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A Multi-Paradigm Modelling Foundation for Twinning

Within the Context of Systems Engineering

Randy Paredis

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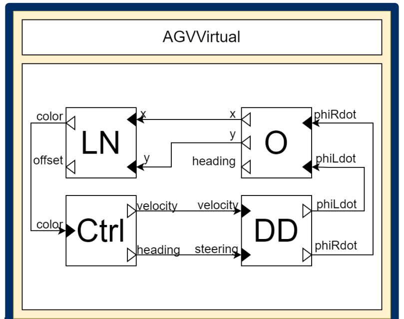
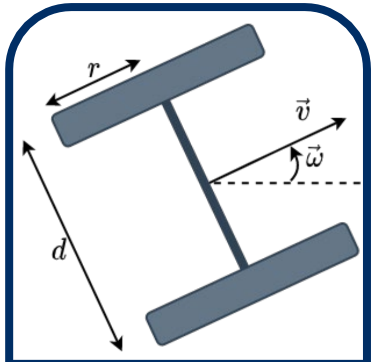


Causal Block Diagram

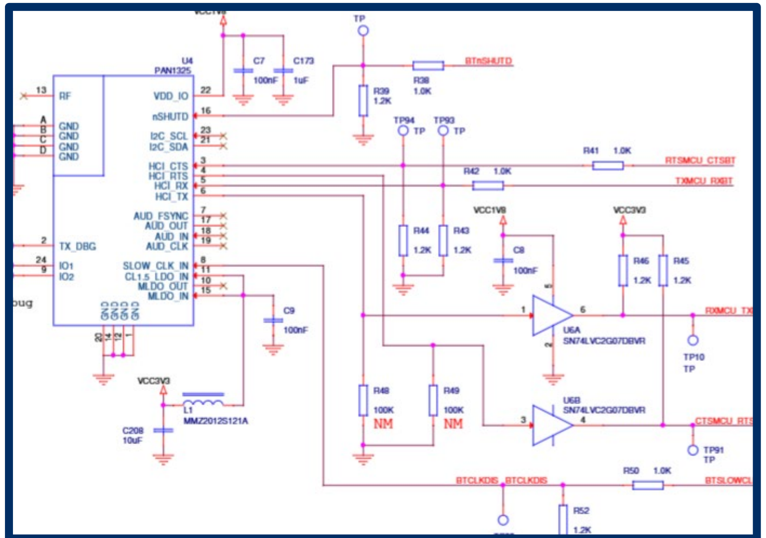
$$\dot{\phi}_L = \frac{1}{r}\left(\dot{v} - \frac{\dot{\omega} \cdot d}{2}\right)$$

$$\dot{\phi}_R = \frac{1}{r}\left(\dot{v} + \frac{\dot{\omega} \cdot d}{2}\right)$$

Kinematic model as ODEs



Kinematic model as Free Body Diagram



Hardware Model as Electric Schematics

R. Paredis, and H.Vangheluwe. 2021. “*Exploring A Digital Shadow Design Workflow By Means Of A Line Following Robot Use-Case*”. In Proceedings of ANNSIM 2021.

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A Multi-Paradigm Modelling Foundation for Twinning Within the Context of Systems Engineering

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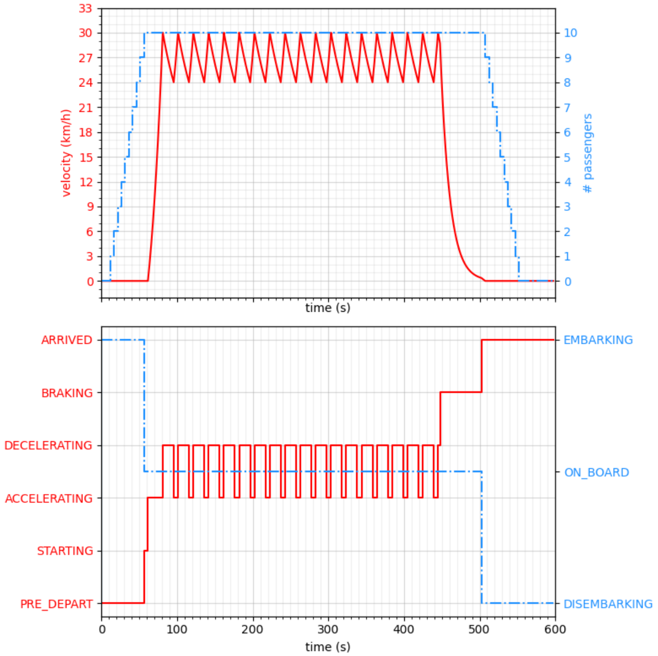
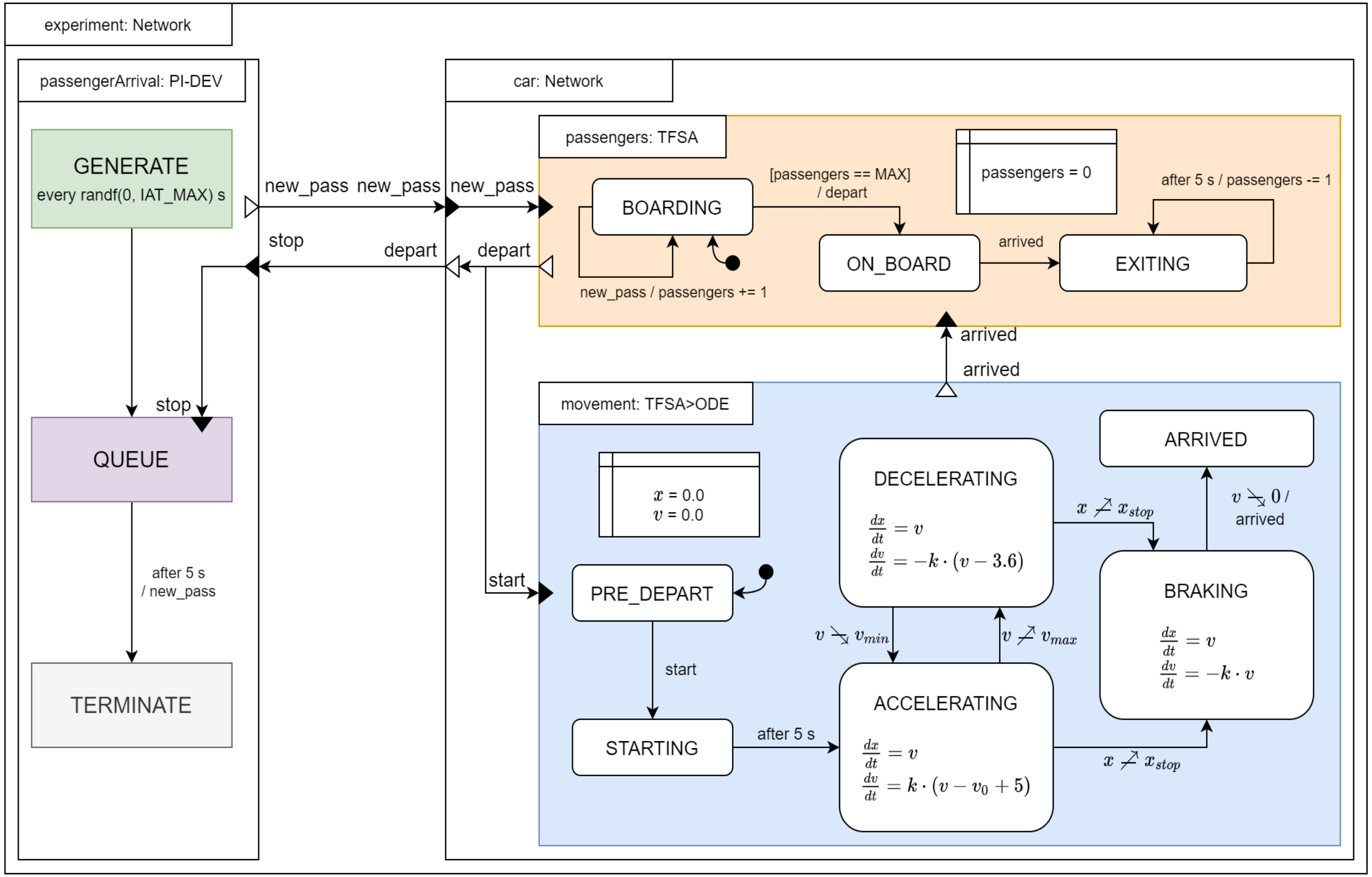
MPM: Using the most appropriate…





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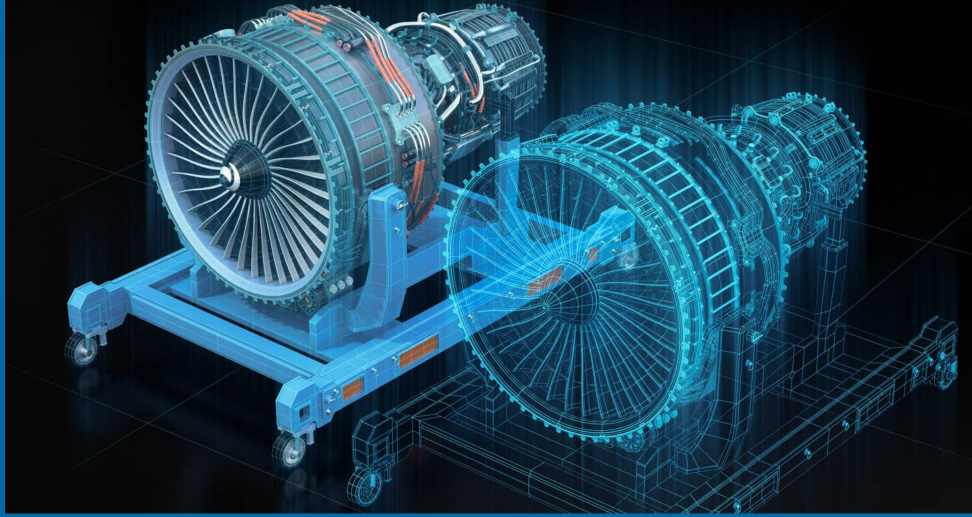
R. Paredis, J. Denil, and H.Vangheluwe. 2021. "*Specifying and Executing the Combination of Timed Finite State Automata and Causal-Block Diagrams by Mapping onto DEVS*". In Proceedings of WSC 2021.



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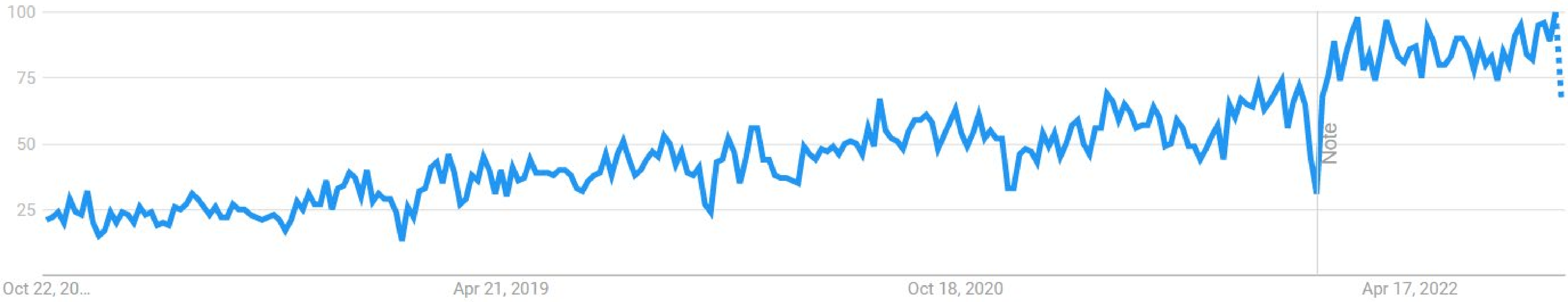
Digital Twin

Google Trends



1	China	100
2	Singapore	57
3	St. Helena	48
4	South Korea	47
5	Hong Kong	35

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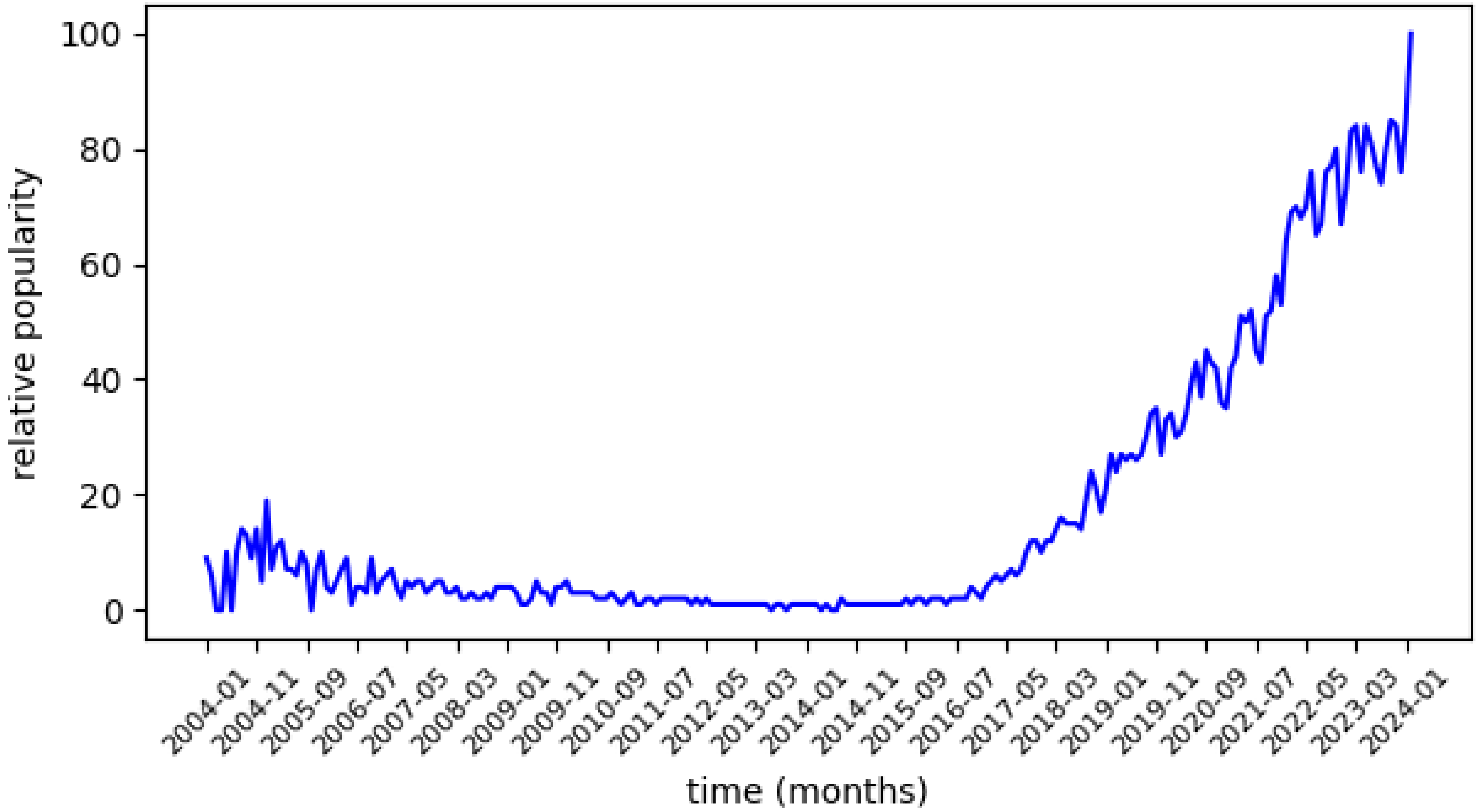
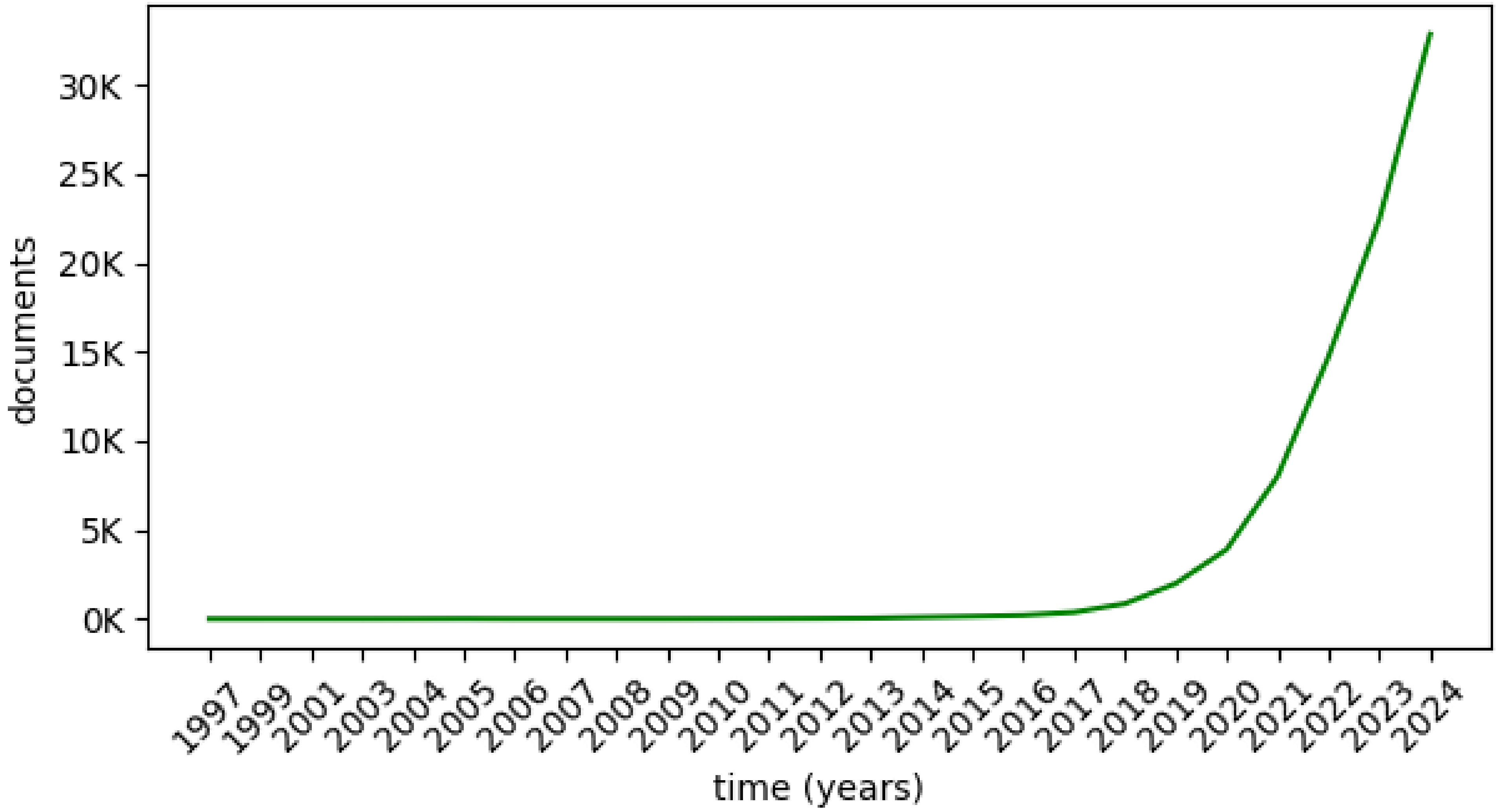
Results of Search Term “Digital Twin” of the Last 5 Years; Accessed October 20th 2022

Google Trends



Google Trends for the term “Digital Twin”, Accessed: 7 February 2024

Scopus



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

Digital Twin?

Digital Twins consist of three components, a physical product, a virtual representation of that product, and the bi-directional data connections that feed data from the physical to the virtual representation, and information and processes from the virtual representation to the physical. **[1]**

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. At its optimum, any information that could be obtained from inspecting a physical manufactured product can be obtained from its Digital Twin. **[2]**

Digital Twins are a virtual representation of the physical objects, processes and real-time data involved throughout a product life-cycle. **[3]**

A **Digital Twin** is an integrated multi-physics, multi-scale, probabilistic simulation of a vehicle or system that uses the best available physical models, sensor updates, fleet history, etc., to mirror the life of its flying twin. The digital twin is ultra-realistic and may consider one or more important and interdependent vehicle systems. **[5]**

A **Digital Twin** is an ultra-realistic virtual counterpart of a real-world object. **[4]**

A **Digital Twin** is a coupled model of the real machine that operates in the cloud platform and simulates the health condition with an integrated knowledge from both data driven analytical algorithms as well as other available physical knowledge. **[7]**

A **Digital Twin** is an ultra-realistic, cradle-to-grave computer model of an aircraft structure that is used to assess the aircraft's ability to meet mission requirements. **[6]**

Digital Twins is a unified system model that can coordinate architecture, mechanical, electrical, software, verification, and other discipline-specific models across the system lifecycle, federating models in multiple vendor tools and configuration-controlled. **[8]**

Digital Twins are software systems comprising data, models and services to interact with a CPPS for a specific purpose. **[9]**

… and many more!

[1] D. Jones et al. 2020. "*Characterising the Digital Twin: A systematic literature review*". In *CIRP Journal of Manufacturing Science and Technology*.
[2] M. Grieves. 2017. "*Digital Twin: Mitigating Unpredictable, Undesirable Emergent Behavior in Complex Systems*". In *Transdisciplinary Perspectives on Complex Systems*.
[3] W. D. Lin and M. Y. H. Low. 2019. "*Concept and implementation of a cyber-physical digital twin for a SMT line*". In *2019 IEEE International Conference on Industrial Engineering and Engineering Management (IEEM)*.
[4] H. Park et al. 2019. "*Challenges in Digital Twin Development for Cyber-Physical Production Systems*". In *Cyber-Physical Systems. Model-Based Design*.
[5] E. Glaessgen and D. Stargel. 2012. "*The digital twin paradigm for future NASA and U.S. Air Force vehicles*". In Proc. 53rd AIAA/ASME/ASCE/AHS/ASC Struct. Struct. Dyn. Mater. Conf.
[6] B. T. Gockel et al. 2012. "*Challenges with Structural Life Forecasting using Realistic Mission Profiles*". In *53rd AIAA/ASME/ASCE/AHS/ASC Struct. Struct. Dyn. Mater. Conf*.
[7] J. Lee. et al. 2013. "*Recent advances and trends in predictive manufacturing systems in big data environment*". In *Manufacturing Letter 1*.
[8] M. Bajaj, D. Zwemer and B. Cole. 2016. "*Integrating System Models with Architecture to Geometry*". In *AIAA Sp. Forum*.
[9] P. Bibow et al. 2020 "*Model-Driven Development of a Digital Twin for Injection Molding*". In *CAiSE 2020. LNCS*.

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-Salguerol, 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
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- "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
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- "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
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- "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
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- "An integrated model that represents, connects, and synchronizes a part of or the whole physical manufacturing system or process, enabled by historical and real-time data from the physical system or process". G.Shao, D. Kibira. Digital manufacturing: Requirements and challenges for implementing digital surrogates. In: Proceedings - Winter Simulation Conference, 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
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- "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
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- "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 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
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- "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 Machine Engineering, 2019
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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
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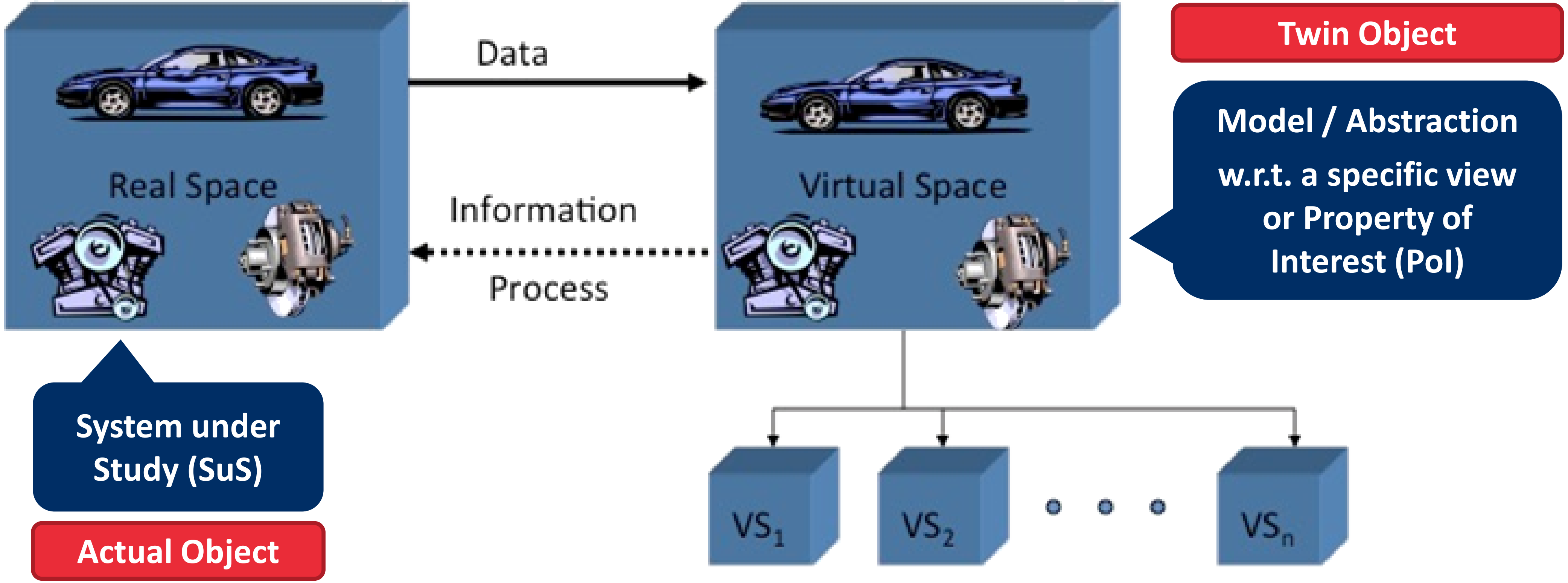
- "The new technology, accessing to realistic models of the current state of the process and their own behaviors in interaction with their environment in the real world is called the "Digital Twin". "Digital twin is an integrated multi-physics, multiscale and probabilistic simulation of a complex product 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 improved decision making.". D. Preuveneers, W. Joosen, E. Ilie-Zudor. Robust Digital Twin Compositions

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

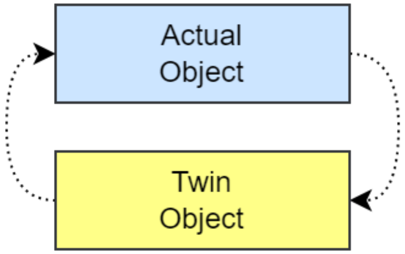
Conceptual Ideal for PLM

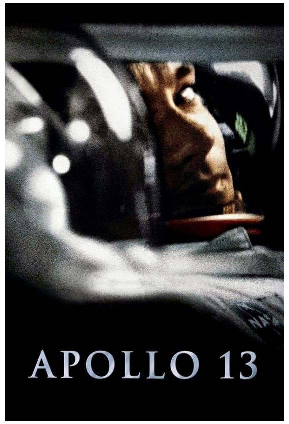


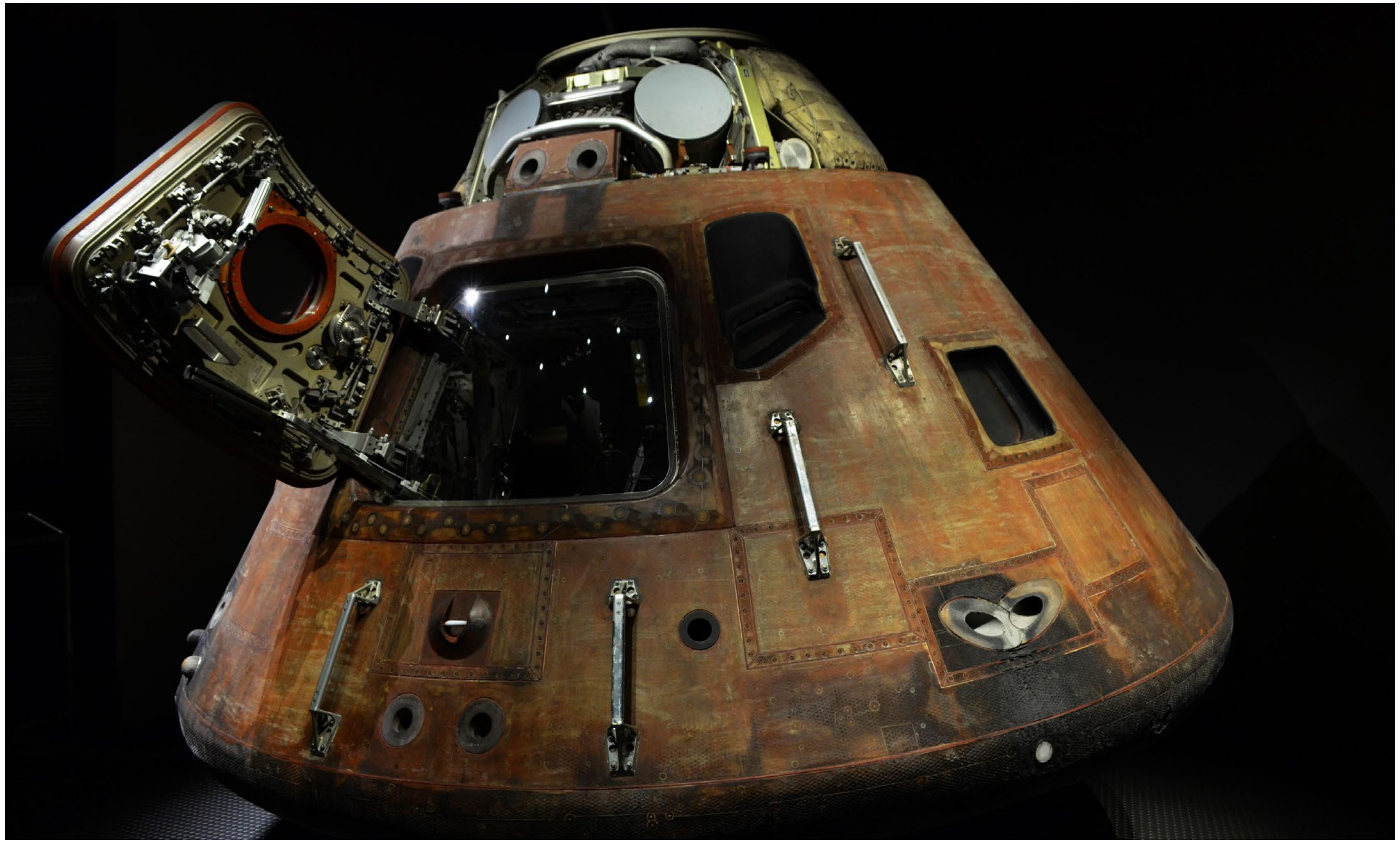
M. Grieves. 2016. “*Origins of the Digital Twin Concept*”.

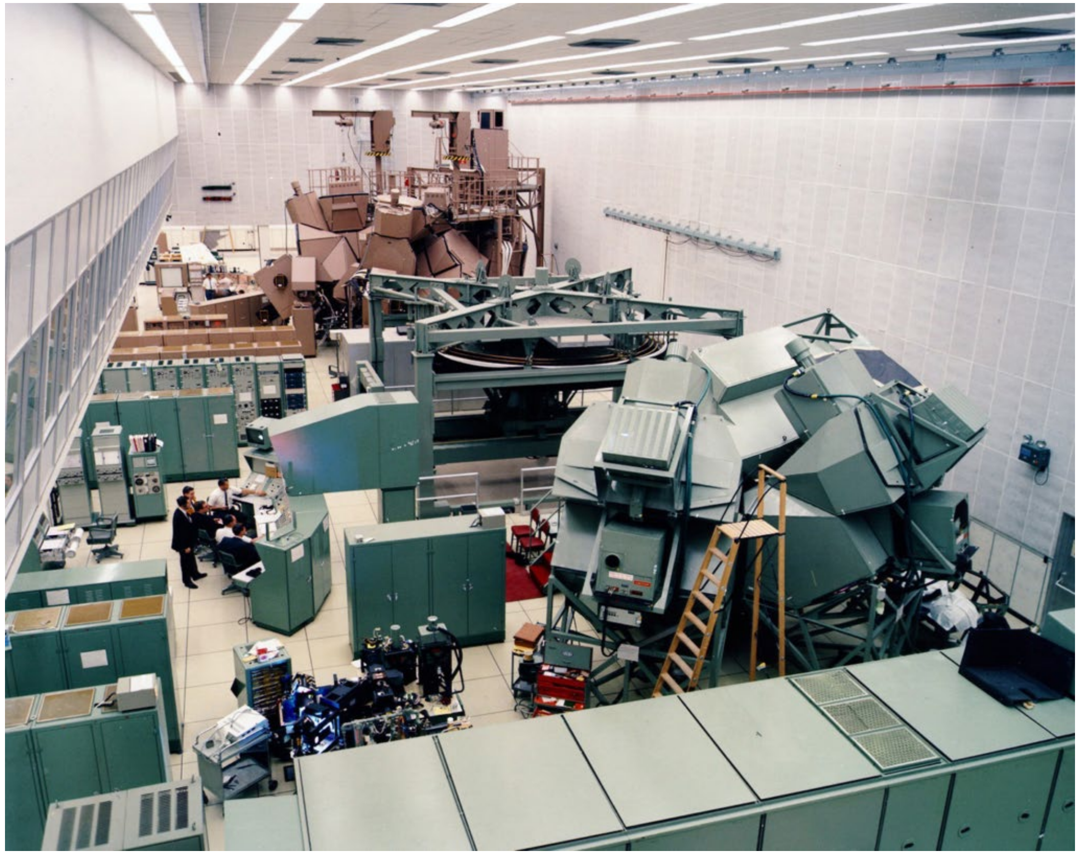
Digital Twin

Apollo 13





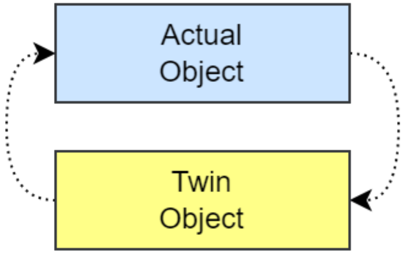




https://blogs.sw.siemens.com/simcenter/apollo-13-the-first-digital-twin/

Mastering the Nordschleife with hydrogen

Hydrogen Car

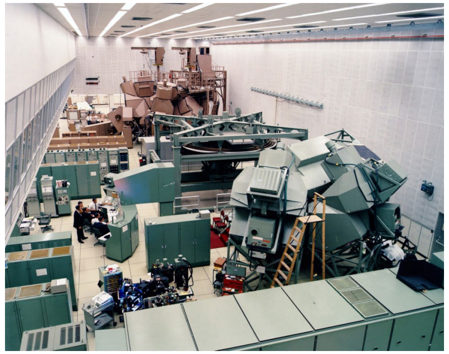


Porsche Engineering tested it in a luxury-segment reference vehicle with a relatively high total weight of 2,650 kg on the Nürburgring Nordschleife – albeit ***entirely virtually***: the drive was carried out using what is known as a ***digital twin***, i.e. a computer-based representation of the real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

https://newsroom.porsche.com/en/2022/innovation/porsche-engineering-simulation-hydrogen-combustion-engines-nuerburgring-nordschleife-29401.html many definitions/alternatives of “Digital Twin”

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

Sensing ← … everything in between … → Simulation



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A Multi-Paradigm Modelling Foundation for Twinning

Within the Context of Systems Engineering

Randy Paredis

Research Questions

- RQ1: *What are the most common reasons/definitions for (creating) Digital Twins (DTs)?*
- RQ2: *Given the large number of existing DTs in the literature, can we unify?*
- RQ3: *What is the relationship between specific DT requirements, the system architecture, the used models, and the eventual deployment?*
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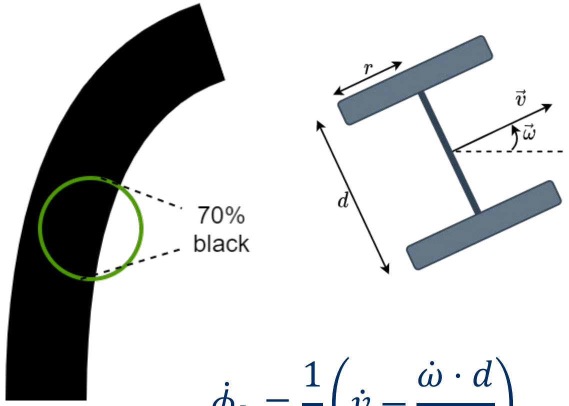
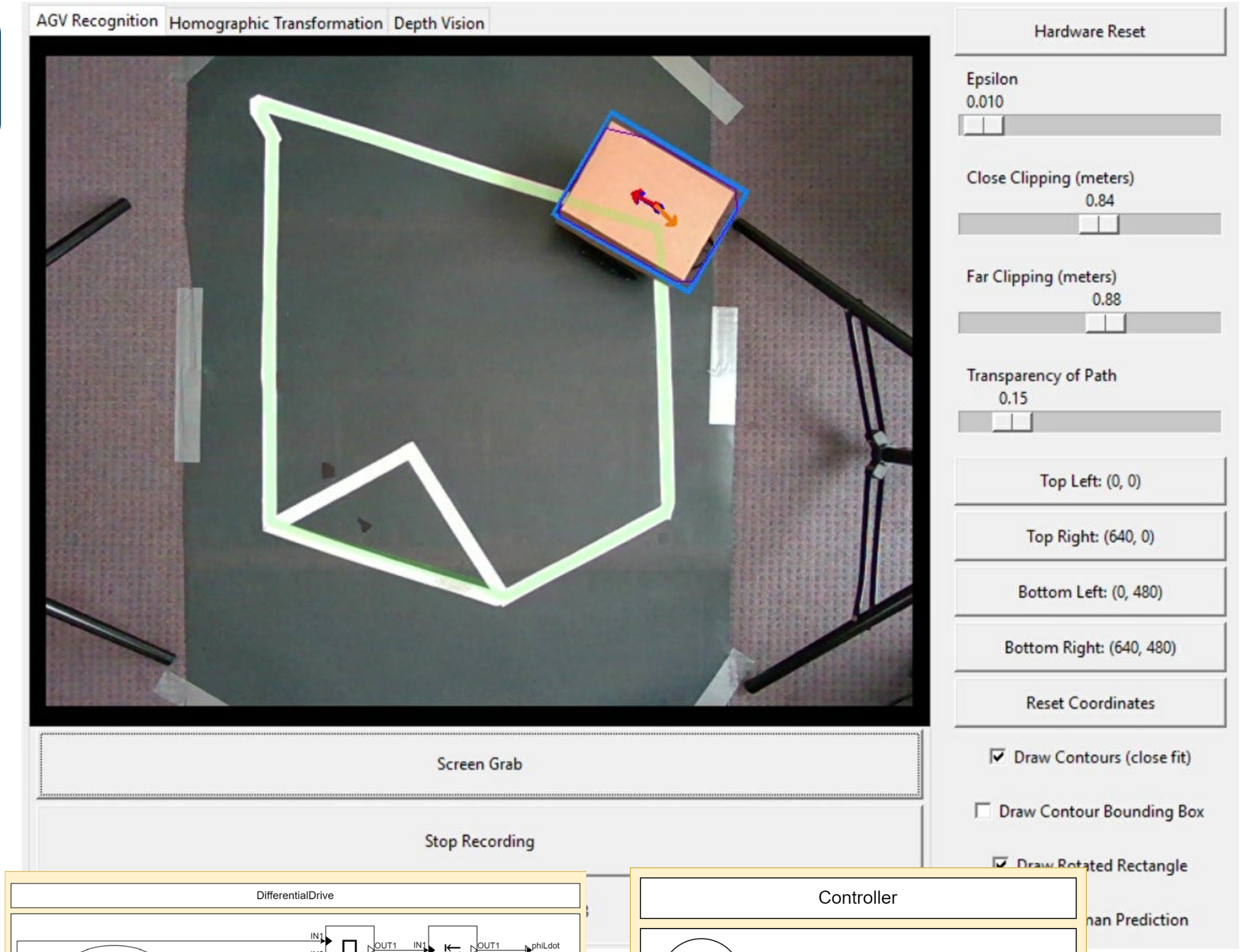
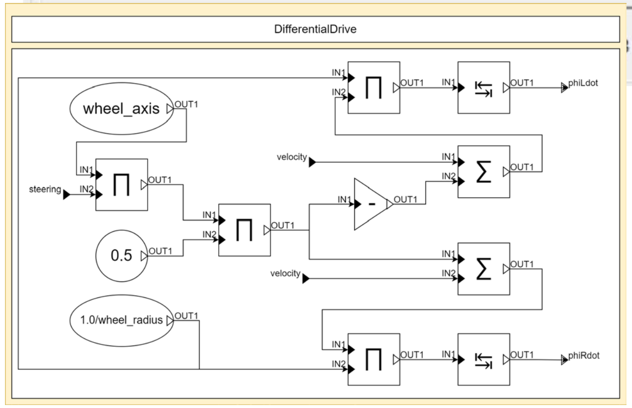
Proof-of-Concept: Line Following Robot

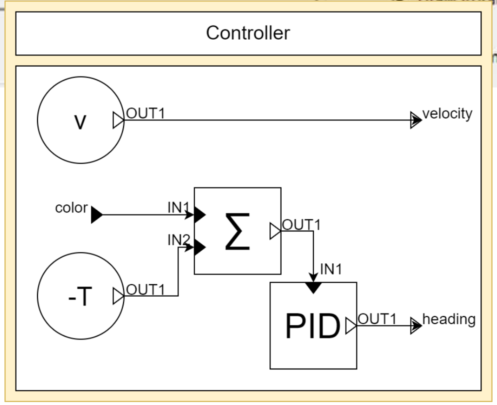


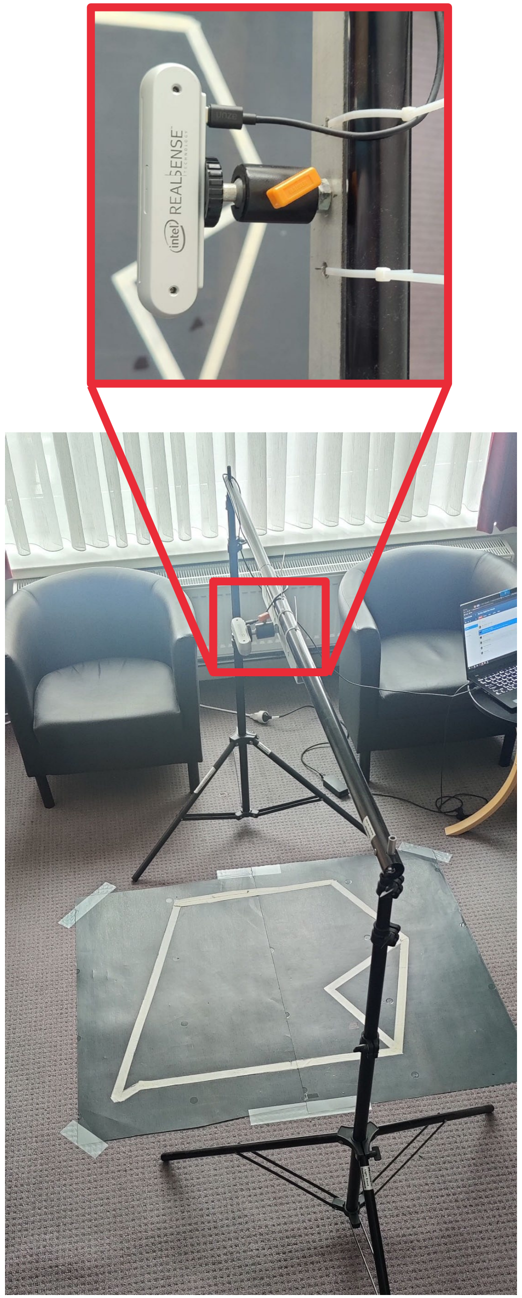
$$\dot{\phi}_L = \frac{1}{r}\left(\dot{v} - \frac{\dot{\omega} \cdot d}{2}\right)$$

$$\dot{\phi}_R = \frac{1}{r}\left(\dot{v} + \frac{\dot{\omega} \cdot d}{2}\right)$$



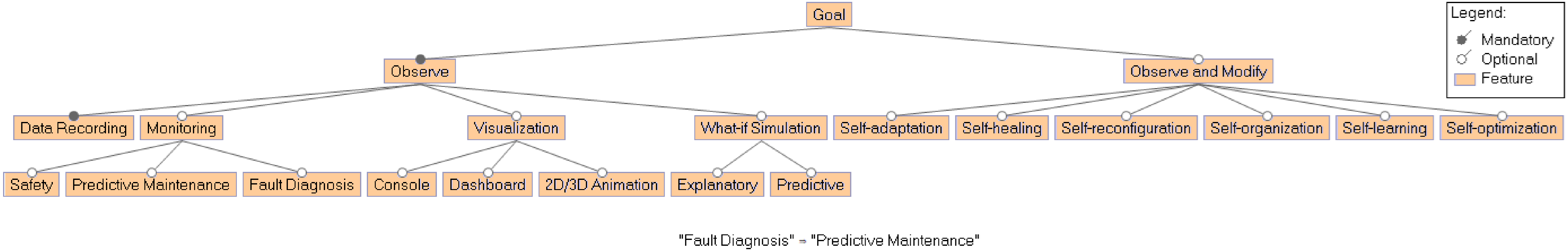


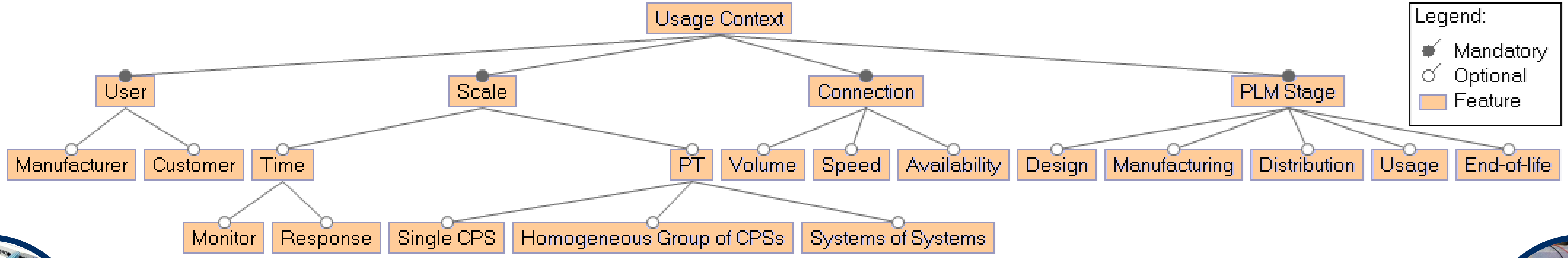


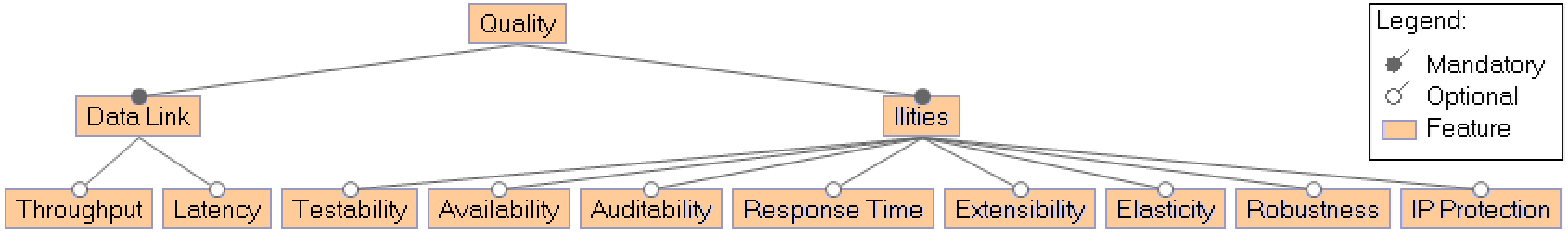


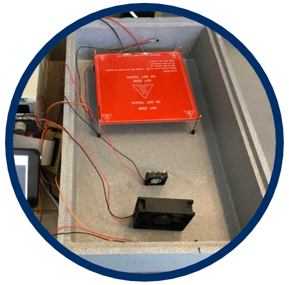
R. Paredis, and H.Vangheluwe. 2021. "*Exploring A Digital Shadow Design Workflow By Means Of A Line Following Robot Use-Case*". In Proceedings of ANNSIM 2021.

LFR vs Incubator



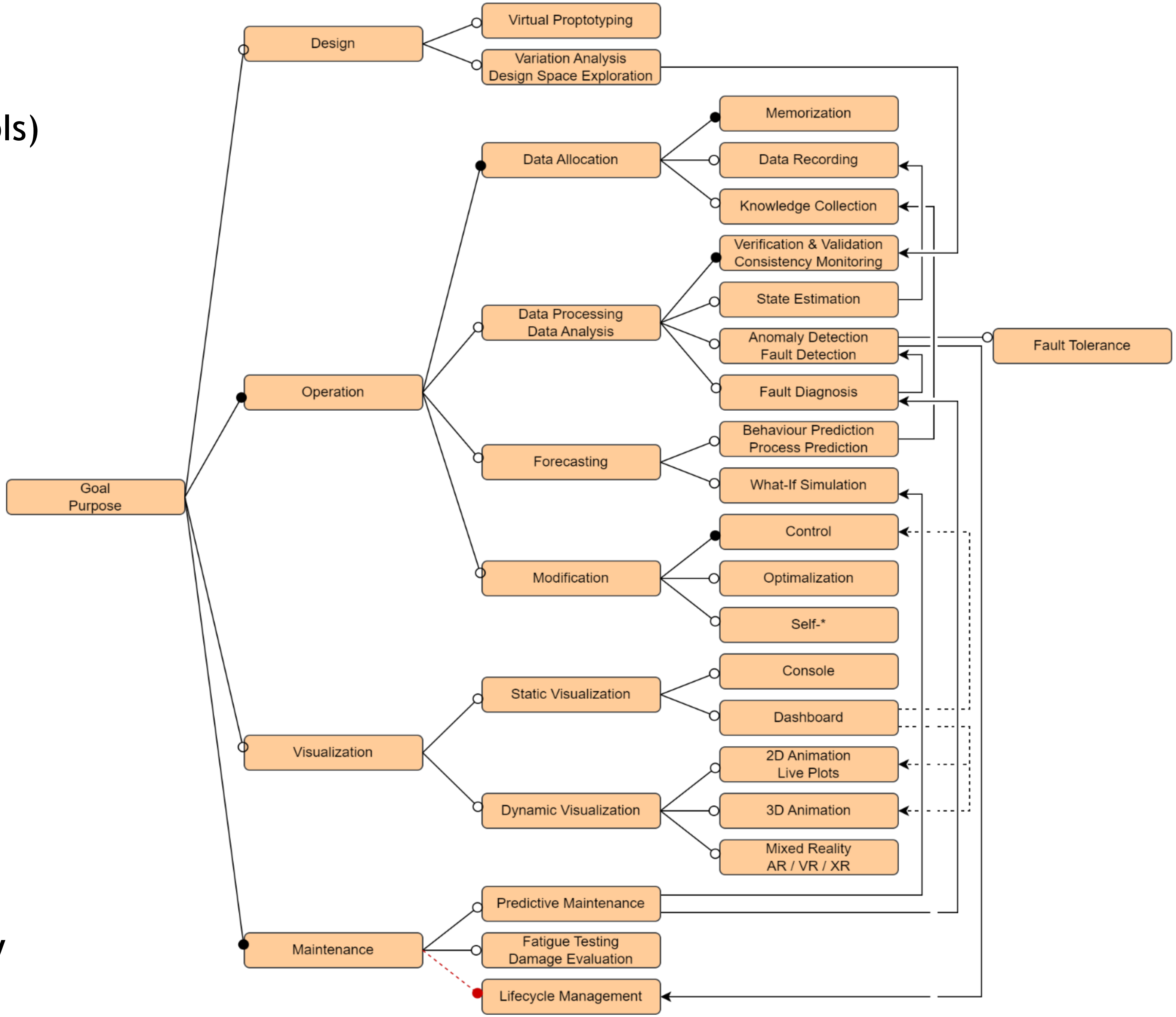






R. Paredis, C. Gomes, and H.Vangheluwe. 2021. “*Towards a Family of Digital Model/Shadow/Twin Workflows and Architectures*”. In Proceedings of IN4PL 2021, pp. 174-182.

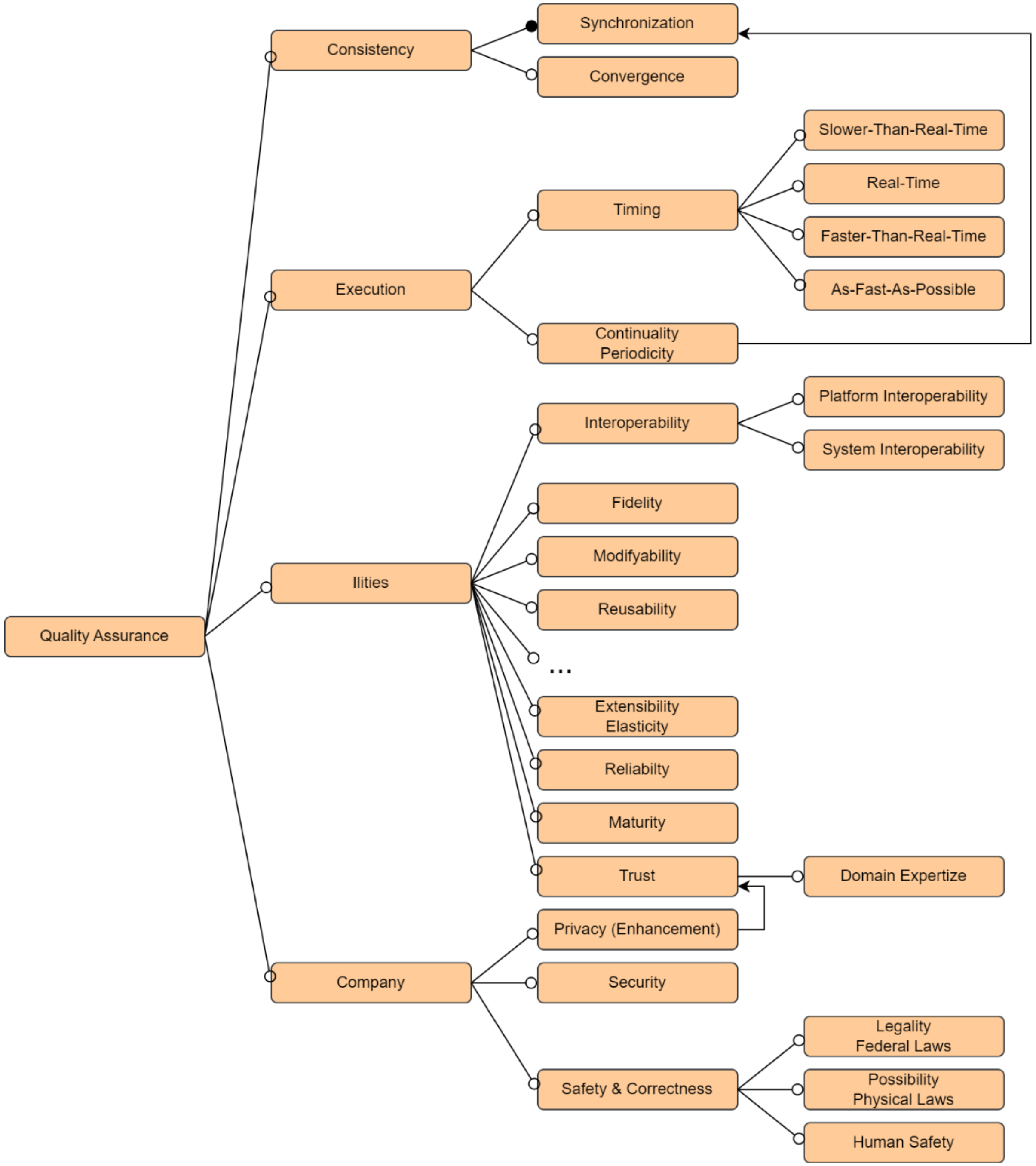
Goals w.r.t. their
Properties of Interest (PoIs)



“feature model”
to capture variability

R. Paredis, H.Vangheluwe, and P.A.R. Albertins. 2024. “*COOCK project Smart Port 2025 D3.1: "To Twin Or Not To Twin"*”. Techical Report.
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



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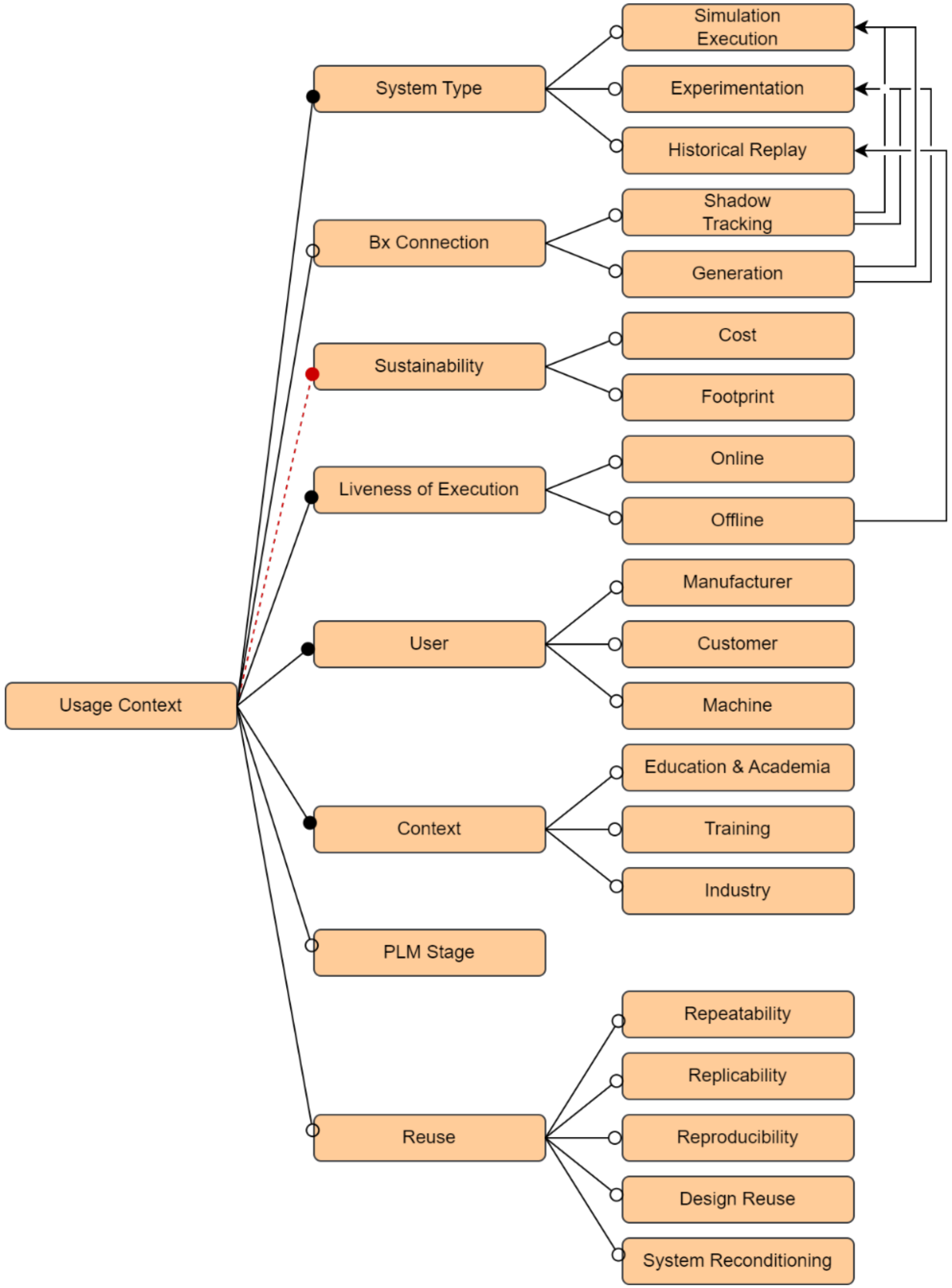
Usage Context



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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.

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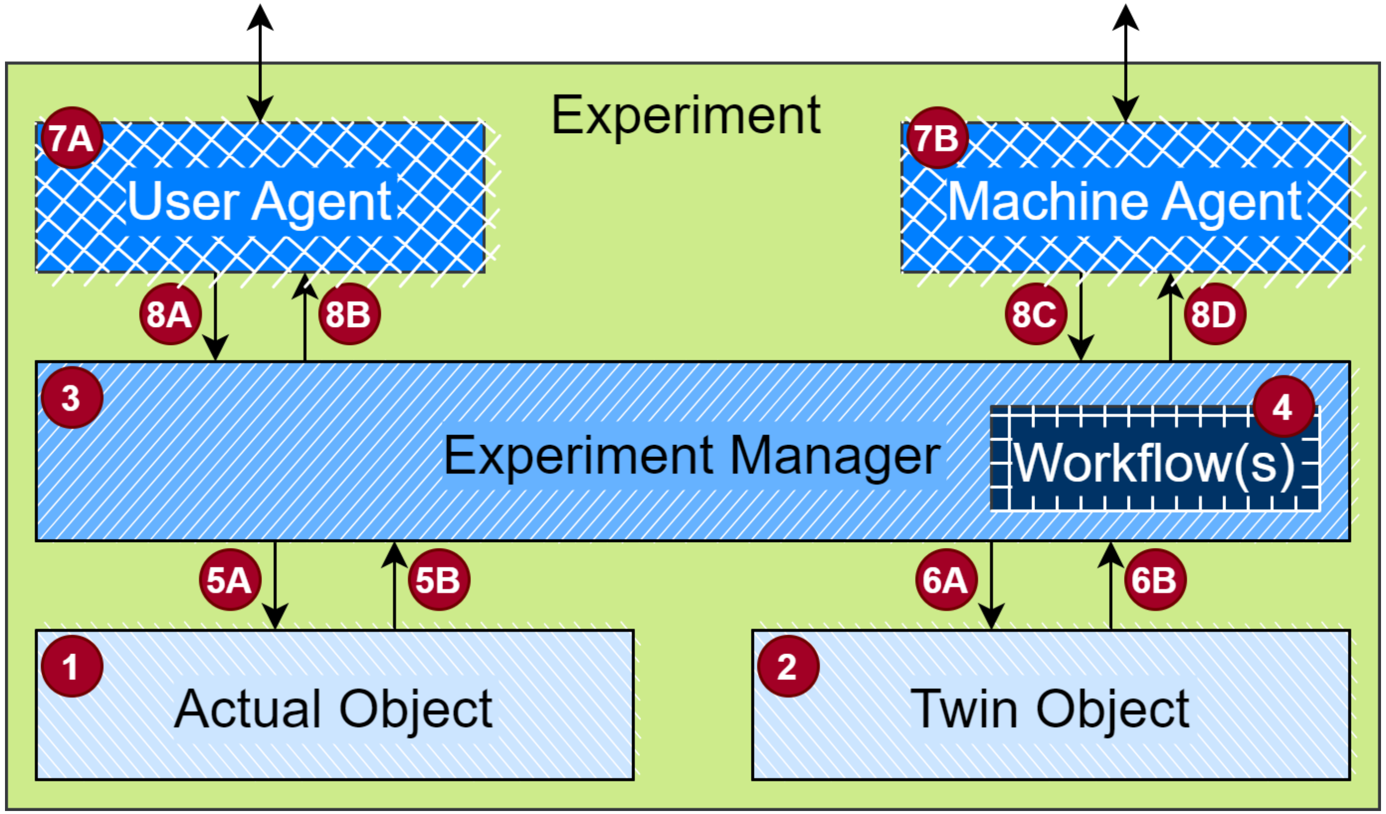
Conceptual Architecture(s)

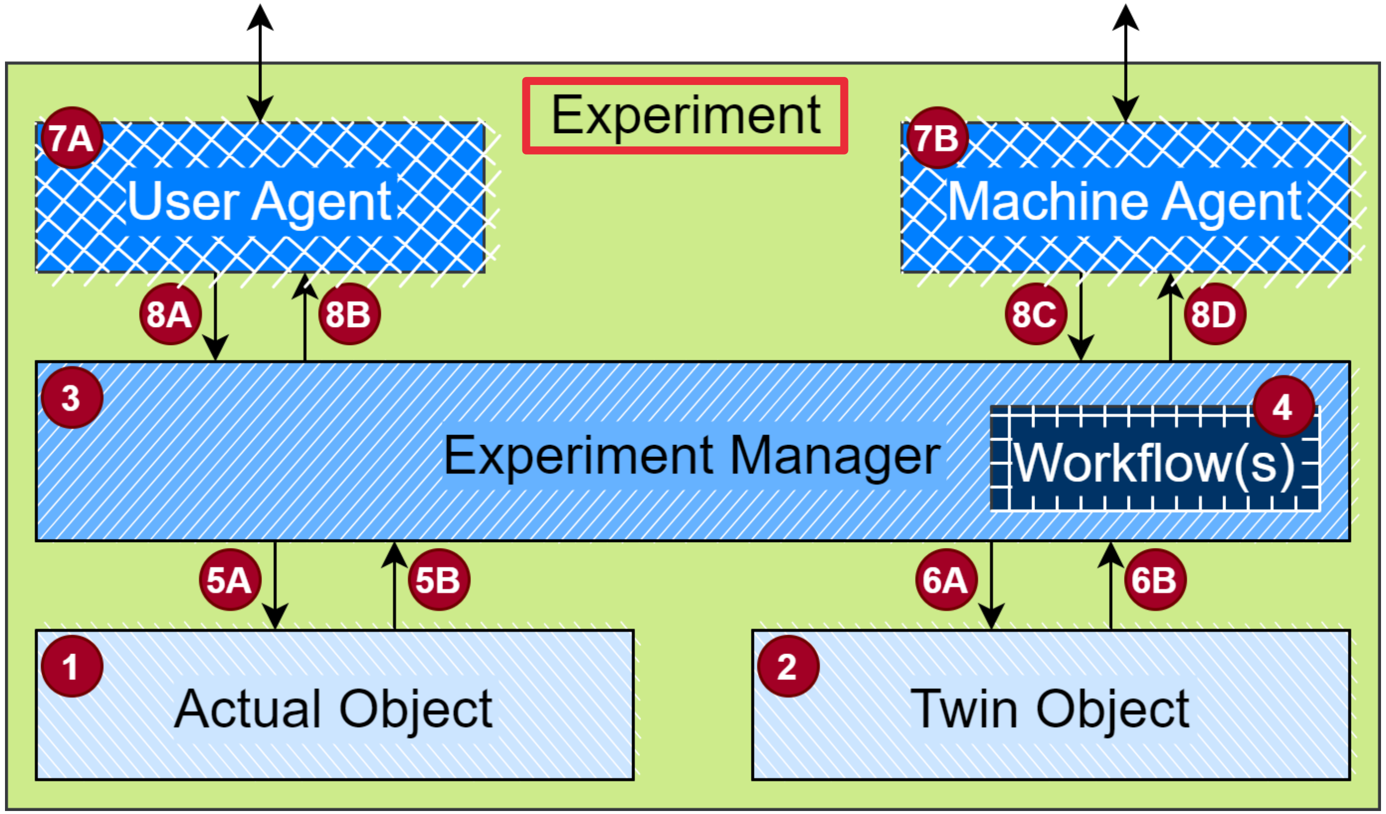


presence conditions
to capture variability

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.

* Agent does not refer to Agent Based Modelling/Simulation; but to "interfaces"

Conceptual Architecture(s)

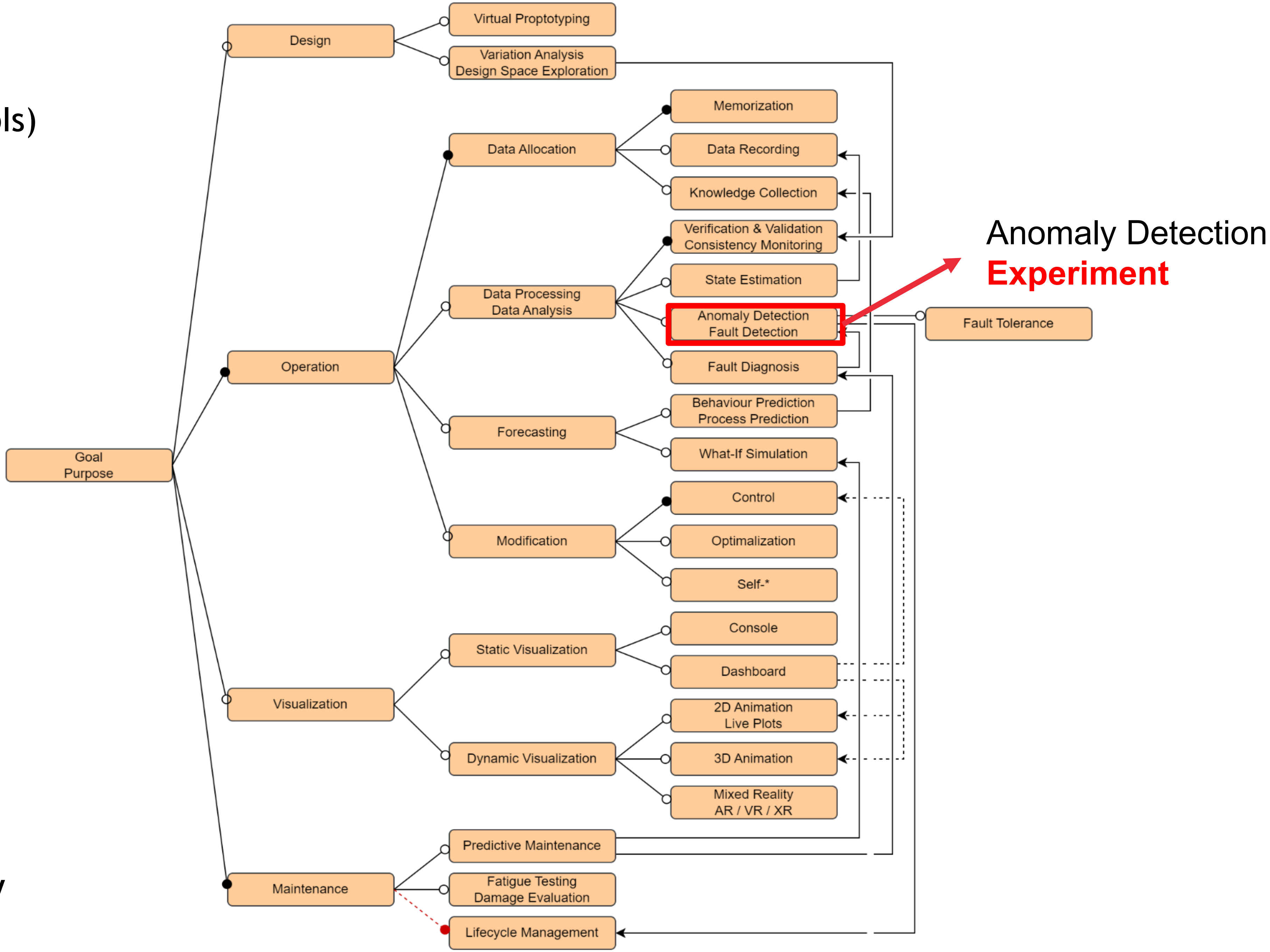


presence conditions to capture variability

An **experiment** is an intentional set of (possibly hierarchically composed) activities, carried out on a specific SuS in order to accomplish a specific set of goals.

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.

Goals w.r.t. their Properties of Interest (PoIs)



“feature model”
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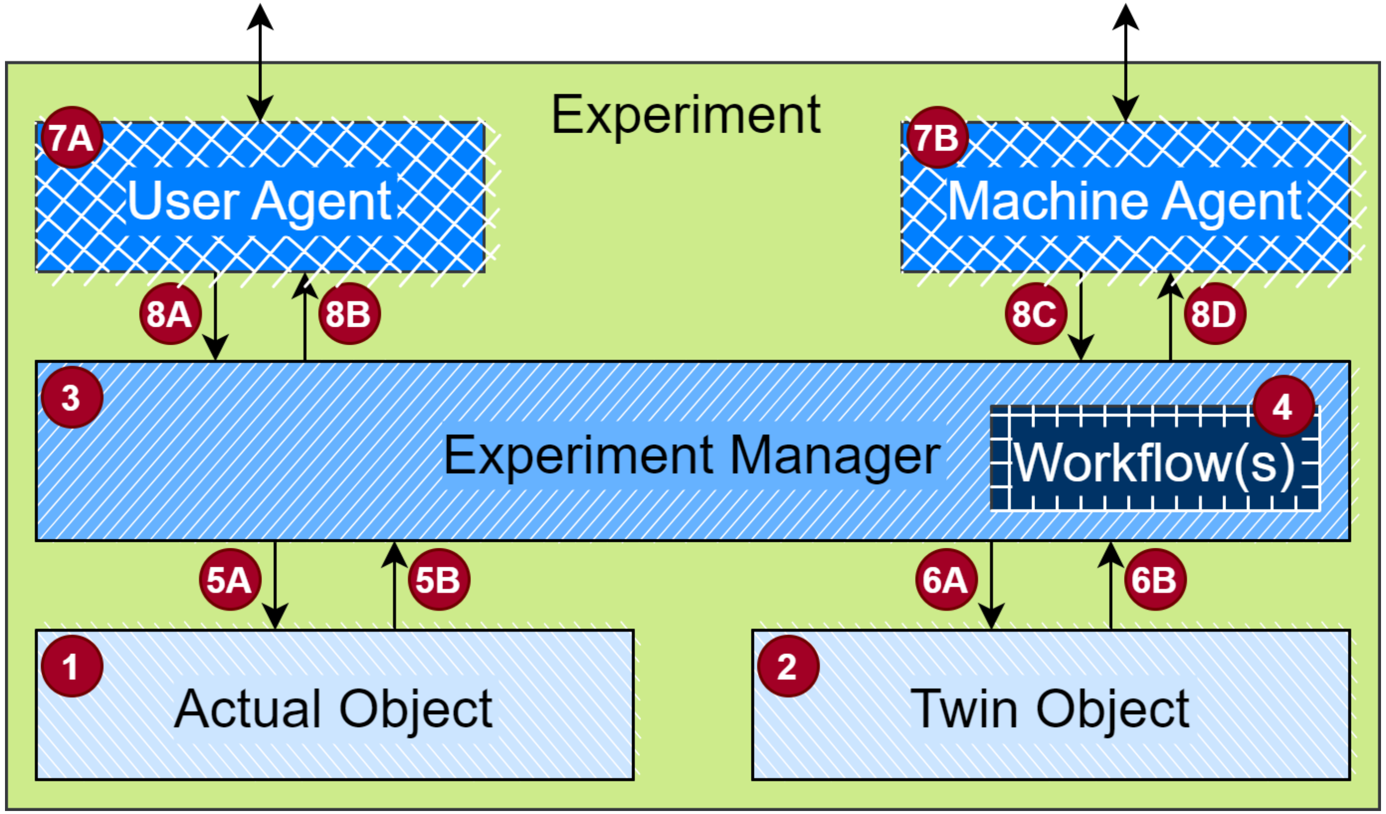

presence conditions
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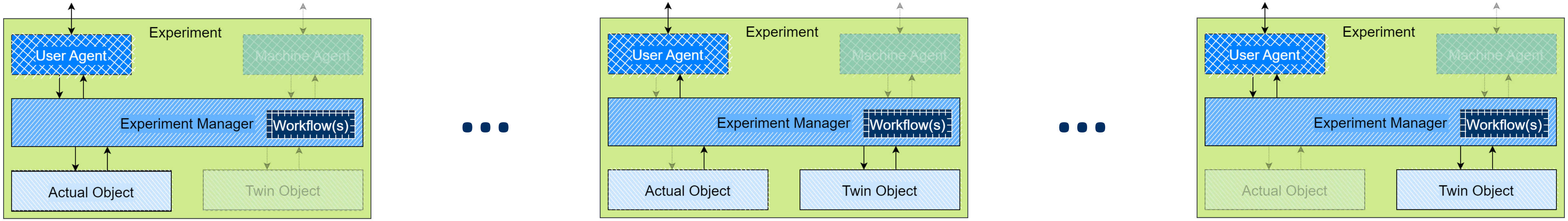
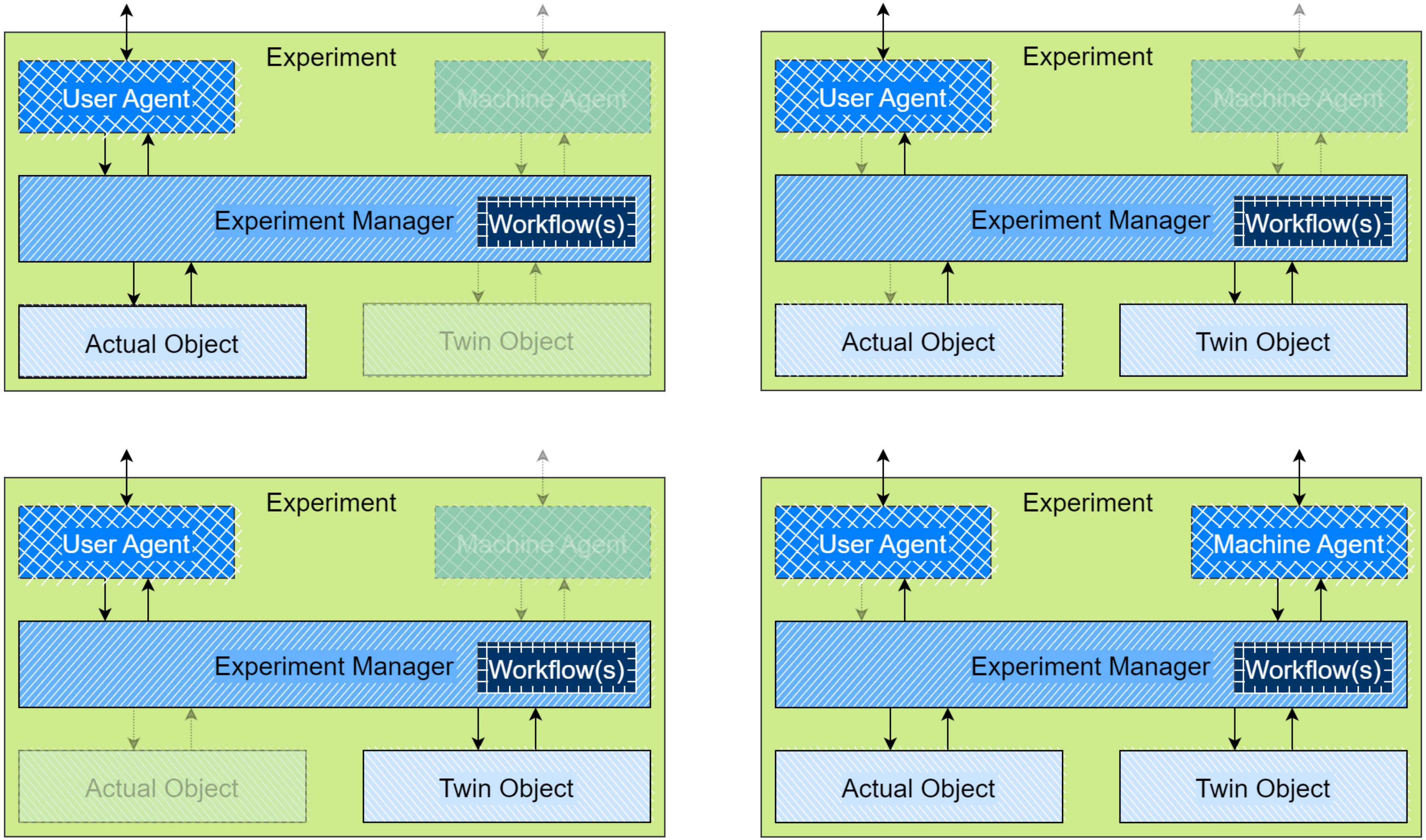
many definitions/alternatives of “Digital Twin”
→ use “**Twinning**” to cover all definitions

Sensing ← … everything in between … → Simulation



Conceptual Architecture Example(s)



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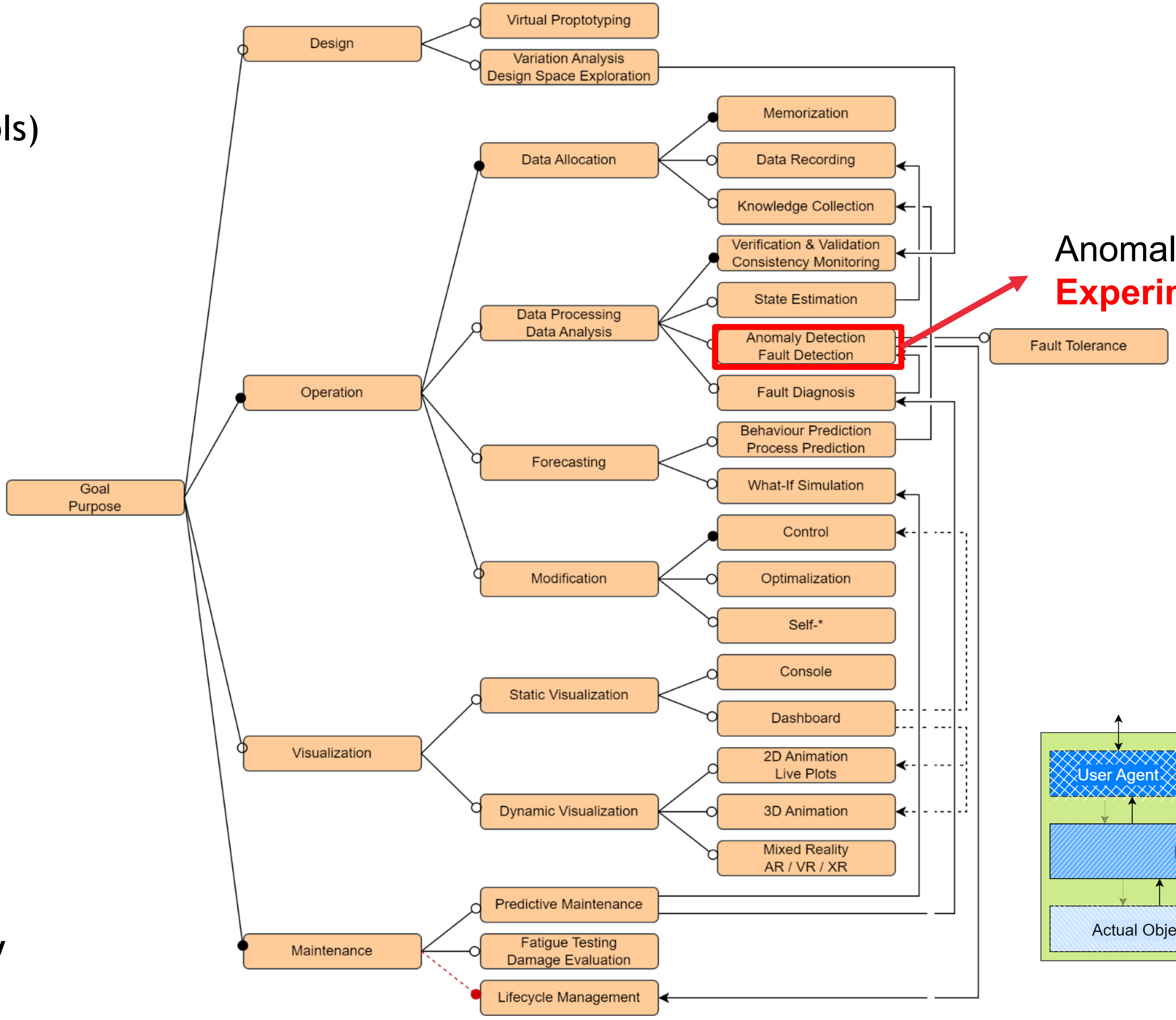
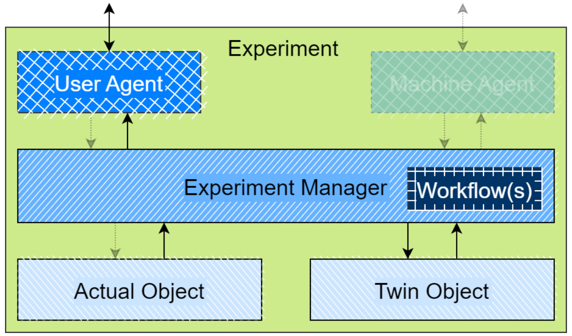


Anomaly Detection
Experiment



“feature model”
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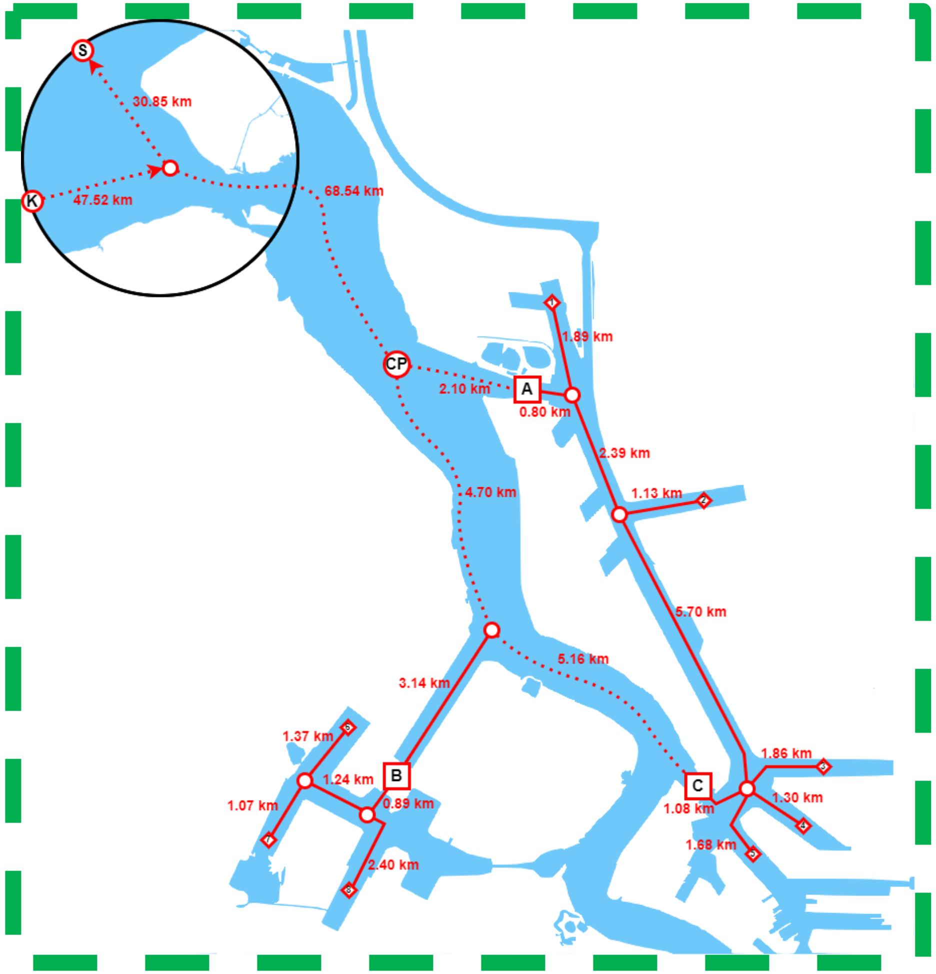
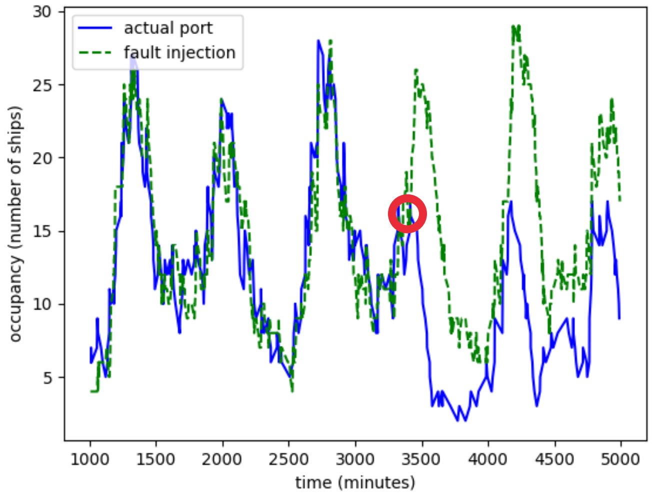
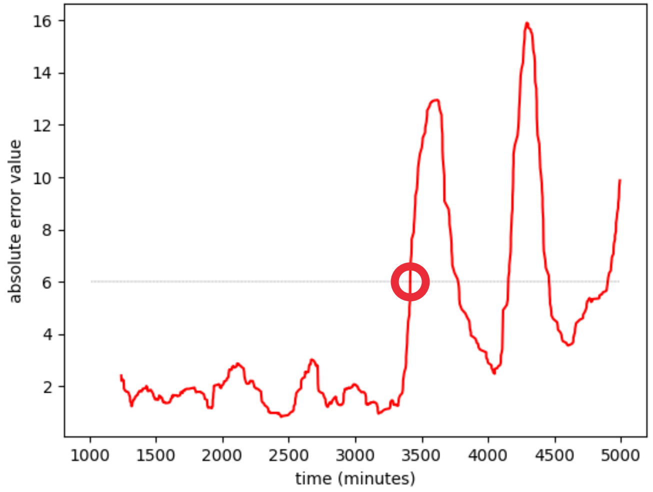
* This example case does not reflect the actual operations of PoAB

Proof-of-Concept: Port of Antwerp

Anomaly Detection







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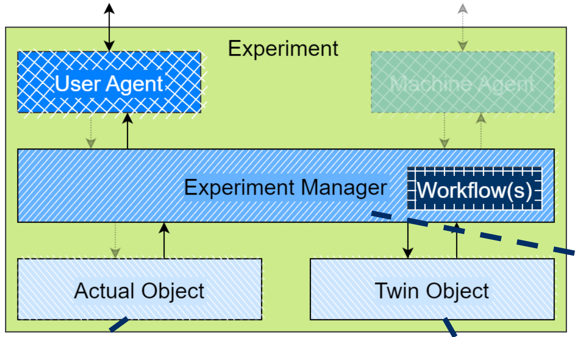
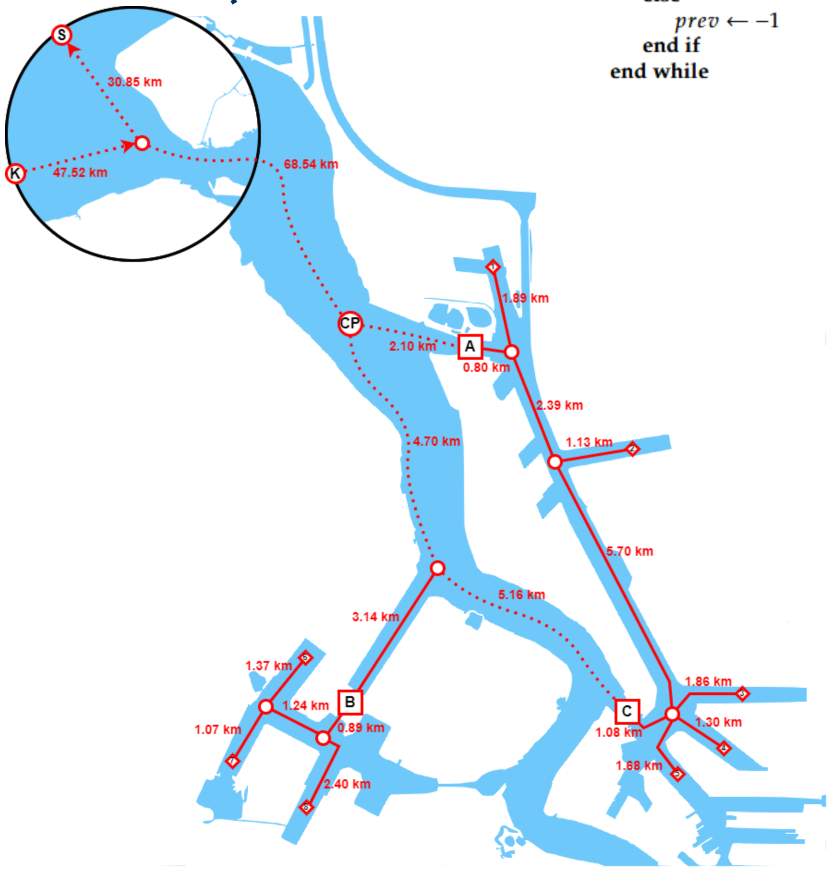
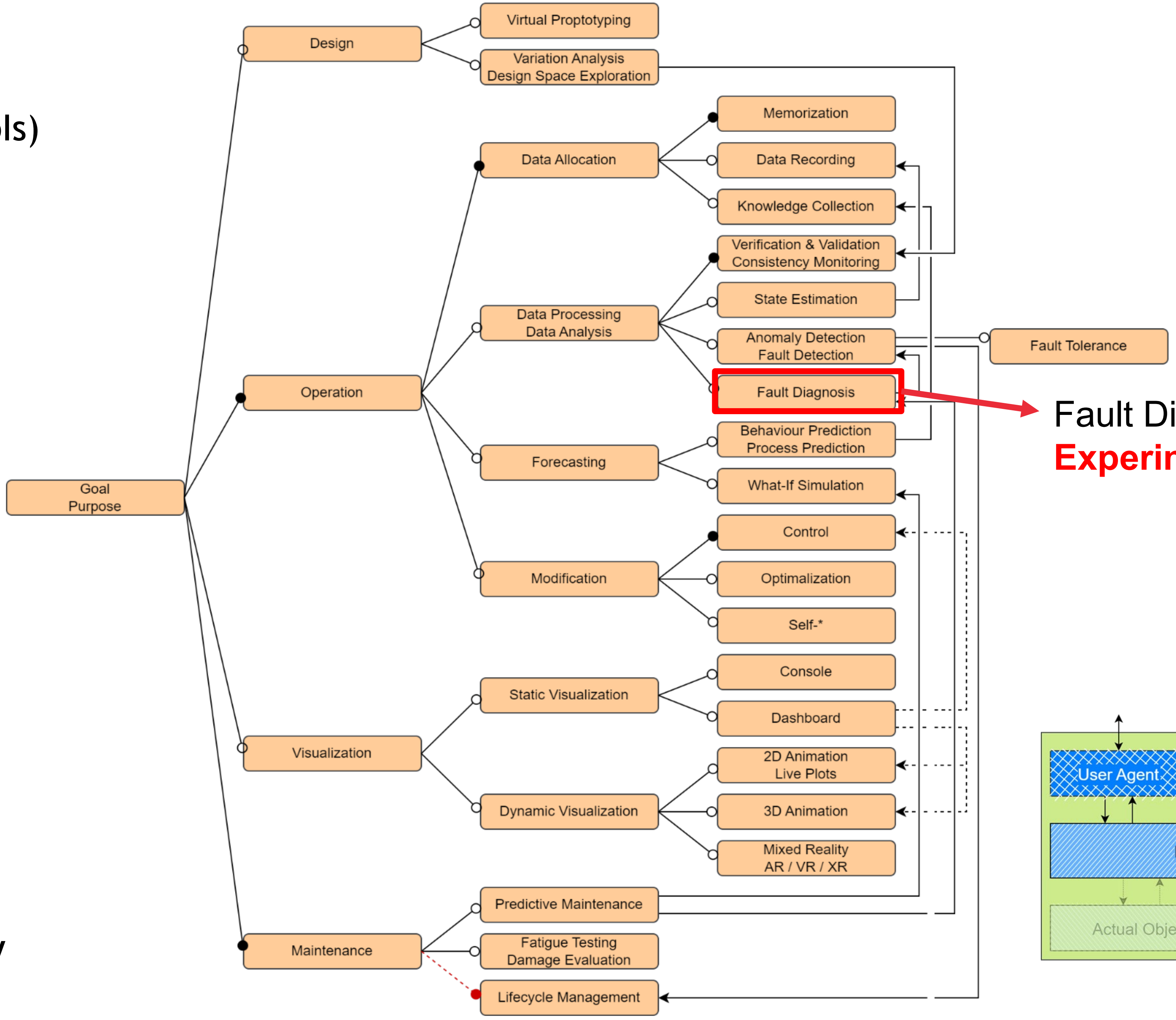


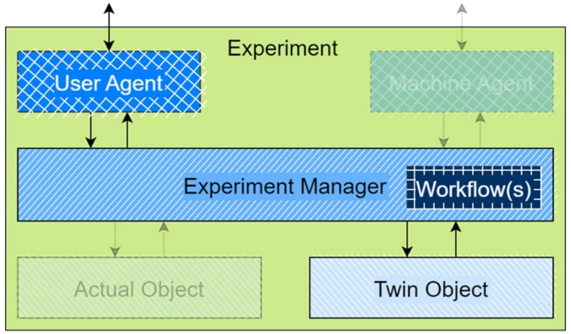

```
D ← Drop-off value for the error.
M ← Maximal allowed time above D.
prev ← −1
while system is running do
    occ_A ← Occupancy value of the AO.
    occ_T ← Occupancy value of the TO.
    T ← Current execution time.
    error ← |occ_A − occ_T|
    if prev > 0 and T − prev > M then
        Raise an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



Goals w.r.t. their Properties of Interest (PoIs)



Fault Diagnosis
Experiment



"feature model"
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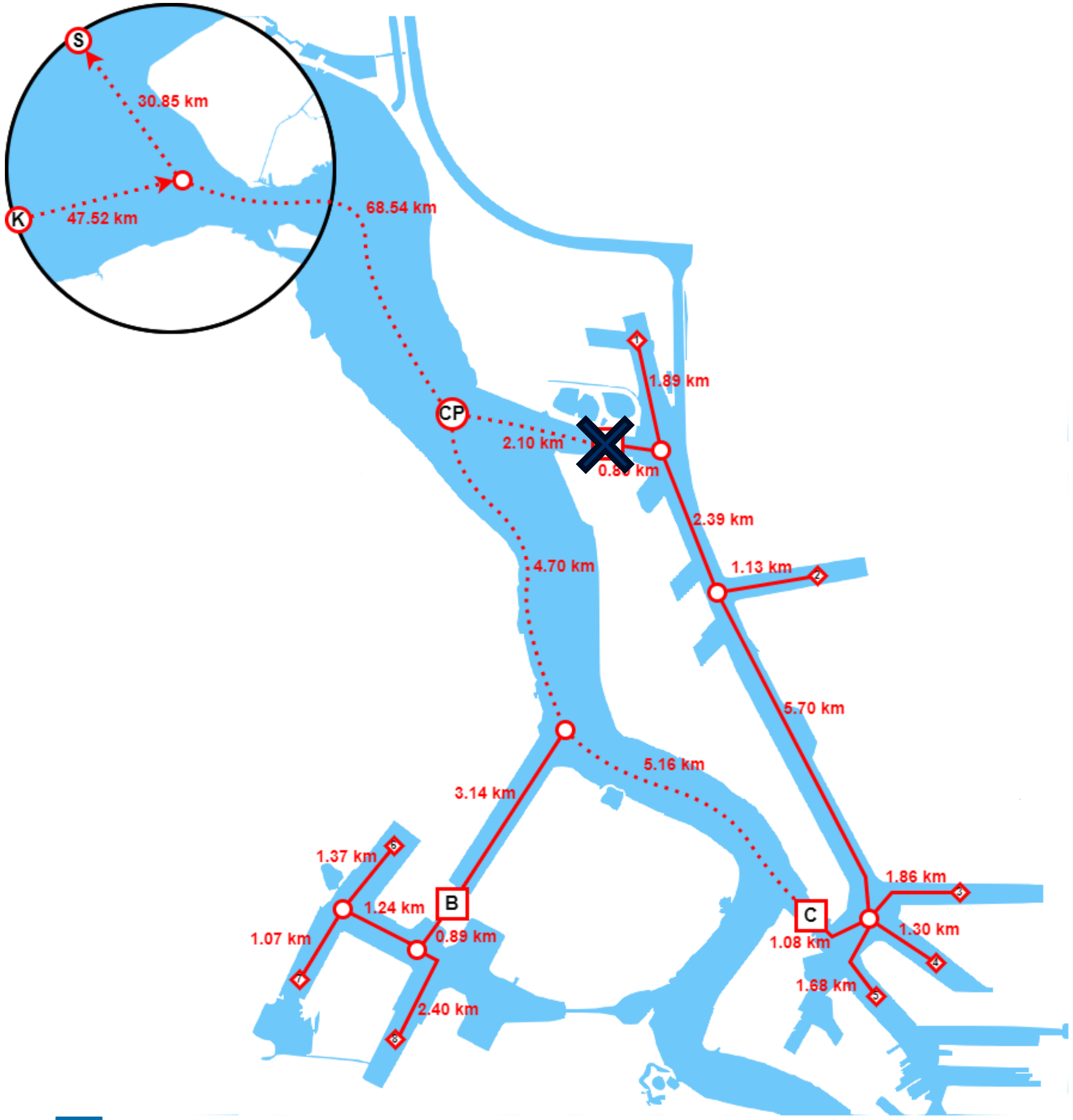
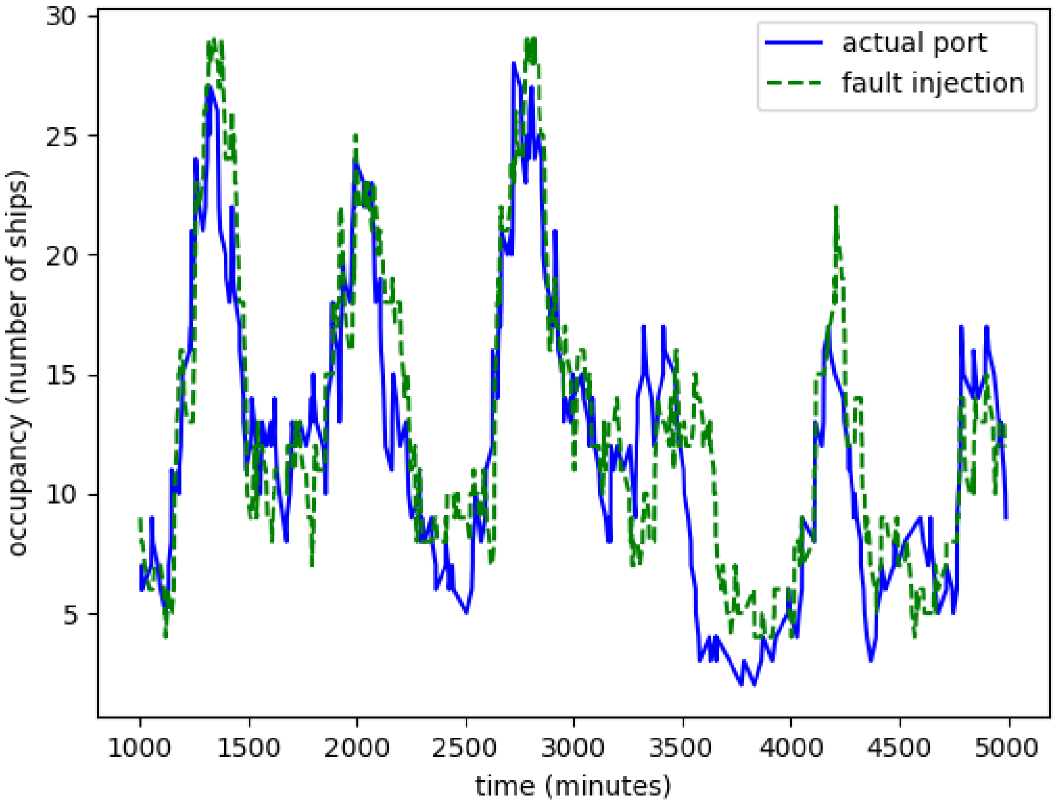


DTW Score = 317
NDW Score = 437.25



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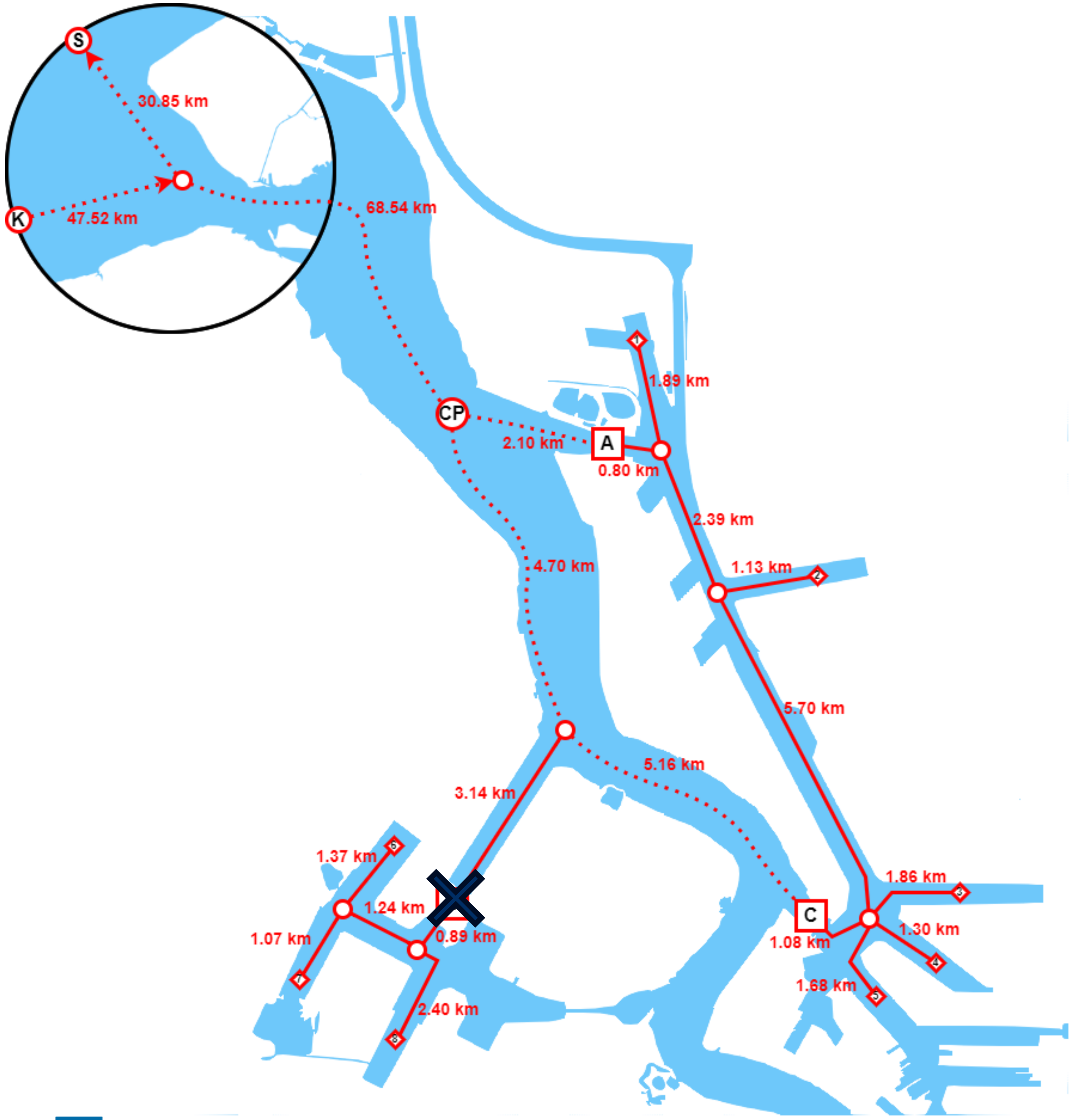
[NDW] P. Muñoz, M. Wimmer, J. Troya, and A. Vallecillo. 2024. "*Measuring the Fidelity of a Physical and a Digital Twin Using Trace Alignments*". In IEEE Transactions on Software Engineering, pp. 3122-3145.

Proof-of-Concept:
Port of Antwerp



DTW Score = 288
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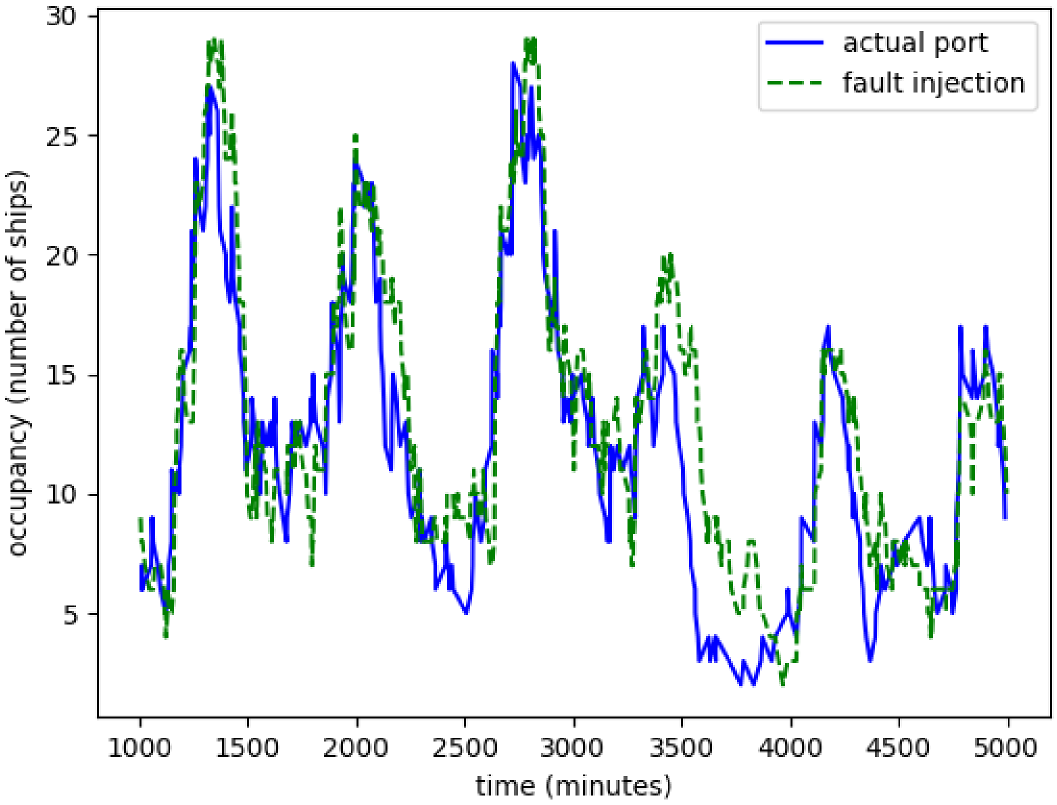

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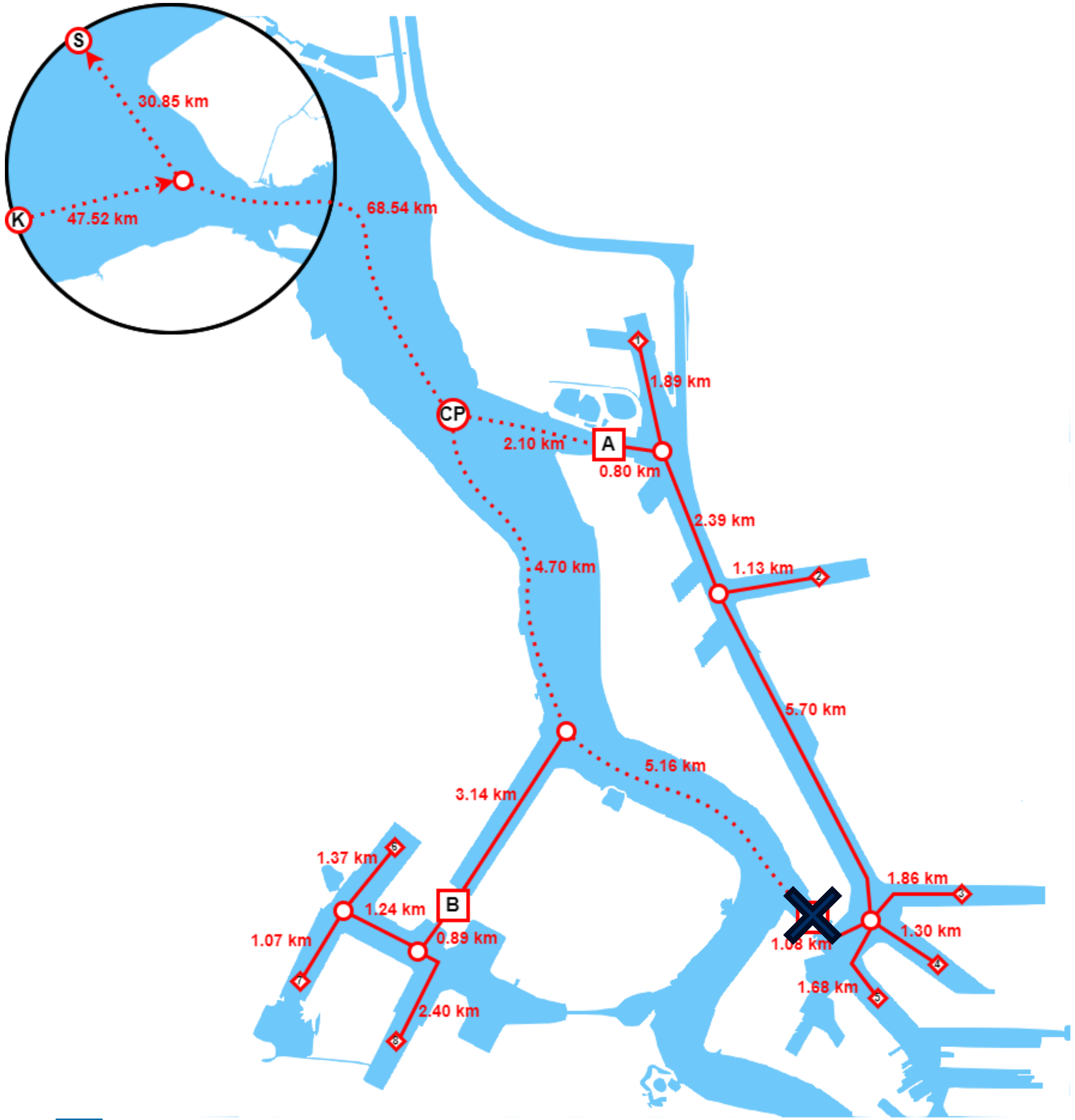
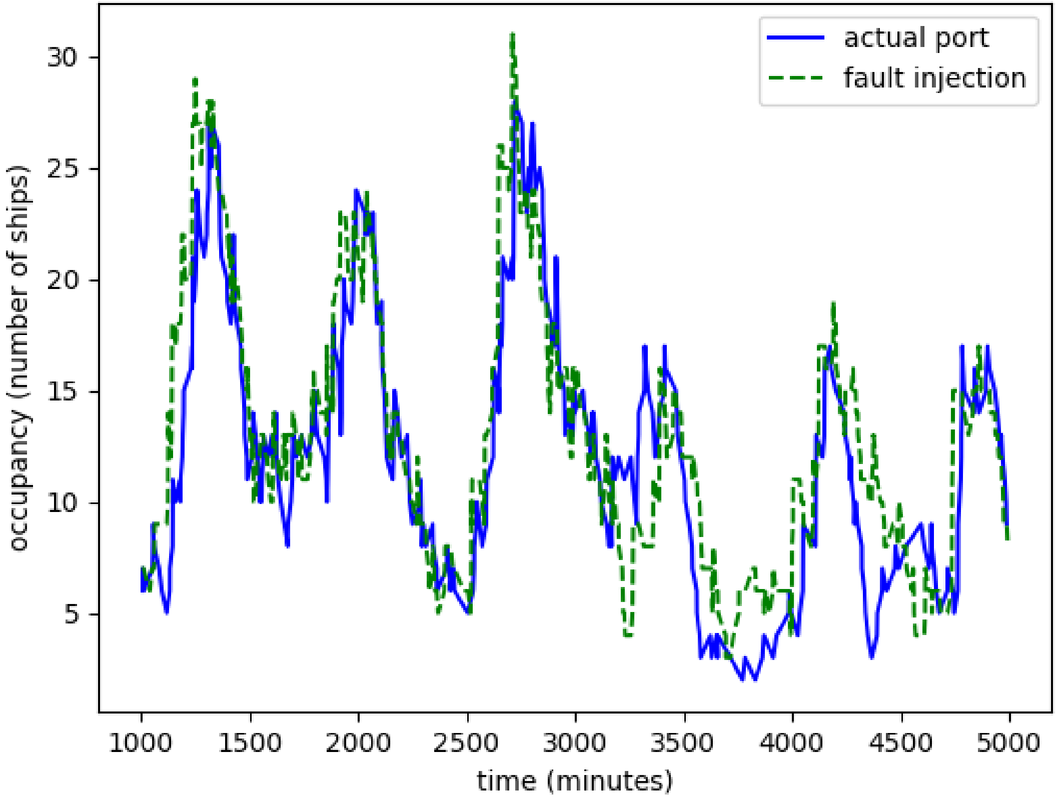


DTW Score = 252
NDW Score = 433.66



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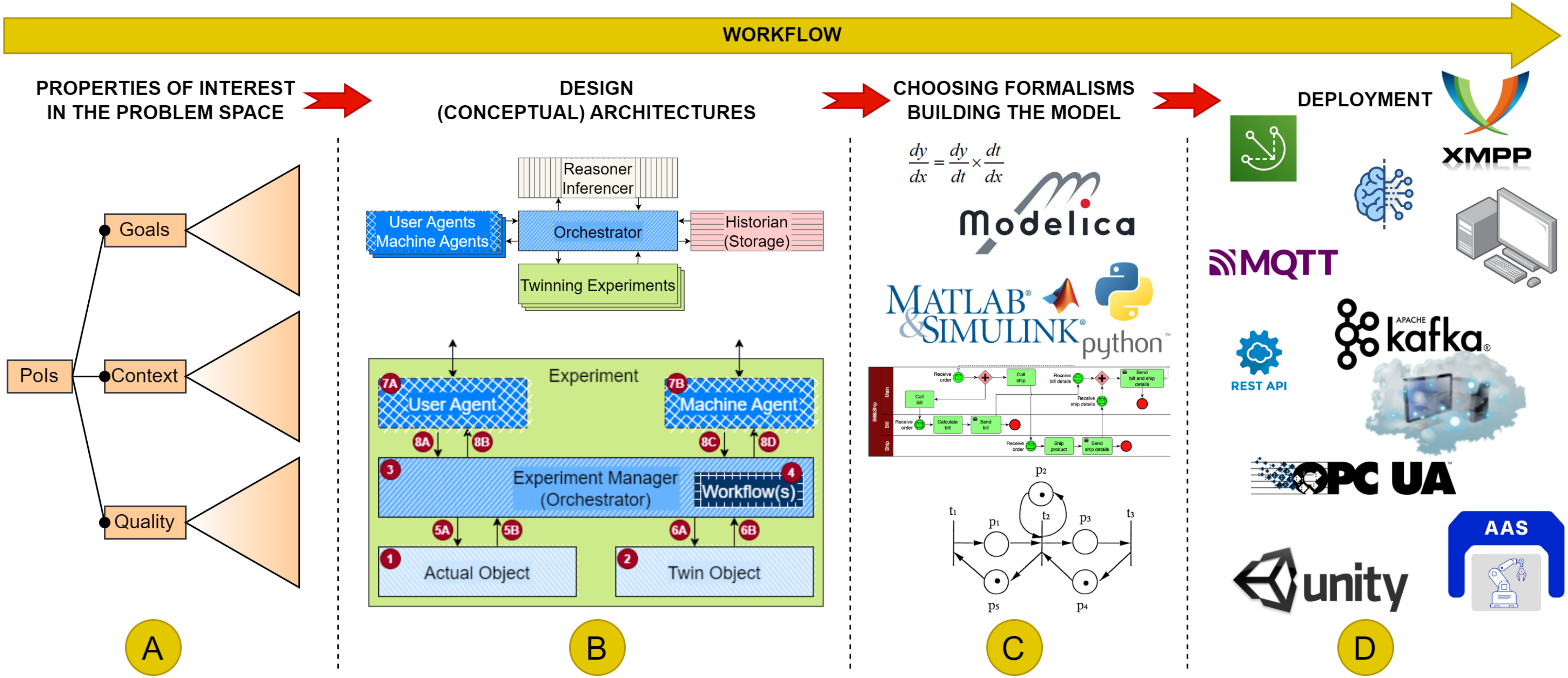
Stages of Twinning Variability



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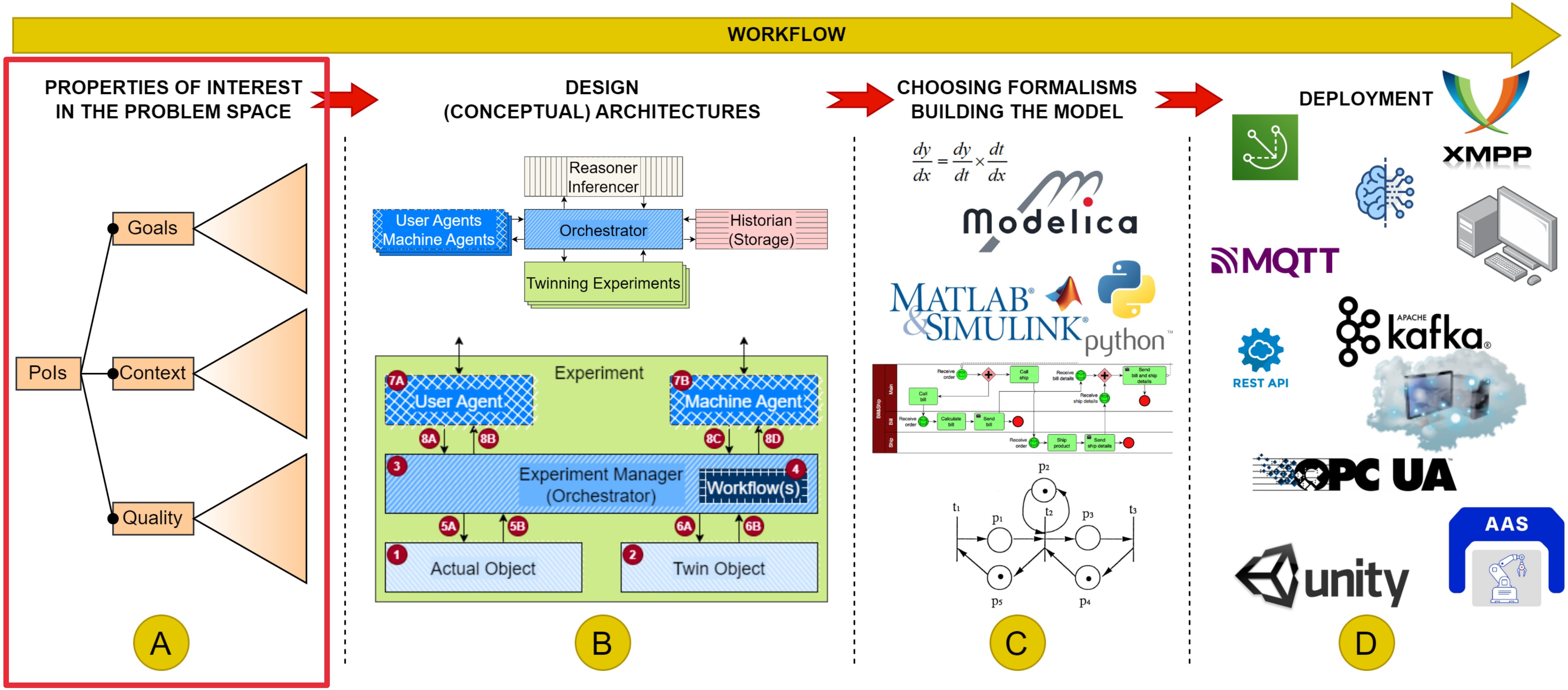
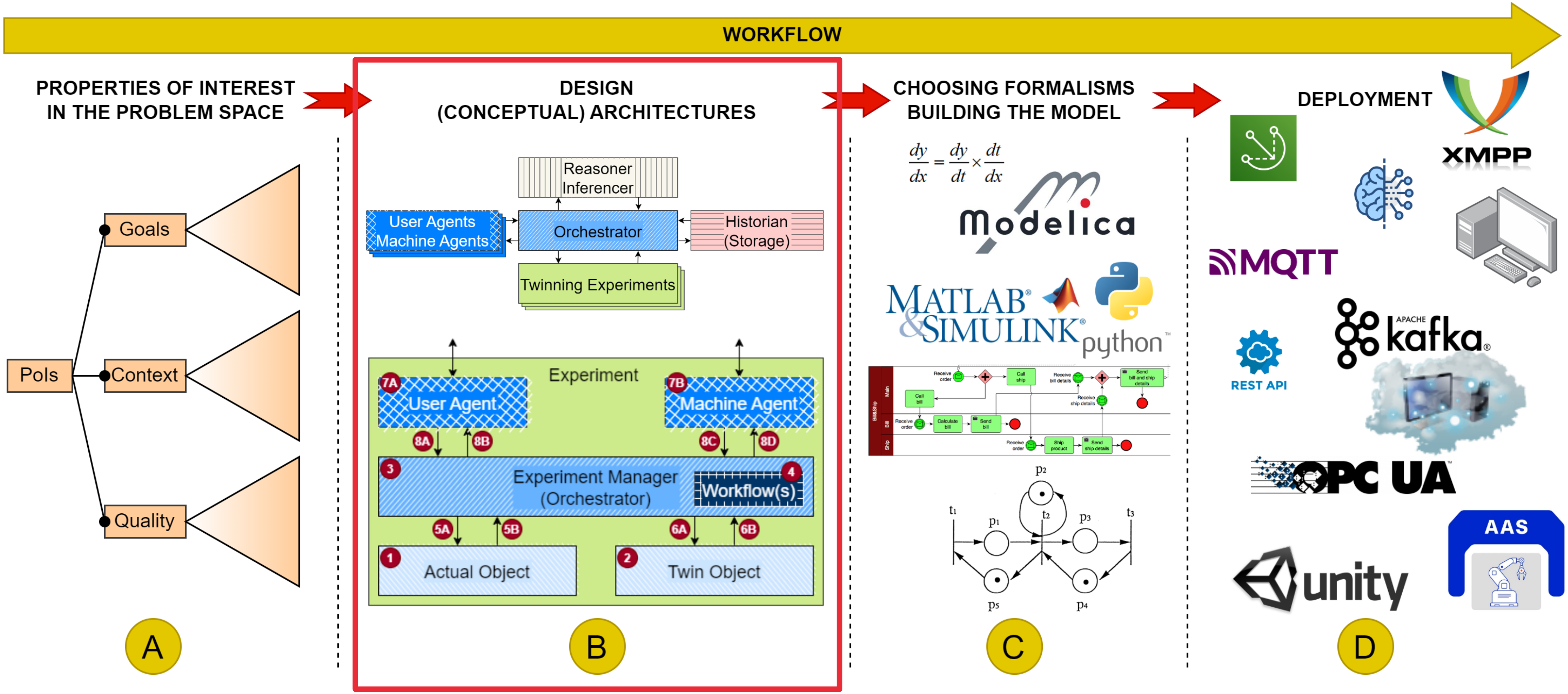
Stages of Twinning Variability – The Problem Space



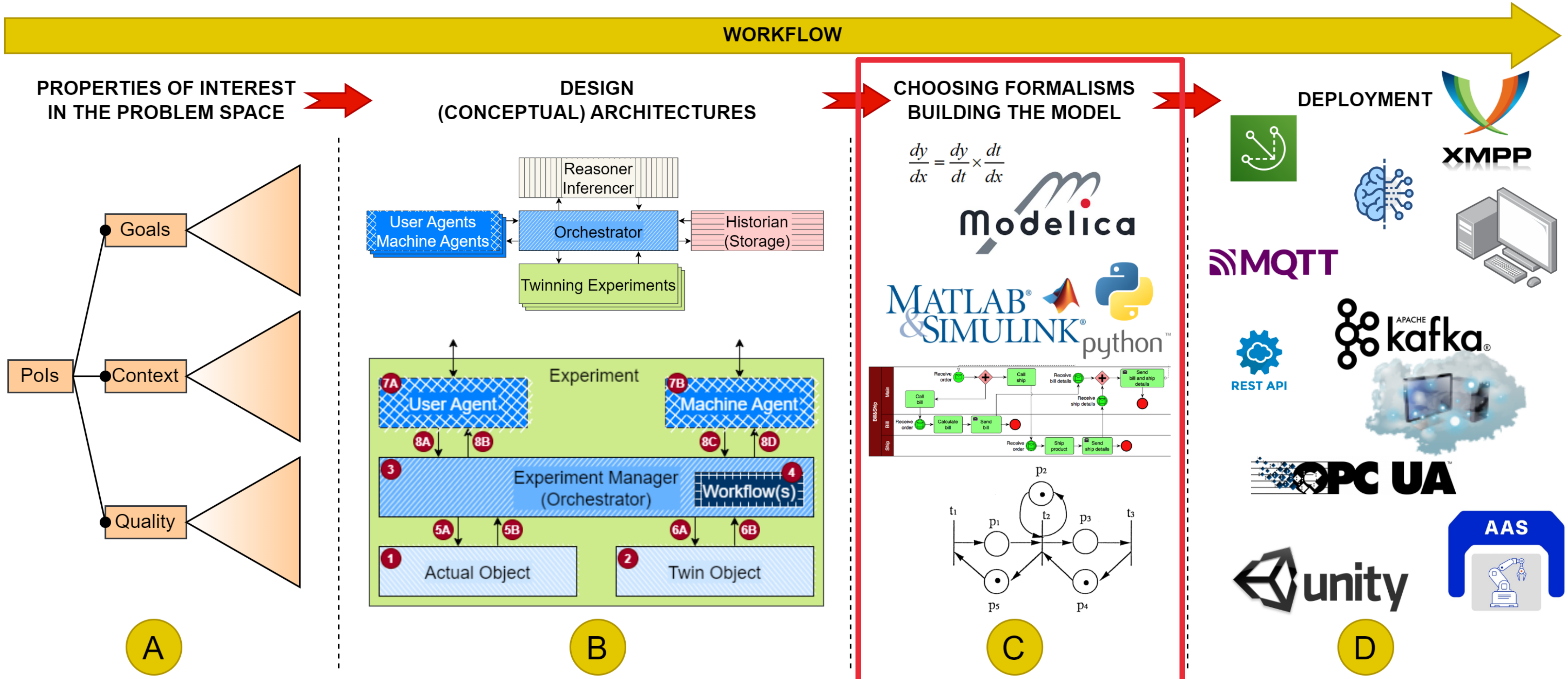
R. Paredis and H.Vangheluwe. 2024. “*Modelling and Simulation-Based Evaluation of Twinning Architectures and Their Deployment*”. In Proceedings of SIMULTECH 2024, pp. 170-182.

Stages of Twinning Variability – Architectures



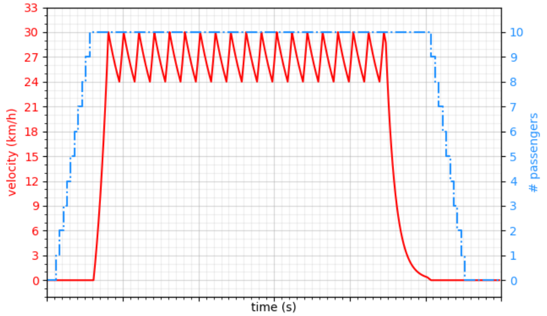
R. Paredis and H.Vangheluwe. 2024. "*Modelling and Simulation-Based Evaluation of Twinning Architectures and Their Deployment*". In Proceedings of SIMULTECH 2024, pp. 170-182.

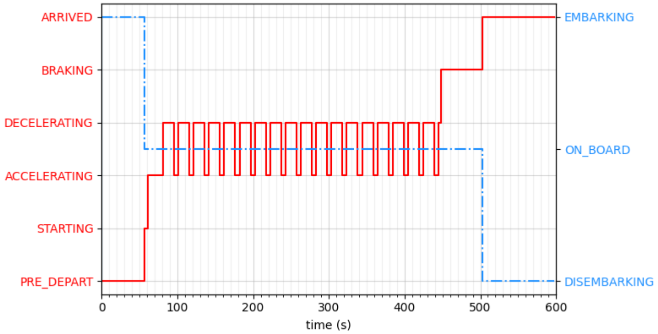
Stages of Twinning Variability – Modelling

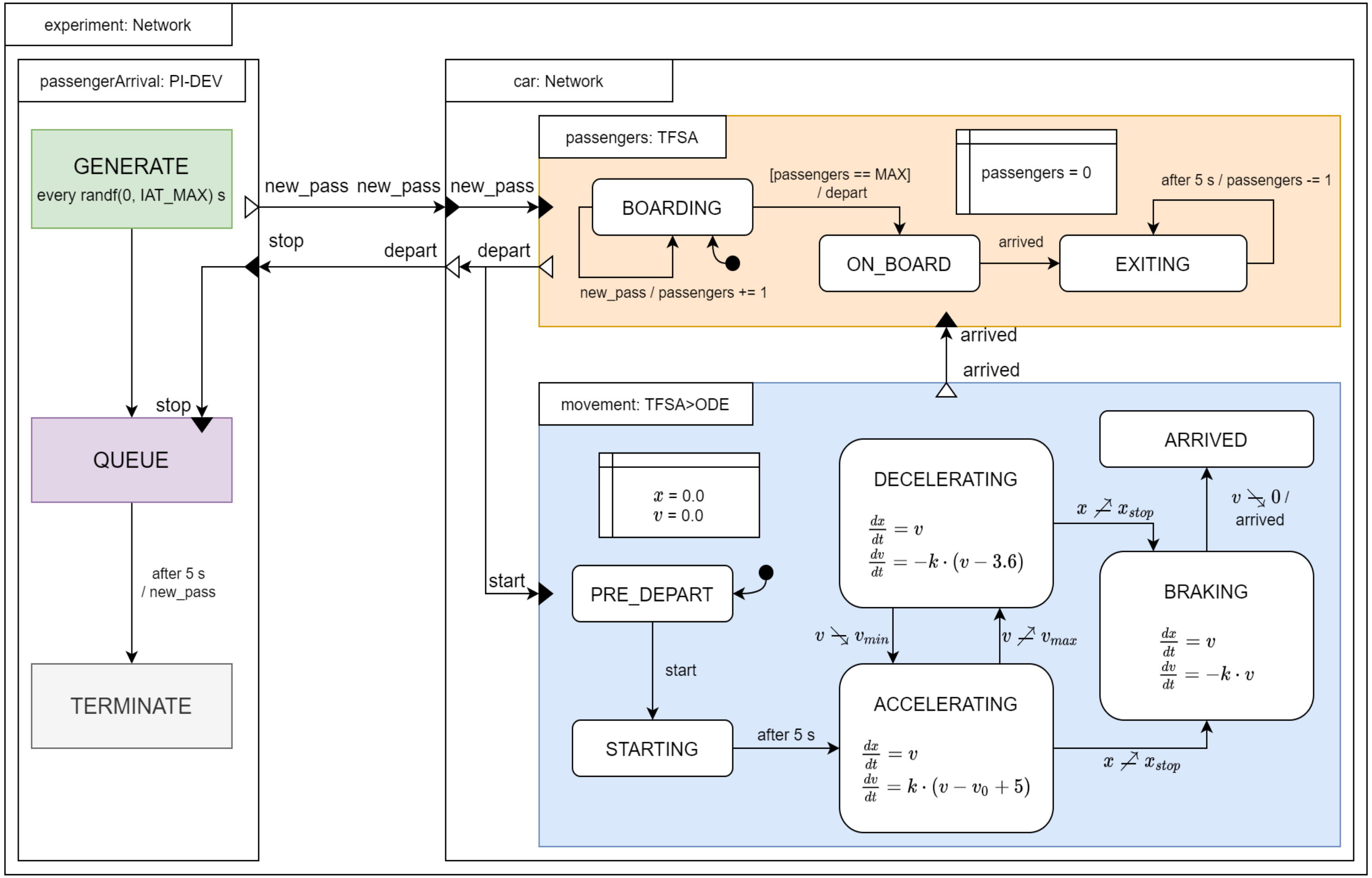


R. Paredis and H.Vangheluwe. 2024. "*Modelling and Simulation-Based Evaluation of Twinning Architectures and Their Deployment*". In Proceedings of SIMULTECH 2024, pp. 170-182.

MPM: Using the most appropriate…

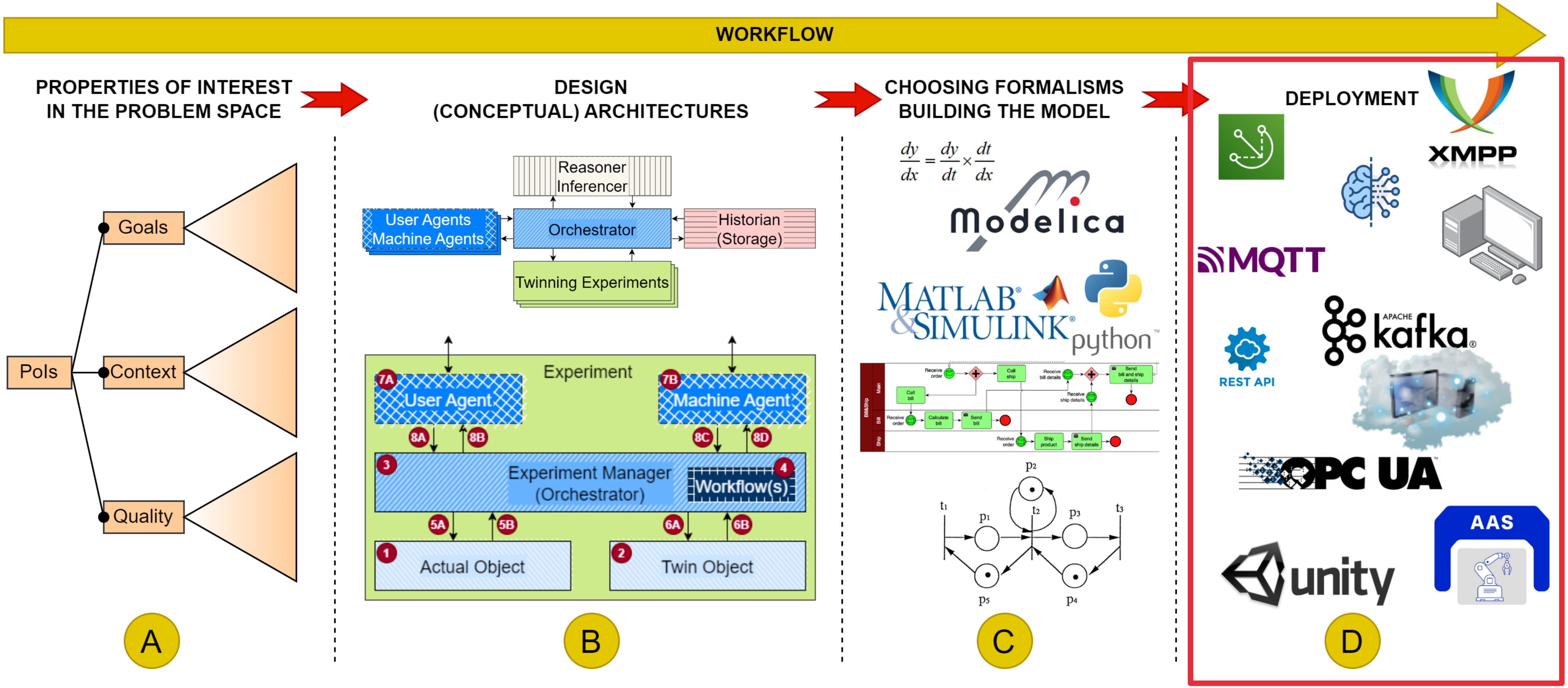






R. Paredis, J. Denil, and H.Vangheluwe. 2021. “*Specifying and Executing the Combination of Timed Finite State Automata and Causal-Block Diagrams by Mapping onto DEVS*”. In Proceedings of WSC 2021.

Stages of Twinning Variability – Deployment



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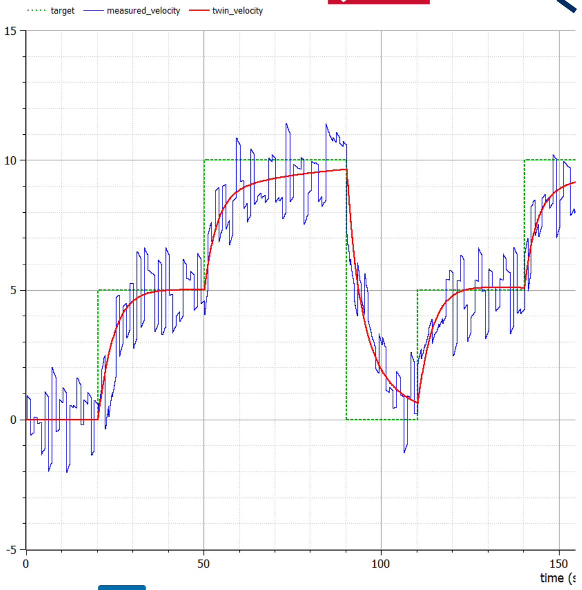
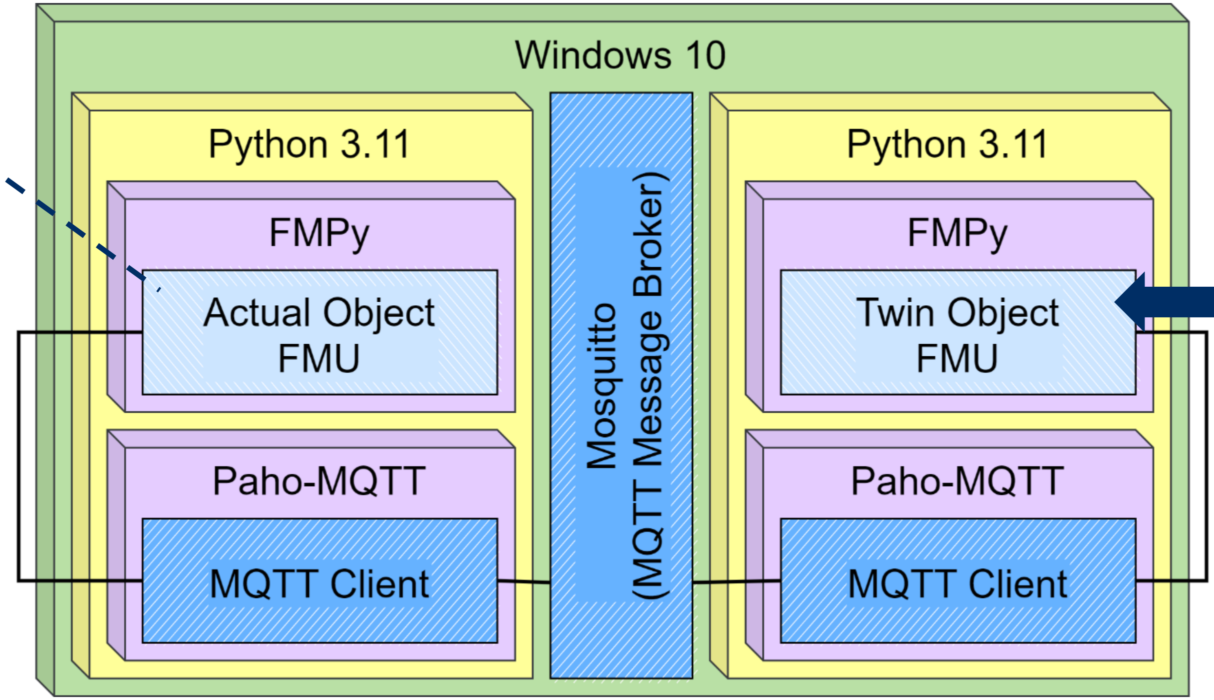
Deployment

Proof-of-Concept: 1D Behaviour of a Ship

$$
\begin{cases}
F_R = \frac{1}{2} \cdot \rho \cdot v^2 \cdot S \cdot C_f \\
C_f = \frac{0.075}{(\log_{10}(Re) - 2)^2} \\
Re = \frac{v \cdot L}{k}
\end{cases}
$$

```
package Ship
  model Plant
    import Con = Modelica.Constants;
    Modelica.Blocks.Interfaces.RealInput FT annotation( ...);
    Modelica.Blocks.Interfaces.RealOutput v(start = 0) annotation( ...);
    Modelica.Blocks.Interfaces.RealOutput x(start = 0) annotation( ...);
    parameter Real mass = 32000;
    //parameter Real area = 263; //261;
    parameter Real L = 21.54;
    parameter Real B = 5.33;
    parameter Real D = 1.47;
    //parameter Real FT = 400;
    parameter Real density = 1025;
    parameter Real viscosity = 1.188 * 10 ^ (-6);
    Real Re(start = 0.0);
    Real Cf(start = 0.0);
    Real area = 2 * Con.pi * ((L * B) ^ 1.6 + (B * D) ^ 1.6 + (L * D) ^ 1.6) ^ (1 / 1.6) / 3;
  equation
    if v < 0.000001 then
      Cf = 0;
      Re = 0;
    else
      Re = v * L / viscosity;
      Cf = 0.075 / (log10(Re) - 2) ^ 2;
    end if;
    der(v) = (FT - 0.5 * density * Cf * area * v * v) / mass;
    der(x) = v;
    annotation( ...);
  end Plant;
```





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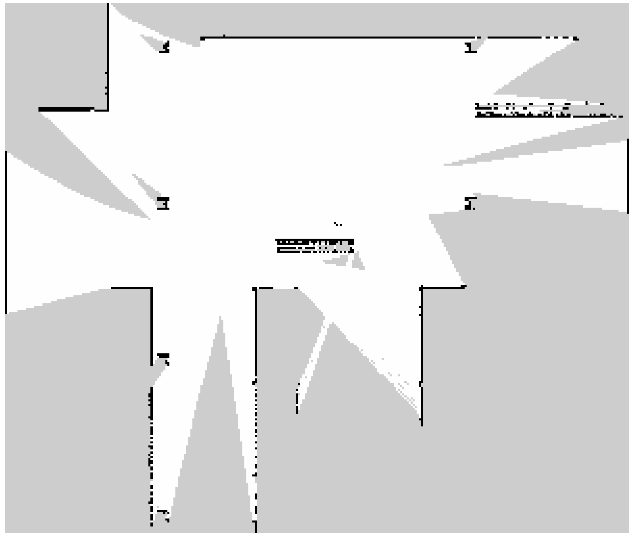
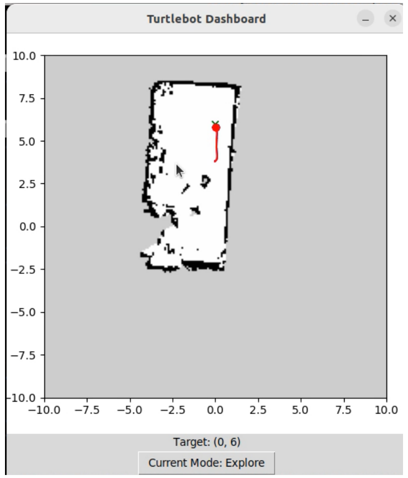
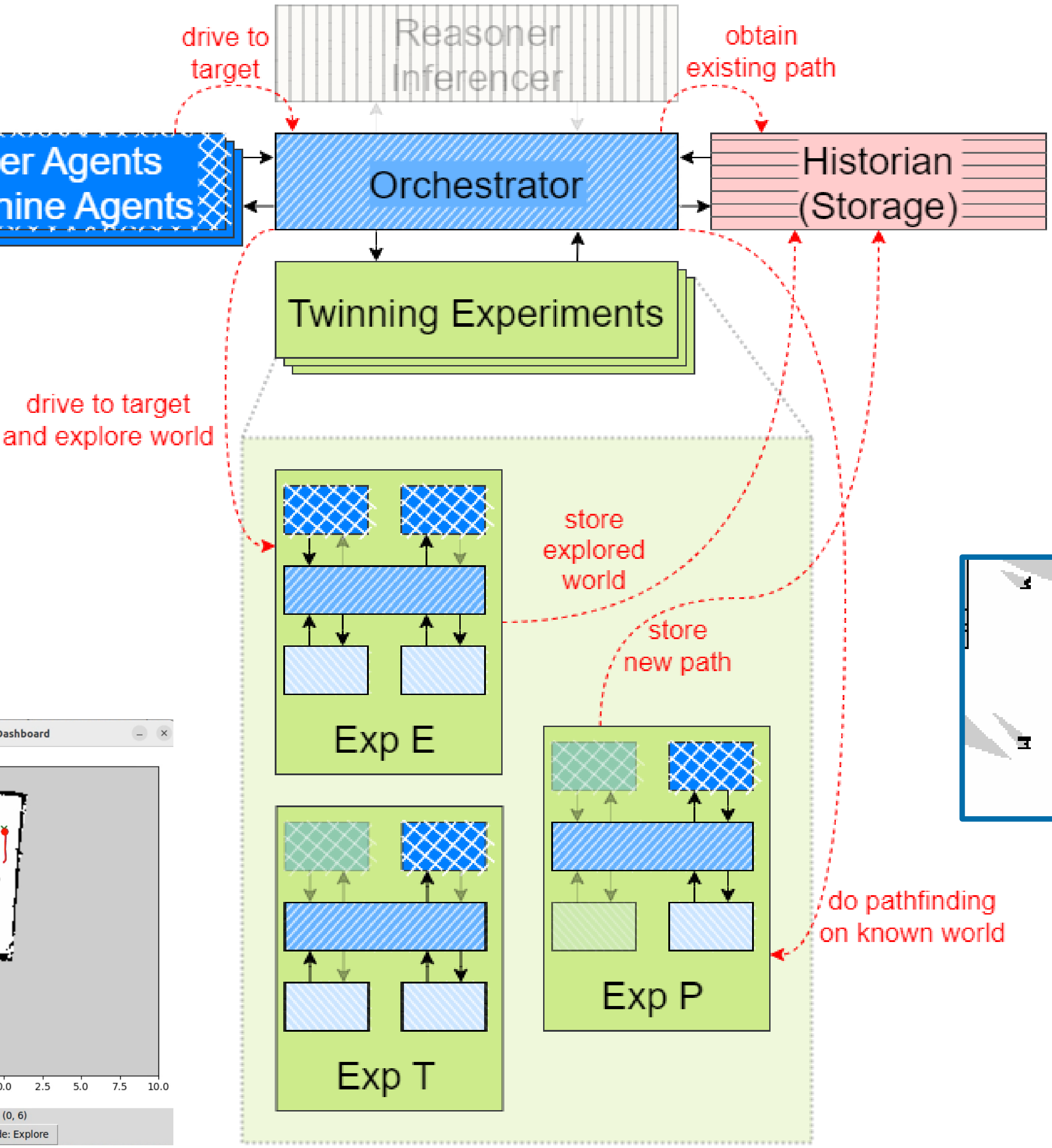
Research Questions

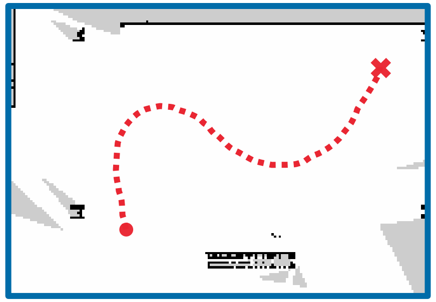
- RQ1: *What are the most common reasons/definitions for (creating) Digital Twins (DTs)?*
- RQ2: *Given the large number of existing DTs in the literature, can we unify?*
- RQ3: *What is the relationship between specific DT requirements, the system architecture, the used models, and the eventual deployment?*
- RQ4: *How to quantitatively support deployment choices?*
- RQ5: *How can we combine multiple DTs into a larger system?*

Proof-of-Concept: Turtlebot









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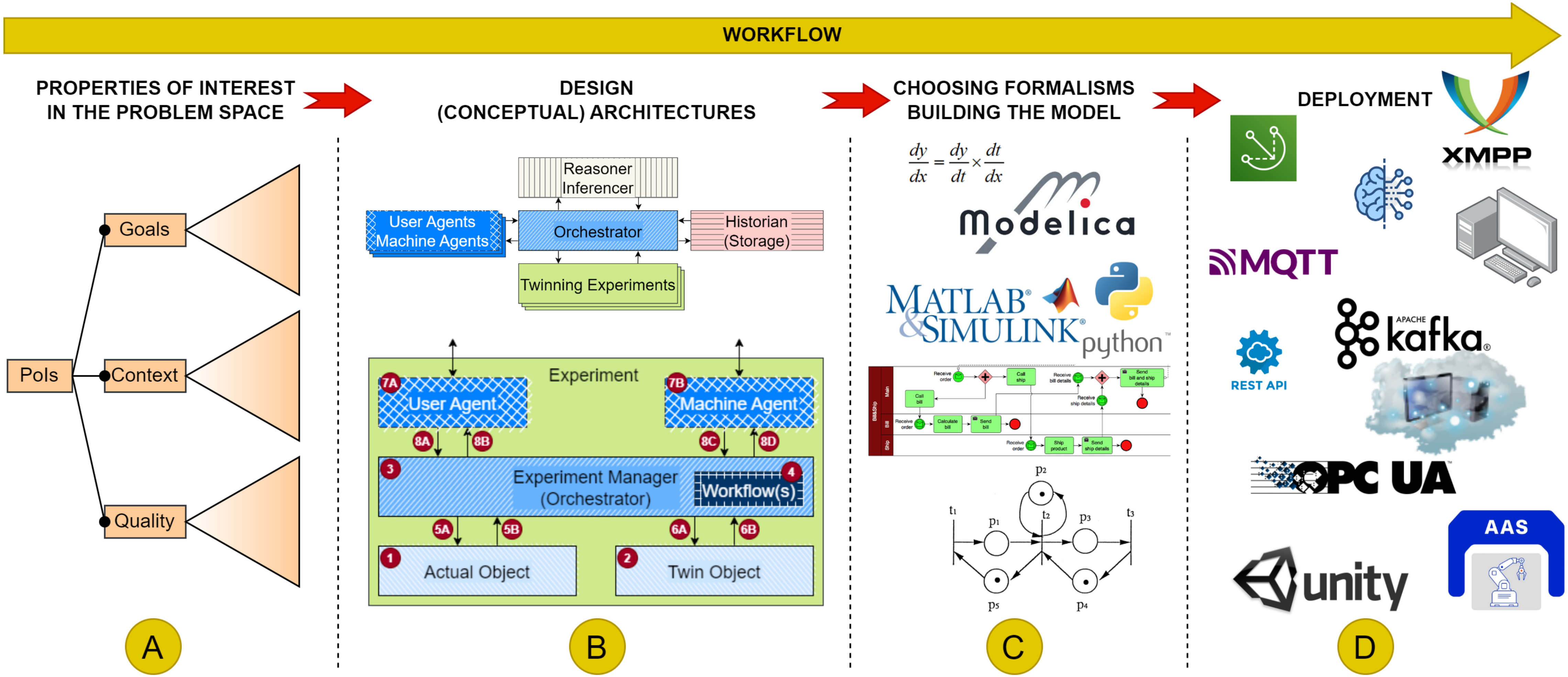
https://shorturl.at/0lXEI

Stages of Twinning Variability



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