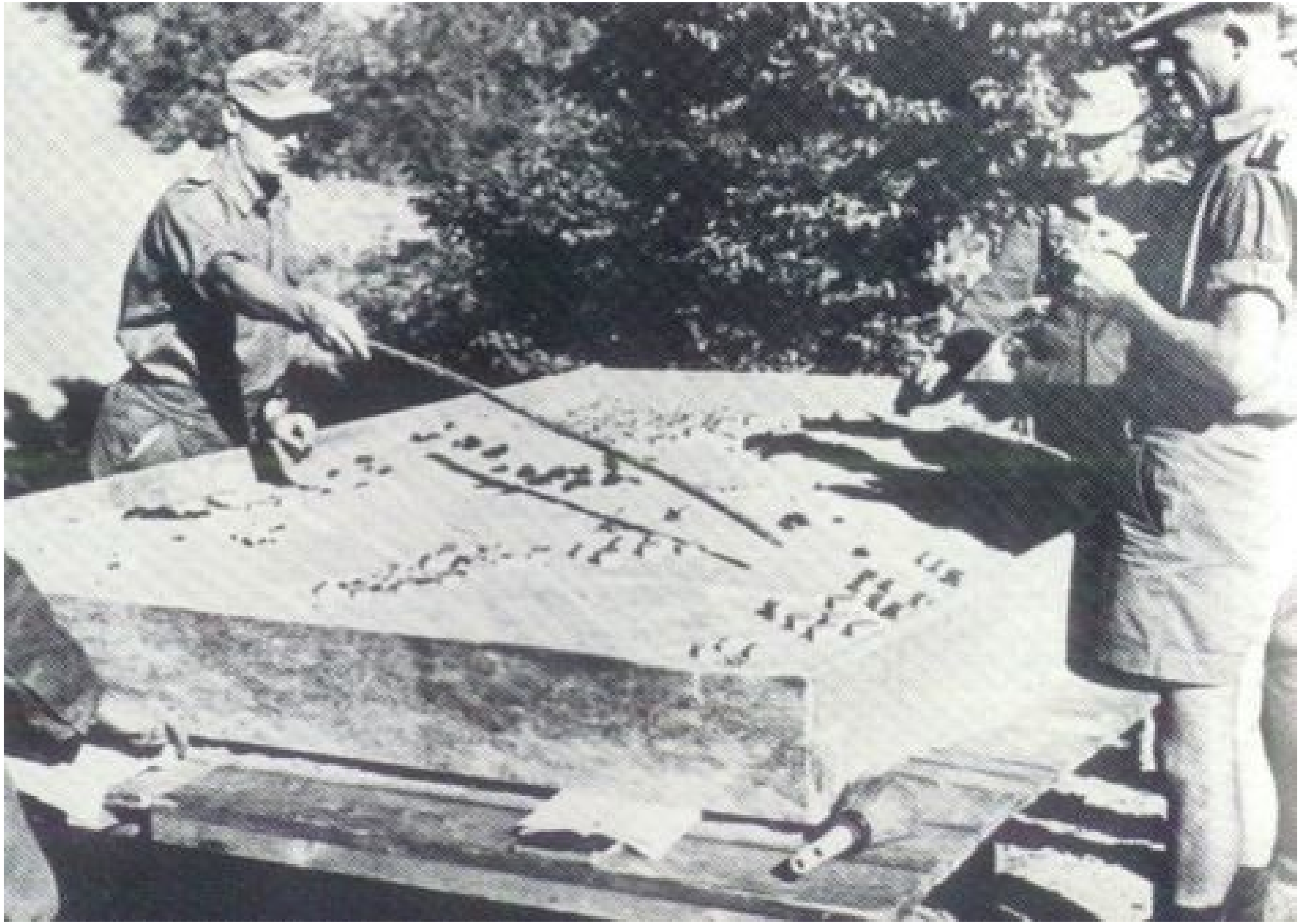
Istvan David [a,*], Hans Vangheluwe [b,c], Eugene Syriani [a]



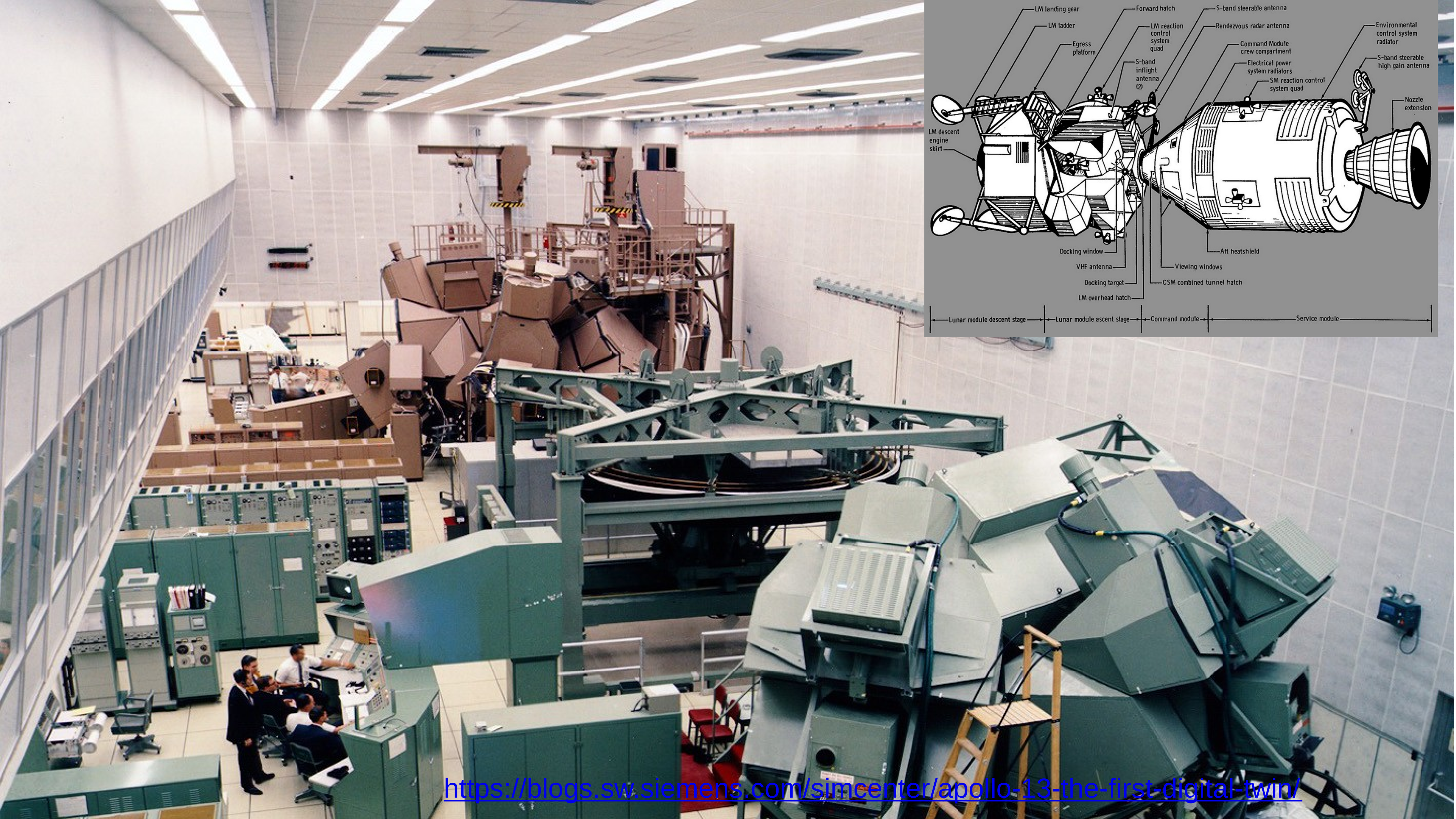
The Twinning concept (paradigm?) has been around for a while

… but not necessarily under that name

sand tables



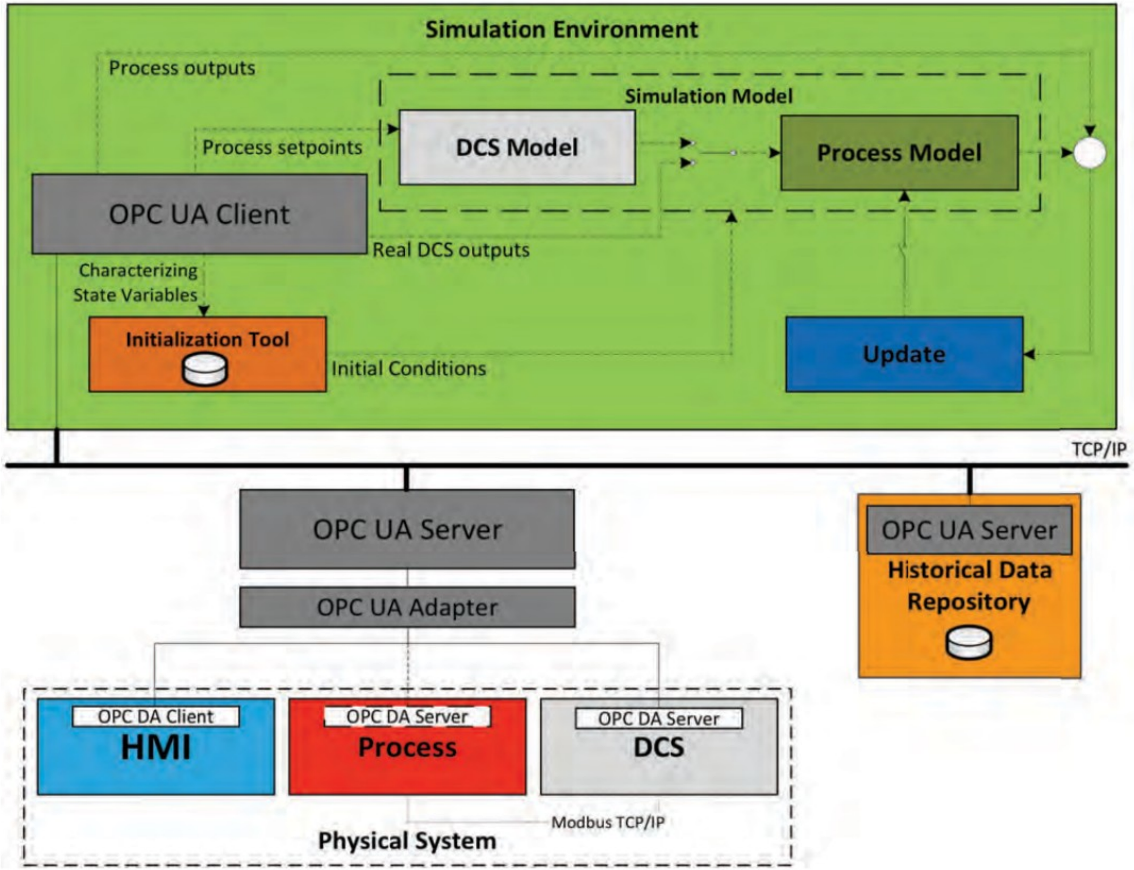
Kirschenbaum, M. 2023. *Granular Worlds: Situating the Sand Table in Media History.* Critical Inquiry 50(1):137–163



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

Tracking Simulation

water heating plant



G. S. Martínez, T. Karhela, V. Vyatkin, T. Miettinen and C. Pang, *An OPC UA Based Architecture for Testing Tracking Simulation Methods*, IEEE Trustcom/BigDataSE/ISPA, Helsinki, Finland, 2015, pp. 275-280.

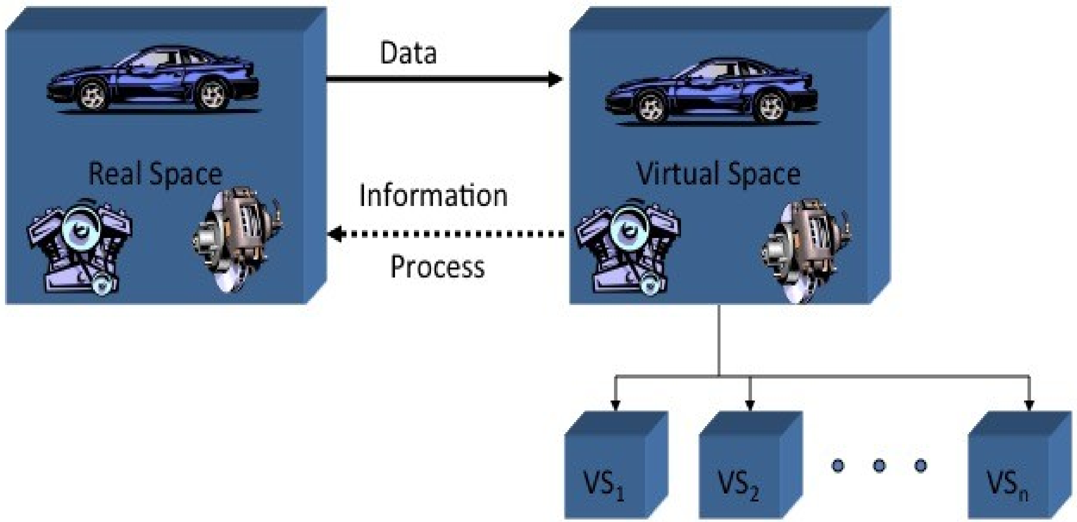
Simulation-based digital twins of industrial process plants: A semi-automatic implementation approach. PhD thesis Gerardo Santillán Martínez. Aalto University, Finland. 2019.

Digital Twin (and variants) terminology

… and some proposed architectures


MANAGEMENT
Virtually
Perfect
Grieves, LLC 2003-

Conceptual Ideal for PLM



Grieves **2002**.
Society of Manufacturing Engineers conference in Troy, Michigan.

Digital Twin (DT) - the Digital Twin is a set of virtual information constructs that fully describes a potential or actual physical manufactured product from the micro atomic level to the macro geometrical level.

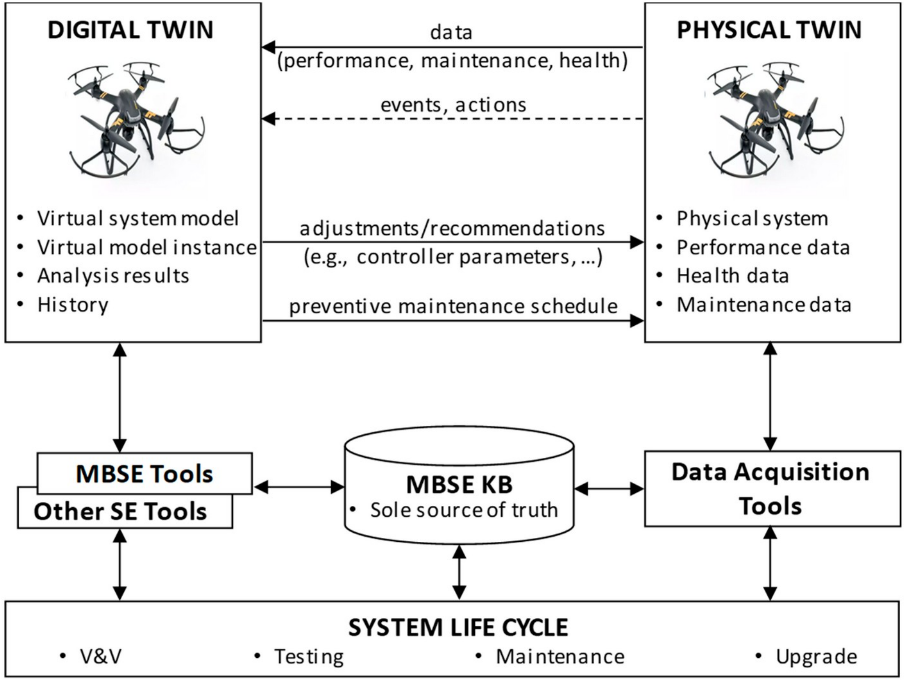
Digital Twin Prototype (DTP) - this type of Digital Twin describes the prototypical physical artifact.

Digital Twin Instance (DTI) - this type of Digital Twin describes a specific corresponding physical product that an individual Digital Twin remains linked to throughout the life of that physical product.

Digital Twin Aggregate (DTA) - this type of Digital Twin is the aggregation of all the DTIs.

Digital Twin Environment (DTE) - this is an integrated, multi-domain physics application space for operating on Digital Twins for a variety of purposes.

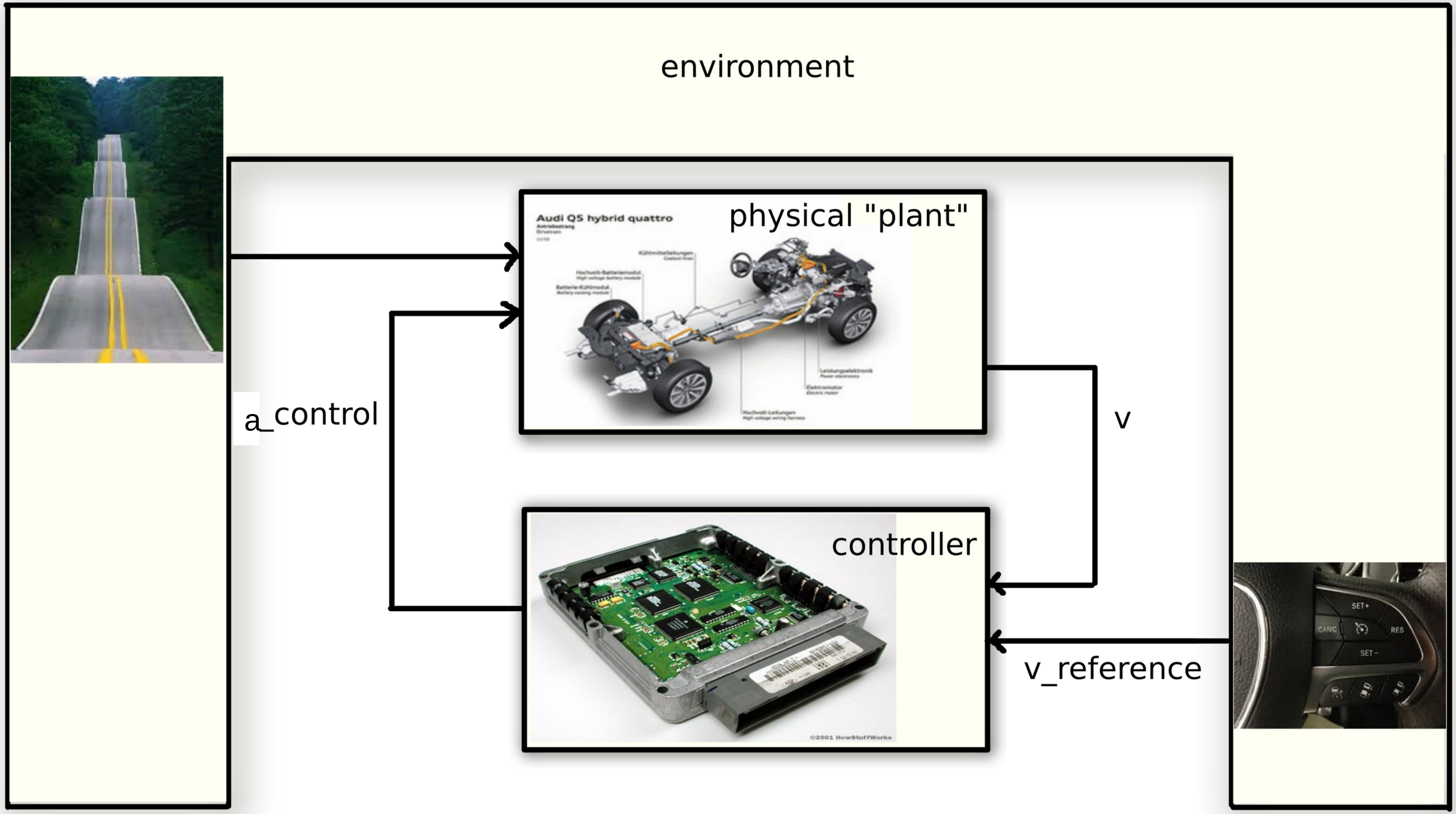
Digital Twin **terminology**



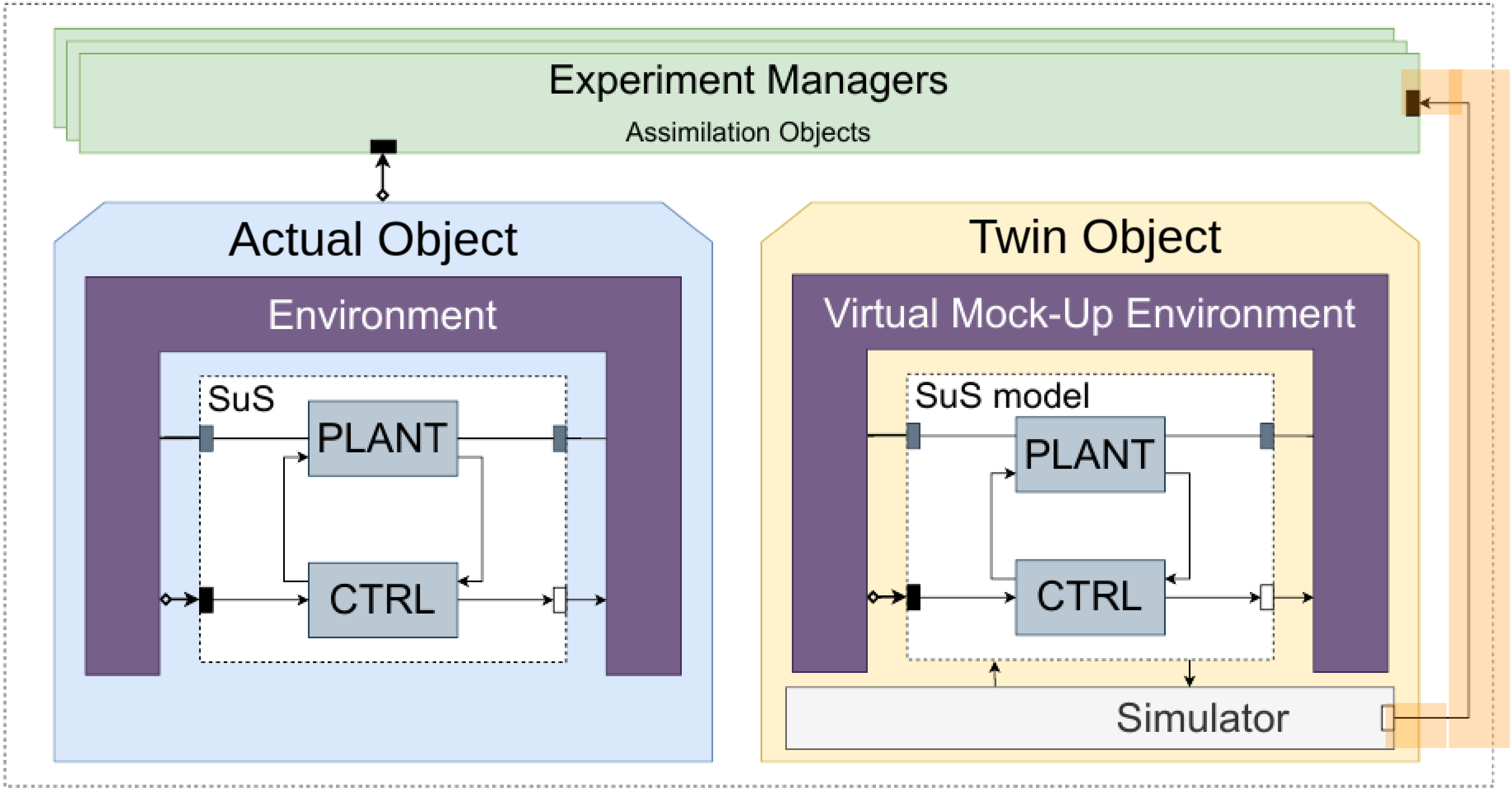
a Digital Twin (DT) is a **virtual instance**
of a **System under Study (SuS)**, the Physical Twin (PT),
that is **continually updated** with
the latter's performance, maintenance, and health **status** data
throughout the (physical) system under study's **life-cycle**

Madni, A.M., Madni, C.C., Lucero, S.D. *Leveraging digital twin technology in model-based systems engineering*. Systems 7(1):7. 2019.

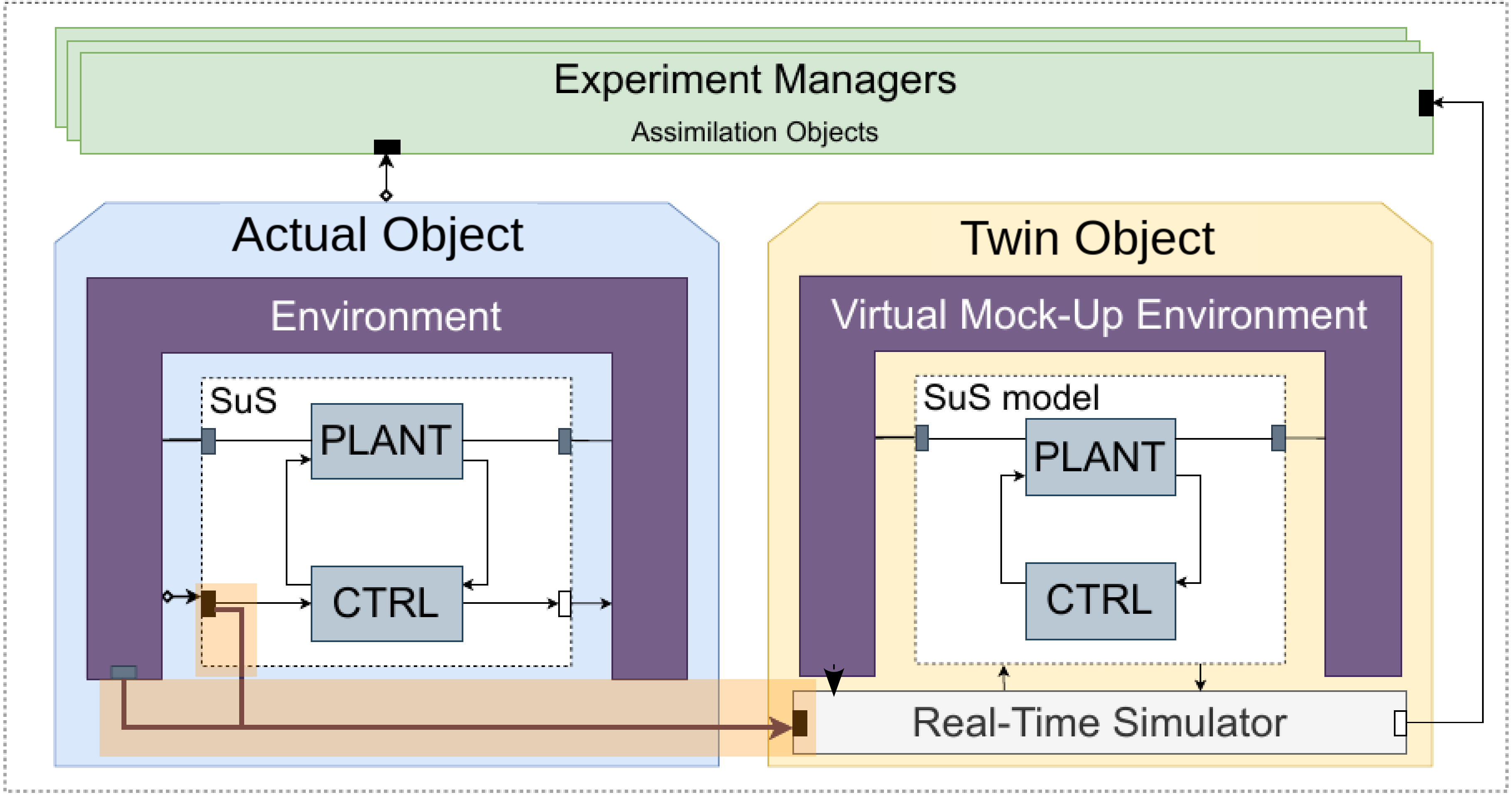
(simple) **system = environment || (“plant” || controller)**



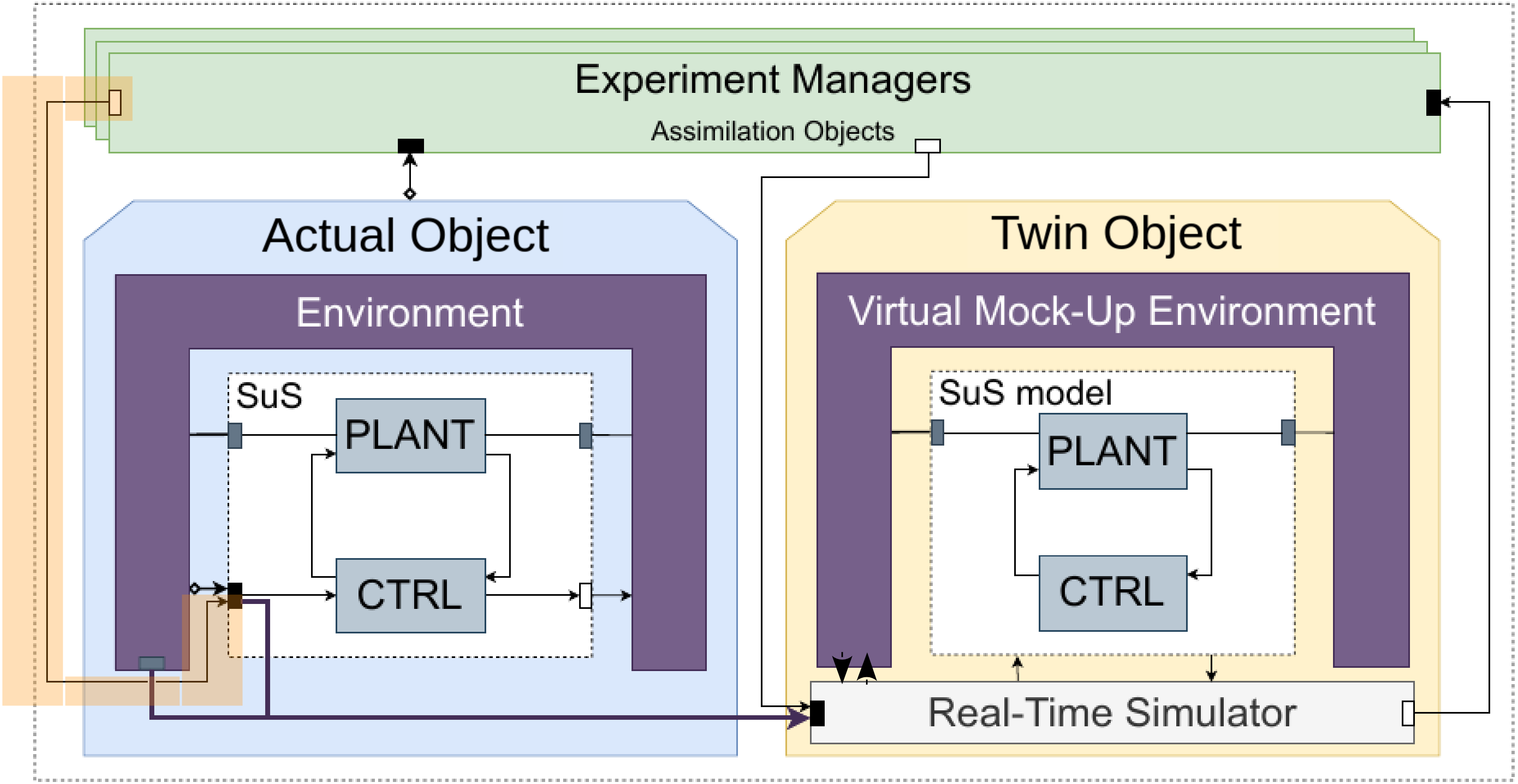
Digital **Model**



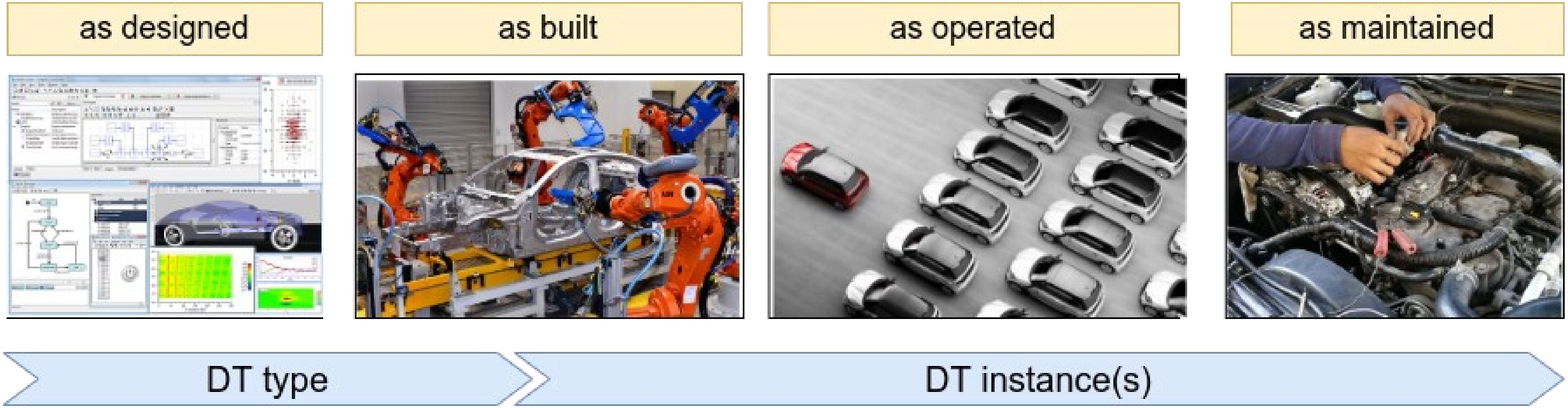
Digital **Shadow** (Monitor)



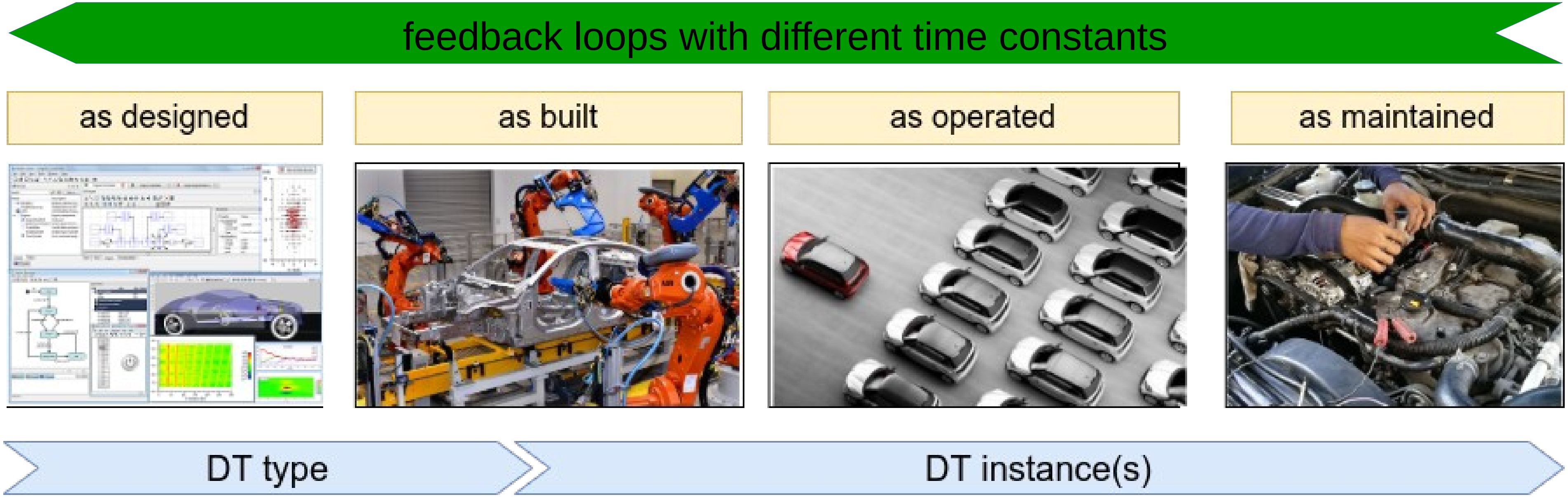
Digital **Twin** (Modify)



a DT is a **virtual instance** …
throughout the **entire** (physical) system under study's **life-cycle**

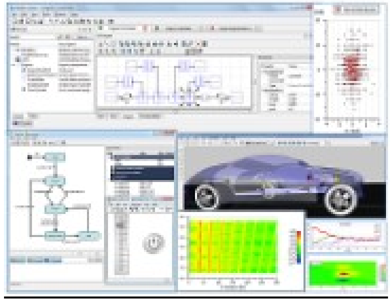


a DT is a **virtual instance** …
throughout the **entire** (physical) system under study's **life-cycle**



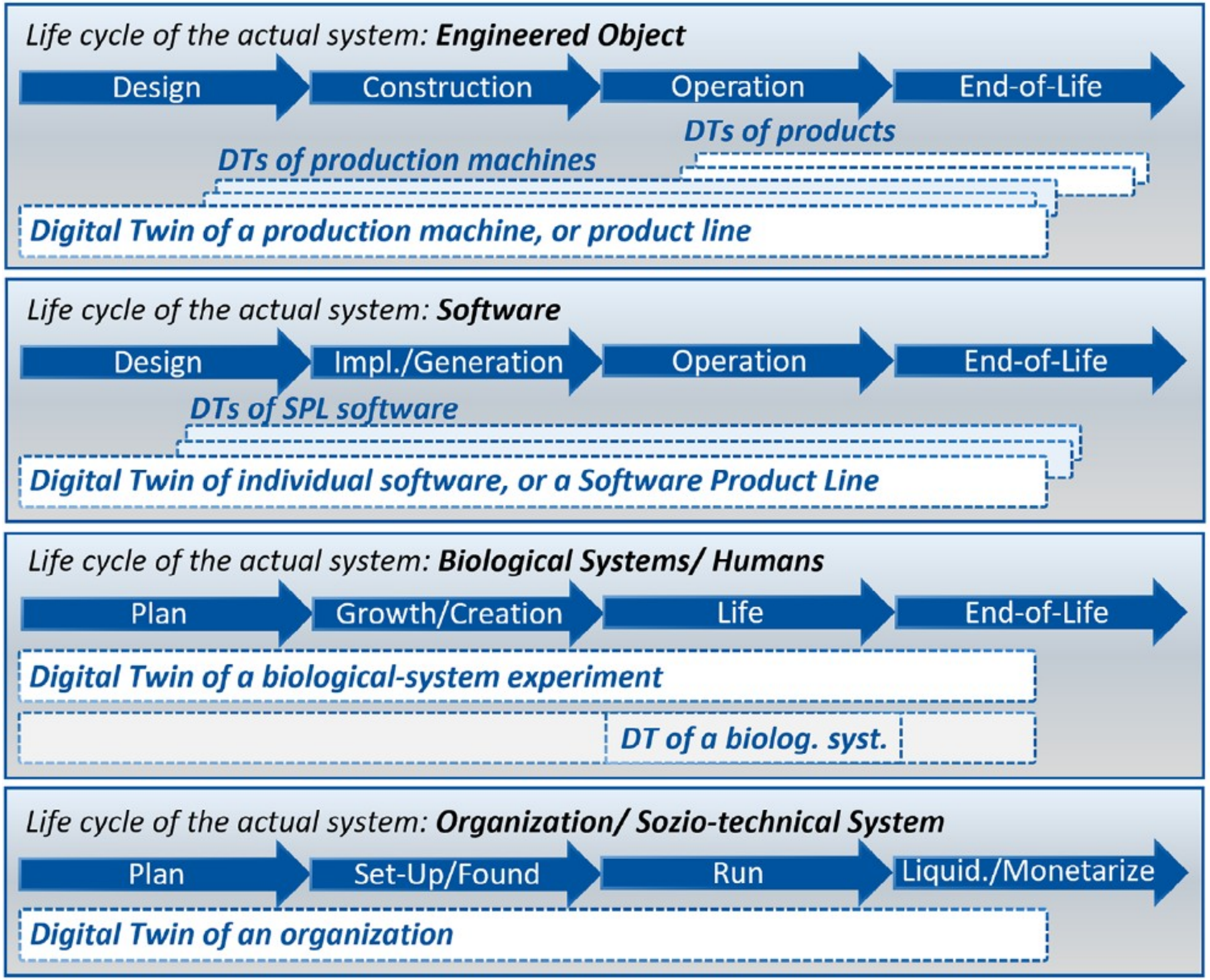
a DT is a **virtual instance** …
throughout the **entire** (physical) system under study's **life-cycle**

feedback loops with different time constants

as designed	as built	as operated	as maintained
			

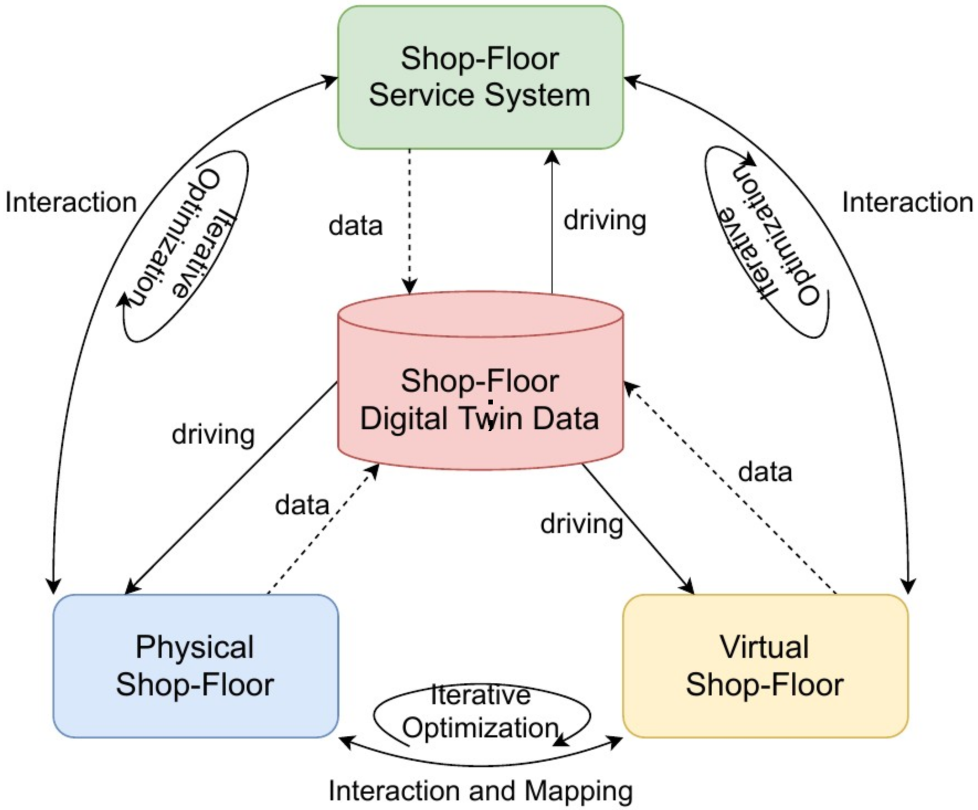
DT type → DT instance(s)

~ Digital **Thread** https://en.wikipedia.org/wiki/Digital_thread
~ **Digital Product Passport** https://circulareconomy.europa.eu/platform/sites/default/files/cisl_digital_products_passport_report_v6.pdf
~ Digital **Bill of Materials** (DboM) https://dbom-project.readthedocs.io/en/latest/what-dbom.html



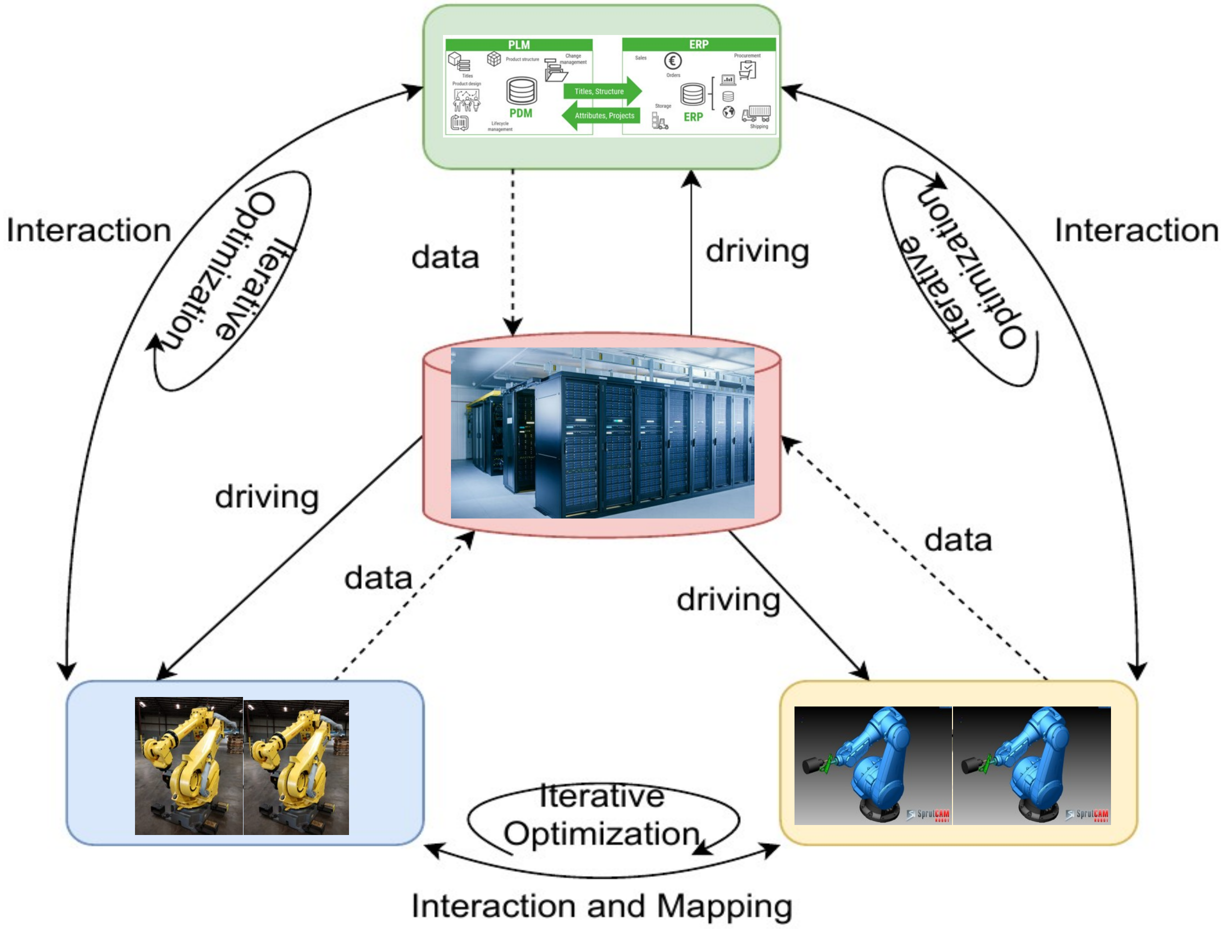
J. Michael, L. Cleophas , S. Zschaler , et al. "Model-Driven Engineering for Digital Twins: Opportunities and Challenges." Systems Engineering 28, no. 5 (2025), 659–670. https://doi.org/10.1002/sys.21815

Five-Dimensional (5D) model of DT



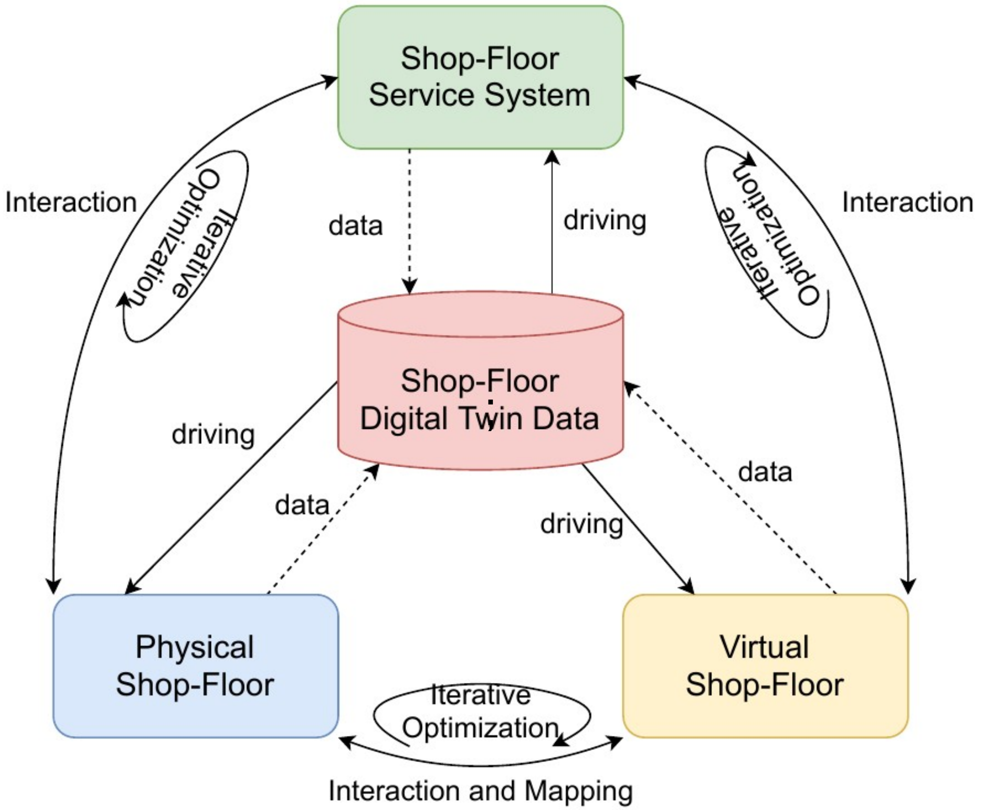
Fei Tao, Meng Zhang, Yushan Liu, A.Y.C. Nee. *Digital twin driven prognostics and health management for complex equipment*. CIRP Annals 67(1):169-172, 2018.

Five-Dimensional (5D) model of DT

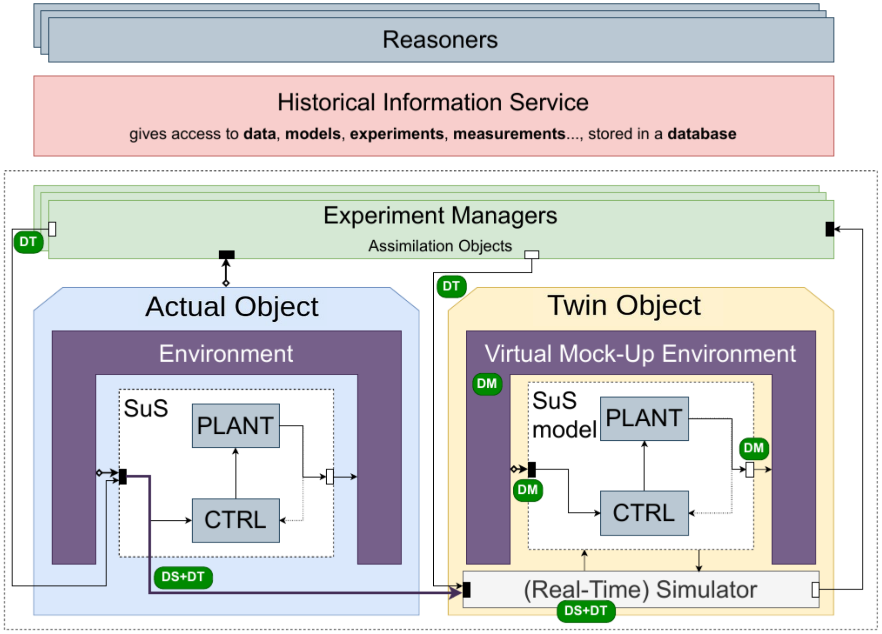


Fei Tao, Meng Zhang, Yushan Liu, A.Y.C. Nee. *Digital twin driven prognostics and health management for complex equipment*. CIRP Annals 67(1):169-172, 2018.

Five-Dimensional (5D) model of DT

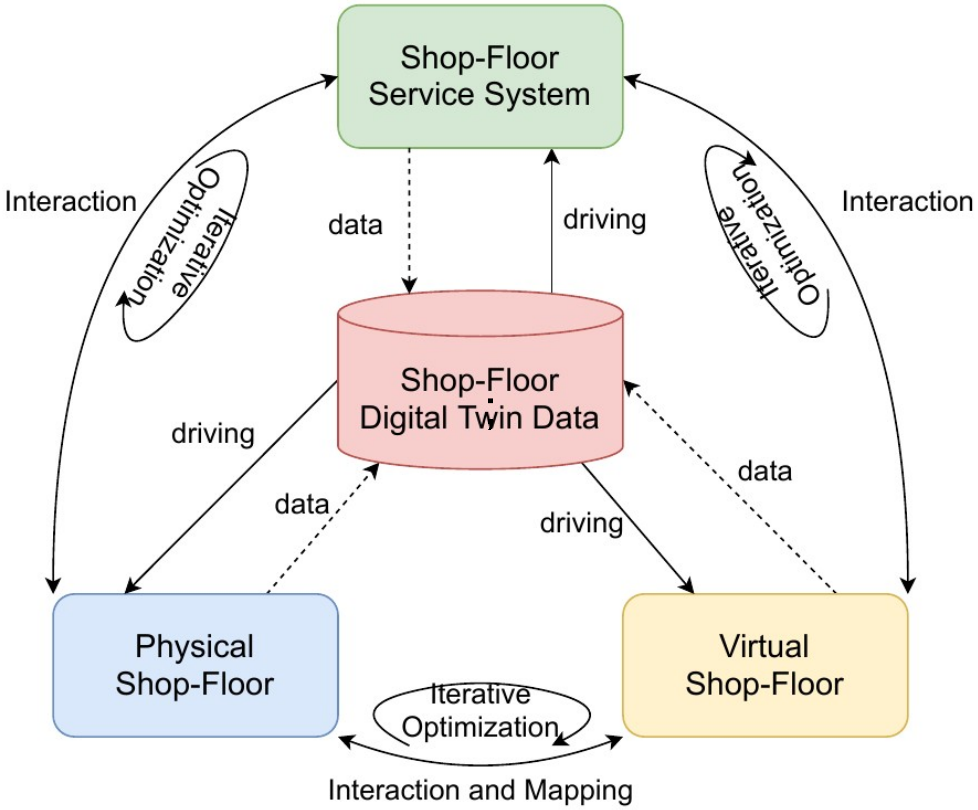


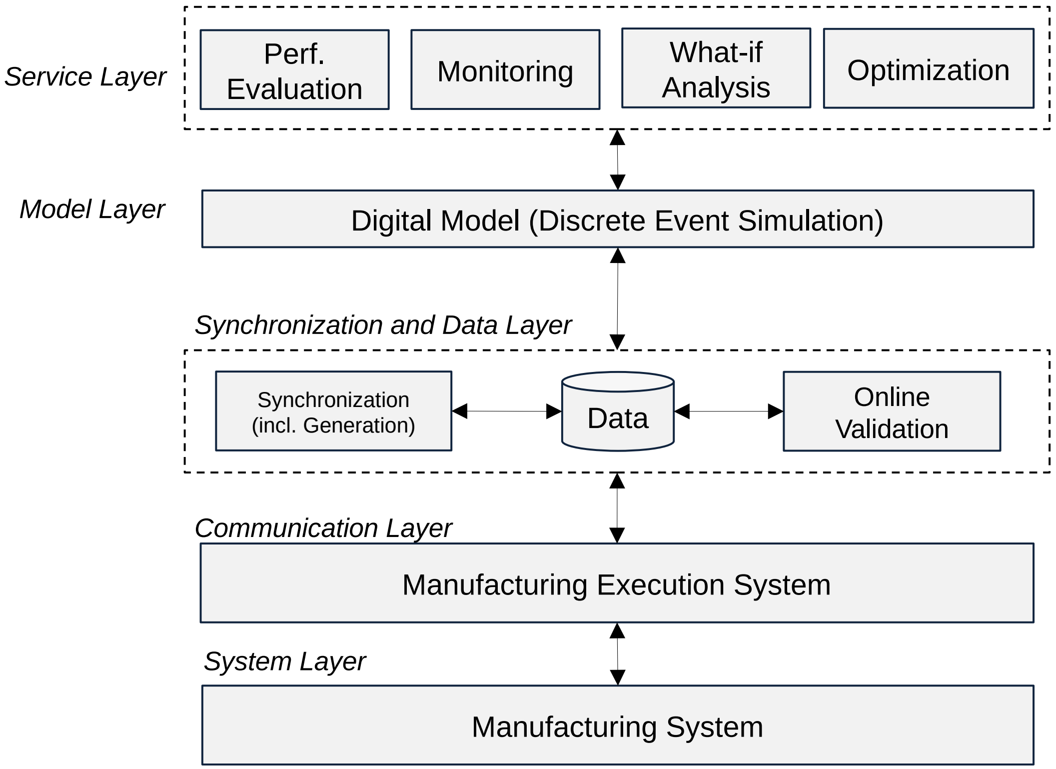
mapped onto our earlier conceptual architecture:



Fei Tao, Meng Zhang, Yushan Liu, A.Y.C. Nee. *Digital twin driven prognostics and health management for complex equipment*. CIRP Annals 67(1):169-172, 2018.

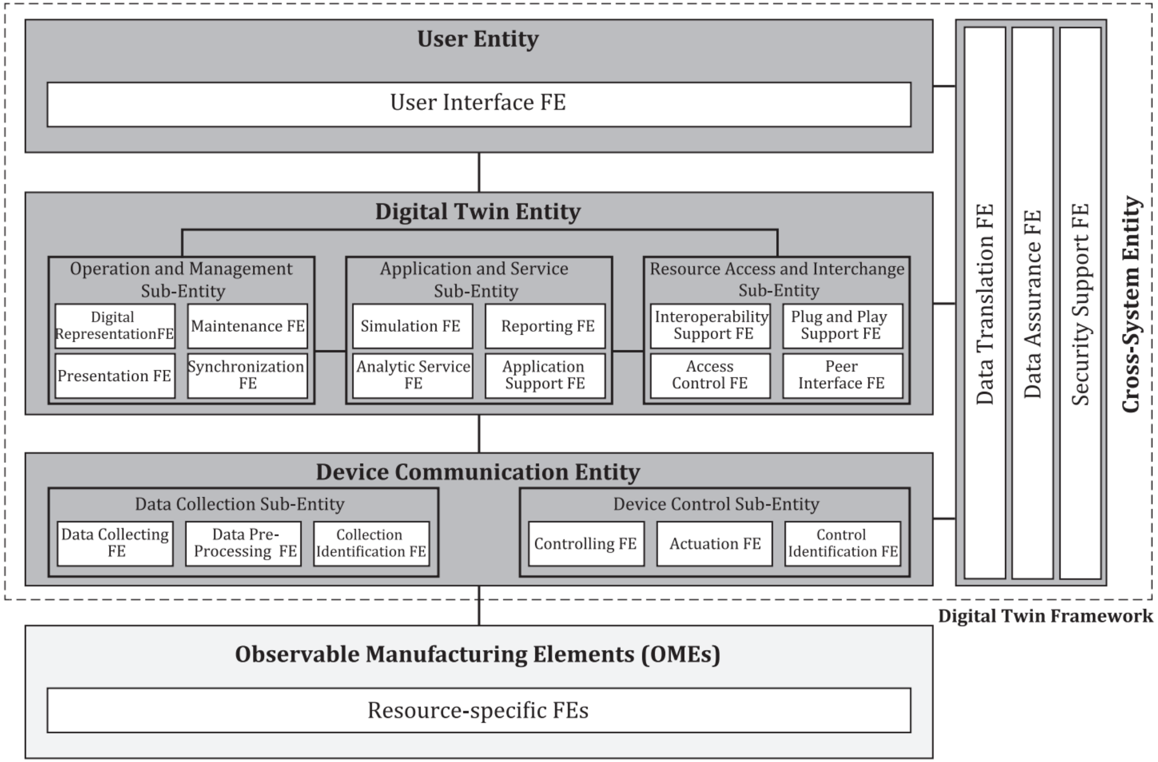
Five-Dimensional (5D) model of DT layered view





Fei Tao, Meng Zhang, Yushan Liu, A.Y.C. Nee. *Digital twin driven prognostics and health management for complex equipment*. CIRP Annals 67(1):169-172, 2018.

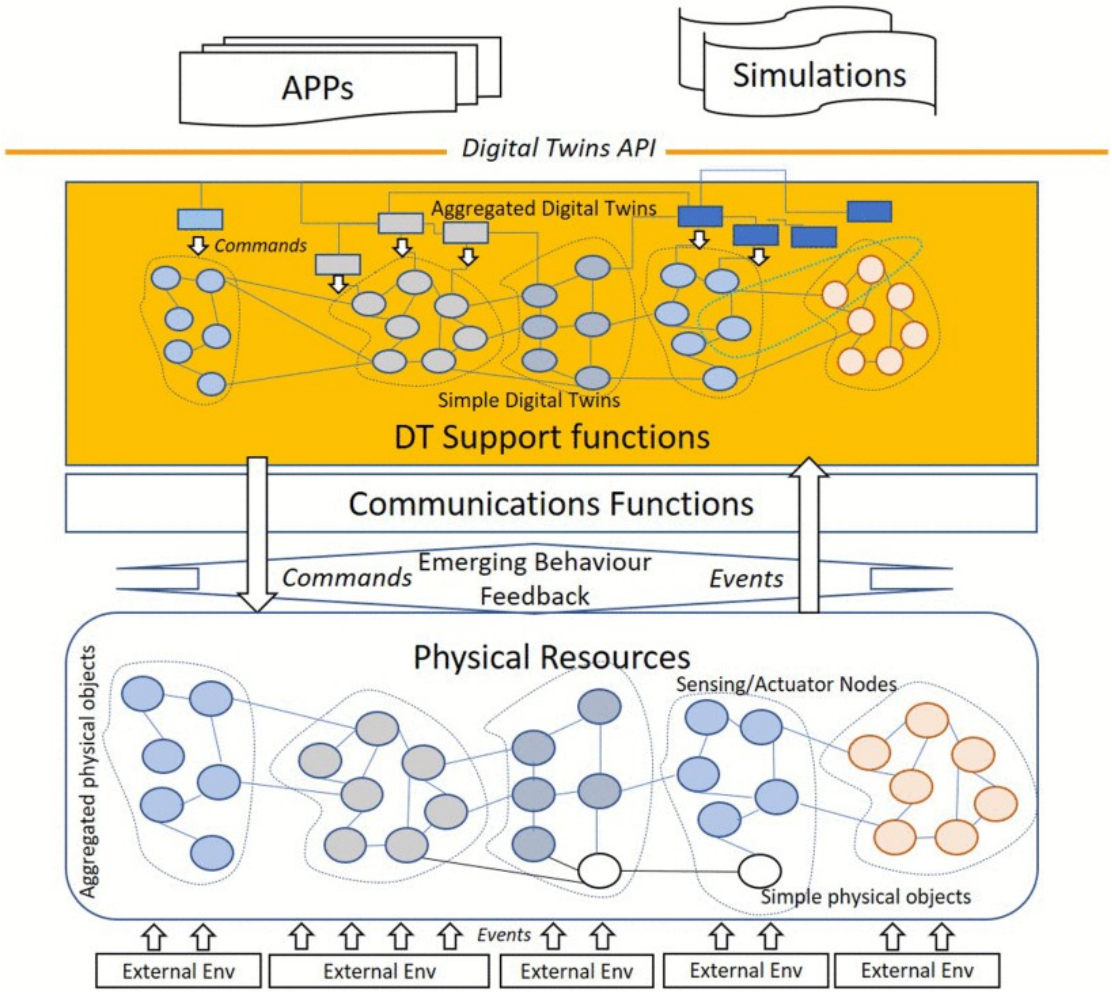
Tao, Fei, et al. *Digital twin in industry: State-of-the-art.* IEEE Transactions on industrial informatics 15.4 (2018): 2405-2415.



ISO 23247-2:2021:
Automation systems and integration. Digital twin framework for manufacturing.
Part 2: Reference architecture

Shao, Guodong. *Use case scenarios for digital twin implementation based on iso 23247*. National institute of standards: Gaithersburg, MD, *USA* (2021).

IoT focus



R. Minerva, G. M. Lee and N. Crespi. *Digital Twin in the IoT Context: A Survey on Technical Features, Scenarios, and Architectural Models.*
In Proceedings of the IEEE, vol. 108, no. 10, pp. 1785-1824, Oct. 2020.

Software Architecture

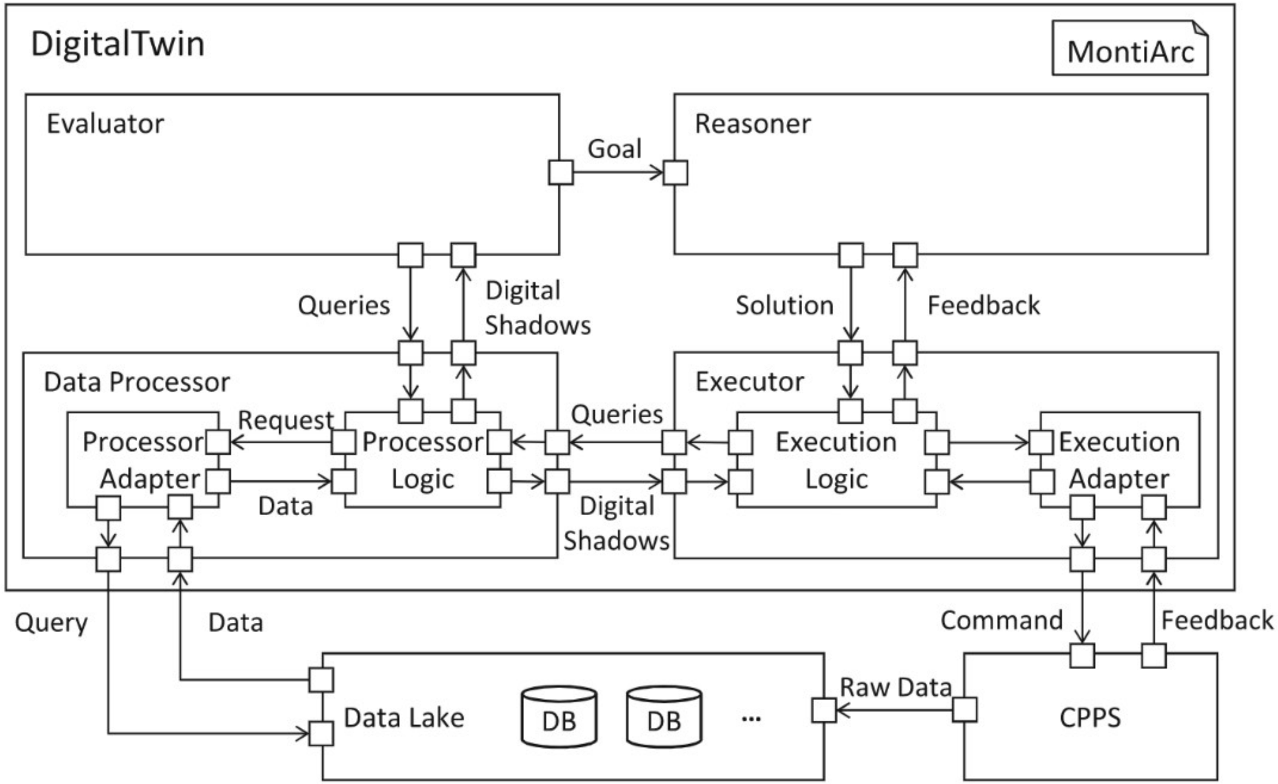
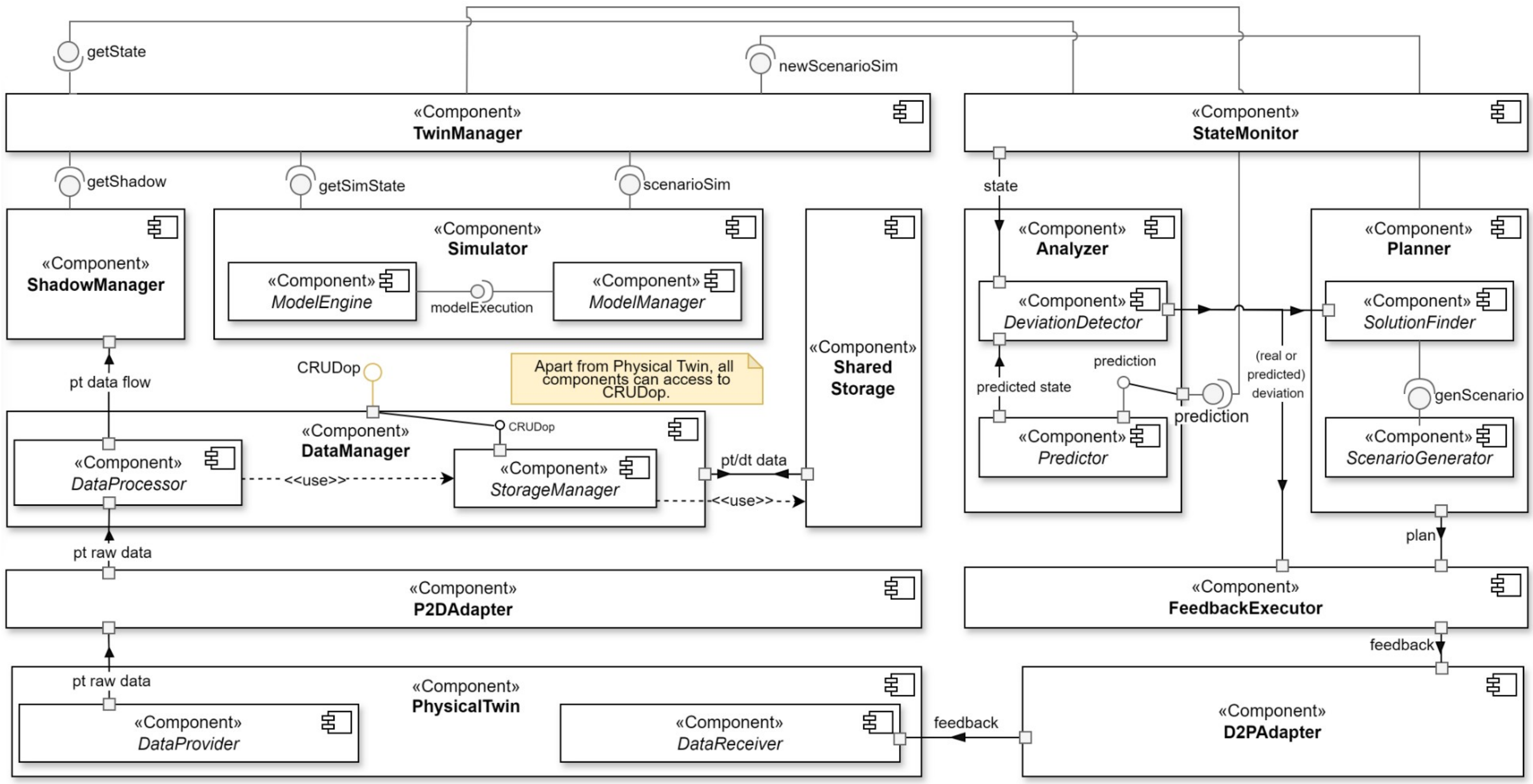


Fig. 1. Digital Twin architecture model

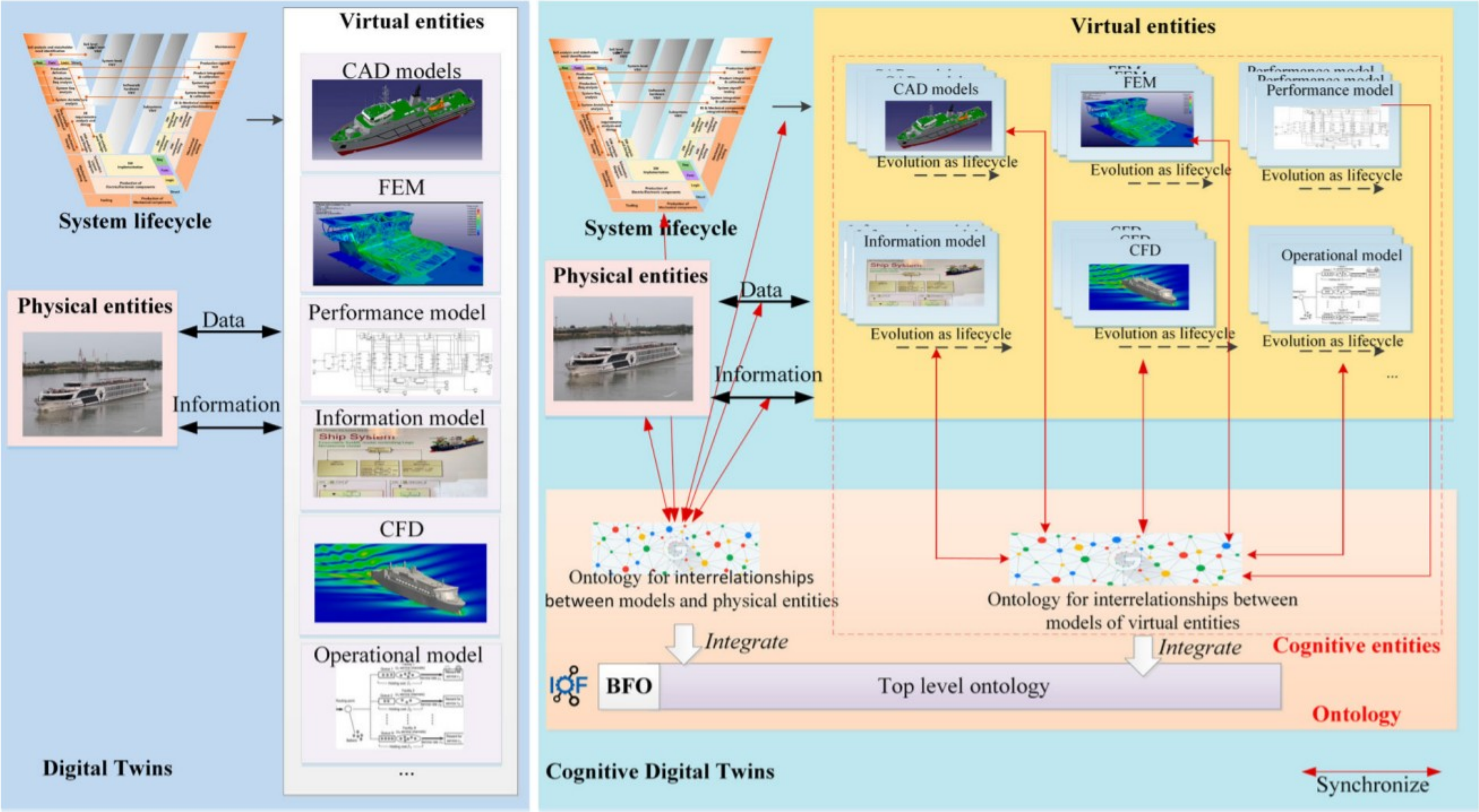
Michael, J., Wortmann, A. (2021). *Towards Development Platforms for Digital Twins: A Model-Driven Low-Code Approach*. In: Dolgui, A., Bernard, A., Lemoine, D., von Cieminski, G., Romero, D. (eds) Advances in Production Management Systems. Artificial Intelligence for Sustainable and Resilient Production Systems. APMS 2021. IFIP Advances in Information and Communication Technology, vol 630. Springer, Cham.

TwinArch: A Digital Twin Reference Architecture: component twin view



Alessandra Somma, Domenico Amalfitano, Alessandra De Benedictis, and Patrizio Pelliccione. 2026.
TwinArch: A digital twin reference architecture. Journal of Systems and Software 231 (2026), 112613. [doi:10.1016/j.jss.2025.112613](https://doi.org/10.1016/j.jss.2025.112613)

Cognitive Digital Twins



Xiaochen Zheng, Jinzhi Lu, Dimitris Kiritsis. *The emergence of cognitive digital twin: vision, challenges and opportunities*, International Journal of Production Research, pp. 1 – 23. 2021. 10.1080/00207543.2021.2014591

Mastering the Nordschleife with hydrogen

PORSCHE

Porsche Engineering tested it in a luxury-segment reference vehicle with a relatively high total weight of 2,650 kg on the Nürburgring Nordschleife – albeit entirely virtually: the drive was carried out using what is known as a **digital twin**, i.e. a computer-based representation of the real vehicle.

https://newsroom.porsche.com/en/2022/innovation/porsche-engineering-simulation-hydrogen-combustion-engines-nuerburgring-nordschleife-29401.html

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. Avventuroso, 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: Processes, 2019
- "the DT is a set of virtual information that fully describes a potential or actual physical production from the micro atomic level to the macro geometrical level". Y. Zheng, S. Yang, H. Cheng. An application framework of digital twin and its case study. In: Journal of Ambient Intelligence and Humanized Computing, 2019
- "a Digital Twin of a real distributed product is a virtual reflection, which can describe the exhaustive physical and functional properties of the product along the whole life cycle and can deliver and receive product information". R. Tharma, R. Winter, M. Eigner. An approach for the implementation of the digital twin in the automotive wiring harness field. In: Proceedings of International Design Conference, DESIGN, 2018
- "the creation on the basis of Unisim Design software-hardware solution "cloud" models of technological units and combining them into a single integrated "cloud" model of the production complex, called "digital twin" which in fact represents a virtual projection of the industrial facility into the "cloud"_ N.R. Yusupbekov, F.R. Abdurasulov, F.T. Adilov, A.I. Ivanyan. Application of cloud technologies for optimization of complex processes of industrial enterprises. In: Advances in Intelligent Systems and Computing, 2019
- "The digital twin concept is a functional system of continous optimization, which includes physical production together with its digital 'copy'.". E. Sujová, H. Čierna, I. Zabińska. Application of digitization procedures of production in practice. In: Management Systems in Production Engineering, 2019"
- "Digital twins of technological equipment are infrastructure components of production companies of the Industry 4.0 functioning in the level of cloud services.". D.A. Zakoldaev, A.V. Gurjanov, D.R. Kochubey, I.O. Zharinov. Application of imitation modelling means to create digital twins of the Industry 4.0 company technological equipment. In: IOP Conference Series: Materials Science and Engineering, 2018
- "the DT is a simulation method that can be used for evaluation and optimization". Y. Tan, W. Yang, K. Yoshida, S. Takakuwa. Application of IoT-aided Simulation for a Cyber-physical System. In: Proceedings of the 2018 Winter Simulation Conference, 2018"

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- "A DT consists of a virtual representation of a production system that is able to use sensory data, connected smart devices, mathematical models, and real-time data elaborations. The DT can be run on different simulation disciplines that are characterized by the synchronization of virtual and real systems". Y. Tan, W. Yang, K. Yoshida, S. Takakuwa. Application of IoT-aided simulation to manufacturing systems in cyber-physical system. In: Machines, 2019
- "The idea behind this [Digital Twin] concept is to have a digital entity that behaves exactly (or as close as possible) as the real entity". D. Mejia, A. Moreno, O. Ruiz-Salguero, Ã. Barandiaran. Appraisal of open software for finite element simulation of 2D metal sheet laser cut. In: International Journal on Interactive Design and Manufacturing (IJIDeM), 2017
- "the digital twin is made up of measured data, managed information and models for the physical evolution of equipment. It simulates the real evolution of equipment, anticipating possible failures". M.F. Milazzo, G. Ancione, G. Scionti, P.A. Bragatto. Assessment and management of ageing of critical equipment at seveso sites. In: Safety and Reliability - Safe Societies in a Changing World - Proceedings of the 28th International European Safety and Reliability Conference, ESREL 2018, 2018
- "In assembly, the physical object has a digital twin, a CAD model that accurately resembles real features". A. Blaga, L. Tamas. Augmented Reality for Digital Manufacturing. In: 2018 26th Mediterranean Conference on Control and Automation (MED), 2018
- "A Digital Twin (DT) is a digital replica of the physical assets of an industrial plant which contains the structure and the dynamics of how the devices and the process operate". G.S. Martinez, S. Sierla, T. Karhela, V. Vyatkin. Automatic generation of a simulation-based digital twin of an industrial process plant. In: Proceedings: IECON 2018 - 44th Annual Conference of the IEEE Industrial Electronics Society, 2018
- "A digital twin is a dynamic digital model of an industrial object or physical device simulating the internal processes, engineering characteristics, and behavior of the actual object". A. K. Tugengold, V. P. Dimitrov, L. V. Borisova, M. V. Grankov, R. N. Voloshin. Autonomous Maintenance of Digital Equipment. In: Russian Engineering Research, 2019
- "In principle, digital twins are model-based representations of entities of the real world such as machines, cars, or persons". D. Schneider, M. Trapp. B-space: dynamic management and assurance of open systems of systems. In: Journal of Internet Services and Applications, 2018
- "Digital twin is a virtual representation, in the cyberspace, of a physical asset, process or system, possessing real-time information about the represented entity and a model of its behavior. ". A. Artem,L. Nazarenko, M. Camarinha-Matos. Basis for an Approach to Design Collaborative Cyber-Physical Systems. In: Technological Innovation for Industry and Service Systems, 2019
- "Digital twin is an exact cyber copy of a physical system that truely represents all of its functionalities.". K. M. Alam, A. El Saddik. C2PS: A Digital Twin Architecture Reference Model for the Cloud-Based Cyber-Physical Systems. In: IEEE Access, 2017
- "A digital twin is a digital model of a real object containing lifecycle records and dynamic status data, which are synchronized in real-time. The model will be used to gain knowledge that can be transferred to the real object.". M. Eisentrager, S. Adler, M. Kennel, S. Moser. Changeability in Engineering. In: 2018 IEEE International Conference on Engineering, Technology and Innovation, ICE/ITMC 2018 - Proceedings, 2018
- "the so-called 'Digital Twin' approach, which is a simplified numerical model.". T. Barszcz, M. Zabaryłło. Concept of automated malfunction detection of large turbomachinery using machine learning on transient data. In: Diagnostyka, 2019
- "Digital twin, first of all, is a virtual replica of physical object's (product's), processes', or systems' operation condition.". E. Kolbachev, V. Zharov, V. Tsukerman. Cost management for PLM systems: A way to improve the competitiveness in digital economy. In: IOP Conference Series: Materials Science and Engineering, 2019
- "A product virtual space is a digital twin that is attached to it to enable manufacturers and their clients to better manufacture, monitor, maintain and operate it throughout its life time cycles, i.e. from the product manufacturing date, through operation and to end of lifespan. ". A.R. Al-Ali, R. Gupta, A.A. Nabulsi. Cyber physical systems role in manufacturing technologies. In: AIP Conference Proceedings, 2018
- "A digital twin is a specialized type of CPS where the physical system's components and attributes are mirroered into the cyber world. A digital twin enables real-time monitoring and decision making for various types of applications including medial and wellbeing applications". F. Arafsha, F. Laamarti, A. El Saddik. Cyber-Physical System Framework for Measurement and Analysis of Physical Activities. In: ELECTRONICS, 2019
- "The basic definition of a Self-aware Digital Twin is that it represents as a set of clusters defined in the selected clustering process.". N. Stojanovic, D. Milenovic. Data-driven Digital Twin approach for process optimization: An industry use case. In: Proceedings - 2018 IEEE International Conference on Big Data, Big Data 2018, 2019
- "A digital twin provides a digital replica of its physical counterpart which is virtually indistinguishable from its physical twin in the sense that it dynamically replicates the behavior and properties of the physical twin as well as enriches the replica with additional information about the physical counterpart. The conceptual model of a digital twin contains three main parts: (i) physical twin in the real world, (ii) digital twin in the virtual world, and (iii) the connections of input data and output command that ties the digital and real counterparts together.". F. Oquendo. Dealing with Uncertainty in Software Architecture on the Internet-of-Things with Digital Twins, 2019
- "virtual digital model of the real network that consists of data from the real network". R. Dong, C. She, W. Hardjawana, Y. Li, B. Vucetic. Deep Learning for Hybrid 5G Services in Mobile Edge Computing Systems: Learn from a Digital Twin. In: IEEE Transactions on Wireless Communications, 2019
- "A digital twin is a concept from the product life-cycle management (PLM) domain introduced by Grieves et al. (2017). It is a virtual representation of a specific physical product. The idea behind this concept is that the digital twin should be linked to the physical product throughout the product's life-cycle and

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constantly mirror it.". R. Bitton, T. Gluck, O. Stan, M. Inokuchi, Y. Ohta, Y. Yamada, T. Yagyu, Y. Elovici, A. Shabtai. Deriving a Cost-Effective Digital Twin of an ICS to Facilitate Security Evaluation. In: Computer Security, 2018

- "A digital twin can be defined as an integrated virtual model of a real-world system containing all of its physical information and functional units.". K. T. Park,Y. W. Nam, H. S. Lee, S. J. Im, S. D. Noh, J. Y. Son, H. Kim. Design and implementation of a digital twin application for a connected micro smart factory. In: INTERNATIONAL JOURNAL OF COMPUTER INTEGRATED MANUFACTURING, 2019
- "More simply, a DTM is a digital replica or virtual counterpart of a real entity, which can be assets, processes, systems, or even services. After being paired with a physical object, the DTM can perform the functions of the monitoring system and data analysing, aiming to catch and remove the problems even before they can occur.". C. S. Shim, N. S. Dang, S. Lon, C. H. Jeon. Development of a bridge maintenance system for prestressed concrete bridges using 3D digital twin model. In: Structure and Infrastructure Engineering, 2019
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- "[...] the digital twin is an object-oriented digital model of a physical asset that comprises all the data about the asset, including system, structural, engineering and technological models". D. Kostenko, N. Kudryashov, M. Maystrishin, V. Onufriev, V. Potekhin, A. Vasiliev. Digital twin applications: Diagnostics, optimisation and prediction. In: Annals of DAAAM and Proceedings of the International DAAAM Symposium, 2018
- "Industrial Digital Twin (DT) - a digital copy of the real manufacturing sytem, which can be controlled and programmed in realtime directly from the computer application model of the industrial robot.". V. Kuts, T. Otto, T. Tähemaa, Y. Bondarenko. Digital twin based synchronised control and simulation of the industrial robotic cell using virtual reality. In: Journal of Machine Engineering, 2019
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- "[...] an accurate simulation model, a digital twin, which can be used throughout the real system's life span is created.". A. Khan, M. Dahl, P. Falkman, M. Fabian. Digital Twin for Legacy Systems: Simulation Model Testing and Validation. In: IEEE International Conference on Automation Science and Engineering, 2018
- "Digital twin or BIM (Building information modeling) [...] BIM is a digital representation of physical and functional characteristics of a facility. A BIM is a shared knowledge resource for information about a facility forming a reliable basis for decisions during its life cycle; defined as existing from earliest conception to demolition.". S. Kaewunruen, N. Xu. Digital twin for sustainability evaluation of railway station buildings. In: Frontiers in Built Environment, 2018
- "Digital Twin (DT) is defined as a very realistic model of the current state of the process and their own behavior in interaction with their environment in the real world [5]. [...] However, the definition of a DT and its requirements are not yet fully established and lack of conceptual basis [3]. The characteristics a DT model should possess to be widely used in industry remains an open question in the literature.". L. Fernando, C. S. DurÃ£o, S. Haag, R. Anderl, K. Schuetzer, E. Zancul. Digital Twin Requirements in the Context of Industry 4.0. In: Product Lifecycle Management to Support Industry 4.0, 2018
- "digital twin, a reference model to realize the convergence between physical and virtual space". F. Tao, M. Zhang. Digital Twin Shop-Floor: A New Shop-Floor Paradigm Towards Smart Manufacturing. In: IEEE Access, 2017
- "Digital twin, a novel concept that refers to virtual substitutes of real world objects[...]. The idea of digital twin is to create a digital counterpart to mimic the characteristics and behaviors of its corresponding twin.". K. Yan, W. Xu, B. Yao, Z. Zhou, D.T. Pham. Digital Twin-Based Energy Modeling of Industrial Robots. In: Communications in Computer and Information Science, 2018
- "Digital twin technology refers to the mehtod of describing and modeling a physical entity's characteristics, behavior, and performance by means of digital technology.". S. Meng, S. Tang, Y. Zhu, C. Chen. Digital Twin-Driven Control Method for Robotic Automatic Assembly System. In: 2ND INTERNATIONAL CONFERENCE ON FRONTIERS OF MATERIALS SYNTHESIS AND PROCESSING, 2019
- "The general digital twin mode for a product consists of three parts, which are the physical entities in physical space, the virtual models in virtual space, and the connected data that tie the physical and virtual worlds. The physical entities are the real product that can be operated by the users.". F. Tao, F. Sui, A. Liu, Q. Qi, M. Zhang, B. Song, Z. Guo, S.C.-Y. Lu, A.Y.C. Nee. Digital twin-driven product design framework. In: International Journal of Production Research, 2019
- "Digital twin is an integrated multi-physics, multiscale, and probabilistic simulation of a complex product and uses the best available physical models, sensor updates, etc., to mirror the life of its corresponding twin. ". F. Tao, J. Cheng,Q. Qi, M. Zhang, H. Zhang, F. Sui. Digital twin-driven product design, manufacturing and service with big data. In: INTERNATIONAL JOURNAL OF ADVANCED MANUFACTURING TECHNOLOGY, 2018
- "the concept of using a digital copy of a physical system to perform real-time optimization is referred to as a DT". F. Tao, Q. Qi, L. Wang, A.Y.C. Nee. Digital Twins and Cyber-Physical Systems toward Smart Manufacturing and Industry 4.0: Correlation and Comparison. In: Engineering, 2019
- "A digital twin (DT) is a digital representation of a real-world entity or system.", "A digital twin is a virtual representation of a physical product or process, used to understand and predict their performance.". L. Rauch, M. Pietrzyk. Digital twins as a modern approach to design of industrial processes. In: Journal of

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making in complex production and logistic enterprises. In: International Journal of Design and Nature and Ecodynamics, 2018

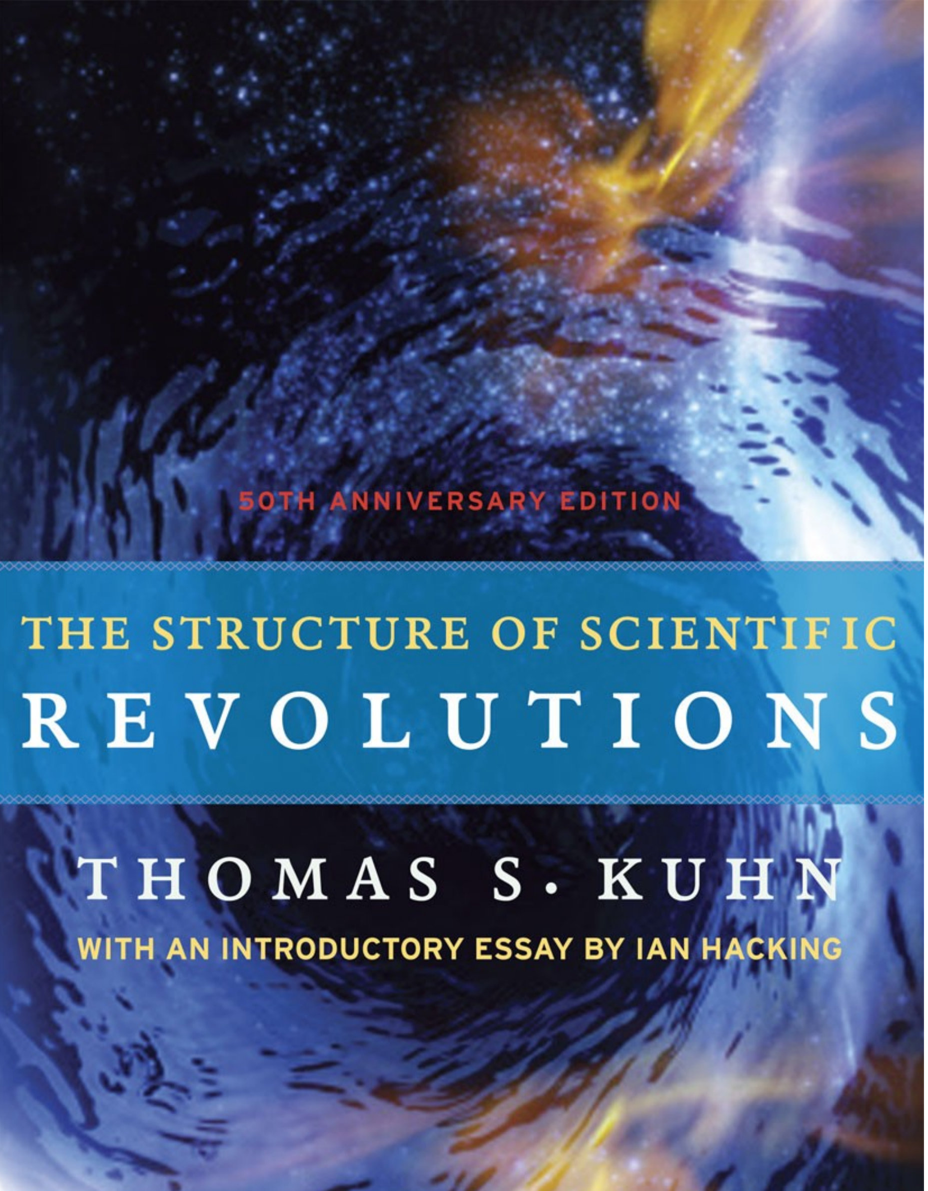
- " A Digital Twin though tightly connects the physical system (e.g., one particular machine) with its computer model, so that the latter closely reflects the architecture, the dynamics and the actual state of this one particular system.". K. Bruynseels, F. S. de Sio, J. van den Hoven. Digital Twins in Health Care: Ethical Implications of an Emerging Engineering Paradigm. In: FRONTIERS IN GENETICS, 2018
- "The term digital twins refers to the development of virtual models of processes, products or services that allow the simulation of system behavior and the early detection of problems before the real system exists.". H.-D. Wuttke, K. Henke, R. Hutschenreuter. Digital Twins in Remote Labs. In: Cyber-physical Systems and Digital Twins, 2020
- "In a short, the digital twin technique deploys various sensors on the physical entities. By sensing the operational state of the physical world, the virtual model that is mutually mapped, mutually interacted and effectively collaborated with the physical entities in the cyberspace.". Y. Shi, J. Xu, W. Du. Discussion on the New Operation Management Mode of Hydraulic Engineering Based on the Digital Twin Technique. In: Journal of Physics: Conference Series, 2019
- "The new technology, accessing to realistic models of the current state of the process and their own behaviors in interaction with their environment in the real world is called the "Digital Twin". "Digital twin is an integrated multi-physics, multiscale and probabilistic simulation of a complex product and uses the best available physical models, sensor updates, etc. to mirror the life of its corresponding twin.". J. Liu, H. Zhou, X. Liu, G. Tian, M. Wu, L. Cao, W. Wang. Dynamic Evaluation Method of Machining Process Planning Based on Digital Twin. In: IEEE Access, 2019
- "a "digital twin" is a virtual representation of a real world subject (person, software system, ...) or a real world object (machine, component, part of the environment, ...)". M. Schluse, J. Rossmann. From simulation to experimentable digital twins: Simulation-based development and operation of complex technical systems. In: 2016 IEEE International Symposium on Systems Engineering (ISSE), 2016
- "digital twin is a digital replica of a physical object, device, system, place or person". A. Fricke, H. Asche. Geospatial Database for the Generation of Multidimensional Virtual City Models Dedicated to Urban Analysis and Decision-Making. In: Computational Science and Its Applications ICCSA 2019, 2019
- "The term digital twin refers to a digital replica of physical assets, processes and systems that can be used in real-time for control and decision purposes.". J. Vatn. Industry 4.0 and real-time synchronization of operation and maintenance. In: Safety and Reliability - Safe Societies in a Changing World - Proceedings of the 28th International European Safety and Reliability Conference, ESREL 2018, 2018
- "Generally, the term [Digital Twin] is used to describe two things: the administration shell of a CPS and simulation models.". J. Reitz, M. Schluse, J. Rossmann. Industry 4.0 beyond the Factory: An Application to Forestry. In: Tagungsband des 4. Kongresses Montage Handhabung Industrieroboter, 2019
- "we define the Digital Twin of a physical object as the sum of all logically related data, i.e. engineering data and operational data, represented by a semantic data model". M. Kunath, H. Winkler. Integrating the Digital Twin of the manufacturing system into a decision support system for improving the order management process. In: Procedia CIRP, 2018
- "In this approach the term is used to describe a virtual representation based on AR-technology of a physical object which can or already exists in the real world.". H. Pargmann, D. Euhausen, R. Faber. 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), 2018
- "The Digital Twin can be defined as an evolving profile of the history of current behaviour of a physical object or a process. That helps to optimize the performance of a production factory.". M. Krajcovic, P. Grznar, M. Fusko, R. Skokan. Intelligent logistics for intelligent production systems. In: Communications - Scientific Letters of the University of Zilina, 2018
- "A DT is the virtual representation of a real technical asset, including its appearance, behavior, and interfaces.". L. Atorf, J. Rossmann. Interactive Analysis and Visualization of Digital Twins in High-Dimensional State Spaces. In: 2018 15th International Conference on Control, Automation, Robotics and Vision, ICARCV 2018, 2018
- "an integrated multiphysics, multiscale simulation of a vehicle or system that uses the best available physical model, sensor updates, fleet history, to mirror the life of its corresponding flying twin".. C. Steinmetz, A. Rettberg, F. G. C. Ribeiro, G. Schroeder, C. E. Pereira. Internet of Things Ontology for Digital Twin in Cyber Physical Systems. In: 2018 VIII Brazilian Symposium on Computing Systems Engineering (SBESC), 2018
- "The concept Digital Twin aims at giving a virtual representation of a physical entity that is as complete-as-possible.". H. Zipper, F. Auris, A. Strahilov, M. Paul. Keeping the digital twin up-to-date - Process monitoring to identify changes in a plant. In: Proceedings of the IEEE International Conference on Industrial Technology, 2018
- "The vision of the digital twin itself includes more or less all information which could be useful in all – the current and subsequent – lifecycle phases". I. Naplekov, I. Zheleznikov, D. Pashchenko, P. Kobysheva, A. Moskvitina, R. Mustafin, M. Gnutikova, A. Mullagalieva, P. Uzlov. Methods of computational modeling of coronary heart vessels for its digital twin. In: MATEC Web of Conferences, 2018
- "A digital twin of a production system is a multi-level digital layout that describes the product, processes and resources in the environment of their functioning". N. Demkovich, E. Yablochnikov, G. Abaev. Multiscale modeling and simulation for industrial cyber-physical systems. In: 2018 IEEE Industrial Cyber-Physical Systems (ICPS), 2018
- "The digital twin is the virtual representation of a physical object or system across its life-cycle. It uses real-time data and other sources to enable learning, reasoning, and dynamically recalibrating for

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

many definitions of “Digital Twin”

→ use “**Twinning**” to cover all definitions

Sensing ← … everything in between ... → Simulation



Using (Digital) Twins, or more generally,

the notion of **Twinning**

is a **paradigm**

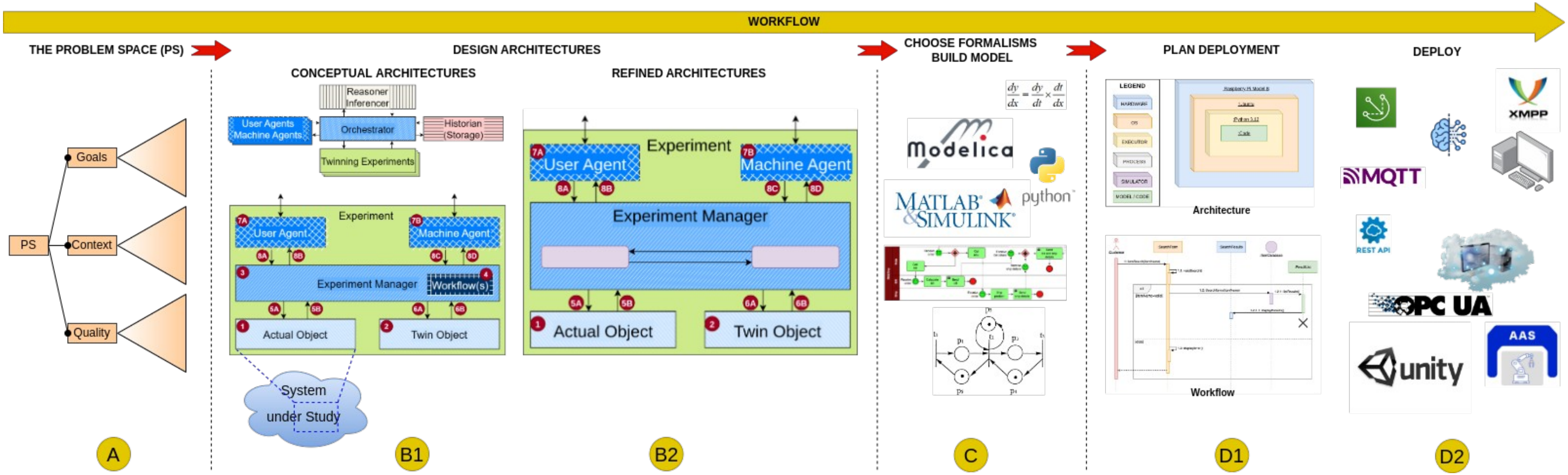
Ubiquitous use of twins is a

“paradigm shift”

Workflow?

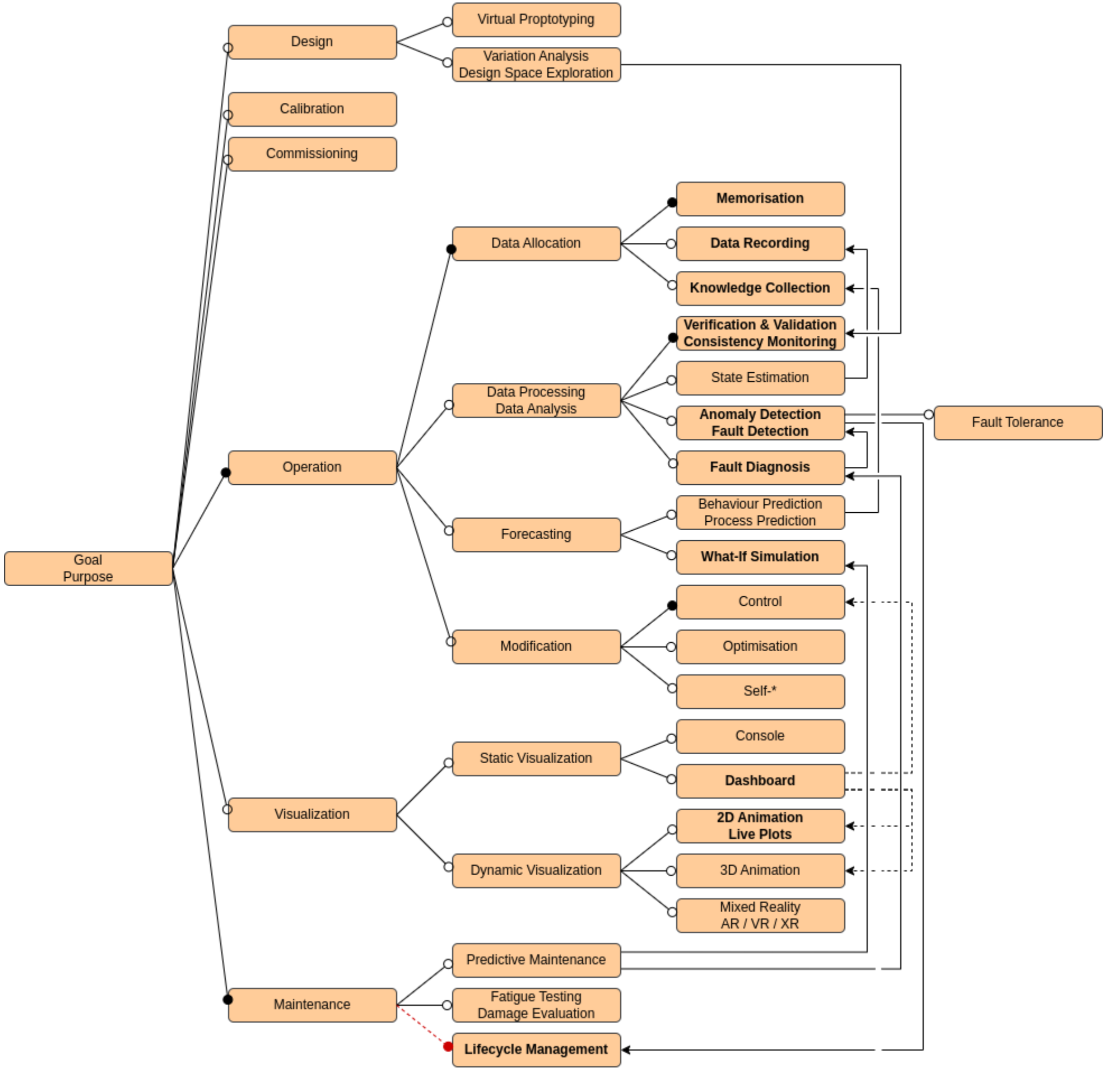
Foundations for Twinning: workflow

Goals → Conceptual Architecture → Formalism choice/Model building → Deployment



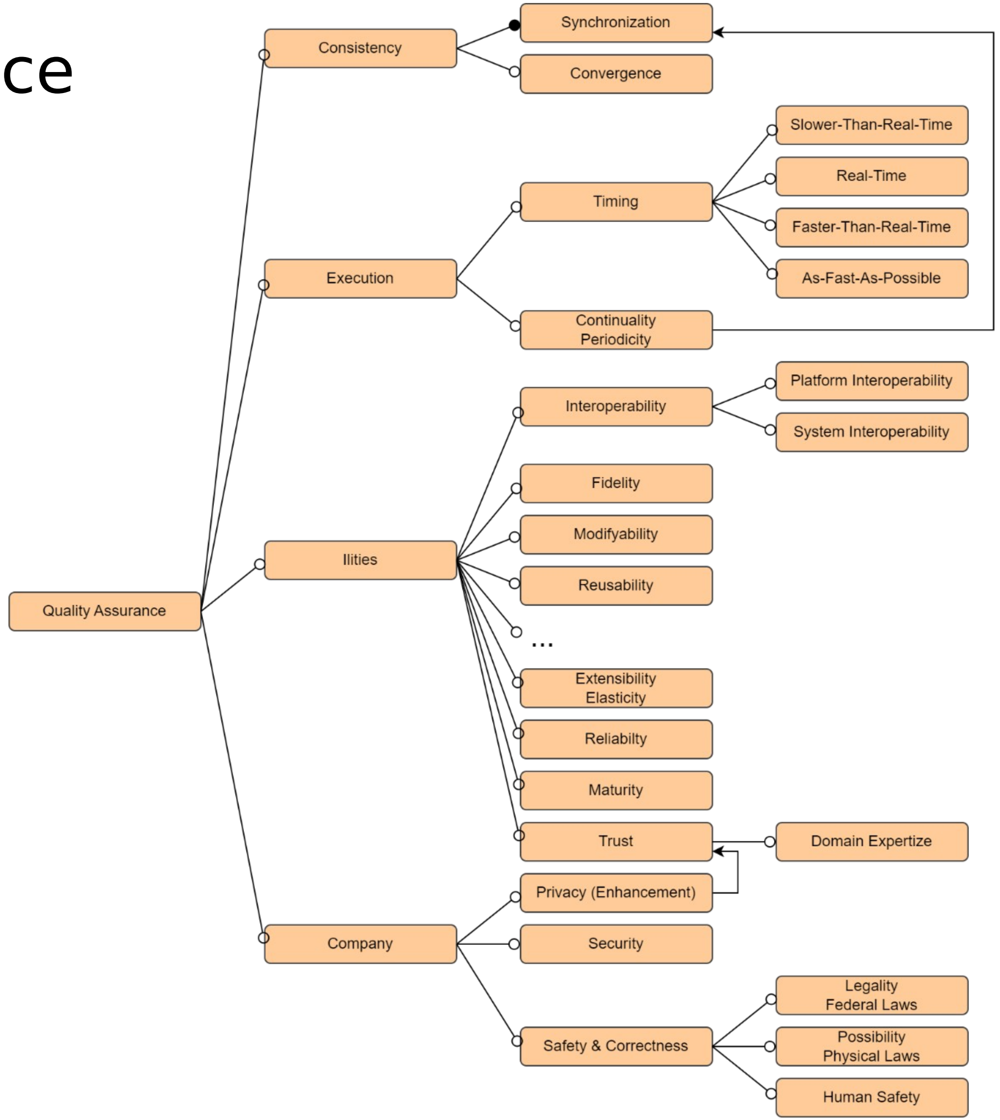
Goals

wrt **Property of Interest** (PoI)

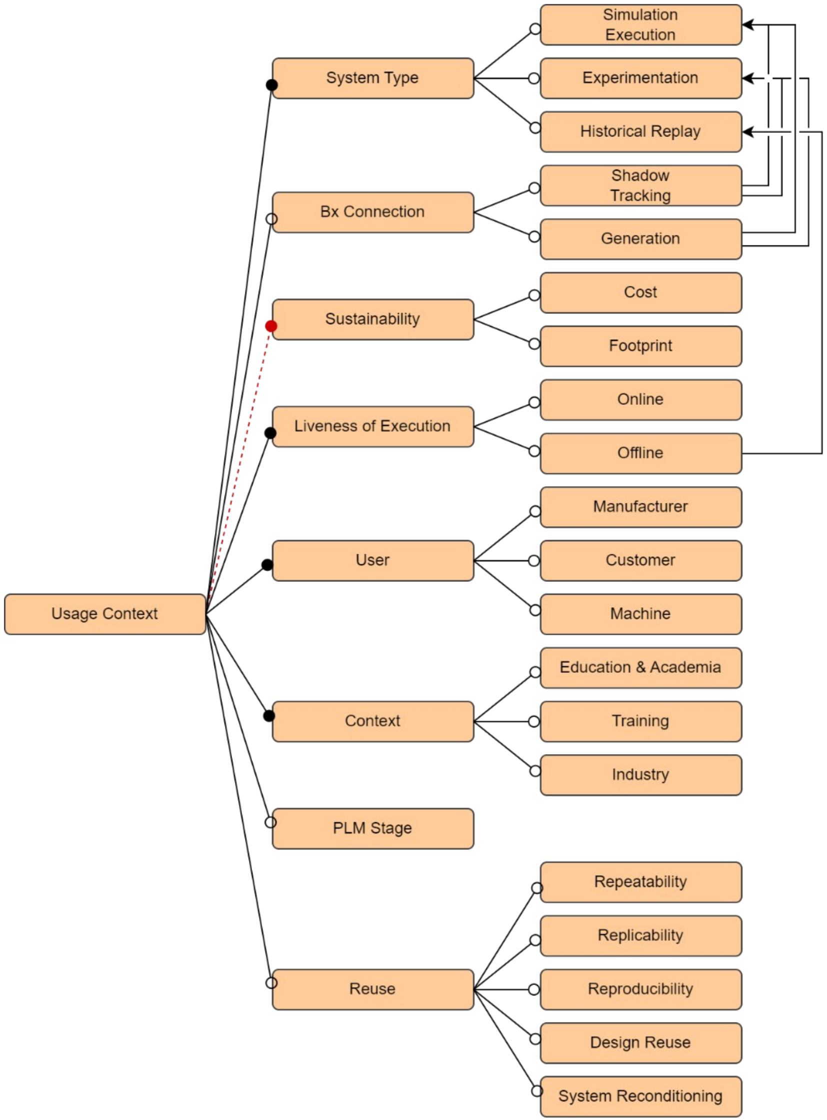


R. Paredis and H.Vangheluwe. 2024. “*Modelling and Simulation-Based Evaluation of Twinning Architectures and Their Deployment*”. In Proceedings of SIMULTECH 2024, pp. 170-182.

Quality Assurance

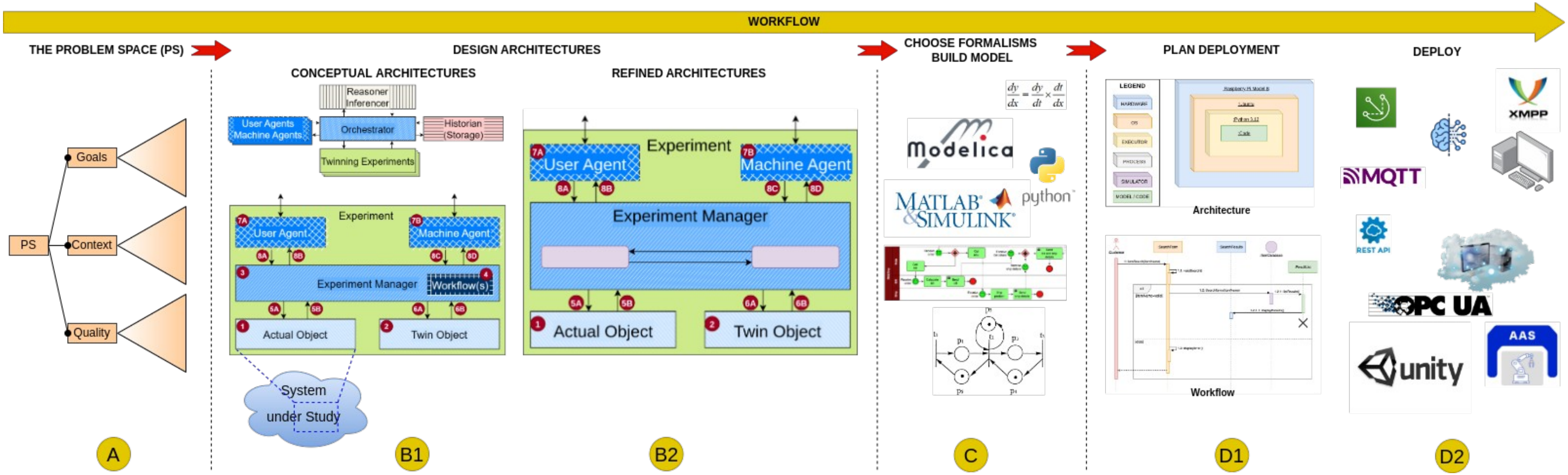


Usage Context

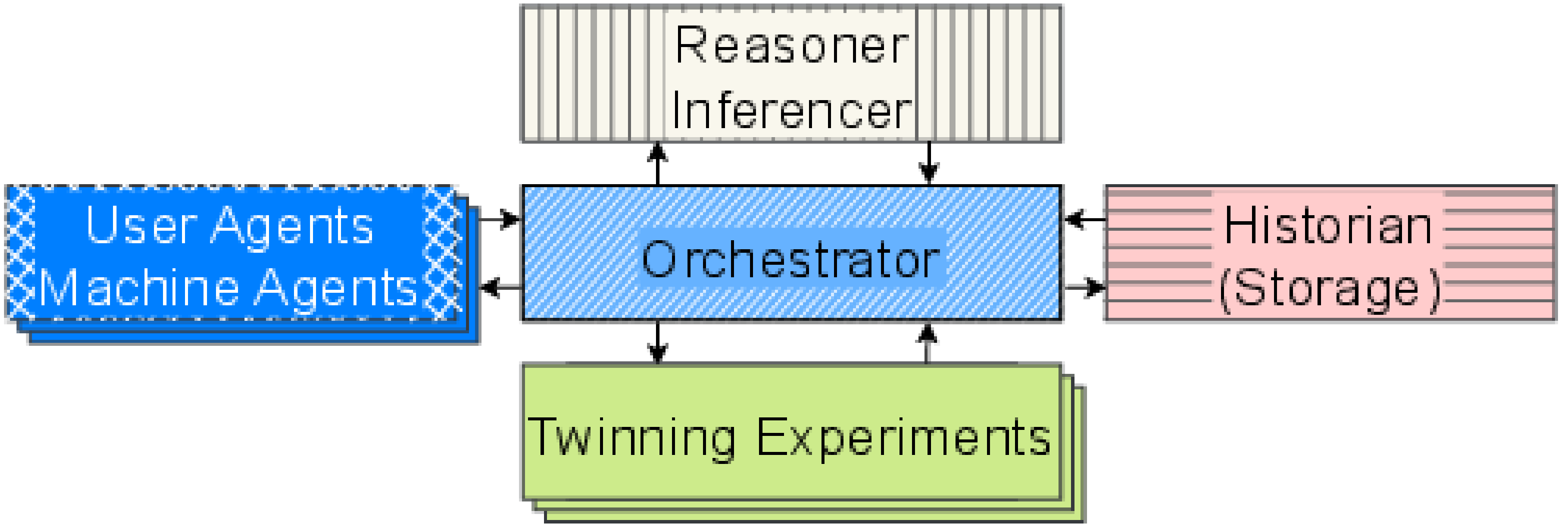


Foundations for Twinning: workflow

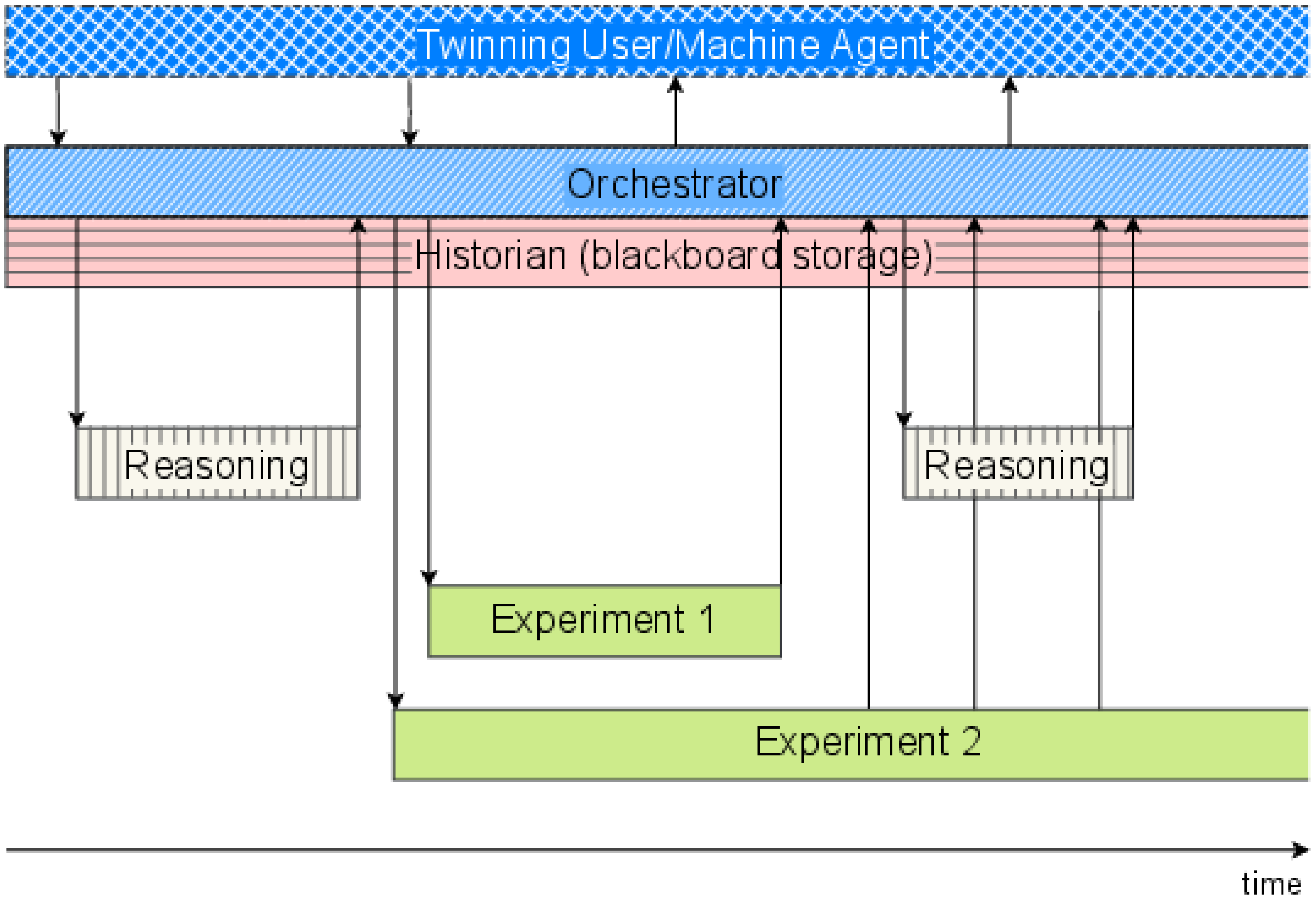
Goals → Conceptual Architecture → Formalism choice/Model building → Deployment



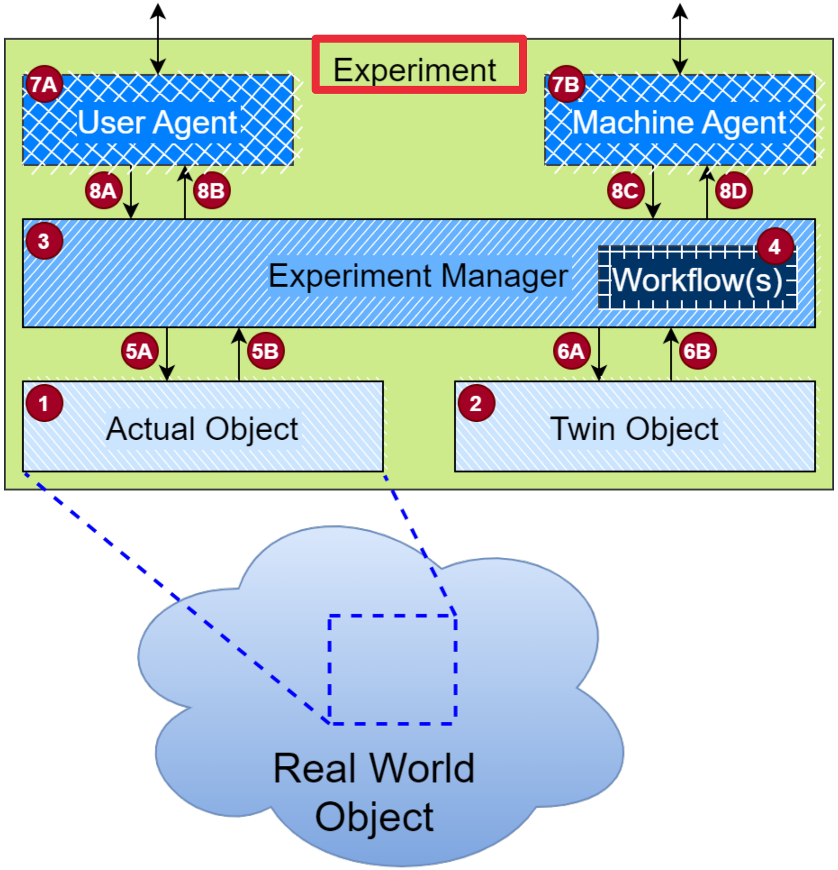
Twinning Experiments in a **Top-Level Conceptual Twinning Architecture**



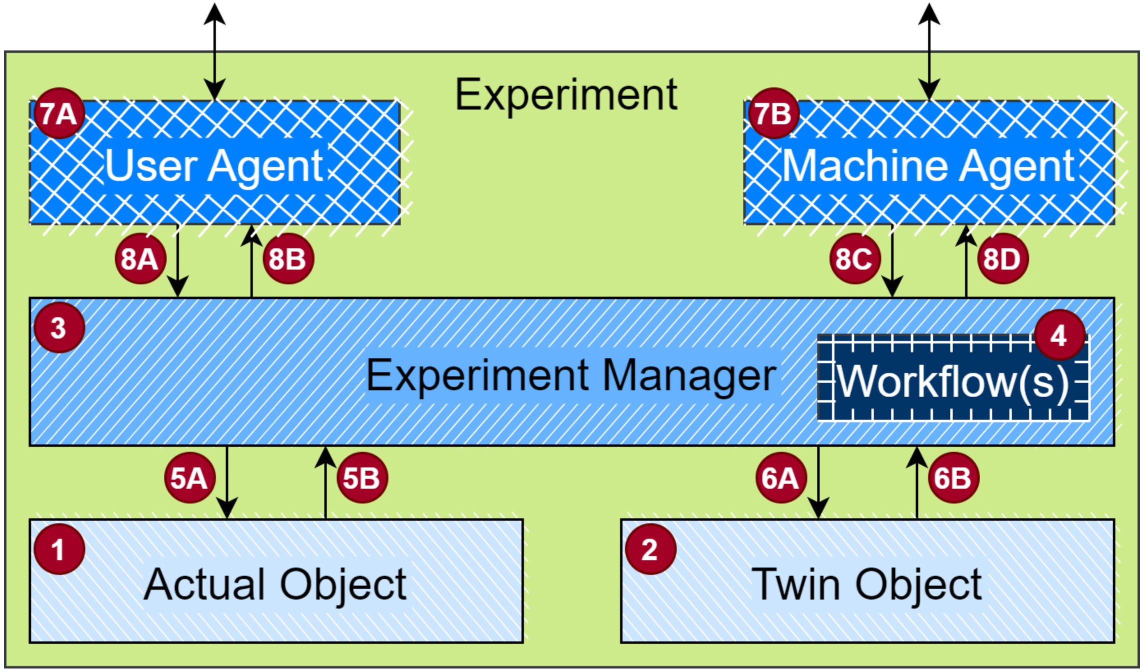
Example “behaviour trace”, spawning multiple Twinning Experiments



Conceptual (digital) Twinning Experiment Architecture(s)



Family of Conceptual Architecture(s)
150% model (using presence conditions)

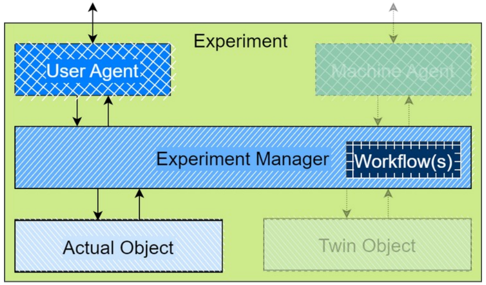


* Agent does not refer to Agent Based Modelling/Simulation (ABMS) but to “interfaces”

many definitions/alternatives of “Digital Twin”

→ use “**Twinning**” to cover all definitions

Sensing ← … everything in between … → Simulation



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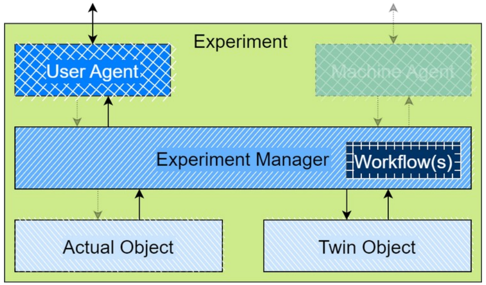

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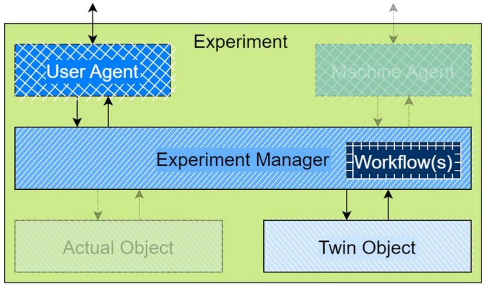
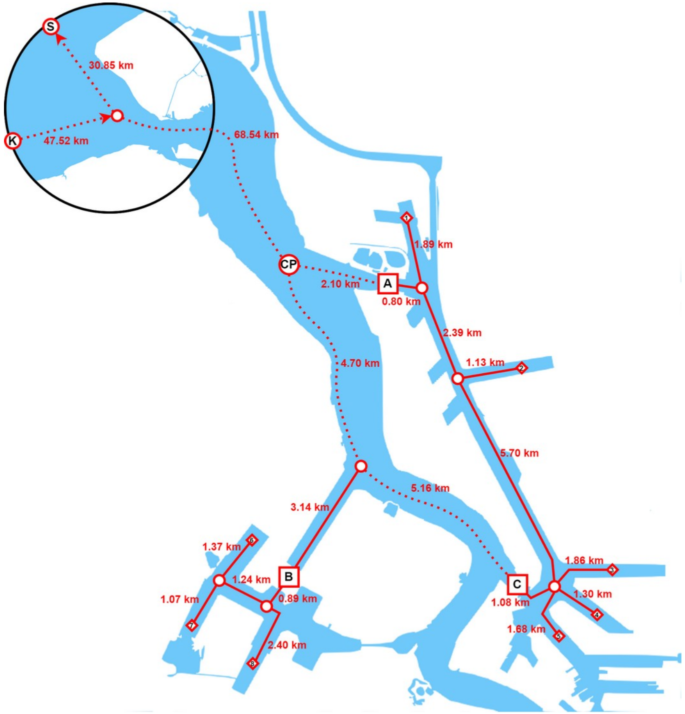
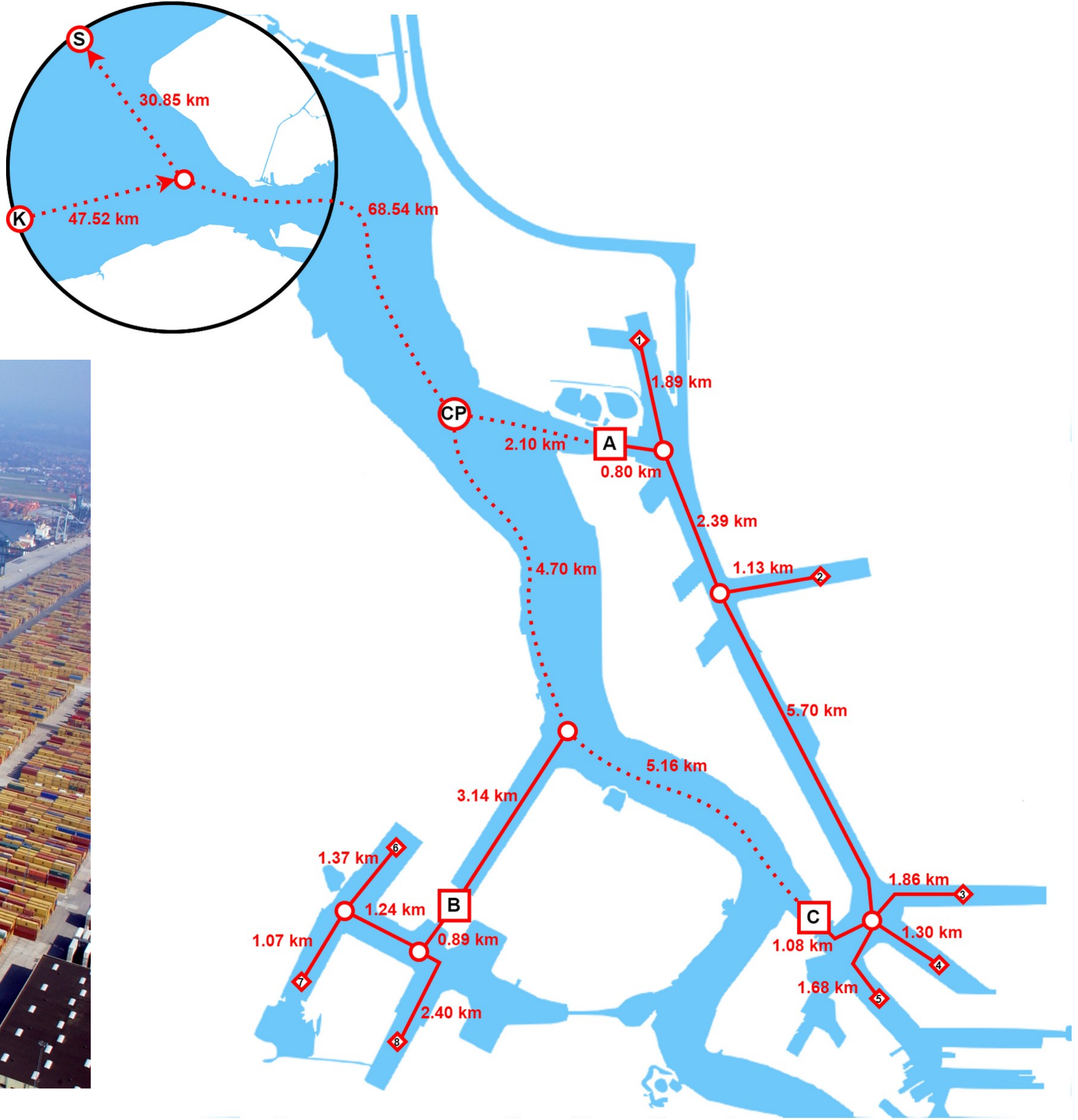


Case: (inspired by the operation of) the Port of Antwerp (PoAB)

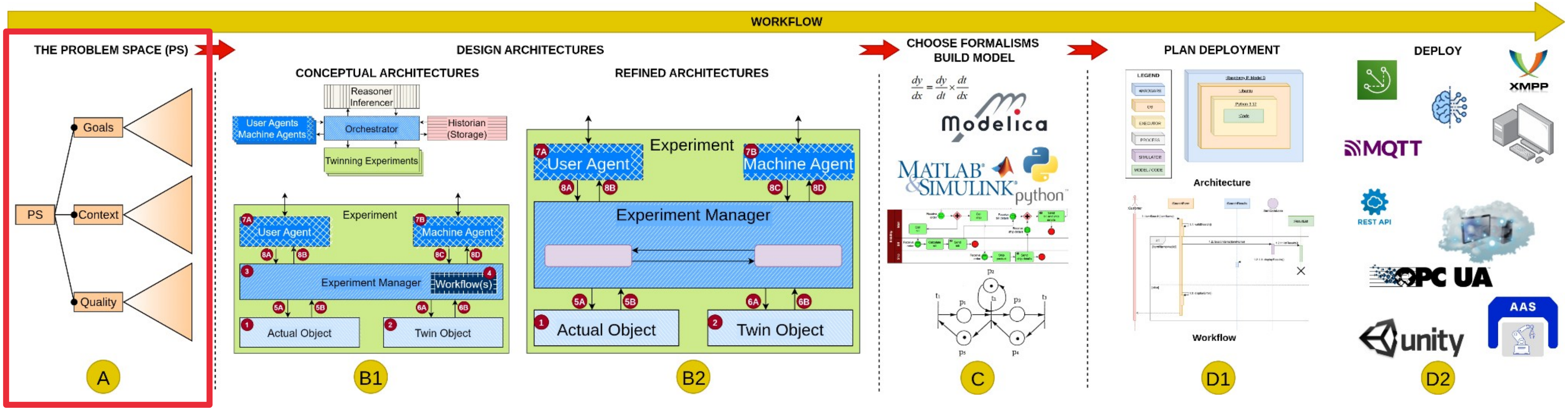
Case: Port of Antwerp (PoAB)



Case: Port of Antwerp

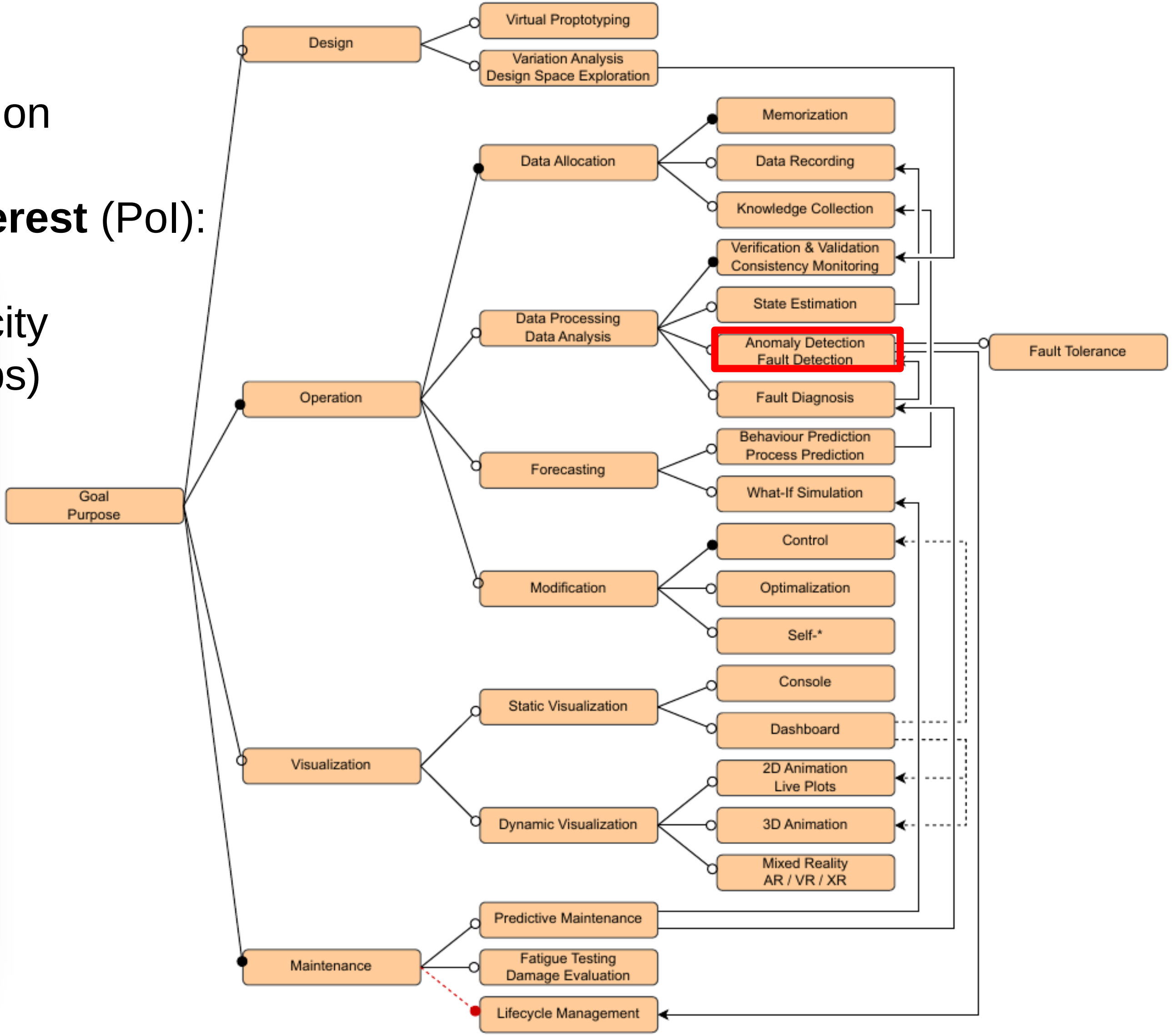


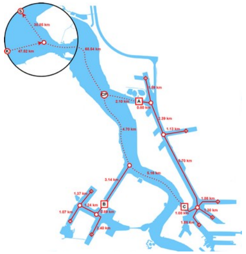
Stages of Twinning – Goal Selection



Goal Selection:
Anomaly Detection

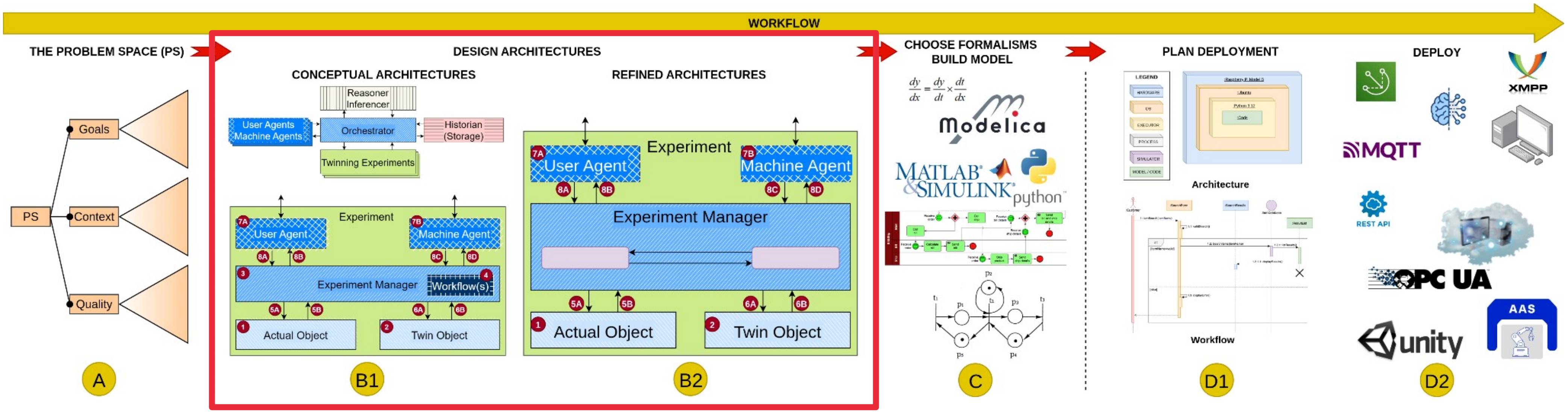
Property of Interest (PoI):
occupancy ~
remaining capacity
(for docking ships)





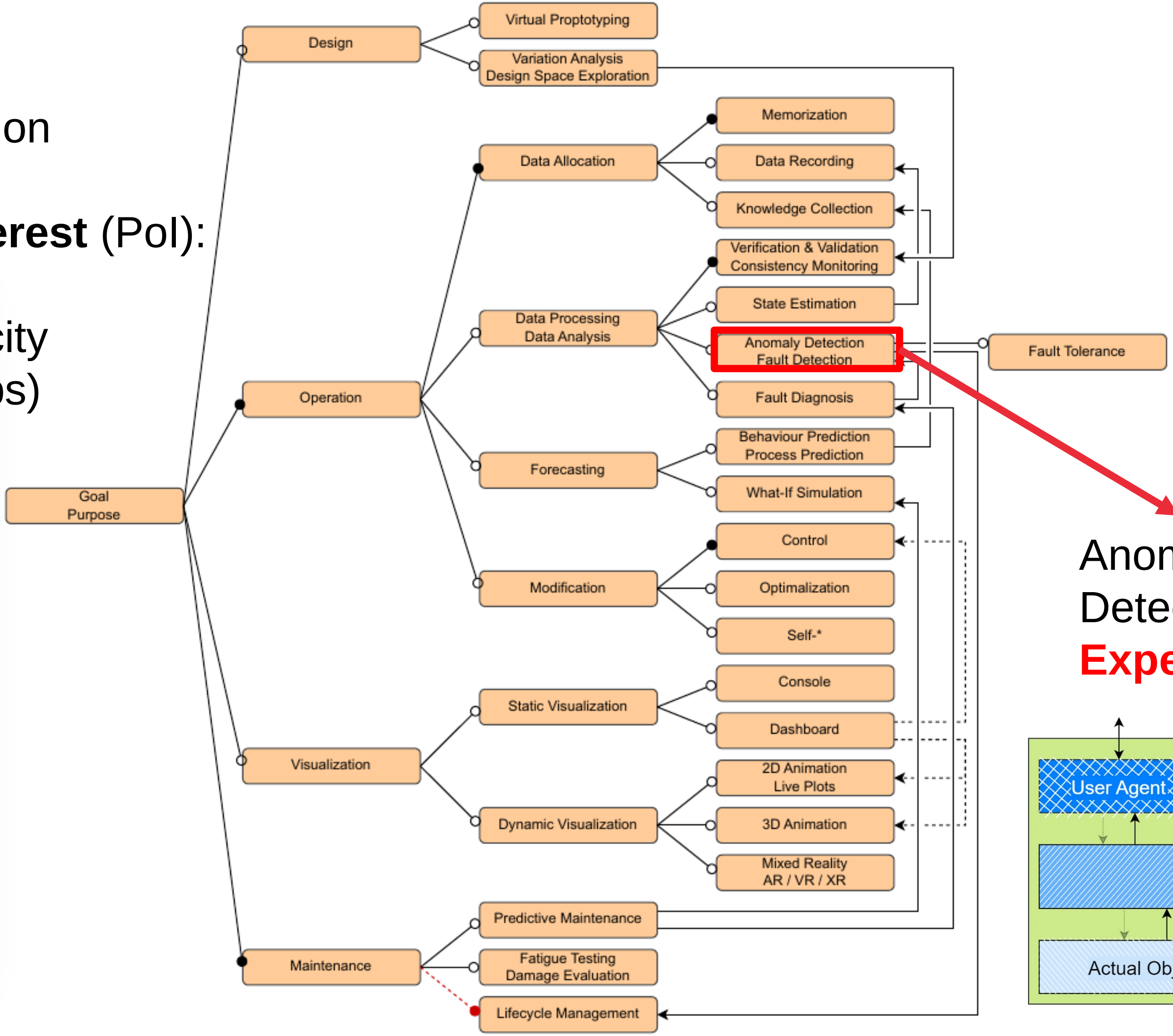
R. Paredis and H.Vangheluwe. 2024. “*Modelling and Simulation-Based Evaluation of Twinning Architectures and Their Deployment*”. In Proceedings of SIMULTECH 2024, pp. 170-182.

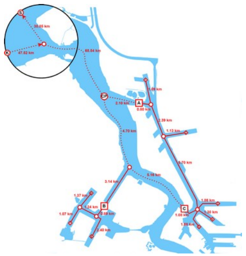
Stages of Twinning – Architecture Selection



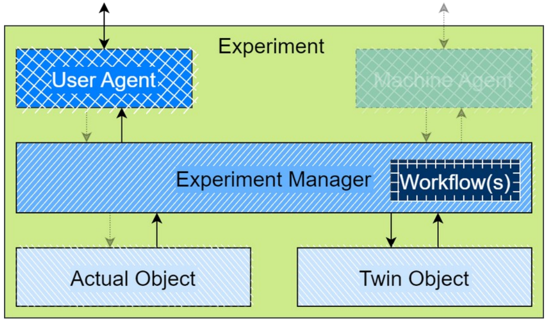
Goal Selection:
Anomaly Detection

Property of Interest (PoI):
occupancy ~
remaining capacity
(for docking ships)



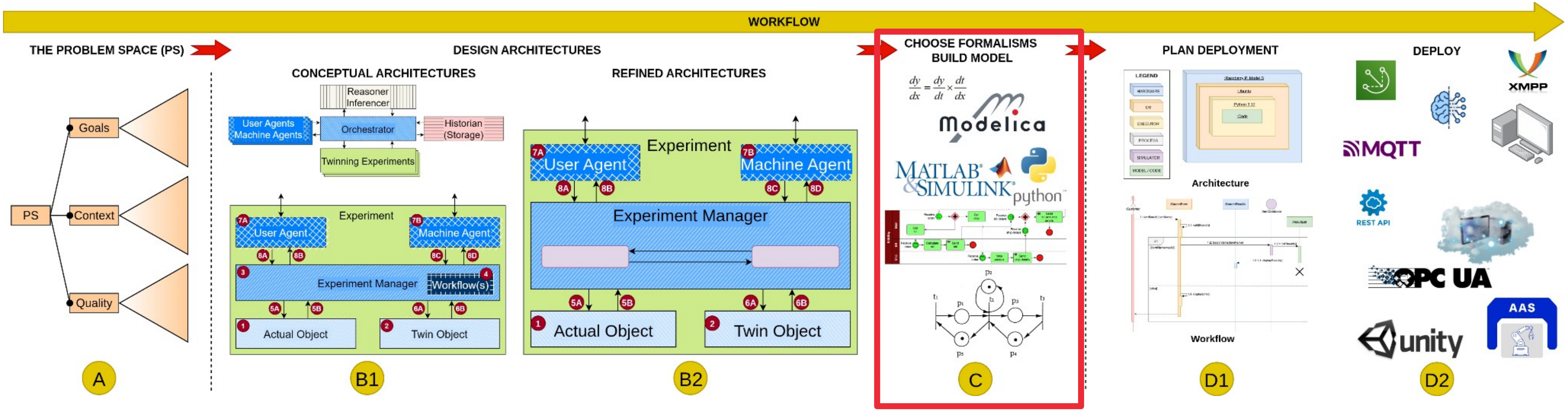


Anomaly
Detection
Experiment



R. Paredis and H.Vangheluwe. 2024. “*Modelling and Simulation-Based Evaluation of Twinning Architectures and Their Deployment*”. In Proceedings of SIMULTECH 2024, pp. 170-182.

Stages of Twinning – Formalism/Model Selection



Formalism/Model Selection: classification

Formalism	DESIGN	REQ	MC	TEST	SIM	CAUSAL	SYNTHESIS	Time Base	TERMS
Trace	X	X	X	Monitor	X	N/A	X	X	
Natural Language	✓	✓	X	X	X	N/A	X	{NOW}, IN, IR	
Requirements Lang.	✓	✓	✓	✓	X	N/A	X	X	
ABD/Modelica	✓	X	X	MUT	✓	X	FMU	IR	Acausal
Alg-CBD	✓	X	X	MUT	✓	✓	✓	{NOW}	Synchronous Data-flow
DT-CBD	✓	X	X	MUT	✓	✓	✓	IN	
CT-CBD	✓	X	X	MUT	✓	✓	✓	IR	
Petri Net	✓	X	✓	MUT	+/-	✓	X	POSET	
State Chart	✓	X	X	MUT	✓	✓	* ✓	IR	
DEVS	✓	X	X	MUT	✓	✓	✓	IR	Discrete-event
LTL/CTL	X	✓	✓	✓	X	N/A	Monitor	POSET	
STL	X	✓	+/-	✓	X	N/A	Monitor	IR	

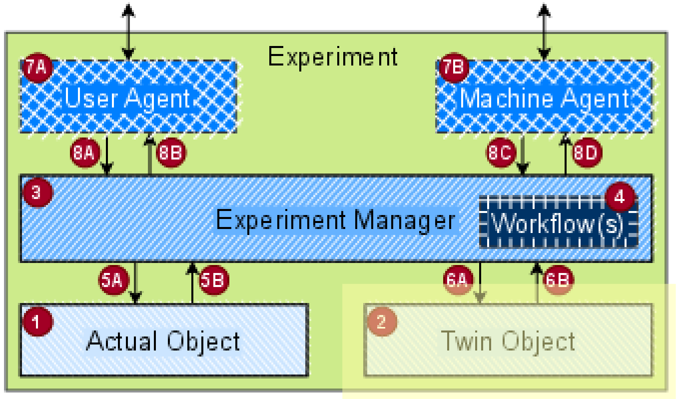
- MUT: model under test
- POSET: partially ordered set
- MC: model checking

++ (orthogonal) stochastic
++ (orthogonal) spatial distribution (grid, continuous, …)
++ (orthogonal) individual-based

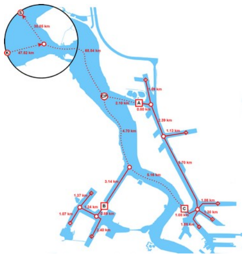
Choice of appropriate formalism
for Twin Object model: **DEVS**

DEVS = Discrete-Event system Specification

Python(P)DEVS

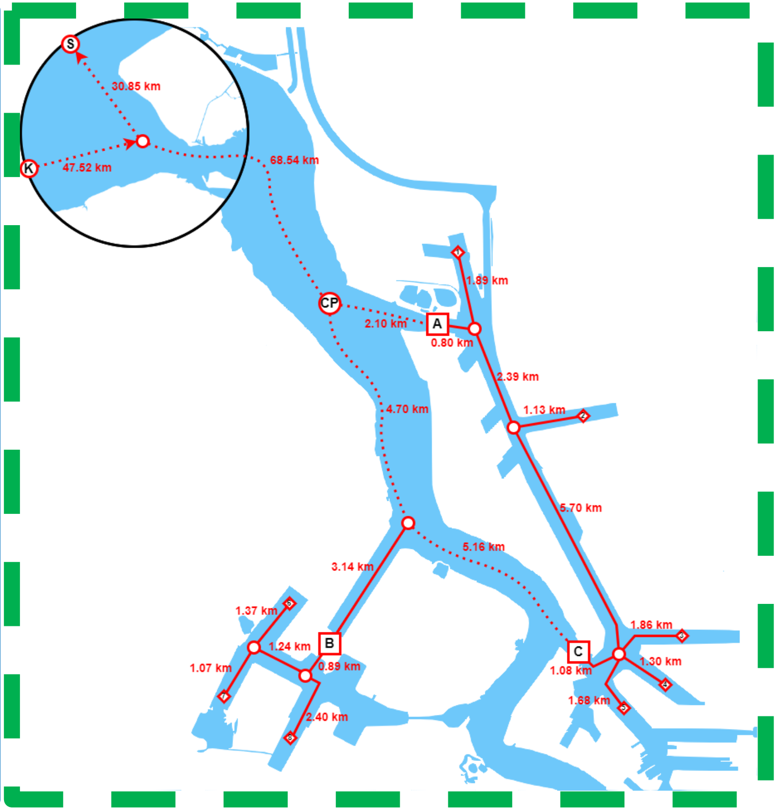


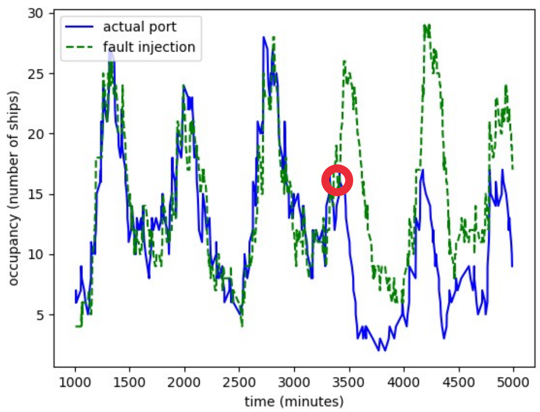

```python
class Confluence(AtomicDEVS):
    def __init__(self, name, segments, quays_out):
        super(Confluence, self).__init__(name)
        self.ins = [self.addInPort("in%i" % x) for x in range(segments)]
        self.outs = [self.addOutPort("out%i" % x) for x in range(segments)]

        self.enc = self.addOutPort("enc")

        # reverse the mapping for better lookup
        self.quay_mapping = {}
        for output_idx, quays in quays_out.items():
            for quay_id in quays:
                self.quay_mapping[quay_id] = output_idx

        self.state = {
            "vessels": []
        }

    def timeAdvance(self):
        if len(self.state["vessels"]) > 0:
            return 0.
        return INFINITY

    def extTransition(self, inputs):
        for inp in self.ins:
            if inp in inputs:
                vessel = inputs[inp]
                vessel.source = vessel.trajectory.pop(0)
                self.state["vessels"].append(vessel)
        return self.state

    def outputFnc(self):
        if len(self.state["vessels"]) > 0:
            vessel = self.state["vessels"][0]
            output = self.quay_mapping[vessel.trajectory[0]]
            return {
                self.outs[output]: vessel
            }
        return {}

    def intTransition(self):
        self.state["vessels"].pop(0)
        return self.state
```

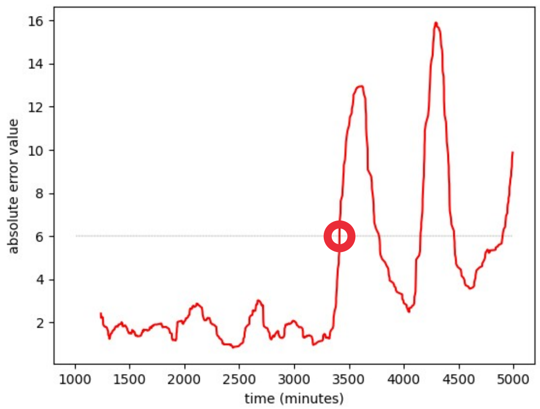


http://msdl.uantwerpen.be/projects/DEVS/PythonPDEVS/

Anomaly Detection







This example case is inspired by the actual operations of PoAB

Caveat: Tracking Simulator

small deviations in PoIs may **not** be **anomalies**

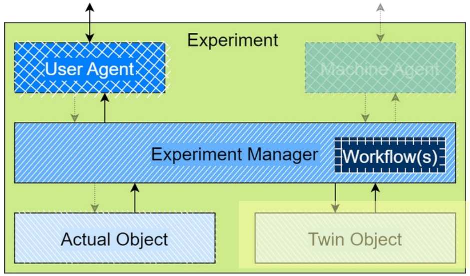
→ “re-align” simulation model state to match “real state”

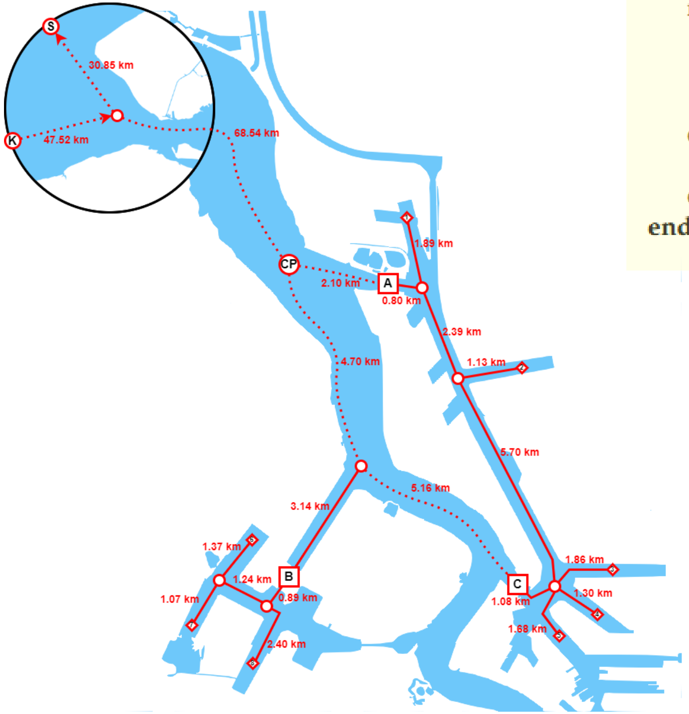
note: “real state” may not be observable, so may have to be estimated.

Caveat: model Validity

even large deviations in PoIs may **not** be **anomalies**

→ maybe the model is wrong (typically used outside its validity frame)



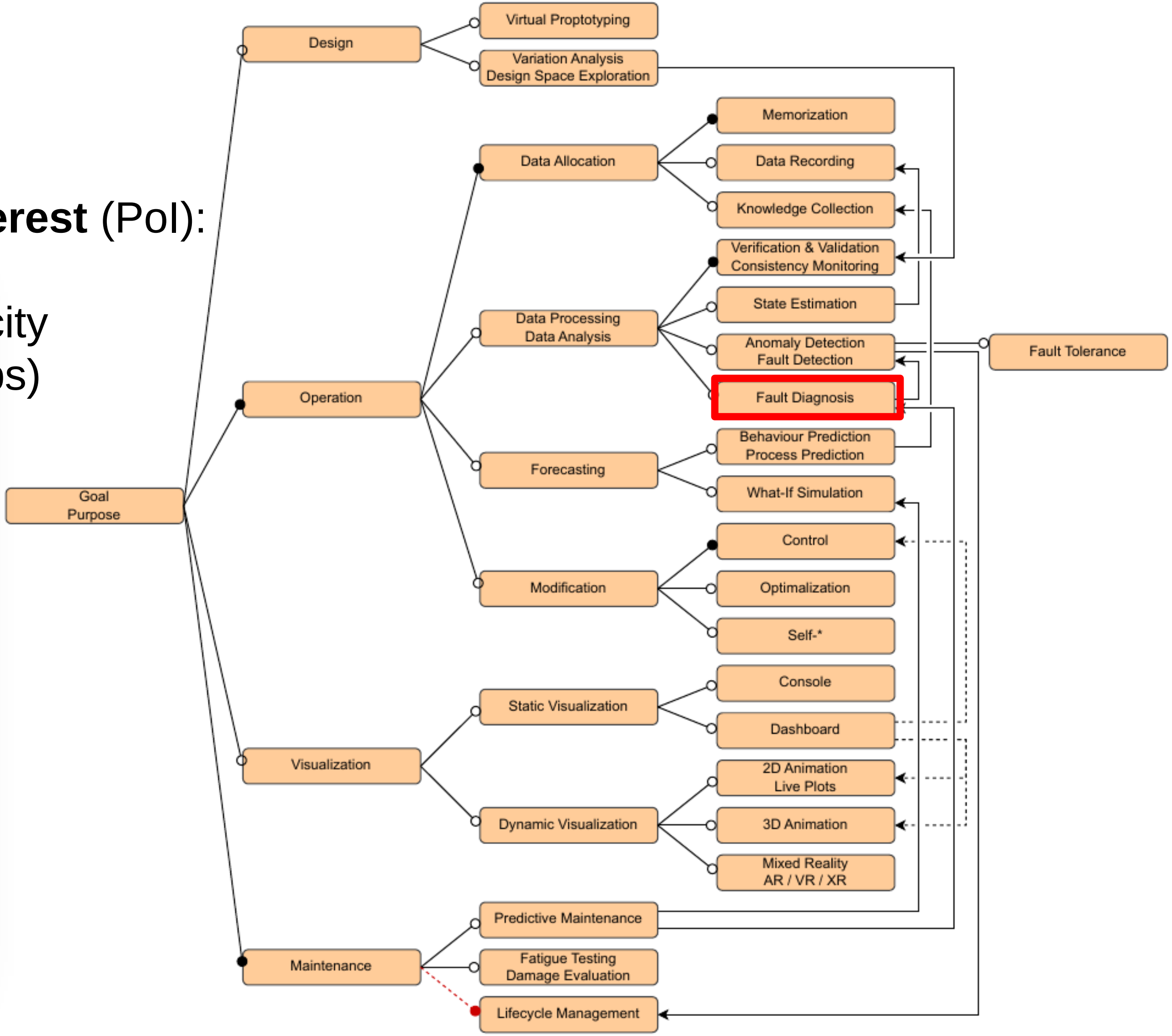


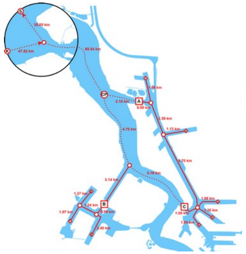
Anomaly Detection Algorithm

$D \leftarrow$ Drop-off value for the error.
$M \leftarrow$ Maximal allowed time above D.
$prev \leftarrow -1$
while system is running **do**
  $occ_A \leftarrow$ Occupancy value of the AO.
  $occ_T \leftarrow$ Occupancy value of the TO.
  $T \leftarrow$ Current execution time.
  $error \leftarrow |occ_A - occ_T|$
  if $prev > 0$ and $T - prev > M$ **then**
    Raise an anomaly.
  end if
  if $error > D$ **then**
    if $prev < 0$ **then**
      $prev \leftarrow T$
    end if
  else
    $prev \leftarrow -1$
  end if
end while

Goal Selection:
Fault Diagnosis

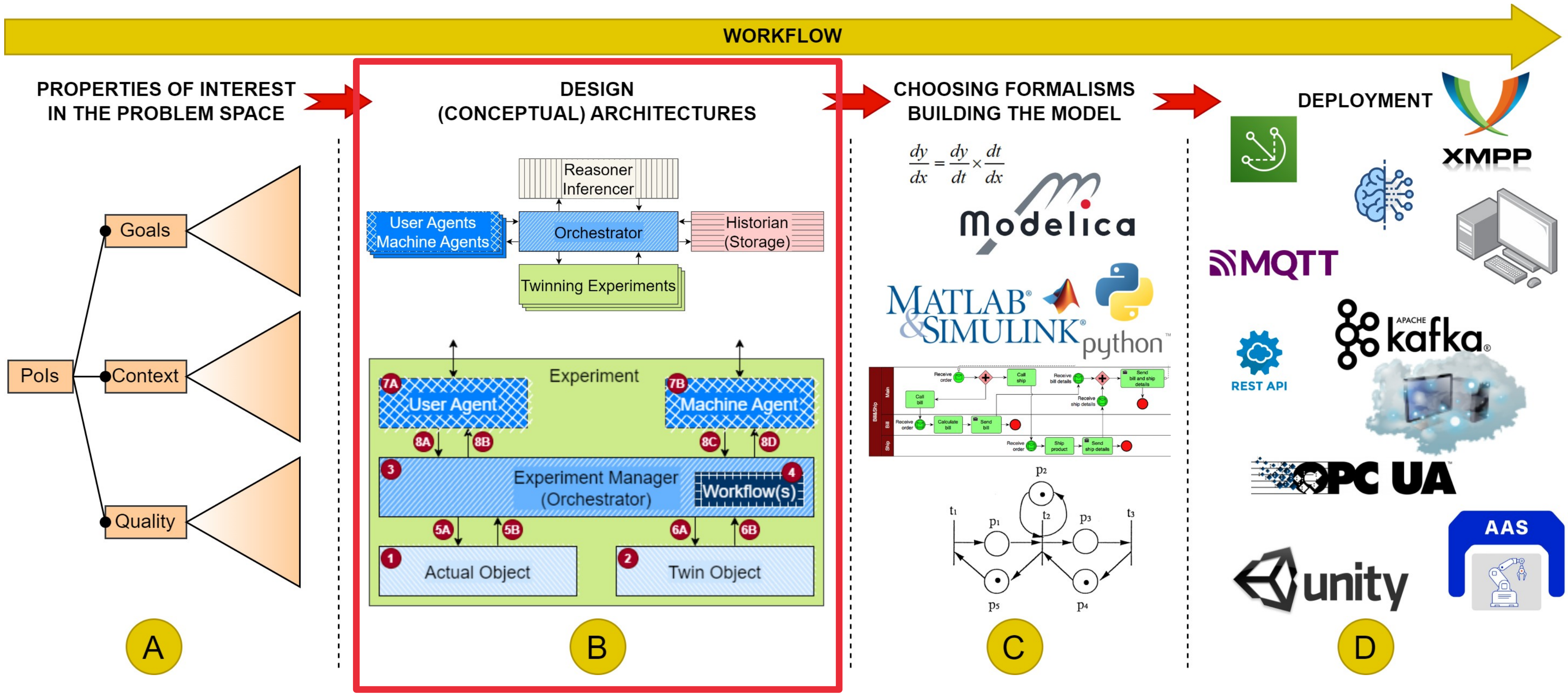
Property of Interest (PoI):
occupancy ~
remaining capacity
(for docking ships)





R. Paredis and H.Vangheluwe. 2024. “*Modelling and Simulation-Based Evaluation of Twinning Architectures and Their Deployment*”. In Proceedings of SIMULTECH 2024, pp. 170-182.

Stages of Twinning – Architecture Selection



Goal Selection:
Fault Diagnosis

Property of Interest (PoI):
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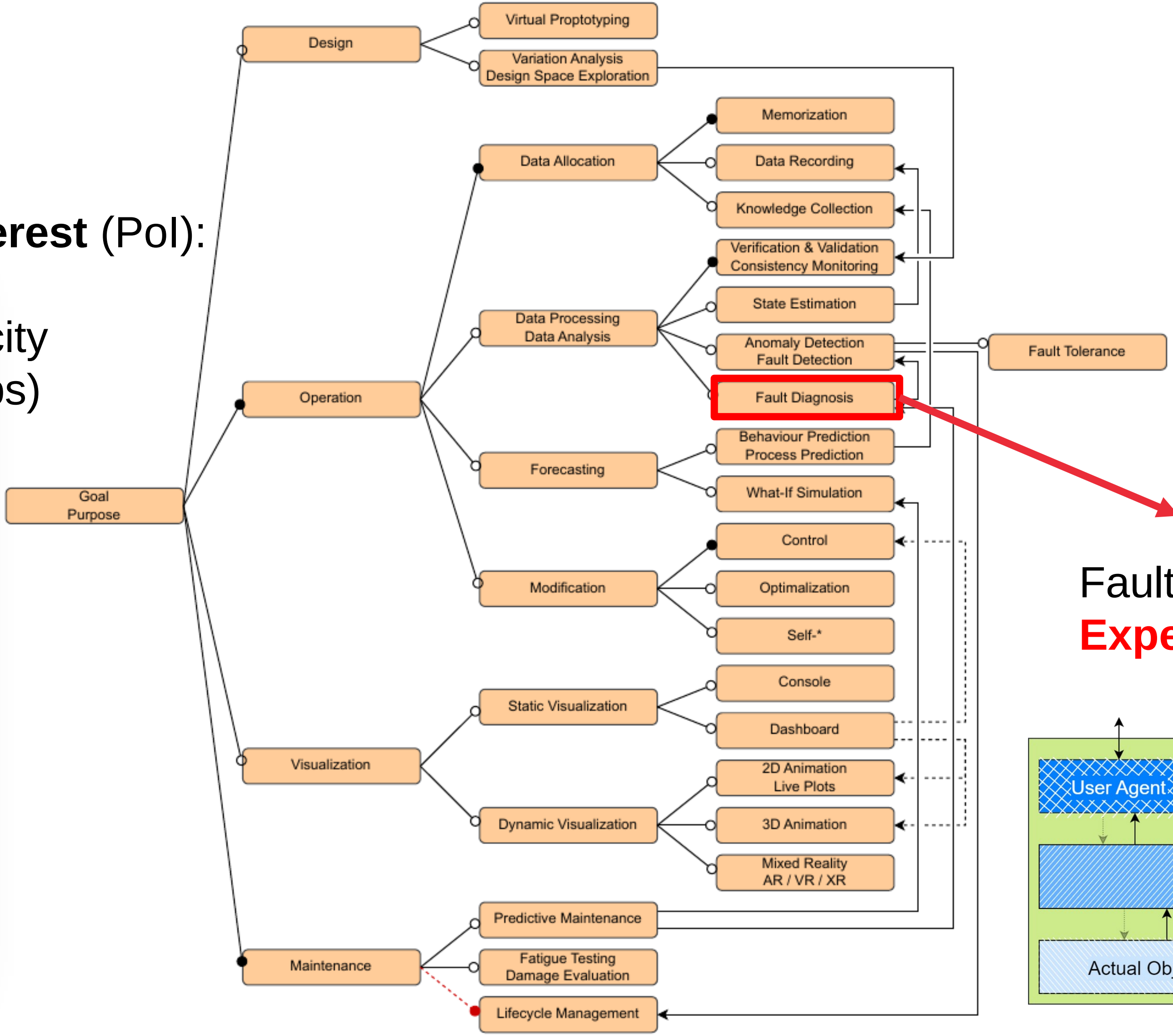
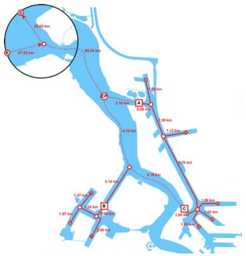
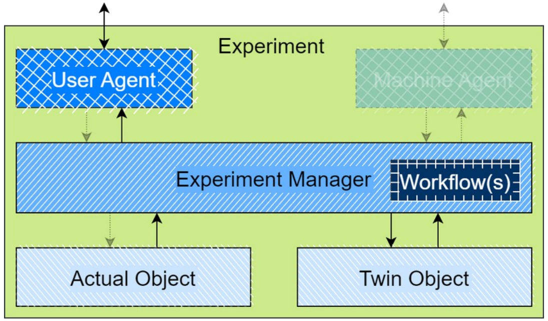


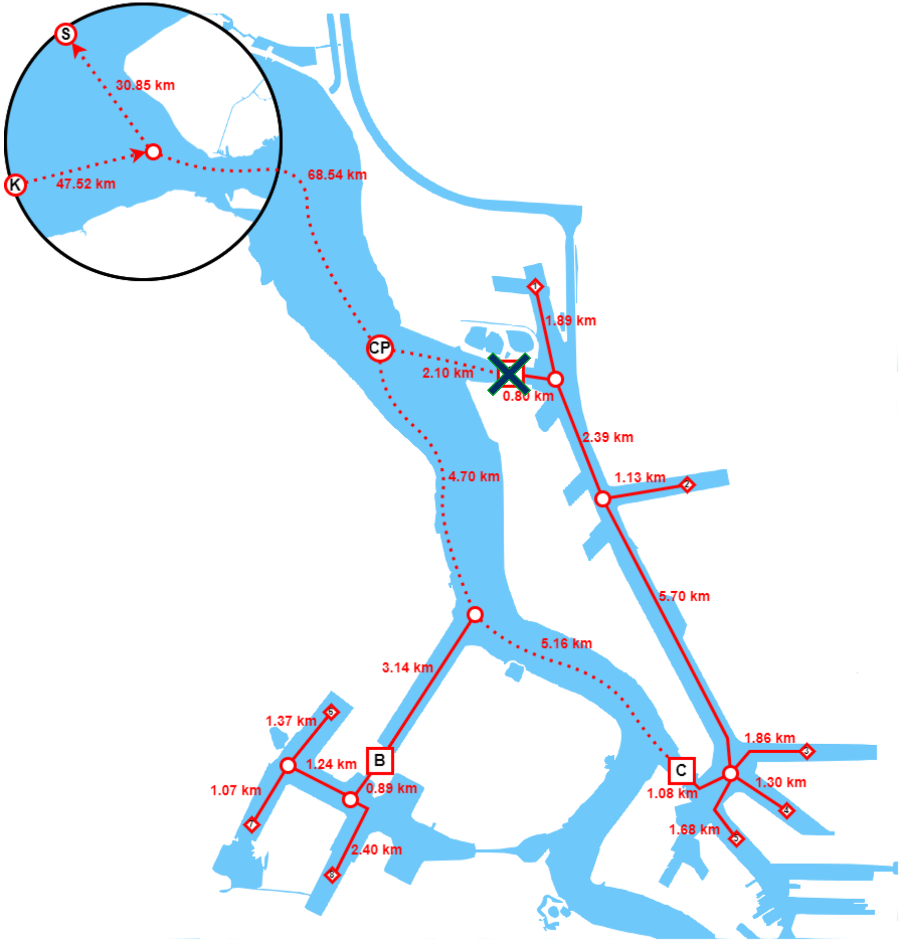


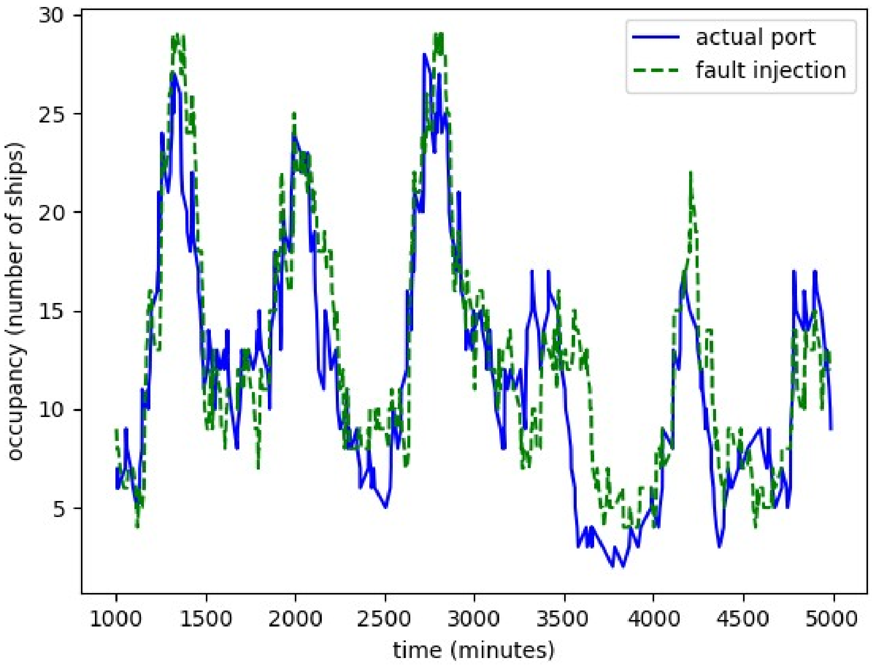
Fault Diagnosis
Experiment



Injected Fault: lock A failure

DTW Score = 317
NDW Score = 437.25



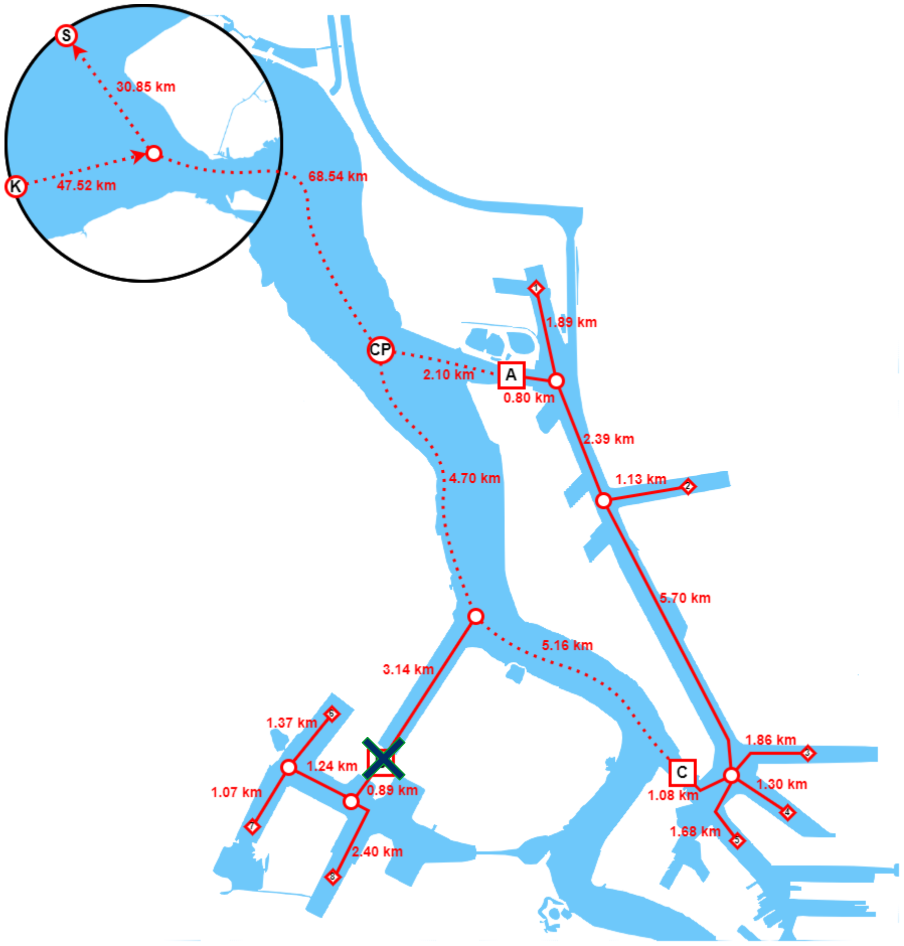


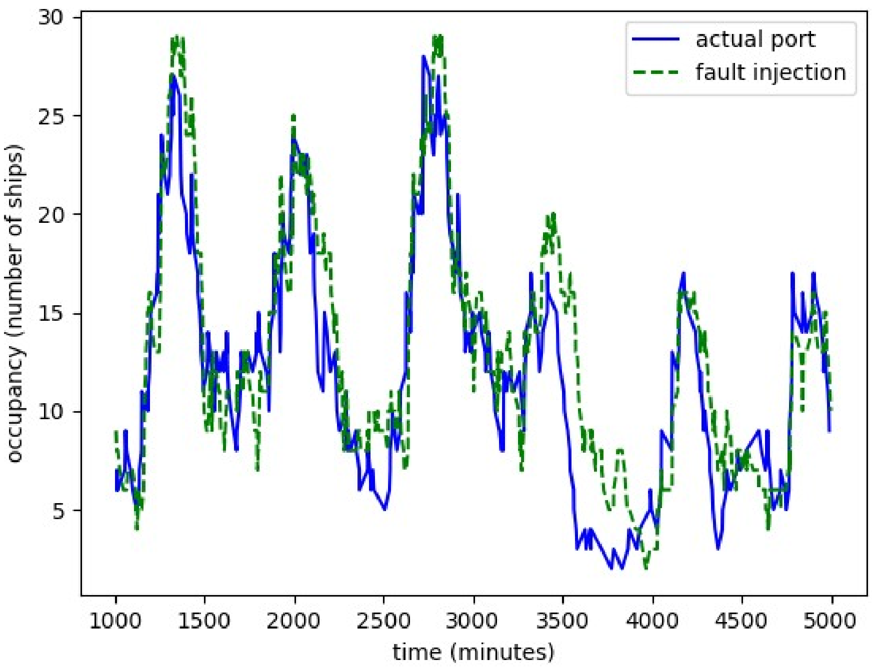
P. Muñoz, M. Wimmer, J. Troya, and A. Vallecillo. 2024. *Measuring the **Fidelity** of a Physical and a Digital Twin Using Trace Alignments*. In IEEE TSE, pp. 3122-3145.

Injected Fault: lock B failure

DTW Score = 288

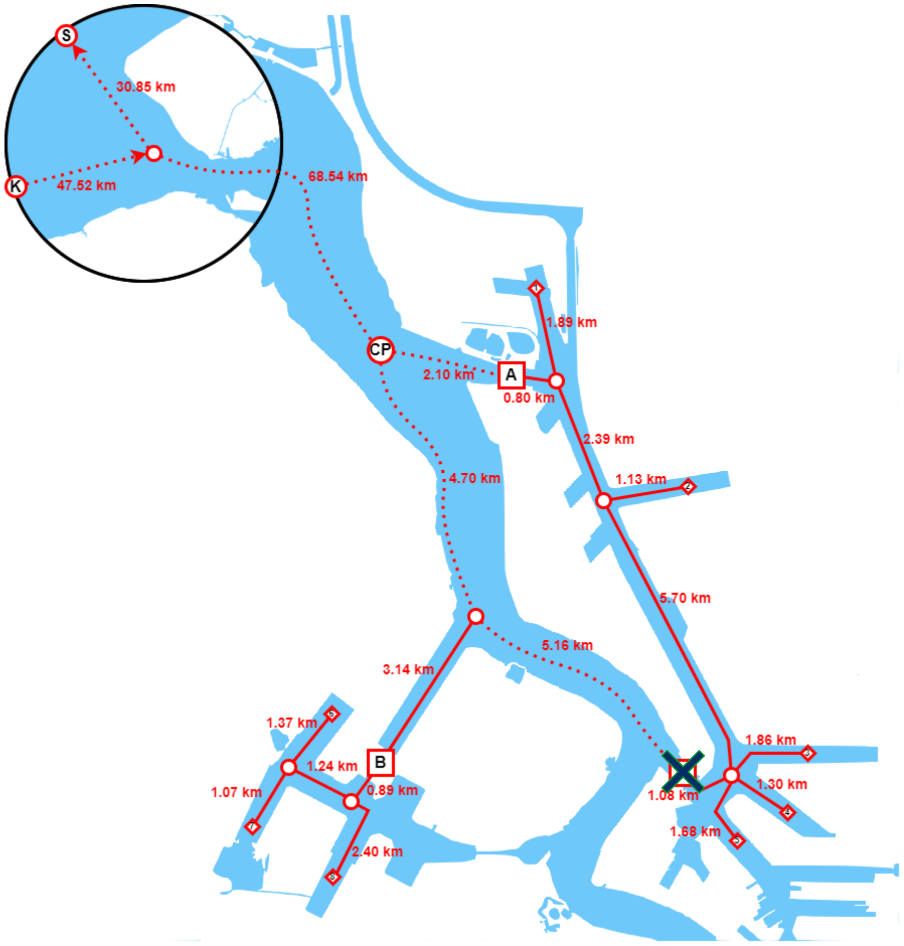
NDW Score = 436.91

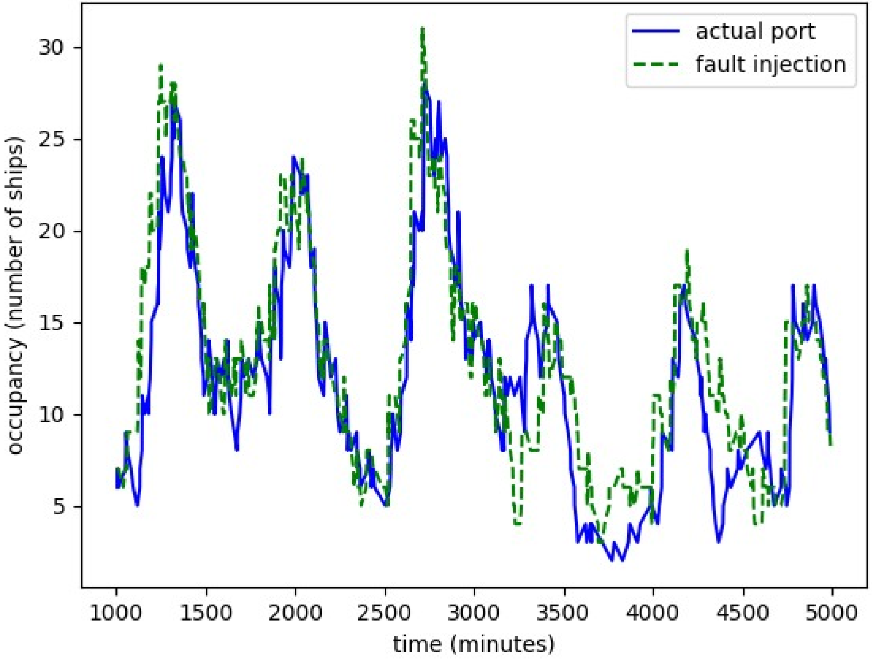




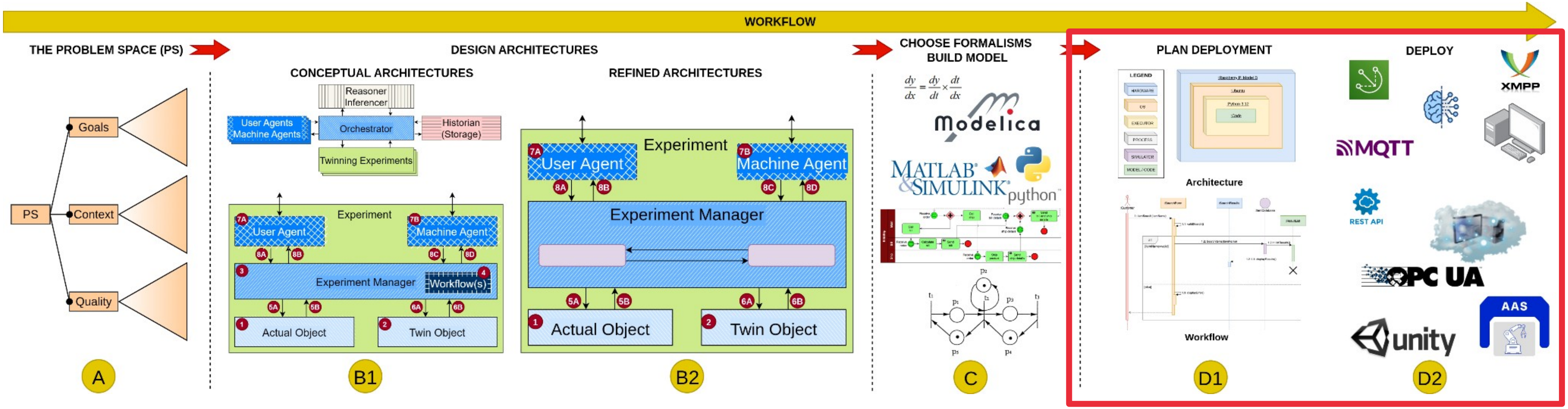
Injected Fault: lock C failure – **best match**

DTW Score = 252
NDW Score = 433.66



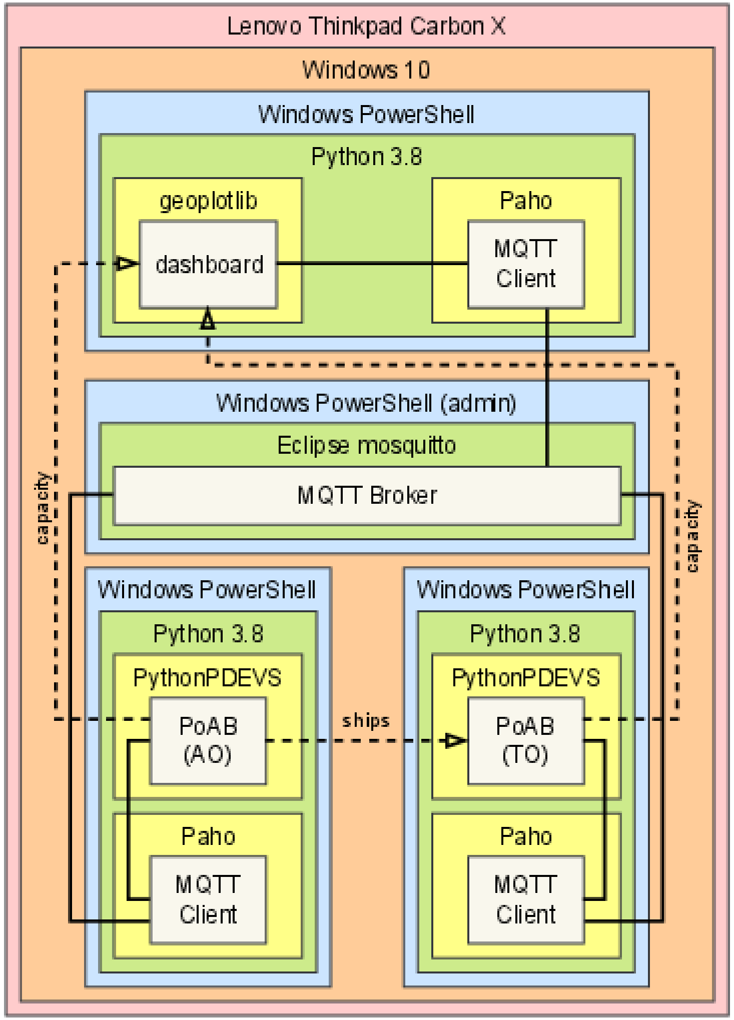


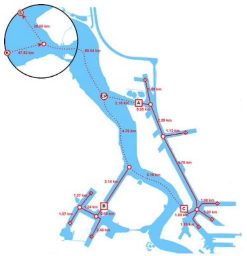
Stages of Twinning – Deployment



Deployment

For each element in the conceptual architecture, choose **technology** and **map**

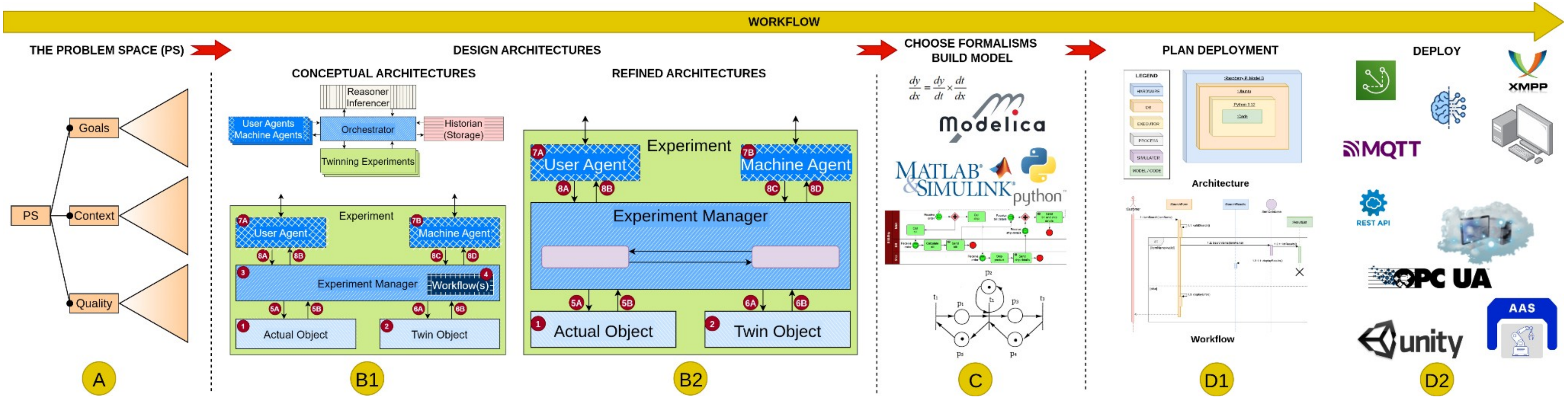




Note: use **simulation** for **performance evaluation** of deployment alternatives. Cfr. Palladio and

Paredis R, Vangheluwe H; INSTICC. Modelling and Simulation-Based Evaluation of Twinning Architectures and Their Deployment. Proceedings of the 14th International Conference on Simulation and Modeling Method- ologies, Technologies and Applications (SIMULTECH). 2024:170-82

Stages of Twinning



Next Goal(s)

Once the fault has been identified:

Explore fixes:

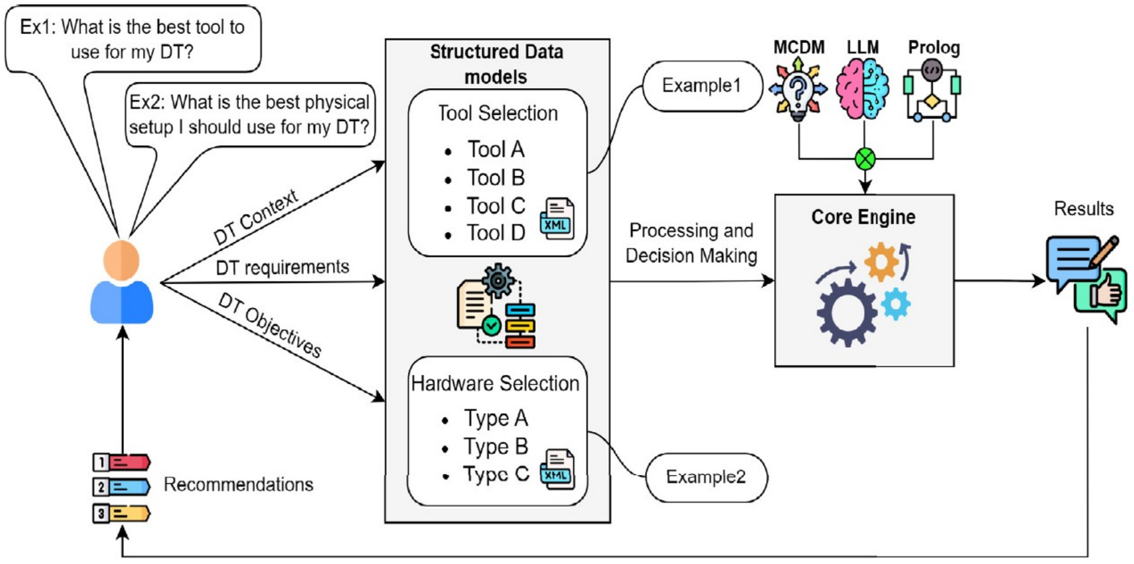
- using rules
- using Design-Space Exploration techniques and as-fast-as-possible simulation

In case of early detection of anomalies:

Schedule predictive maintenance

Decision Support

Hussein Marah, Barış Tekin Tezel, Moharram Challenger, Hans Vangheluwe.
TwinCompass: A multi-criteria and hybrid reasoning decision support framework for Digital Twin engineering in Cyber–Physical Systems.
Journal of Industrial Information Integration, Volume 52, 2026.



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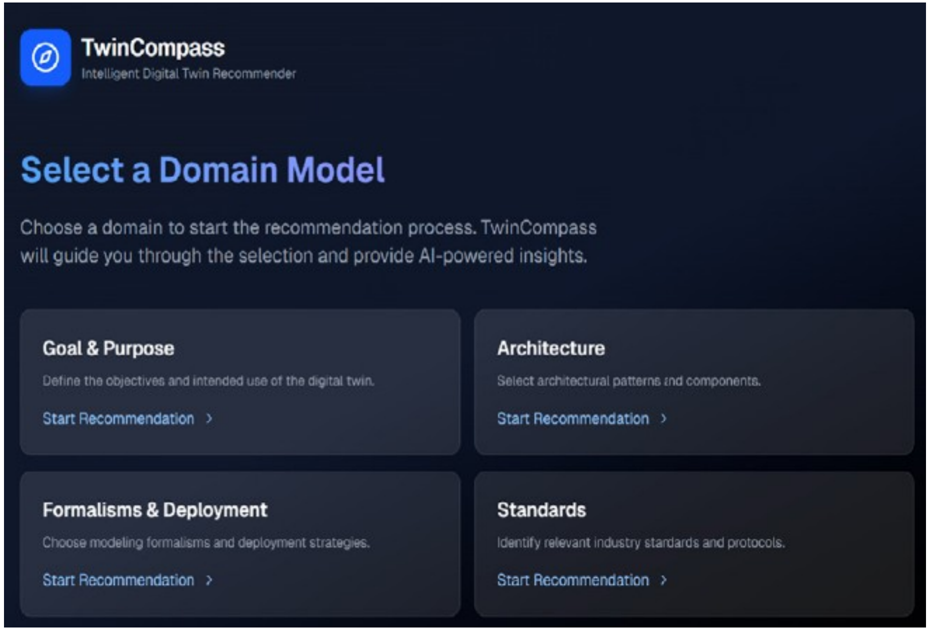

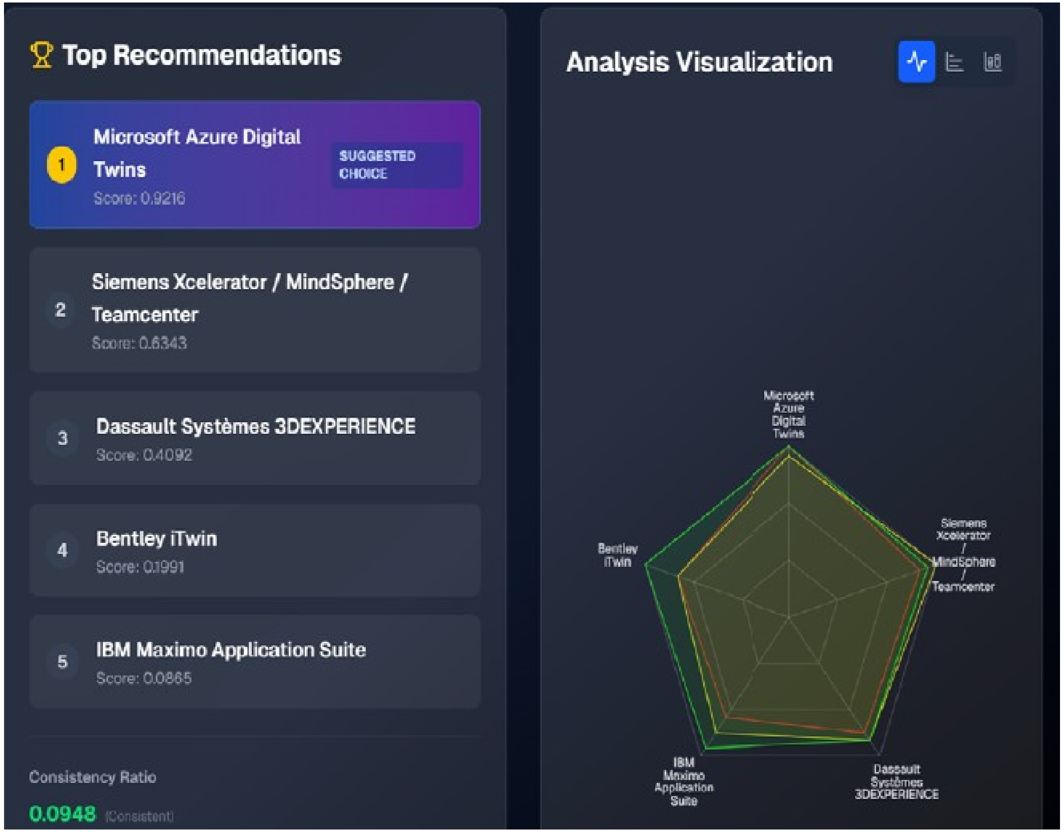

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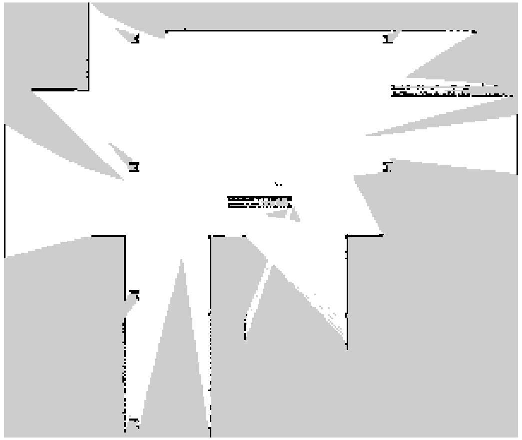
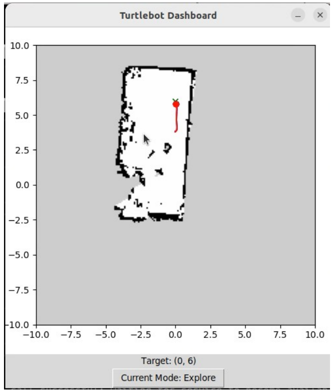
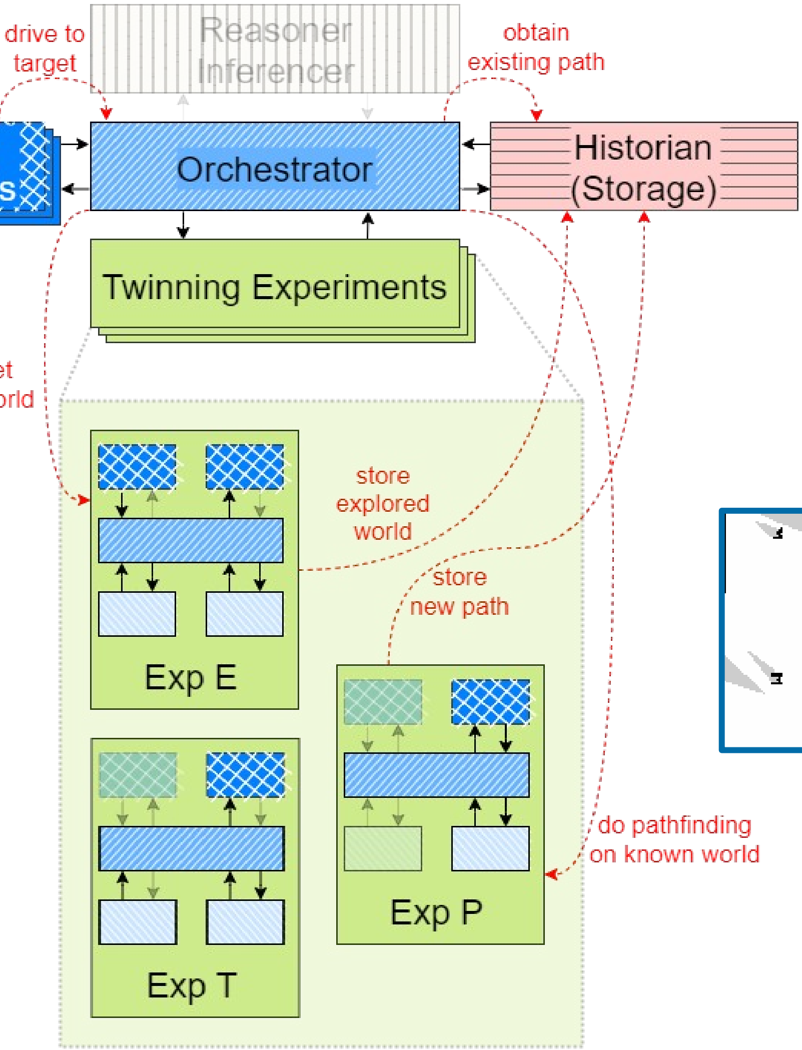
Journal of Industrial Information Integration, Volume 52, 2026.

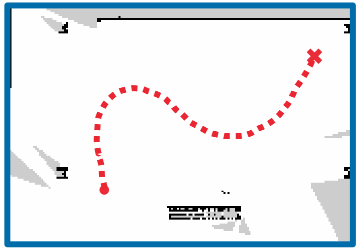
Combining Multiple Twinning Architectures
(in an ecosystem)

Multiple Twins Federation









Combining/Composing (federating?) Twinning Experiments

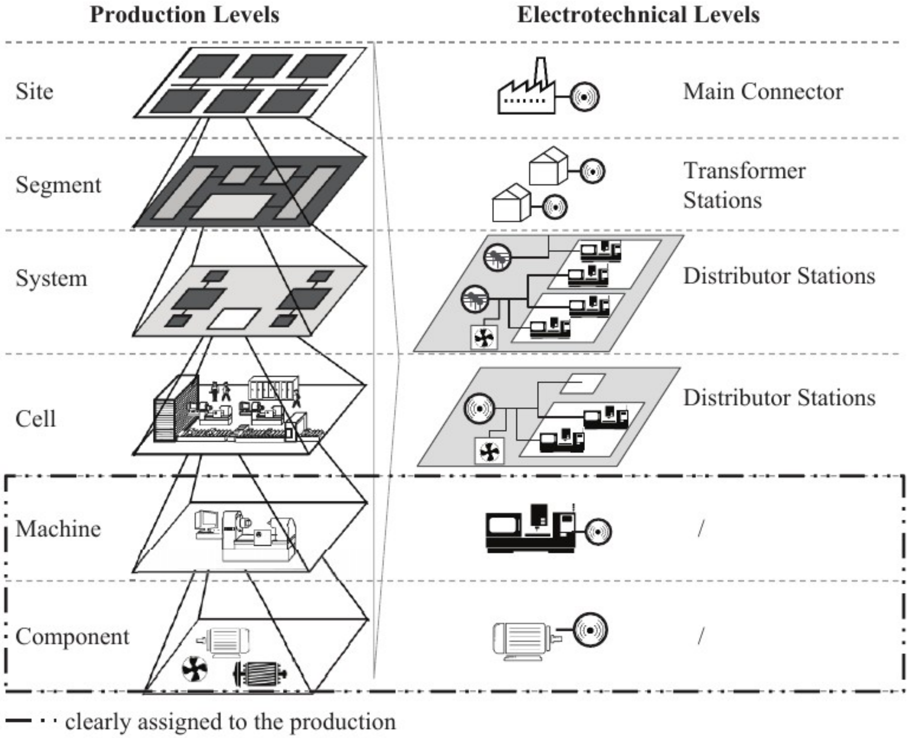
White-box: conceptual architectures may be “merged” before deployment

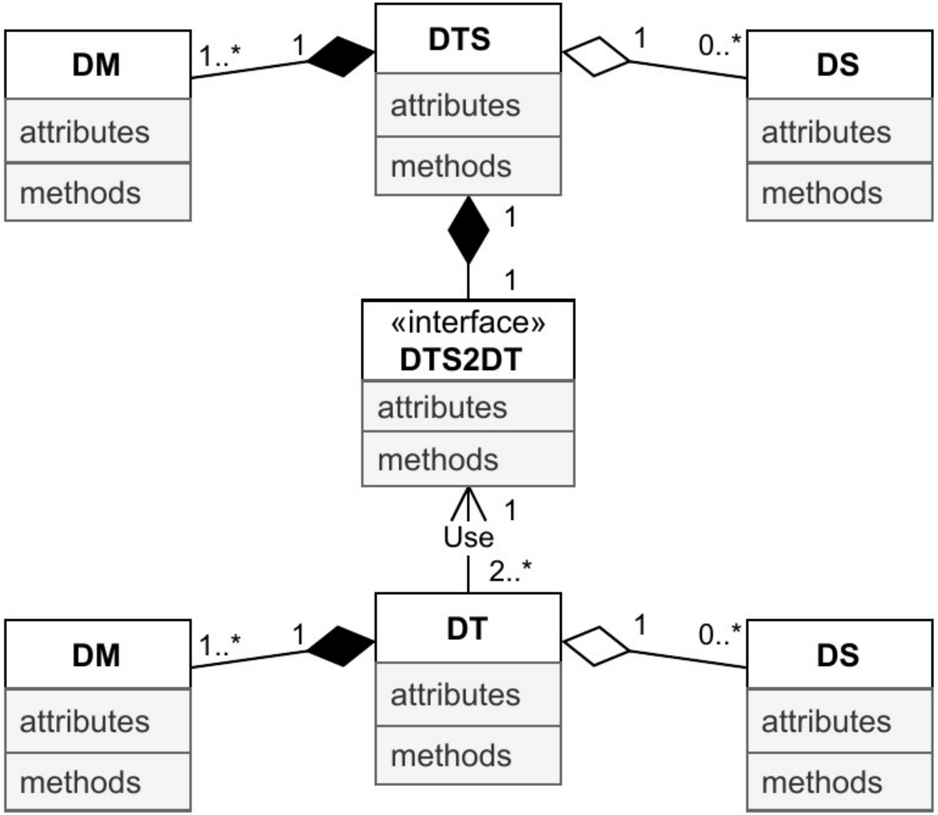
vs.

Black-box: deployed Twinning architectures are “orchestrated”

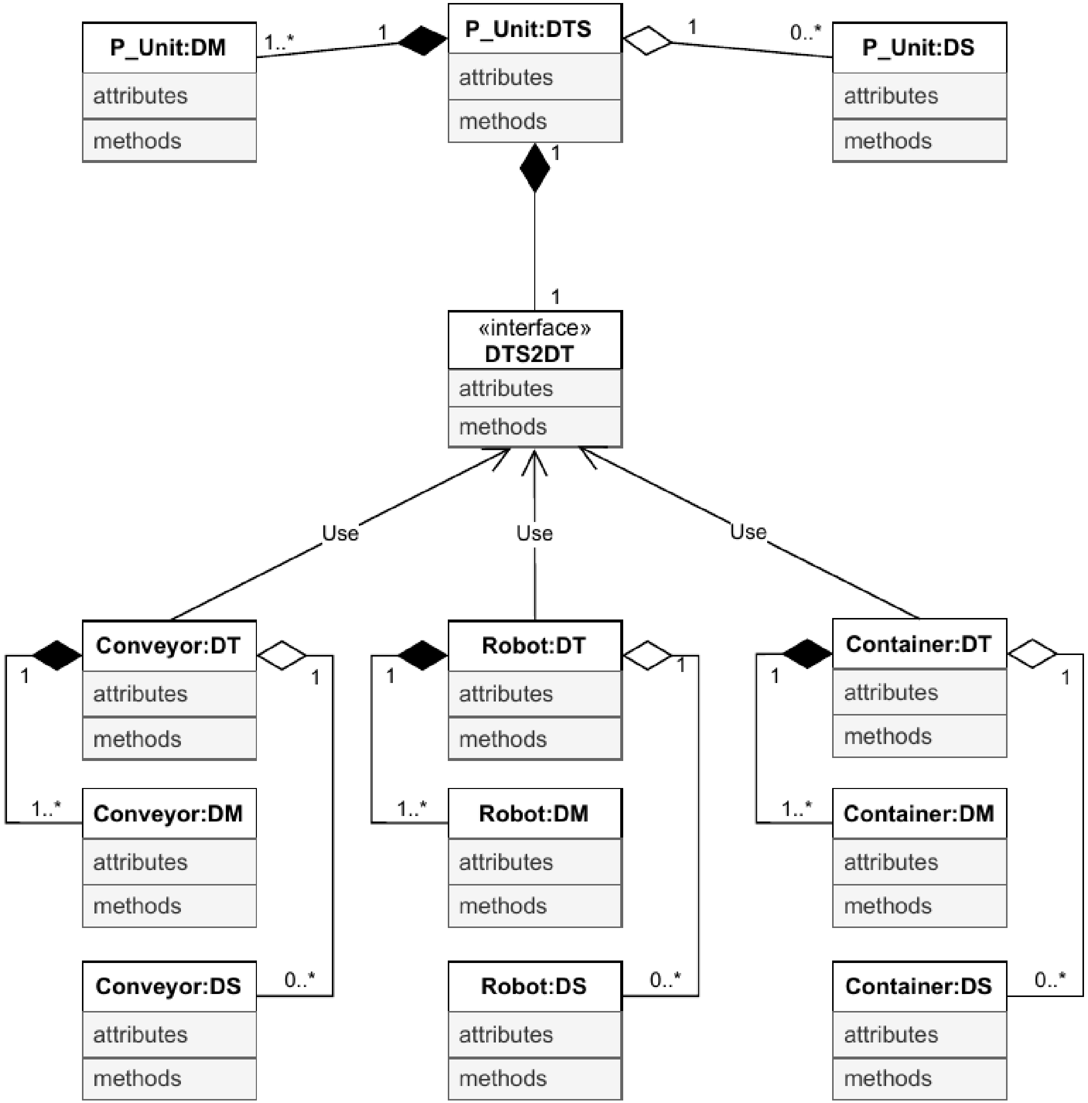
Example:

Hierarchical architecture to mimimic hierarchy in application domain

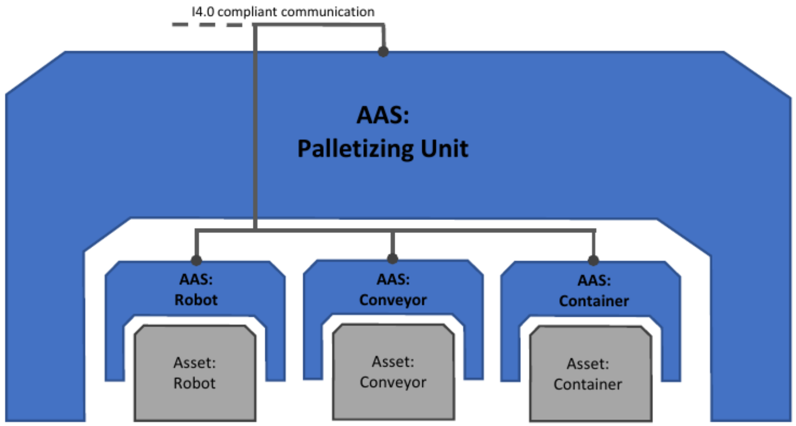




Leif-Thore Reiche, Claas Steffen Gundlach, Gian Frederik Mewes and Alexander Fay. *The Digital Twin of a System: A Structure for Networks of Digital Twins*.
In 2021 26th IEEE International Conference on Emerging Technologies and Factory Automation (ETFA). IEEE Press, pp. 1 – 8. https://doi.org/10.1109/ETFA45728.2021.9613594

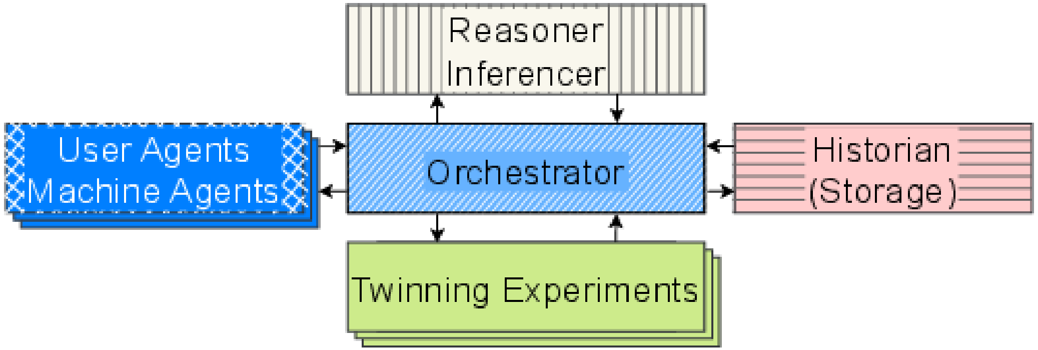


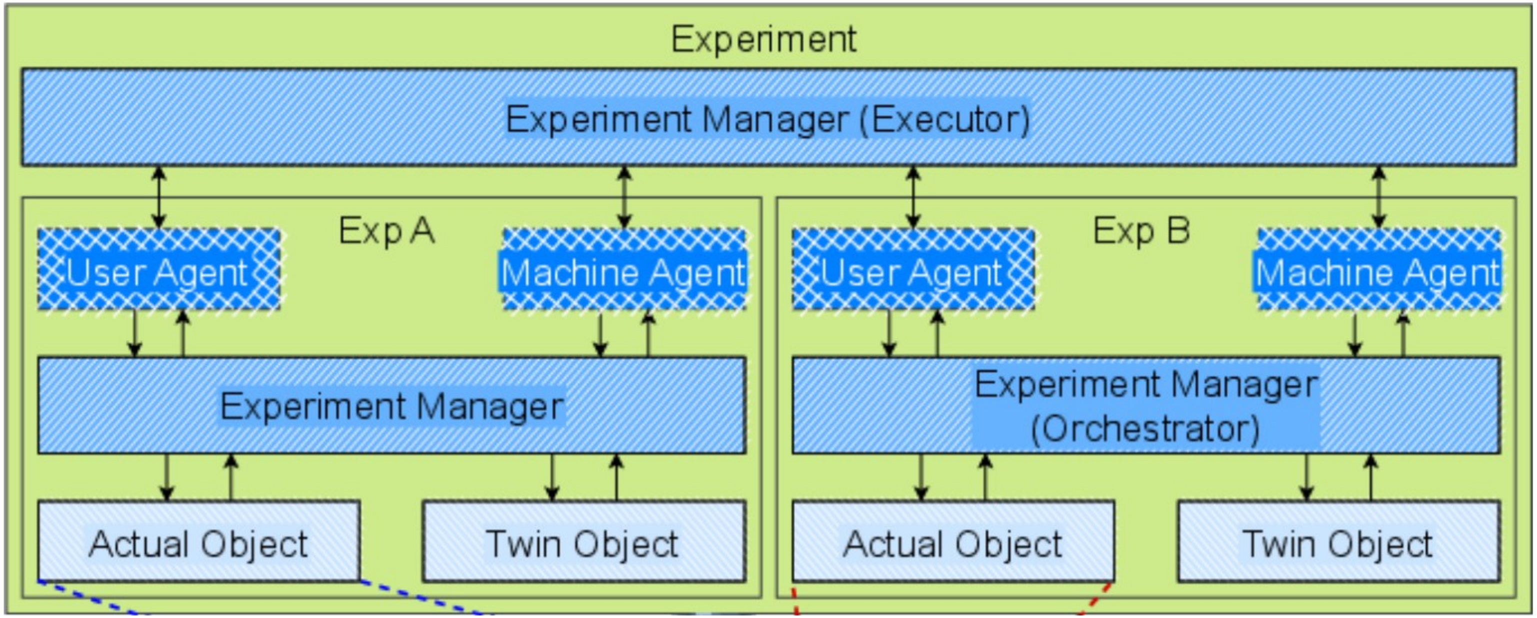
Deployment using the Asset Administration Shell (AAS)



Twinning Architectures may be **combined**.

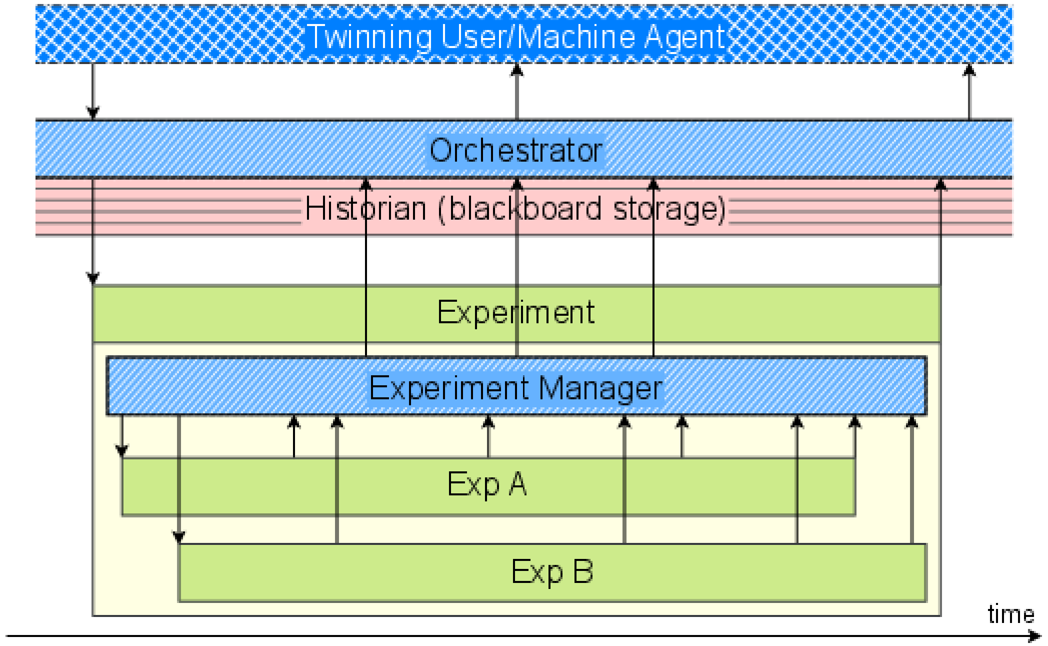
(conceptual) **Architectural View**.





Twinning Architectures may be **combined**.

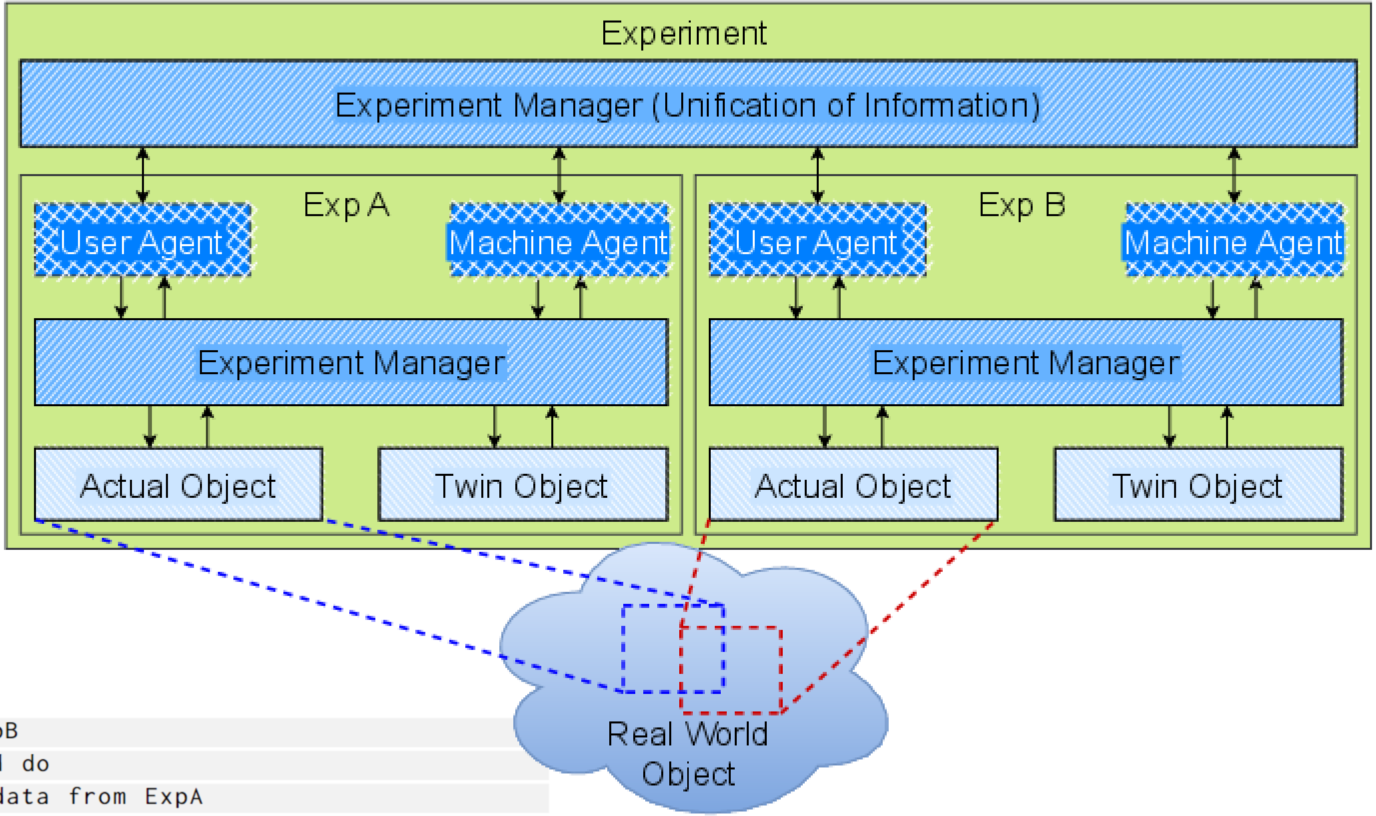
Temporal View.



Starting point for discussion:

Different types of **Combinations** of **Twinning Architectures** (each corresponding to specific Goal)

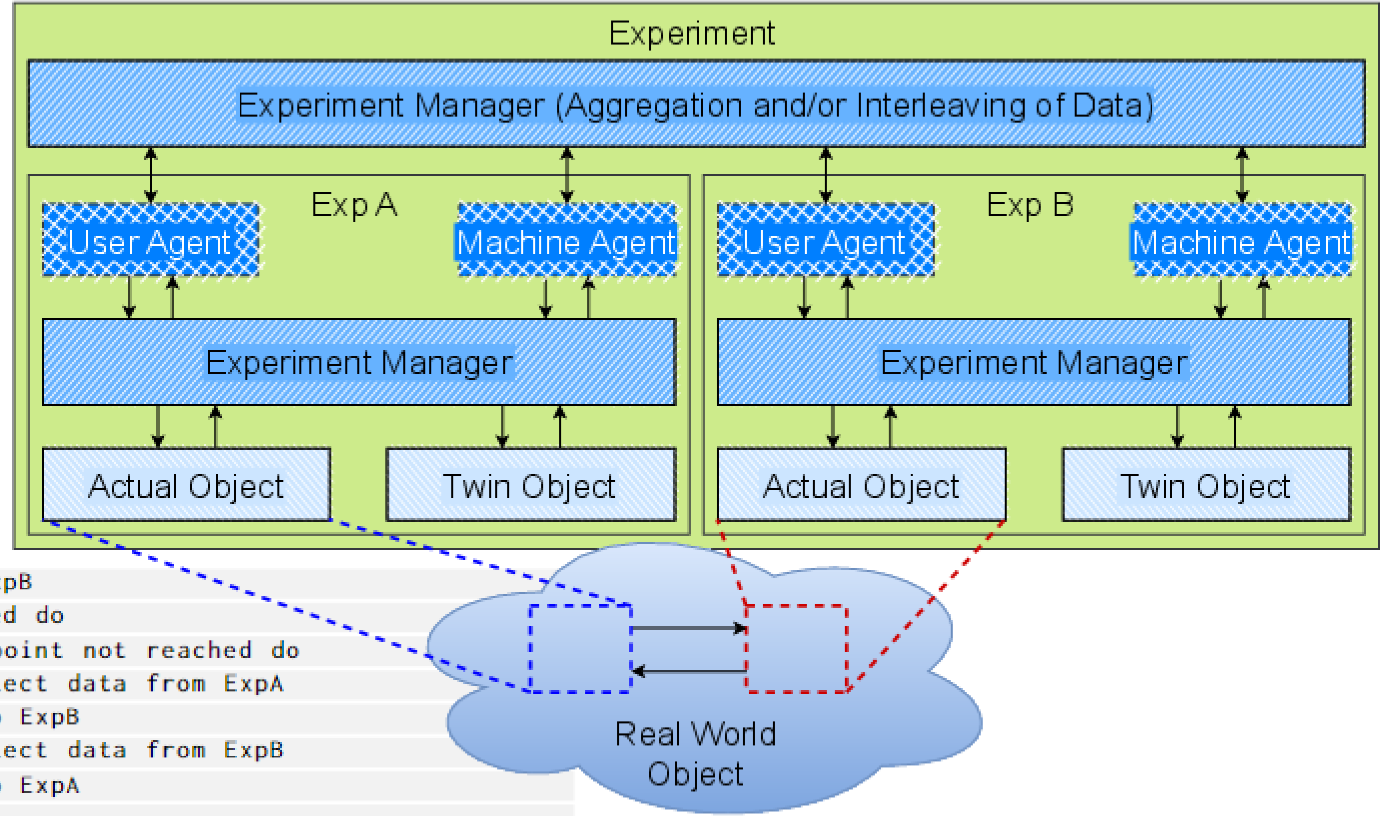
Multiple Twinning Architectures, each
corresponding to **different (possibly overlapping) aspects** (multi-view/PoI) of the **same SuS**.
Experiment manager **unifies (and checks consistency between)** the information obtained from the different Twinning Architectures.




```
start ExpA and ExpB
while not finished do
    A := collect data from ExpA
    B := collect data from ExpB
    yield union of A and B
done
```

Pseudocode for EM with multiple PoIs.

Multiple Twinning Architectures, each
corresponding to a **component** in an architecture. Components interact with/depend on each other.
Experiment manager **combines/interleaves** the component twins.
This combination might result in a set of **emergent PoIs** (i.e., not obtainable from invididual components).

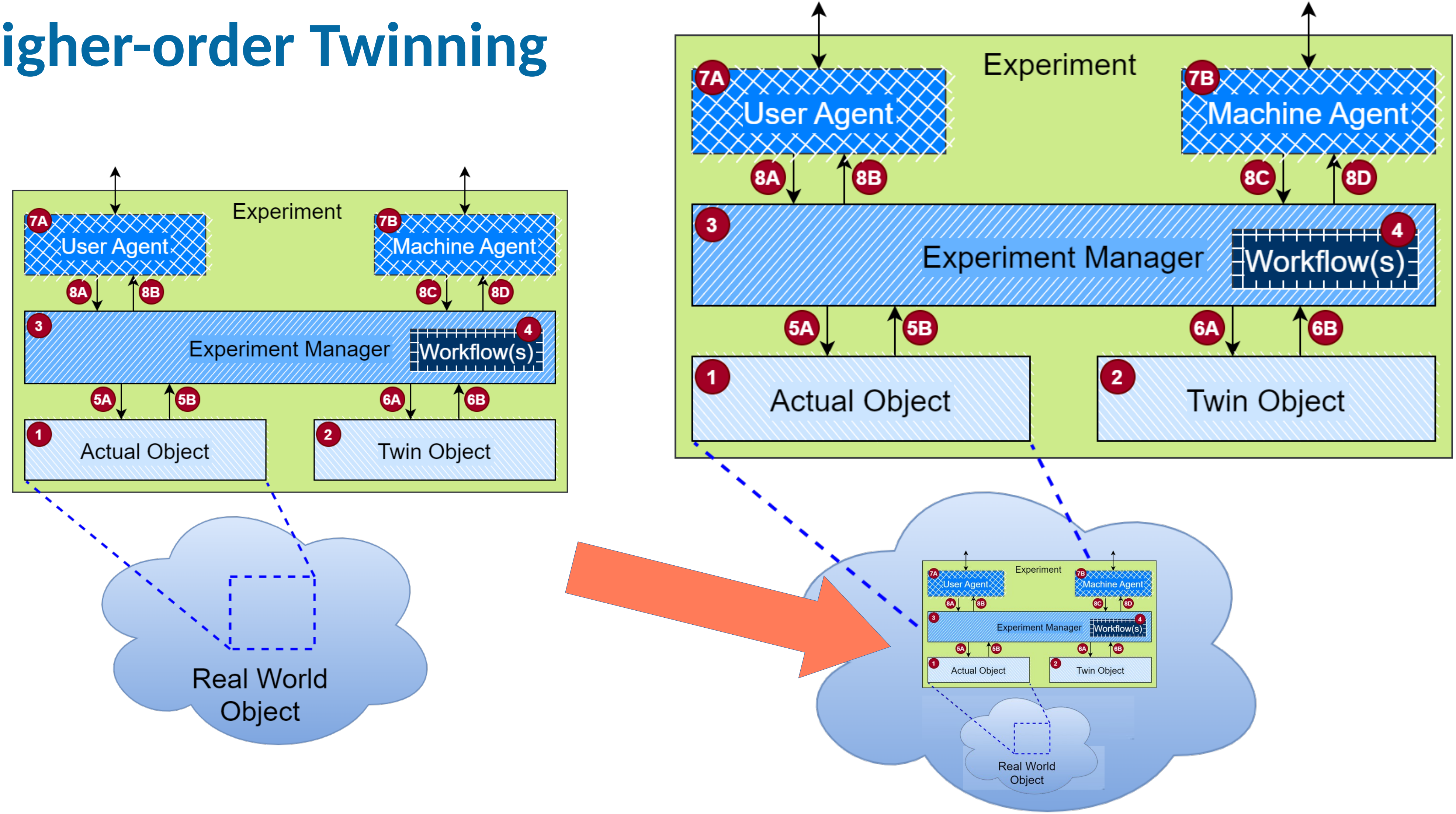



```
start ExpA and ExpB
while not finished do
    while fixed point not reached do
        A := collect data from ExpA
        send A to ExpB
        B := collect data from ExpB
        send B to ExpA
    done
    yield aggregate(A, B)
done
```

: **Pseudocode for EM for dependent TEs.**

~ **orchestration in co-simulatio**n, cfr.
Cláudio Gomes, Casper Thule, David Broman, Peter Gorm Larsen, Hans Vangheluwe:
Co-Simulation: A Survey. ACM Comput. Surv. 51(3): 49:1-49:33 (2018)

Higher-order Twinning



Topic	Challenges	MDE BoK	Action Items
Guidelines and Standards	Ad-hoc development	Modeling languages, model transformations, reference models	Contextualization for digital twin domains with domain experts
Interoperability	Integration complexity due to heterogeneous artefacts, different stakeholders, heterogenous views	Interchange formats, model transformations, code generation, interoperability models **ontologies**	Formalizing structures currently used in specific domains for realizing bidirectional mappings between different digital twin implementation approaches
Multi-paradigm/ Multi-view	System complexity and heterogeneous domain knowledge and needs	Multi-paradigm modeling/multi-viewpoint modeling frameworks including concepts, methods, and tools	Efficient methods to define multiple views on digital twins with consistency ensurance between different views, abstraction levels, etc.
Evolution	Time complexity due to changing realities and long lifetimes	Model evolution and co-evolution approaches, change types, change impact, and repairs	Continous evolution support for running digital twins/actual systems, change categorizations for digital twins and consistency requirements
Continuous Engineering	Costs, system complexity and heterogeneous domain expert backgrounds, gap between design and operation	Model-based DevOps based on models@runtime techniques and tools **design(-space exploration) @ runtime**	Abstraction levels for digital twin data and scalable models@runtime to deal with long-living systems, feedback methods from operation to design
Composition of Digital Twins	Information complexity due to heterob~~e~~genous data and models	Model/modeling language composition operators and theories **co-simulation/agent orchestration**	Development of language support for composing digital twins (both during design-time and runtime)

J. Michael, L. Cleophas , S. Zschaler , et al. “Model-Driven Engineering for Digital Twins: Opportunities and Challenges.” Systems Engineering 28, no. 5 (2025), 659–670. https://doi.org/10.1002/sys.21815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