University of Antwerp
| Faculty of Science

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: *Is there a relationship between specific DT requirements, the system architecture, the used models, and the eventual deployment?*
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Digital Twin?

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 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]**

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 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]**

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]**

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.

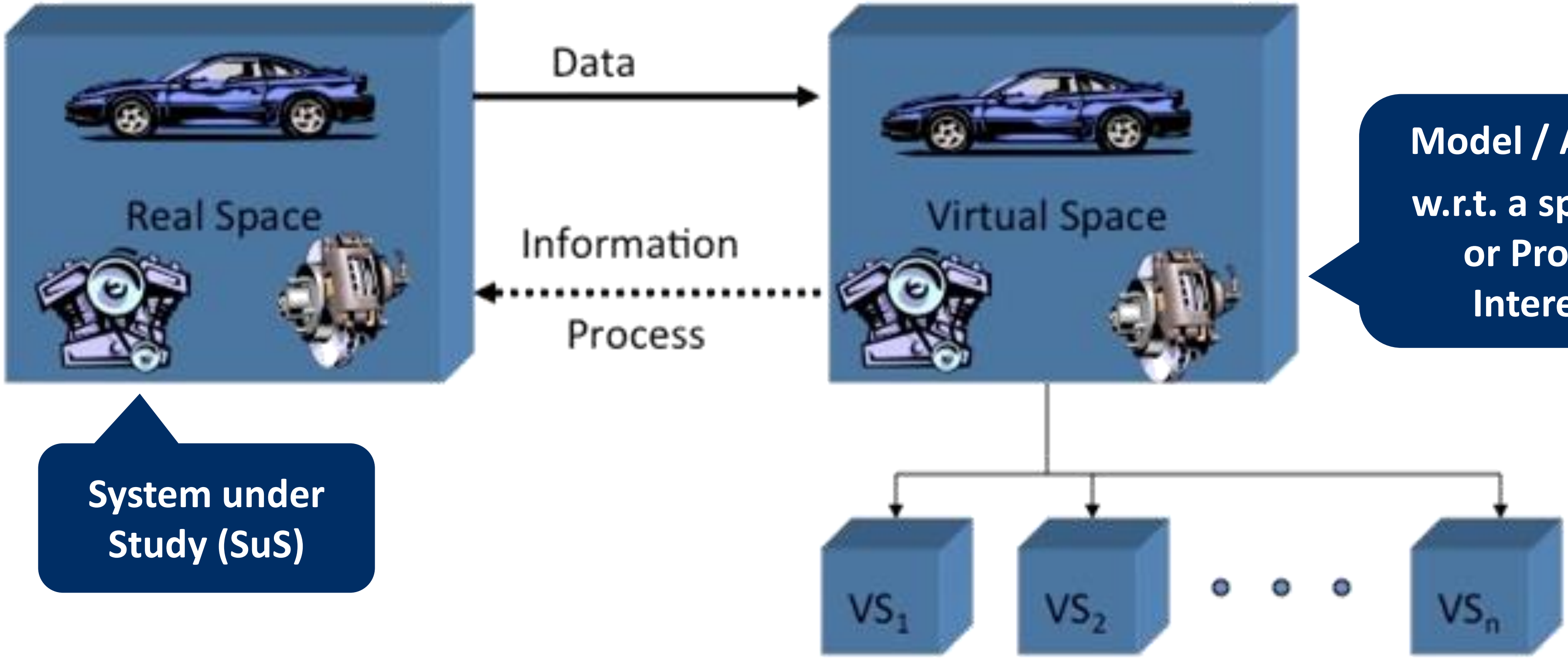
[6] B. T. Gockel et al. 2012. "*Challenges with Structural Life Forecasting using Realistic Mission Profiles*". In *53rd AIAA/ASME/ASCE/AHS/ASC Struct. Struct. Dyn. Mater. Conf.*

[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.*

Conceptual Ideal for PLM

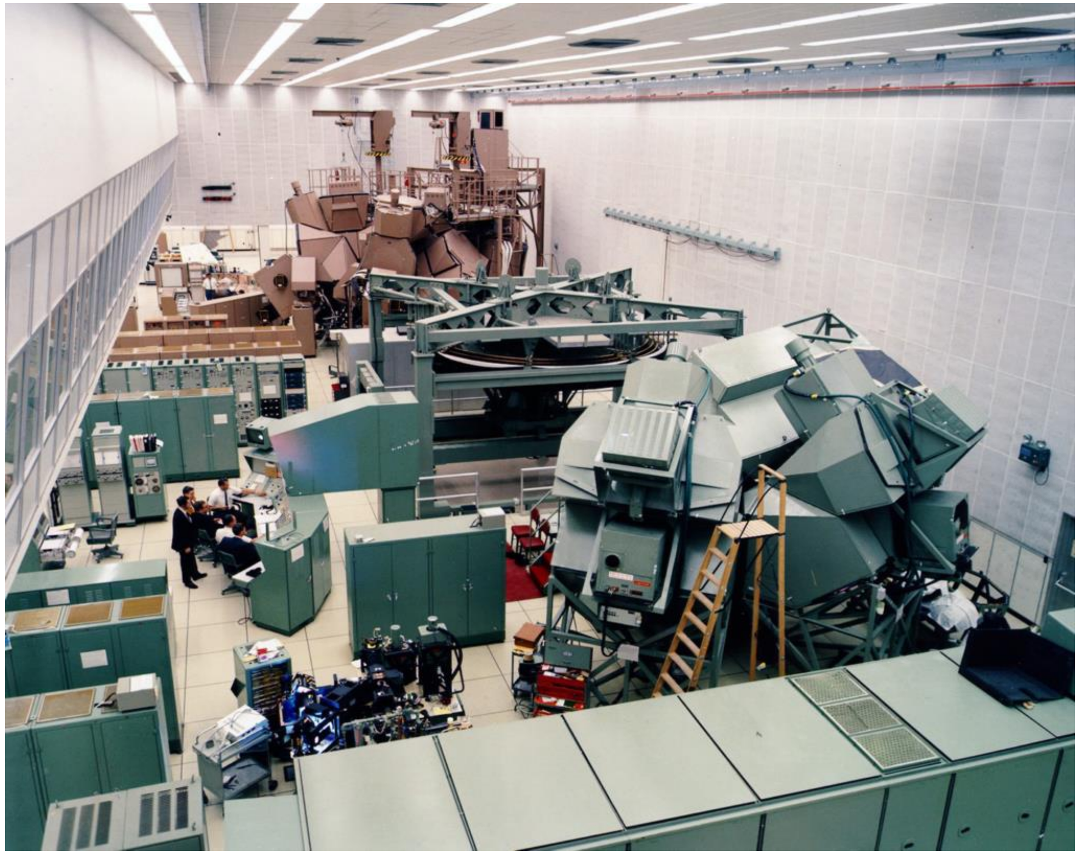


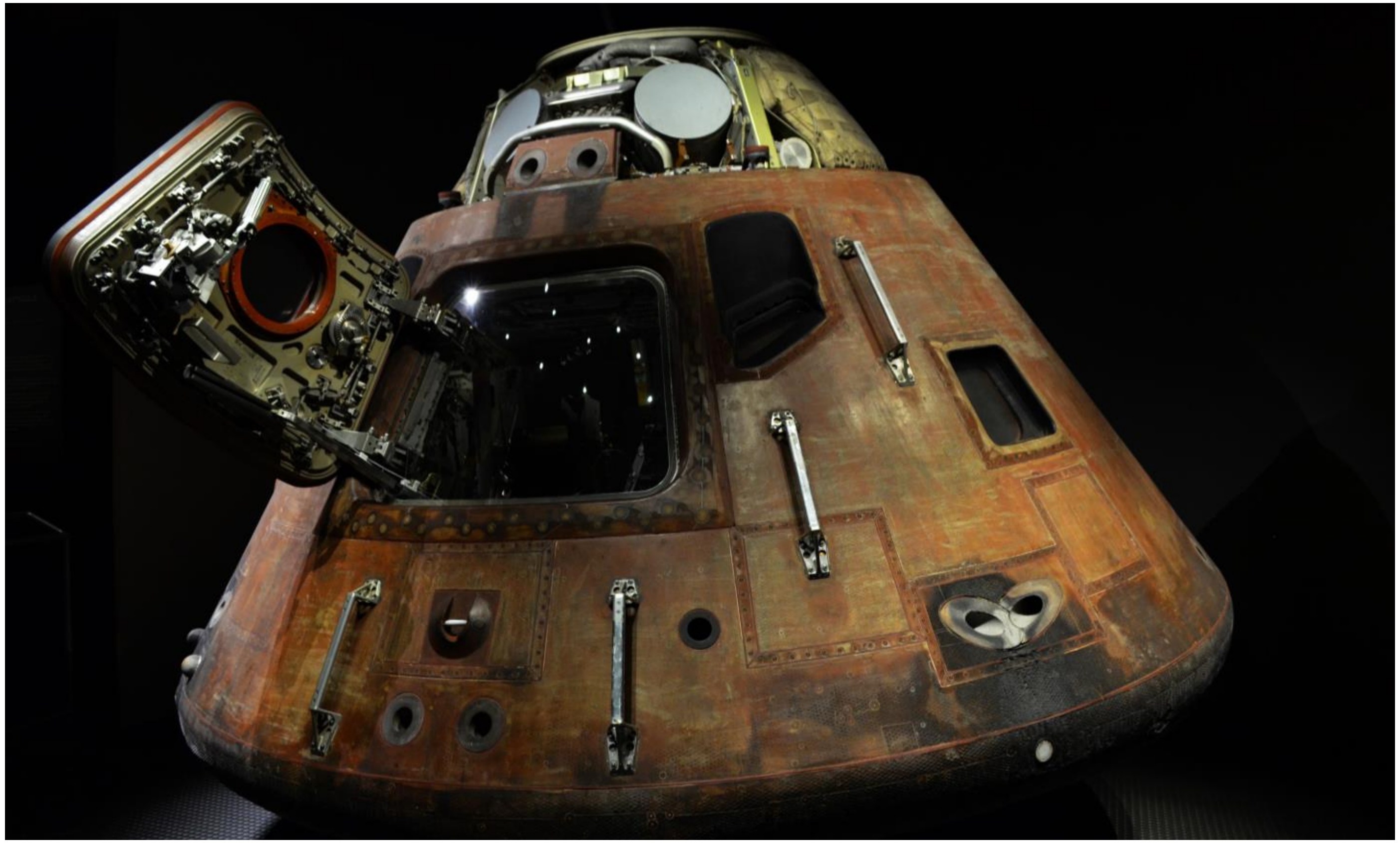
Model / Abstraction w.r.t. a specific view or Property of Interest (PoI)

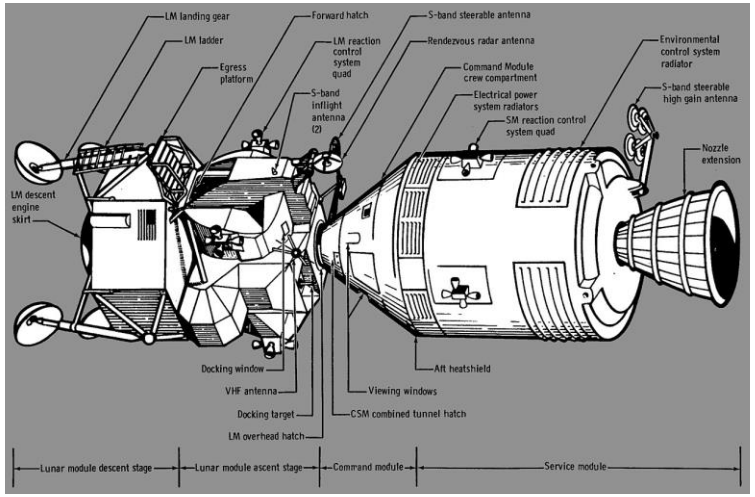
System under Study (SuS)

M. Grieves. 2016. "*Origins of the Digital Twin Concept*".

Apollo 13







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

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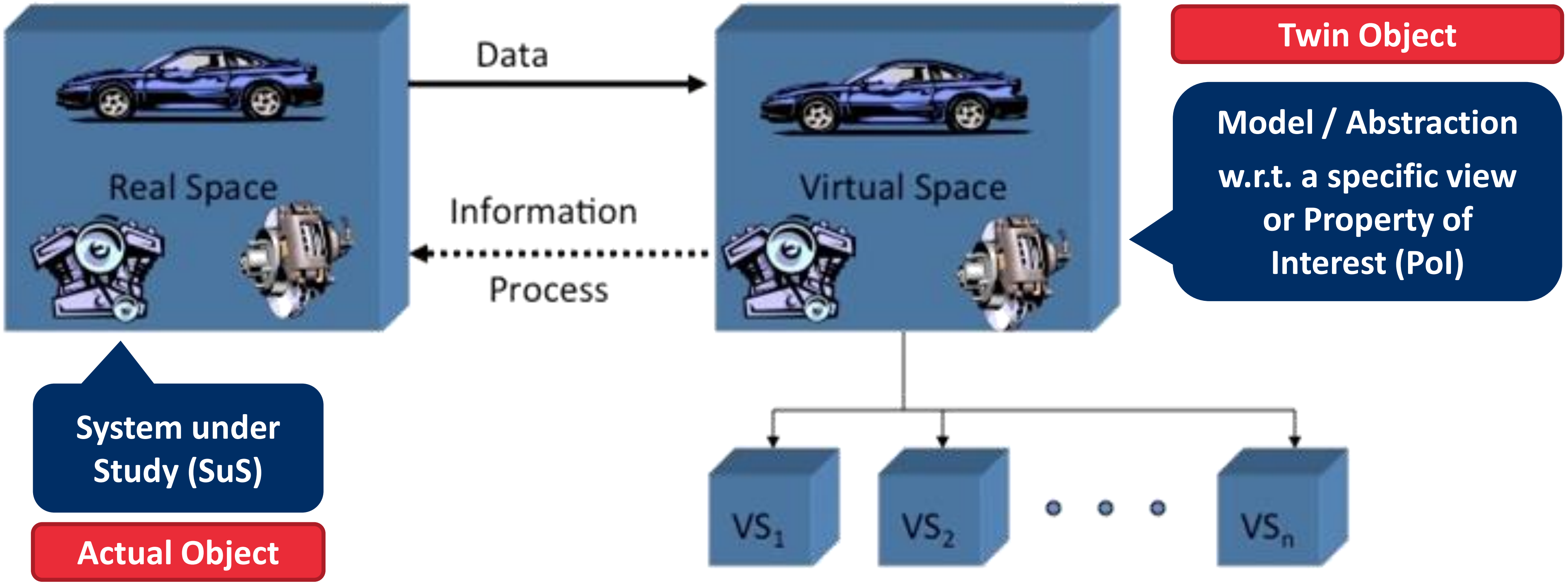

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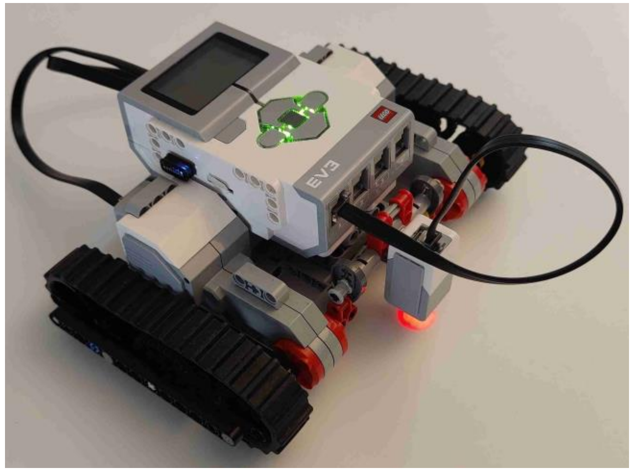
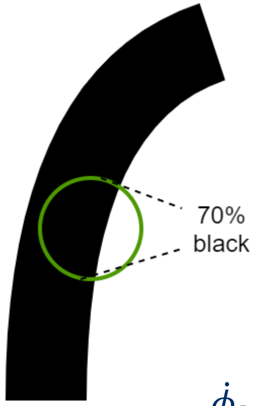
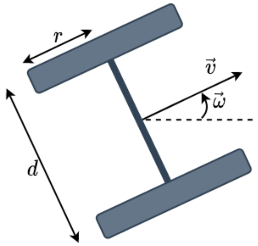
Proof-of-Concept: Line Following Robot

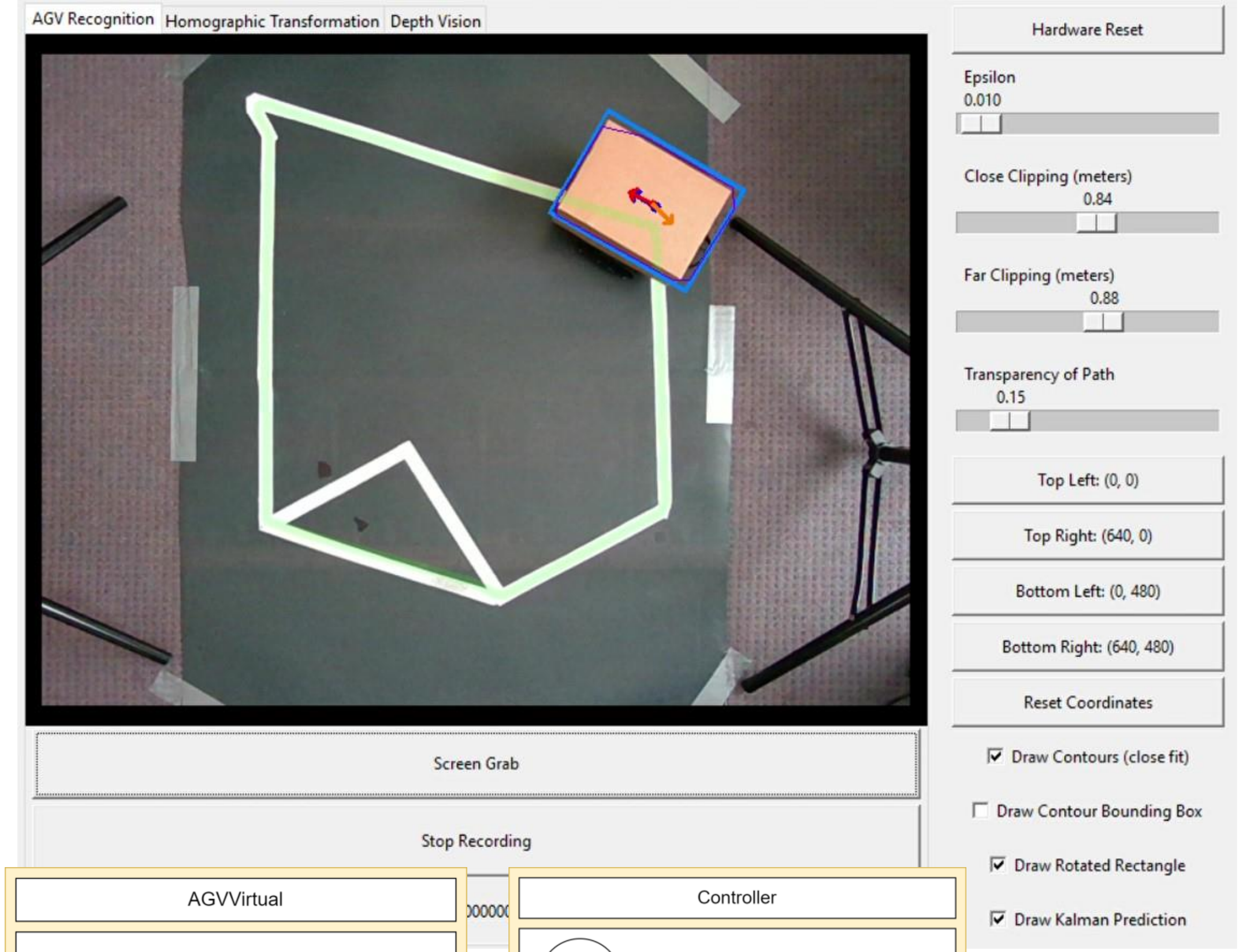


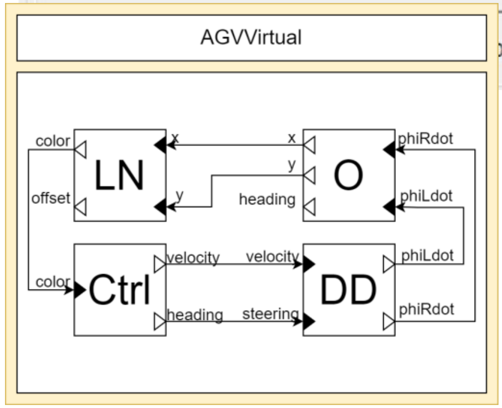


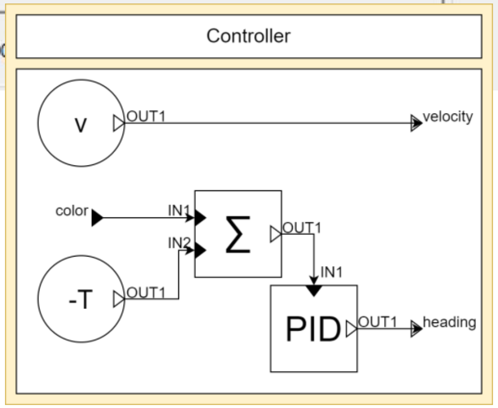


$$\dot{\phi}_L = \frac{1}{r}\left(\dot{v} - \frac{\dot{\omega} \cdot d}{2}\right)$$

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







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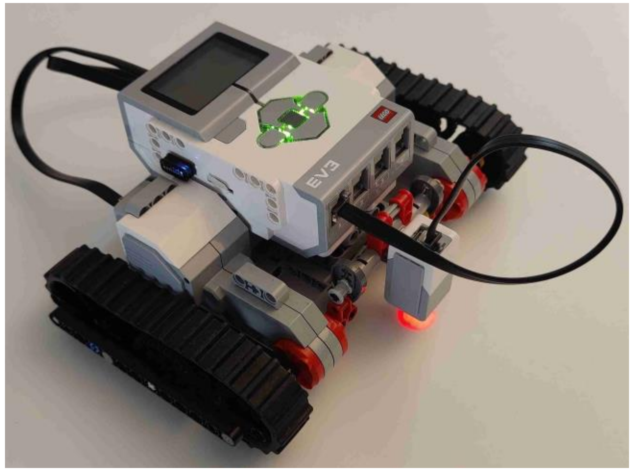

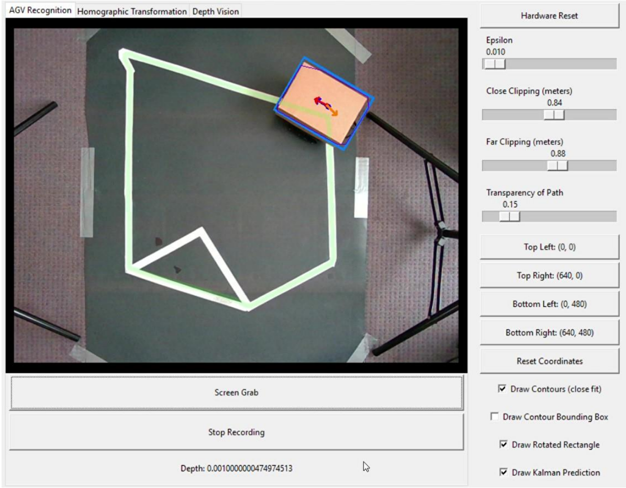

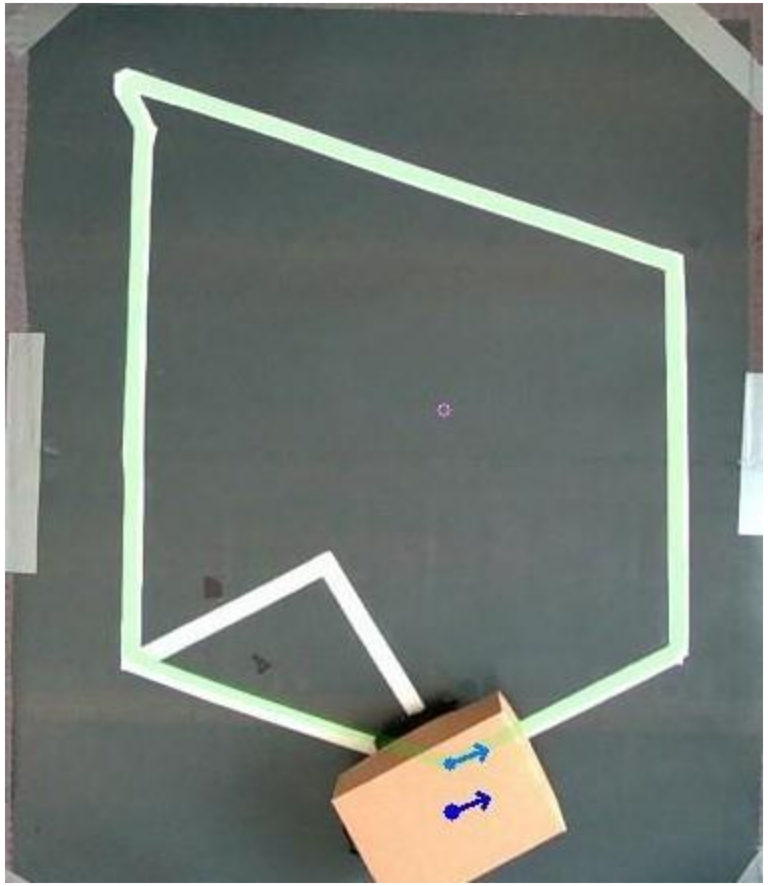

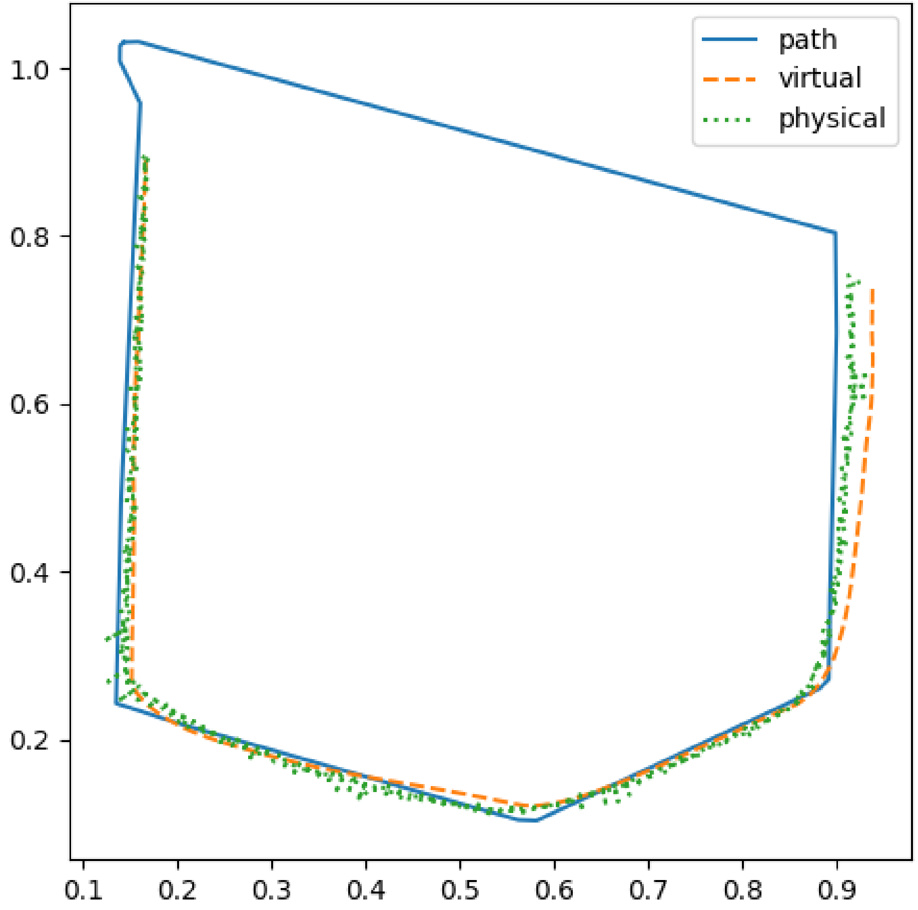

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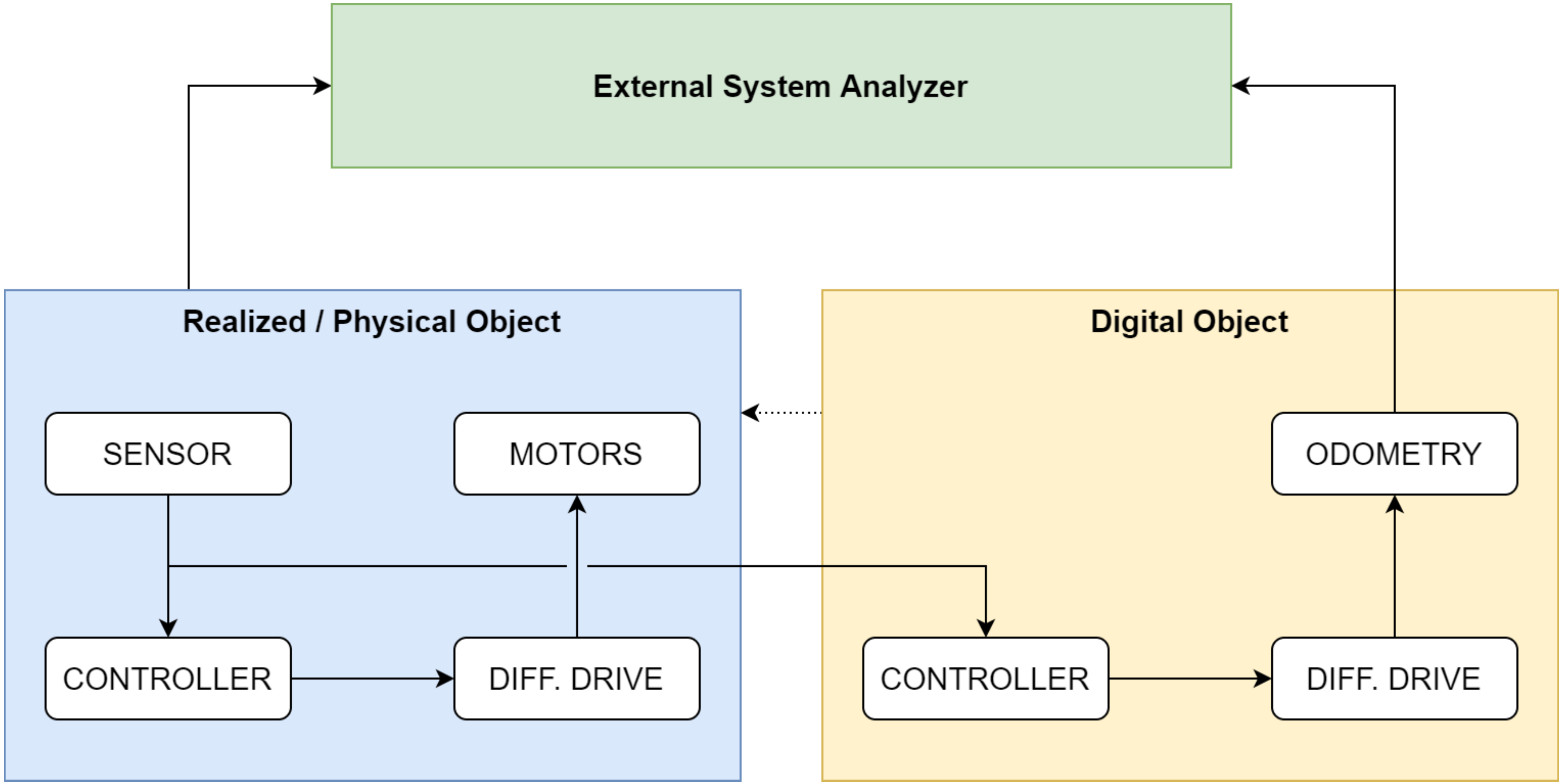

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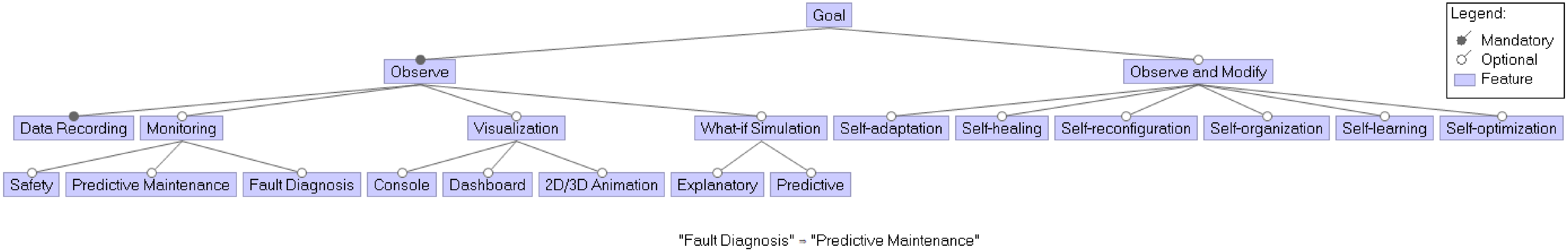
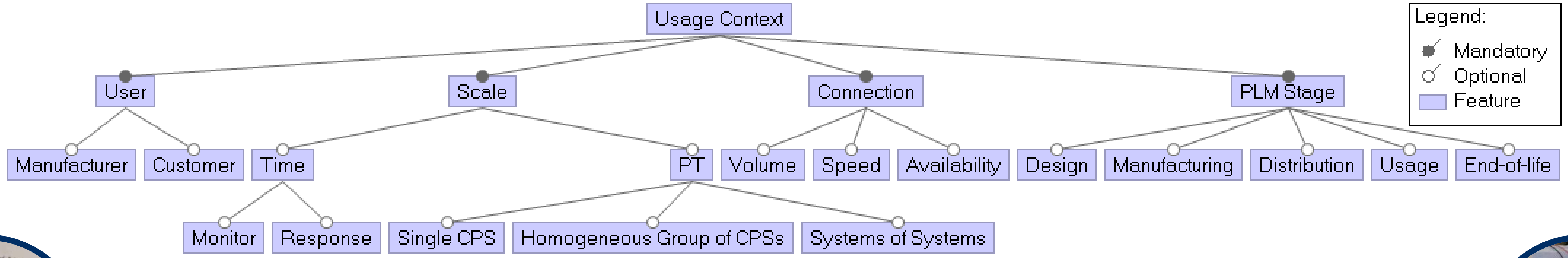
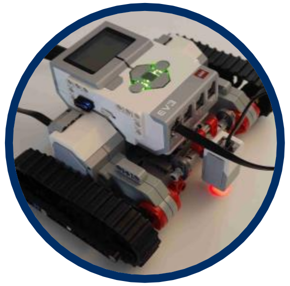
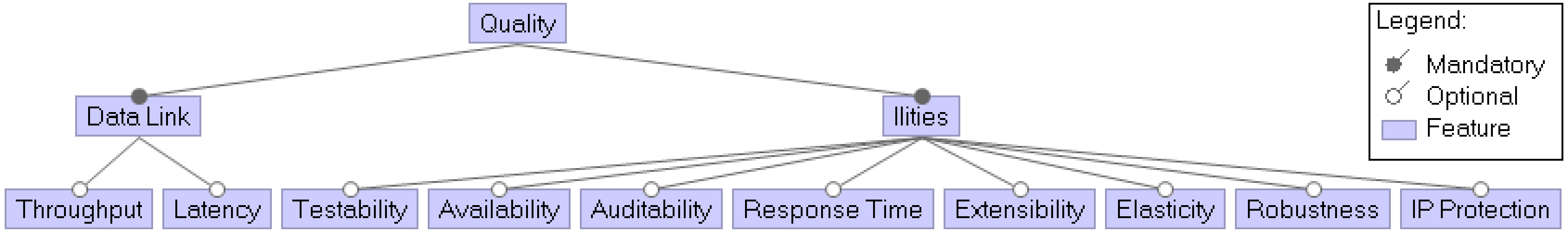
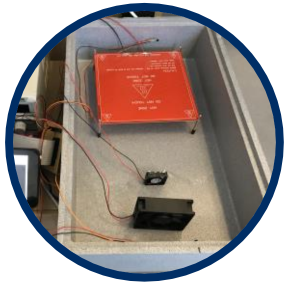
LFR vs Incubator











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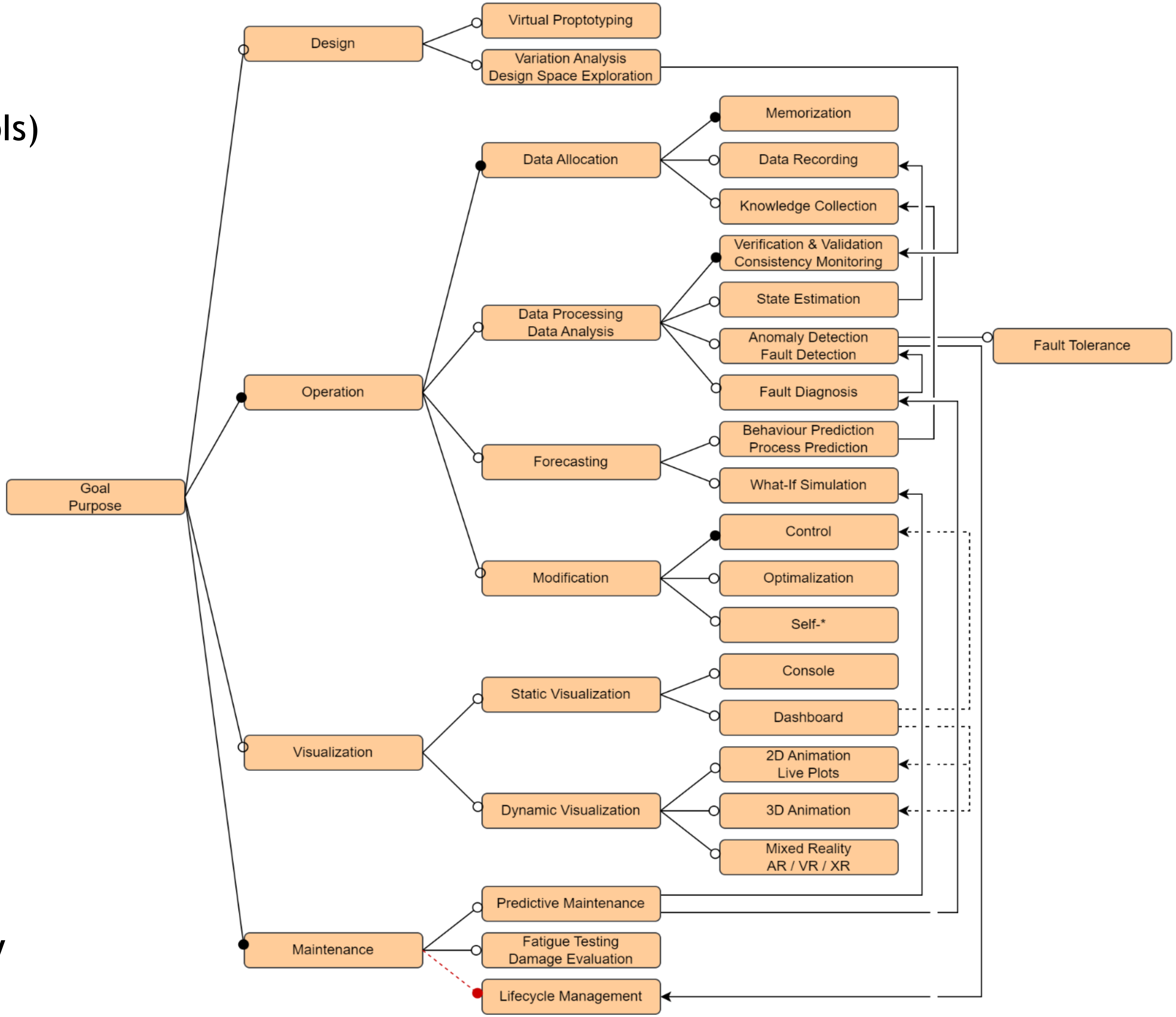
R. Paredis, C. Gomes, and H.Vangheluwe. 2021. "*Towards a Family of Digital Model/Shadow/Twin Workflows and Architectures*". In Proceedings of IN4PL 2021, pp. 174-182.

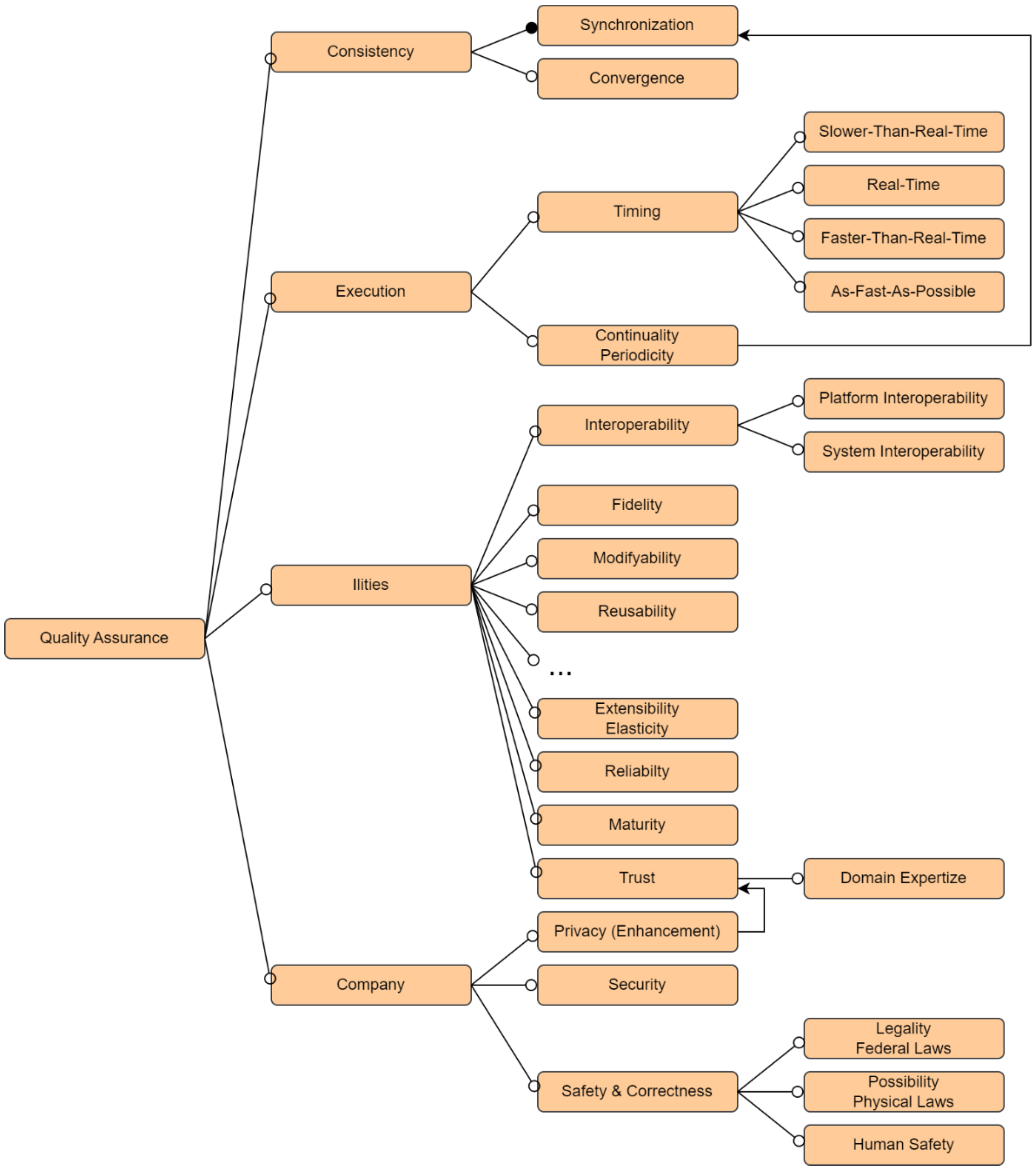
Goals w.r.t. their Properties of Interest (PoIs)



“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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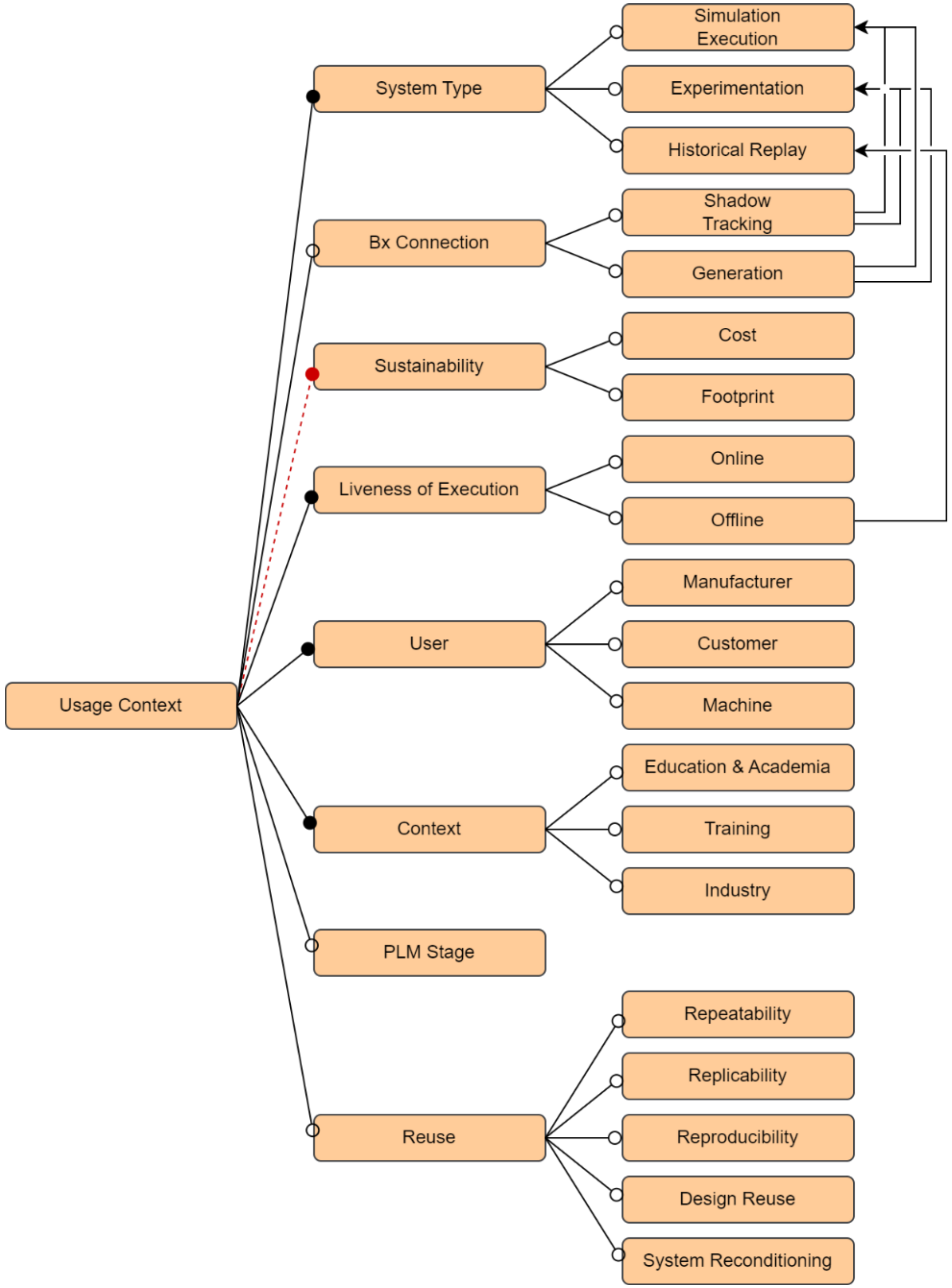
Usage Context



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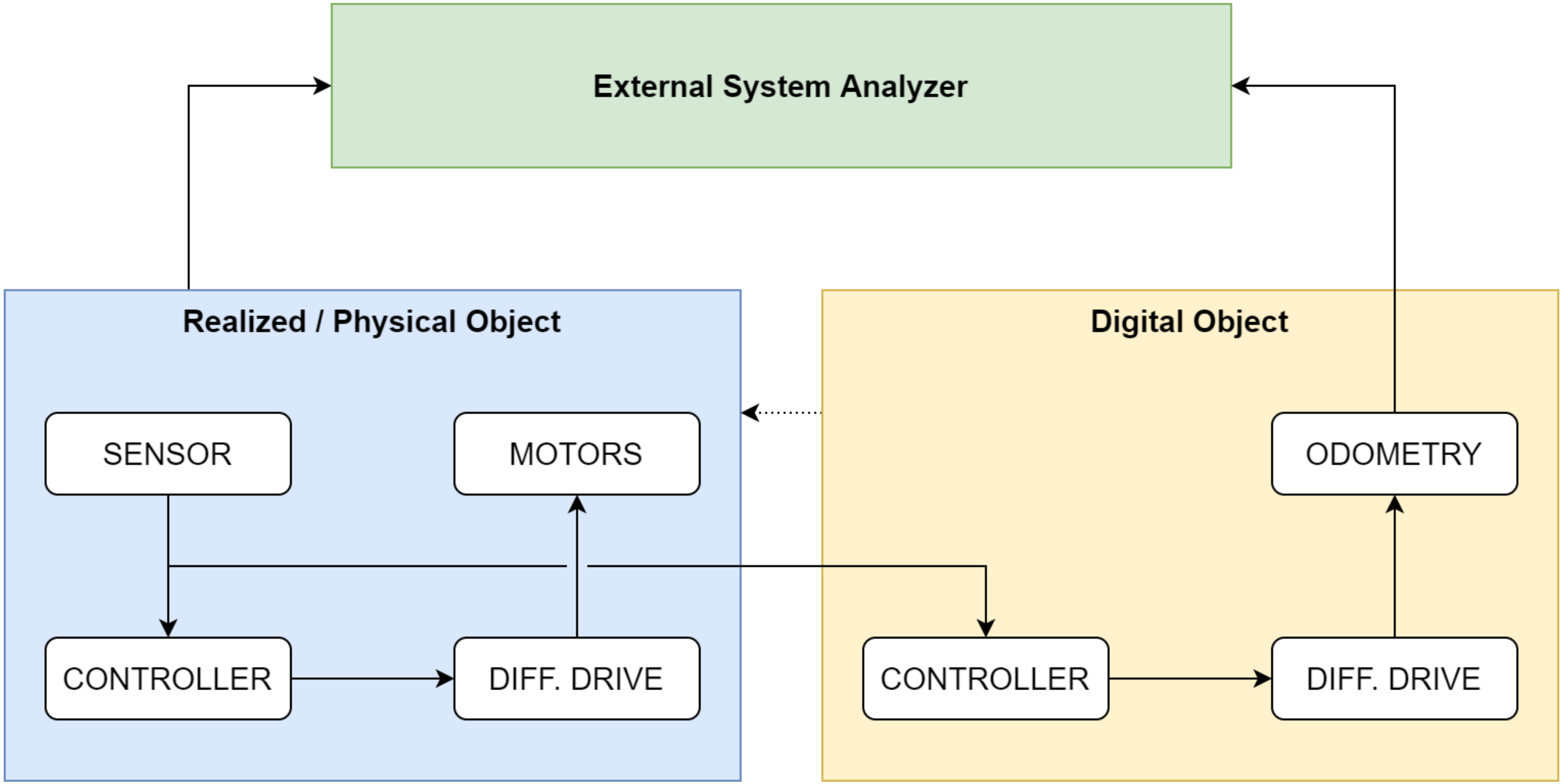

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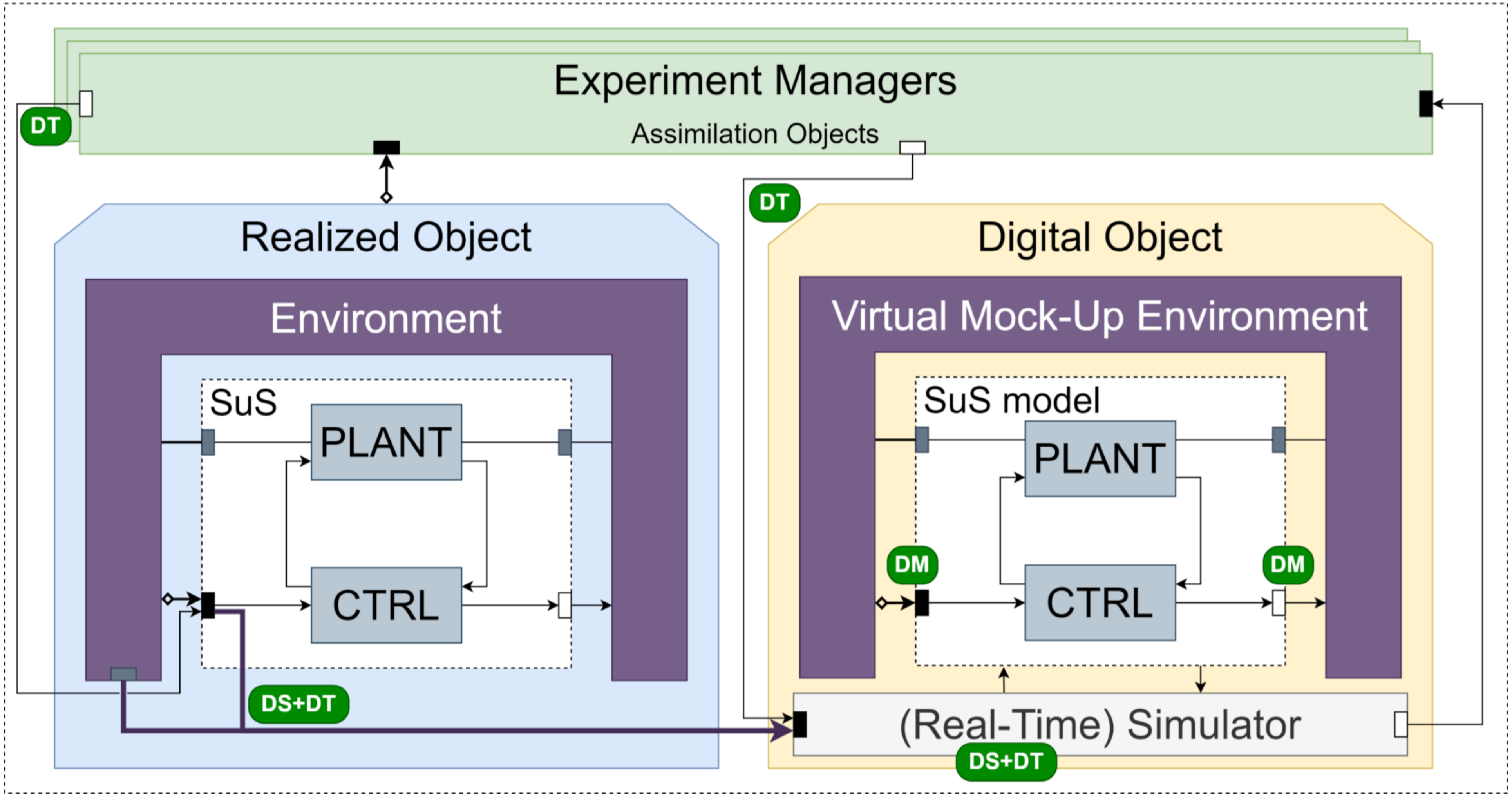
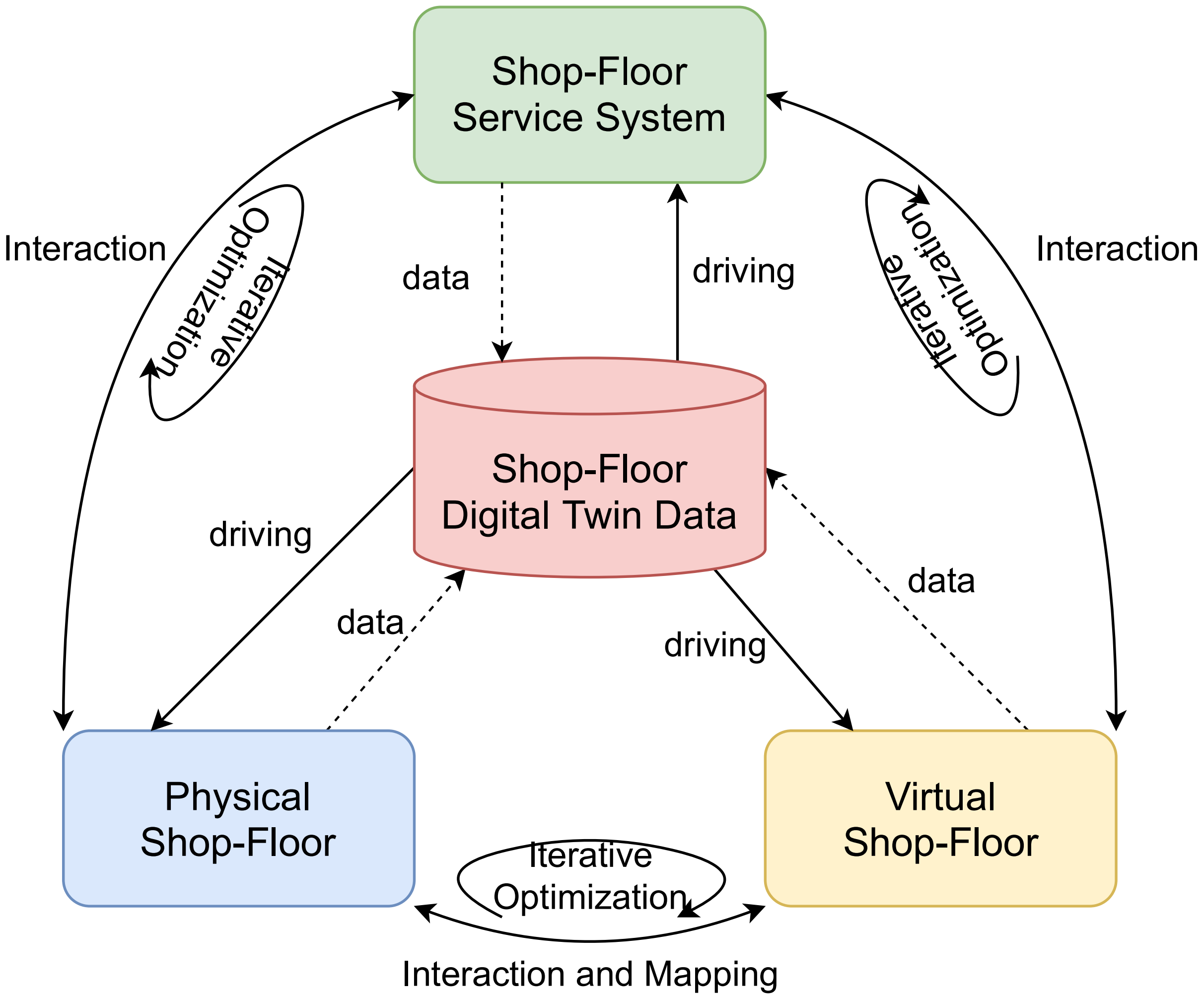
Digital Z Architecture



R. Paredis, and H.Vangheluwe. 2022. "*Towards a Digital Z Framework Based on a Family of Architectures and a Virtual Knowledge Graph*". In Proceedings of MoDELS 2022.

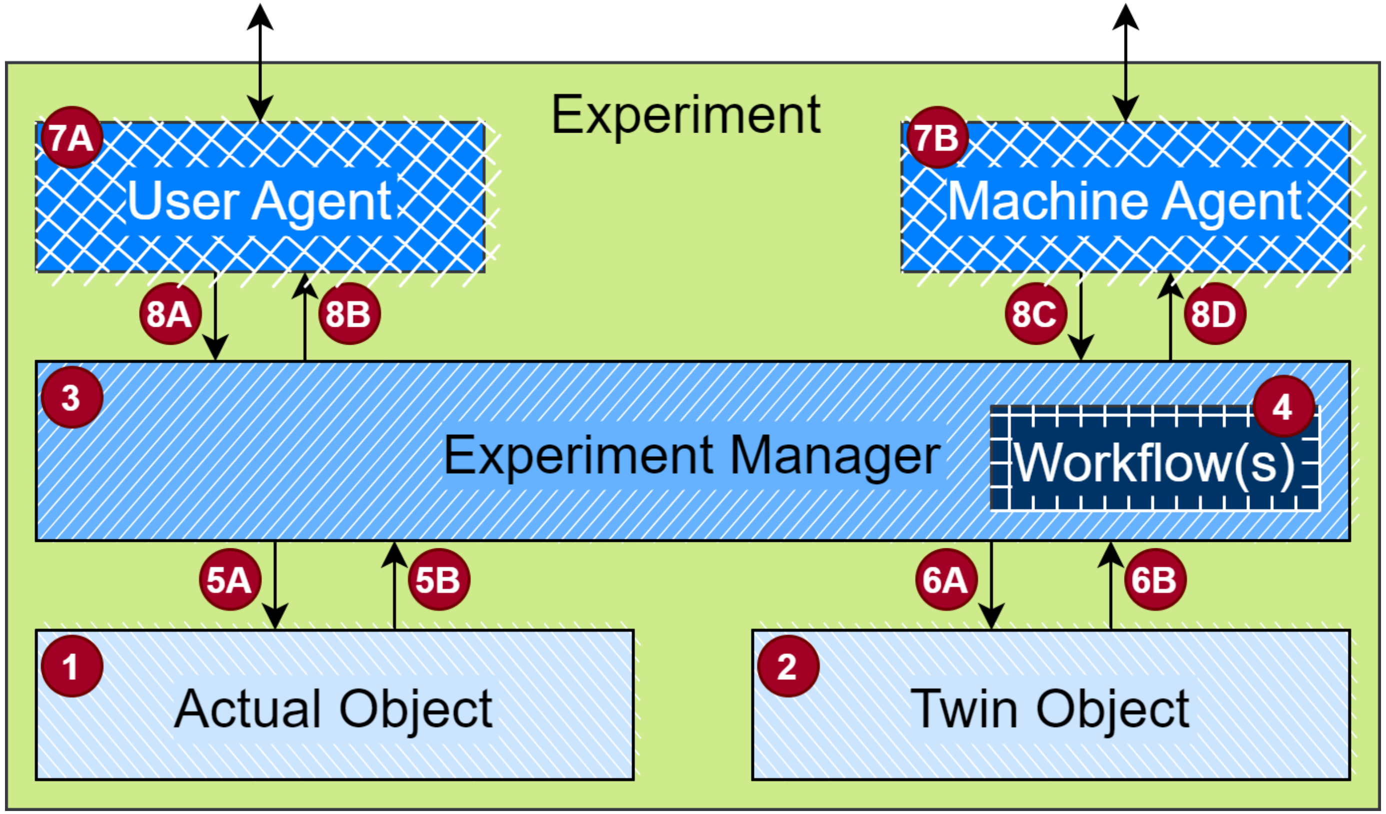
5D Architecture



F. Tao and M. Zhang. 2017. “*Digital Twin Shop-Floor: a New Shop-Floor Paradigm Towards Smart Manufacturing*”. In *IEEE Access 5*, pp. 20418 – 20427.

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

Conceptual Architecture(s)



presence conditions
to capture variability

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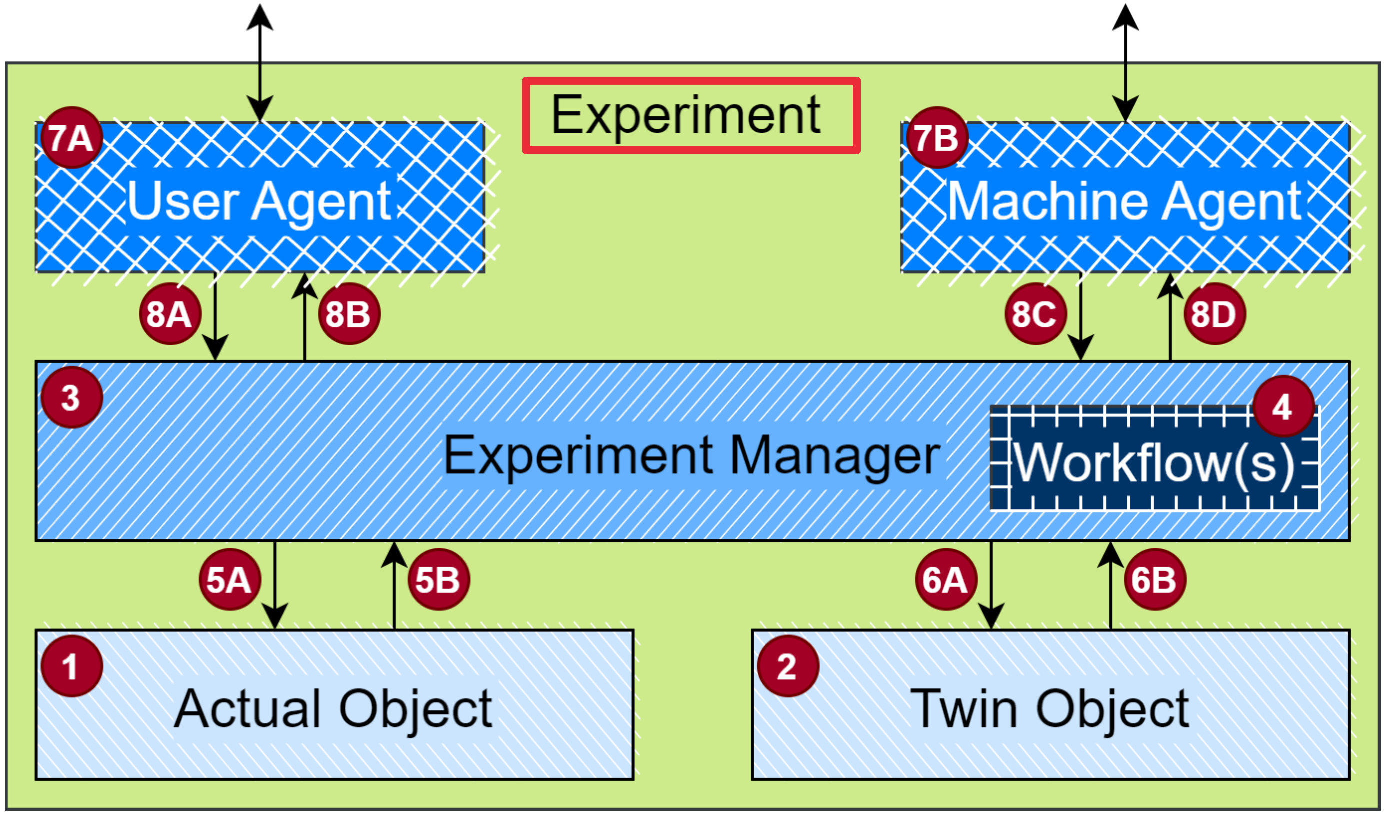

presence conditions
to capture variability

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.

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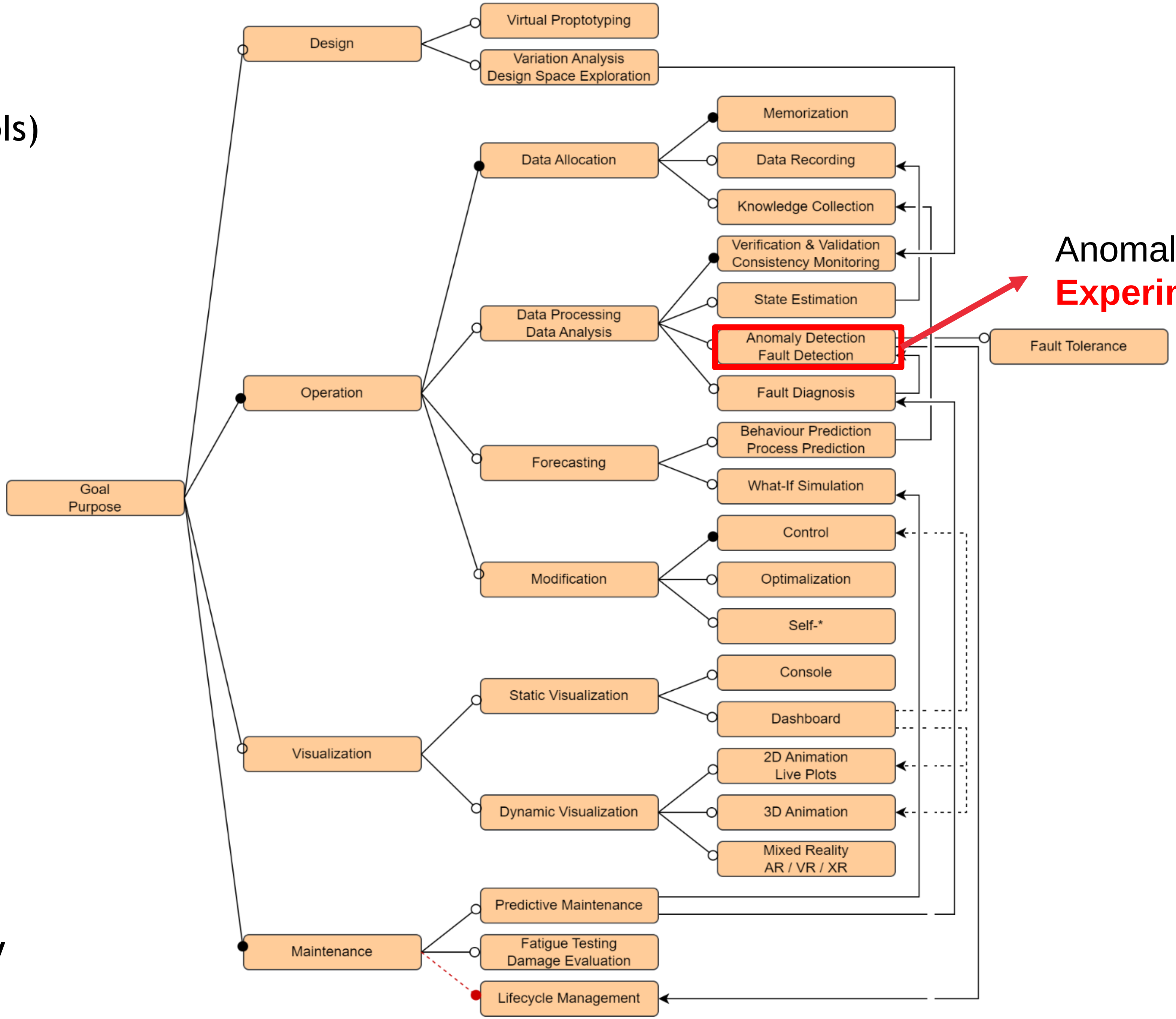

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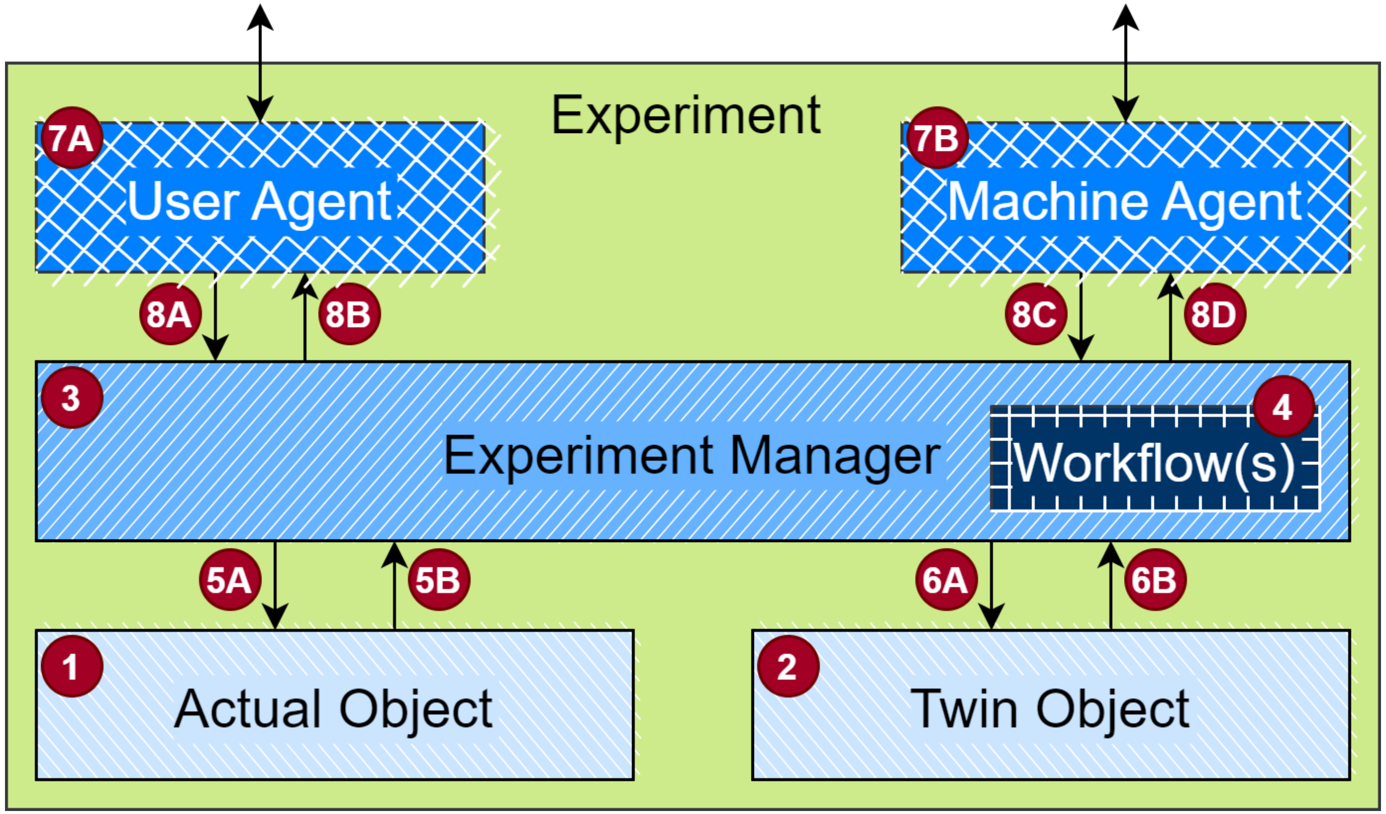
Conceptual Architecture(s)



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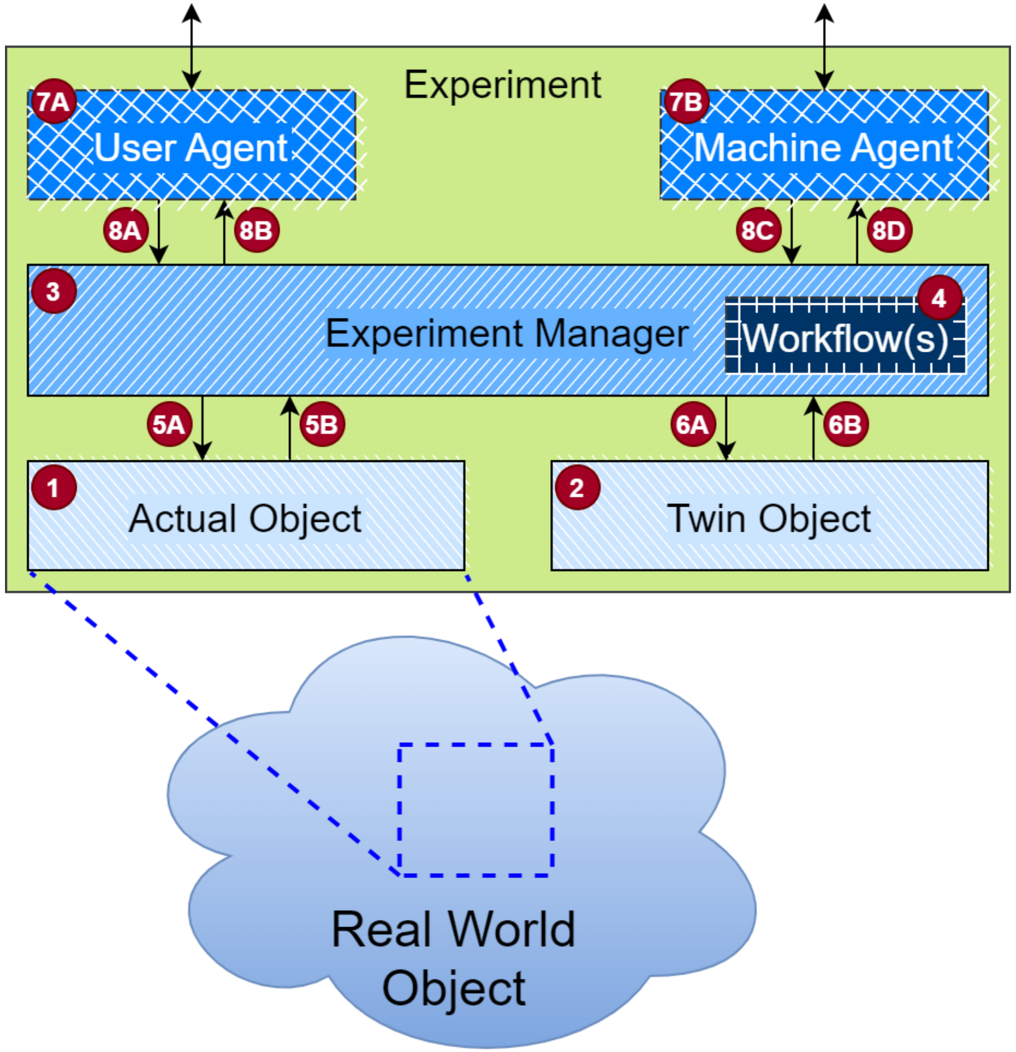

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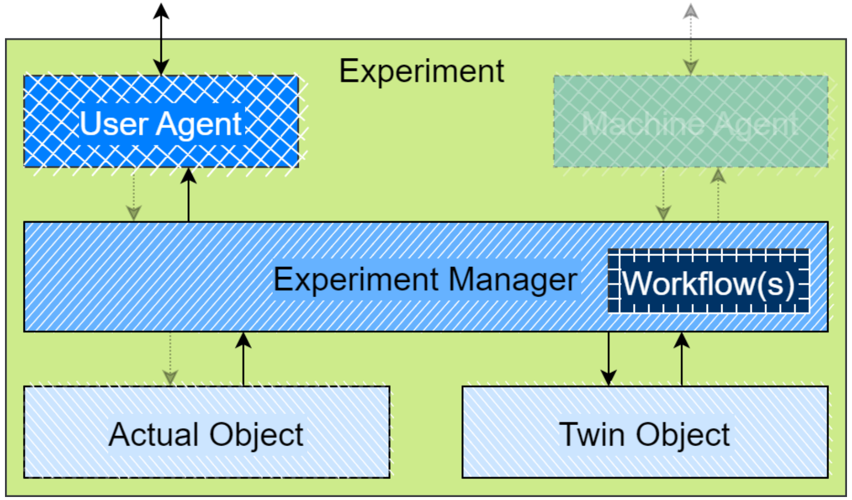
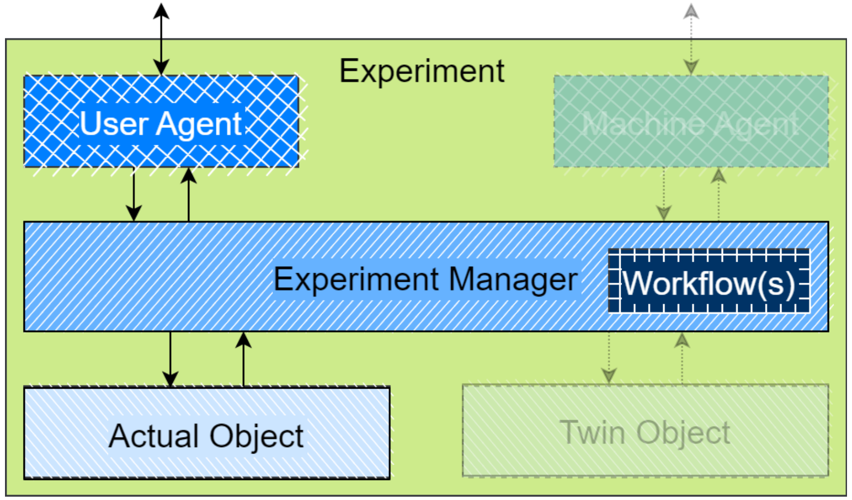
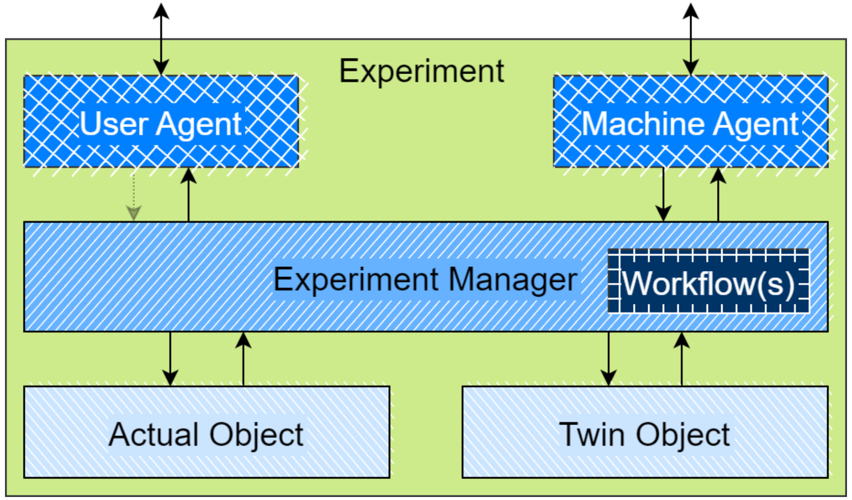
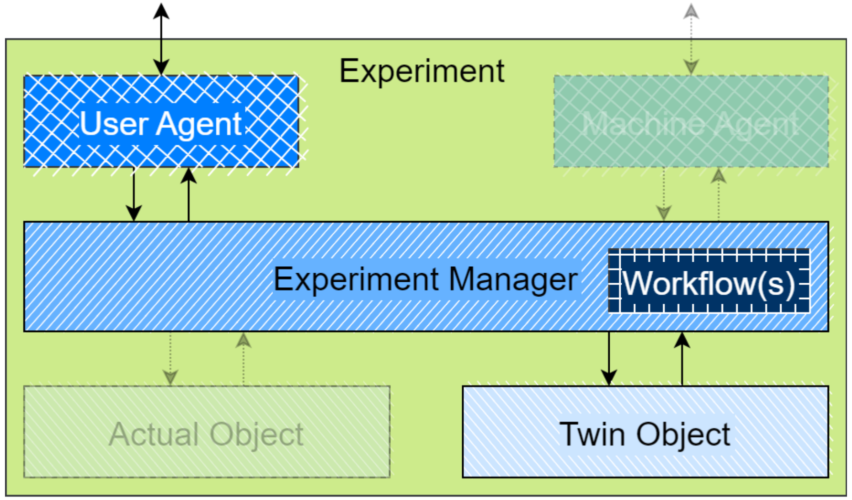
Conceptual Architecture Example(s)









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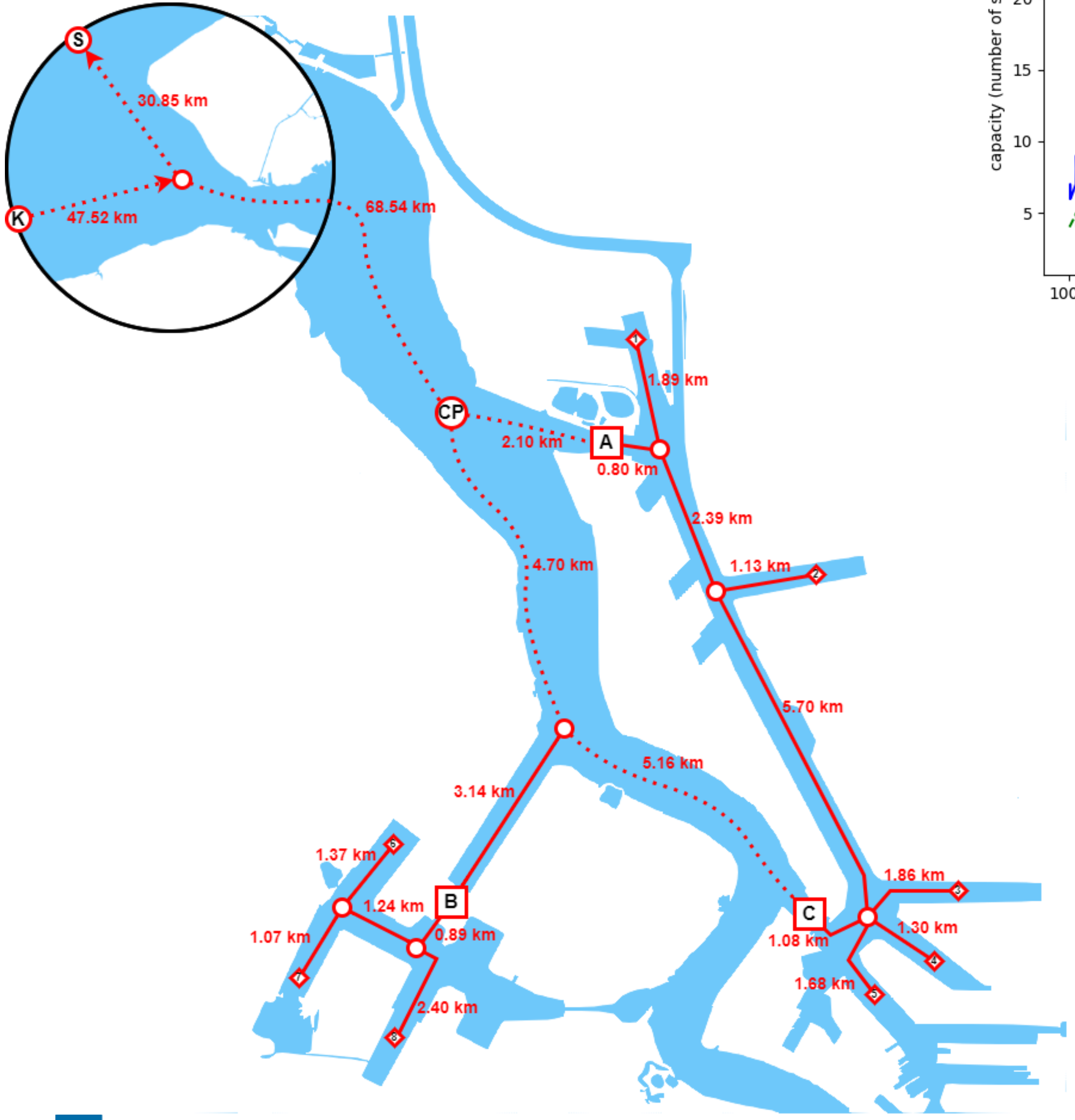
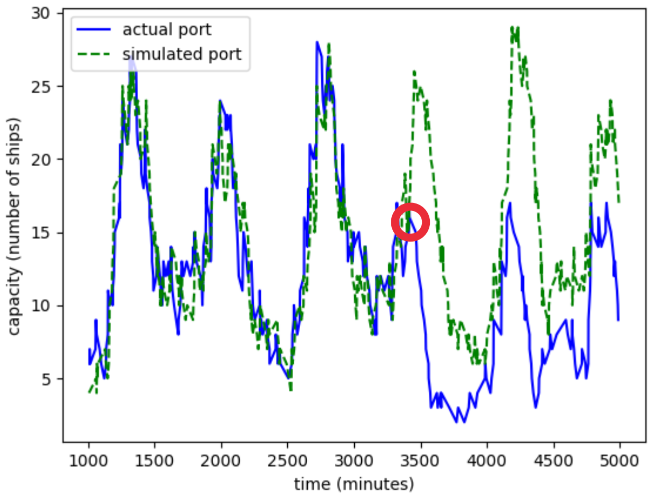
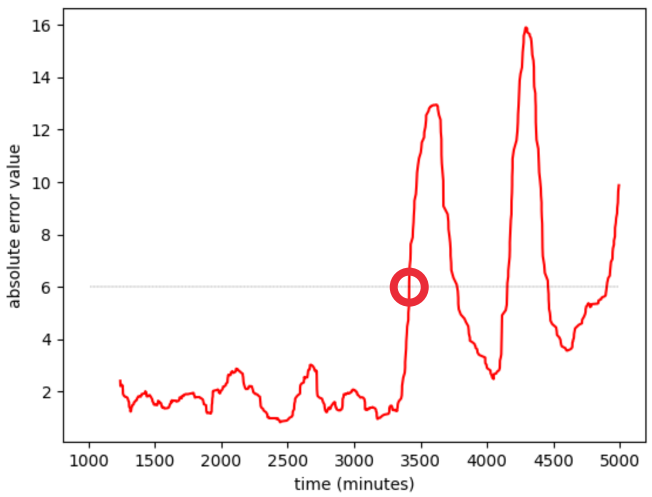
Proof-of-Concept: Port of Antwerp







$D \leftarrow$ Drop-off value for the error.
$M \leftarrow$ Maximal allowed time above D.
$prev \leftarrow -1$
while system is running **do**
  $cap_A \leftarrow$ Capacity value of the AO.
  $cap_T \leftarrow$ Capacity value of the TO.
  $T \leftarrow$ Current execution time.
  $error \leftarrow |cap_A - cap_T|$
  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

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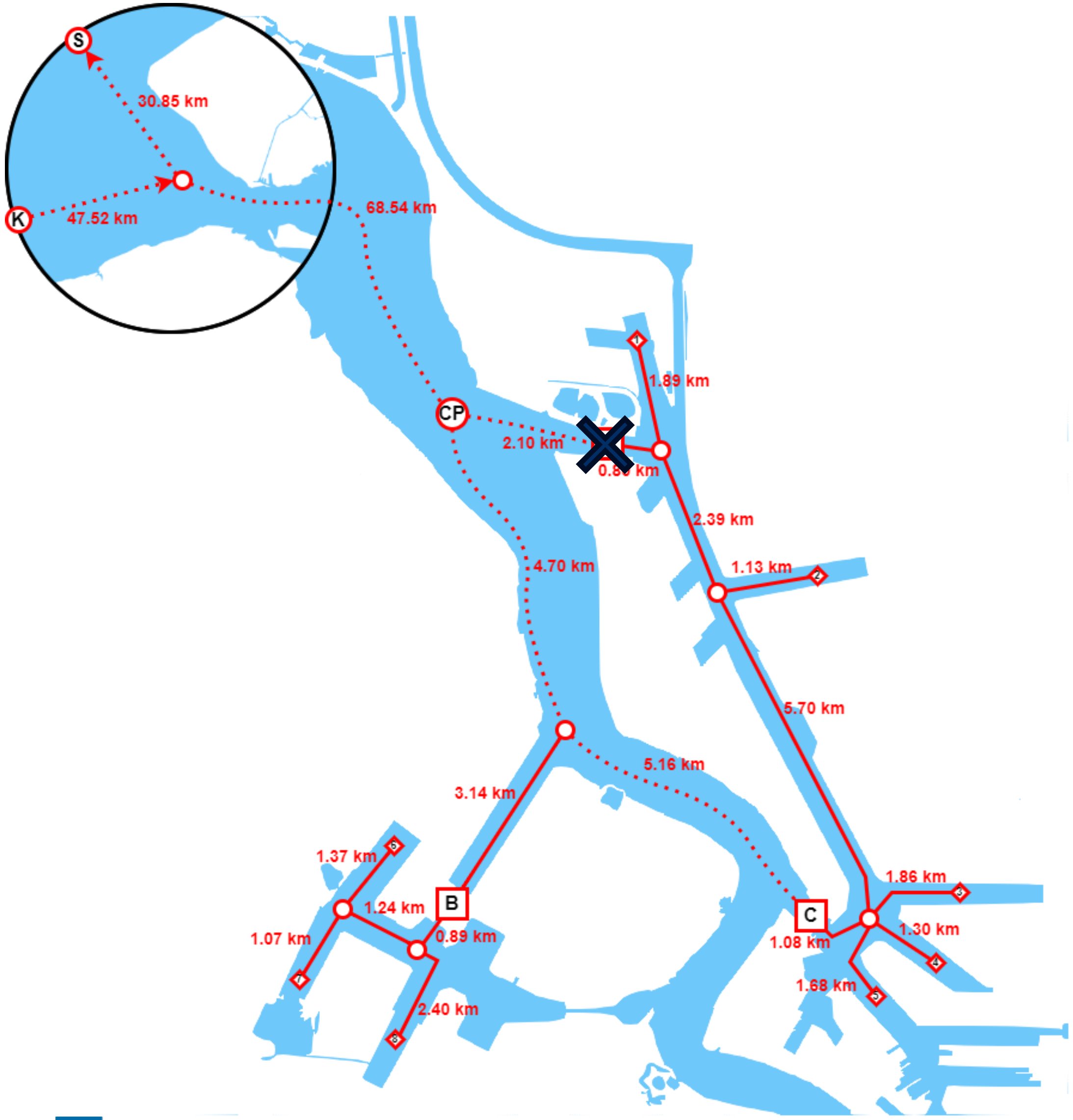

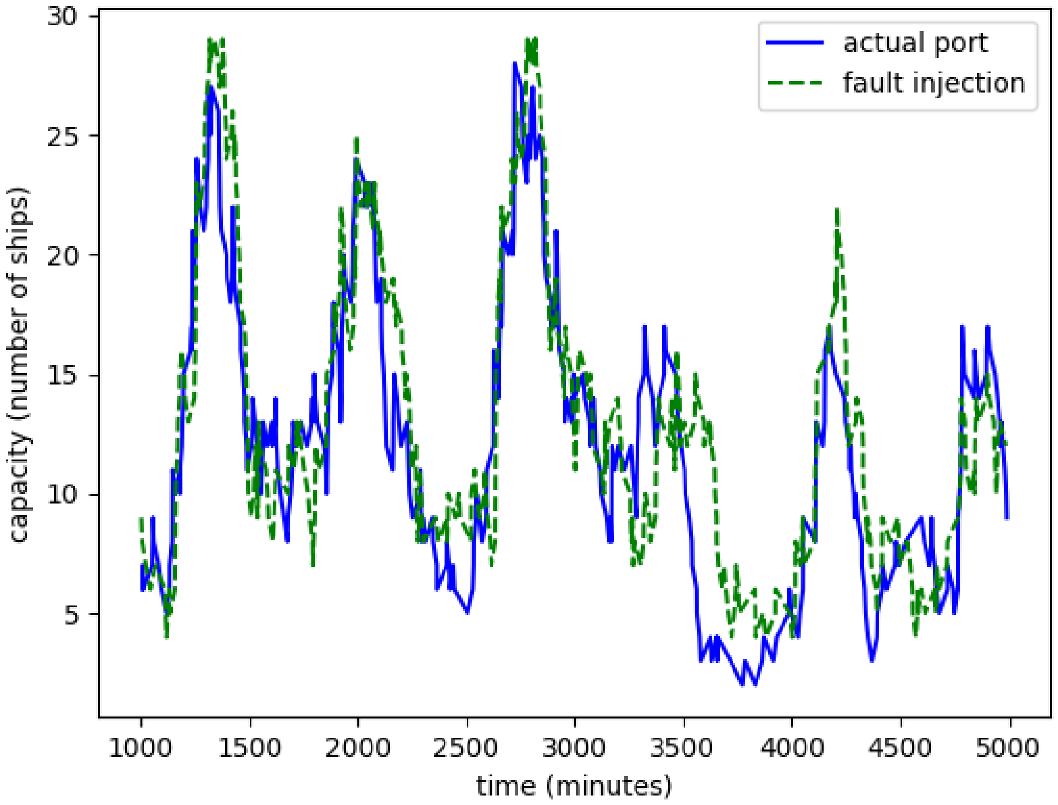

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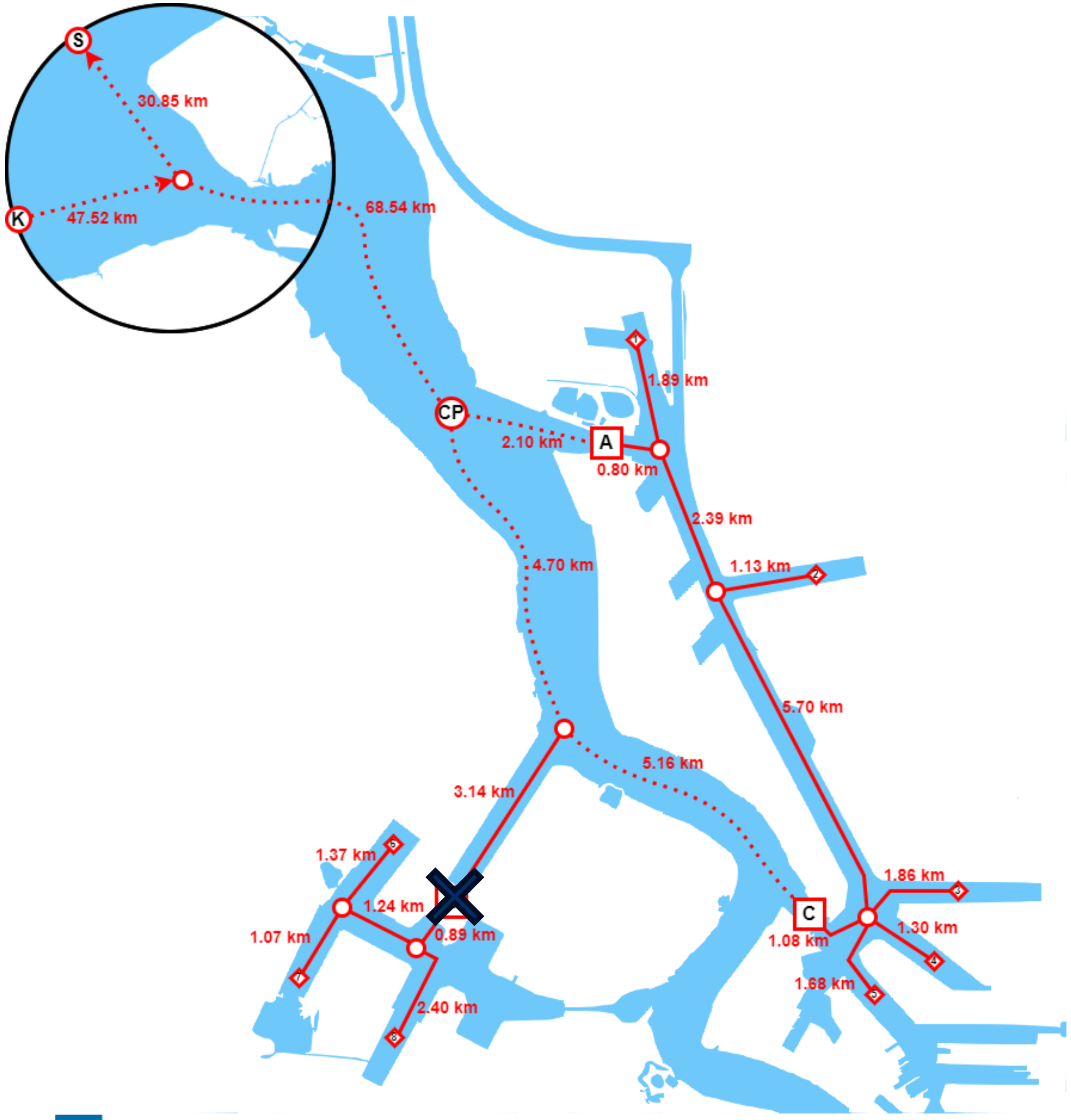

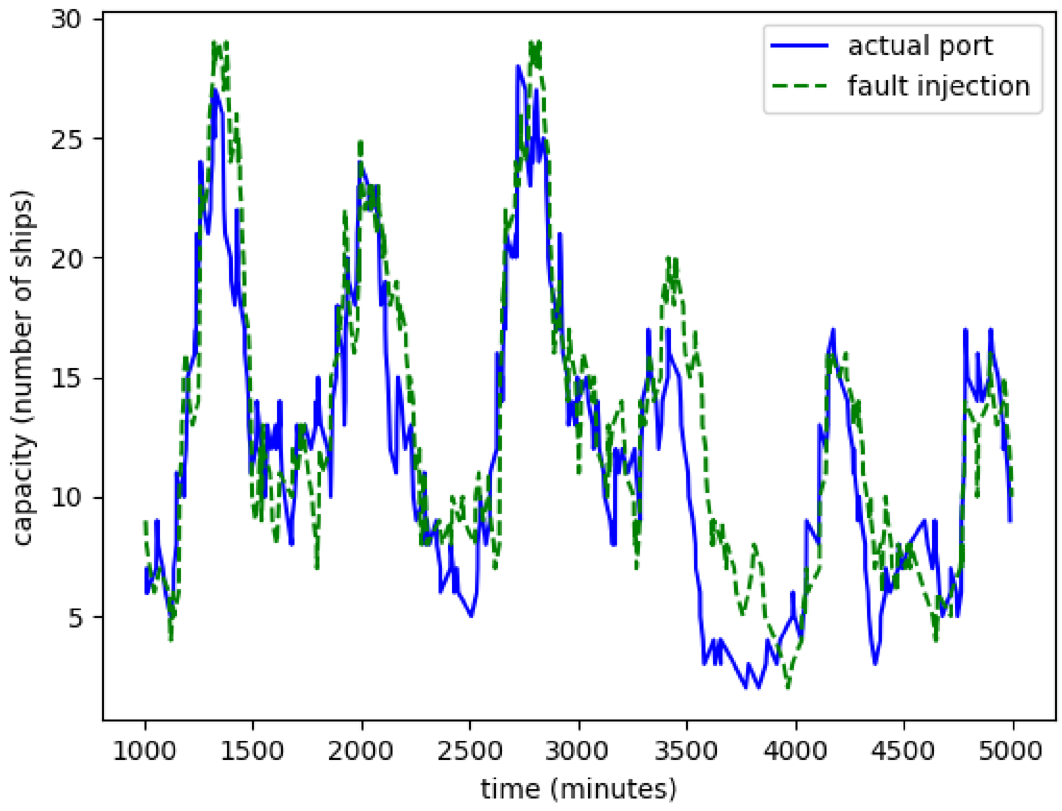

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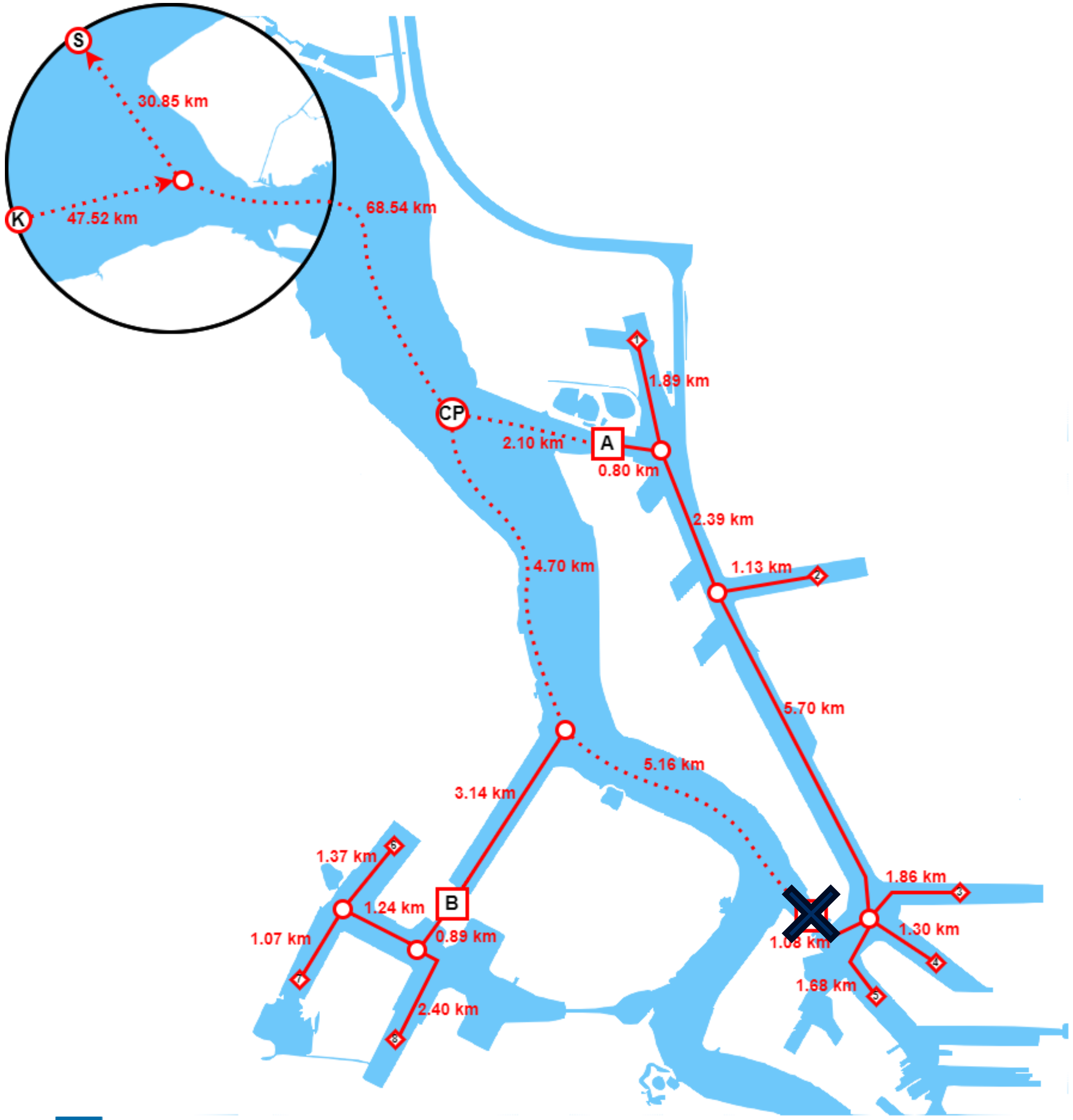

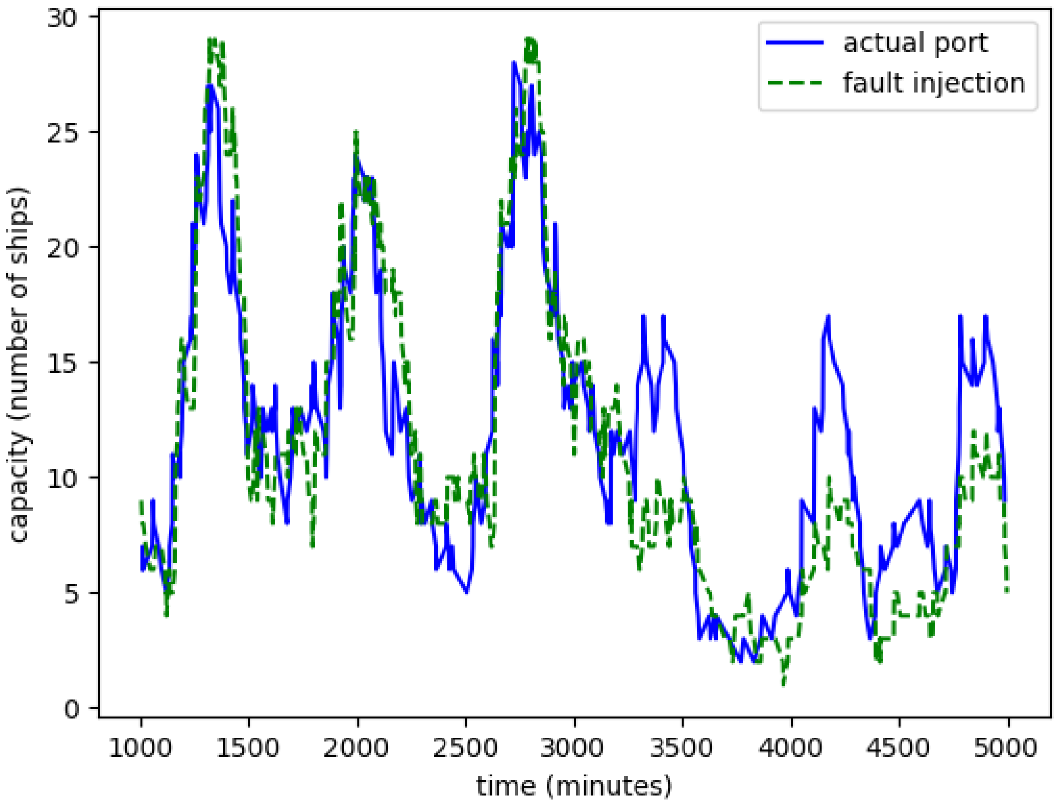

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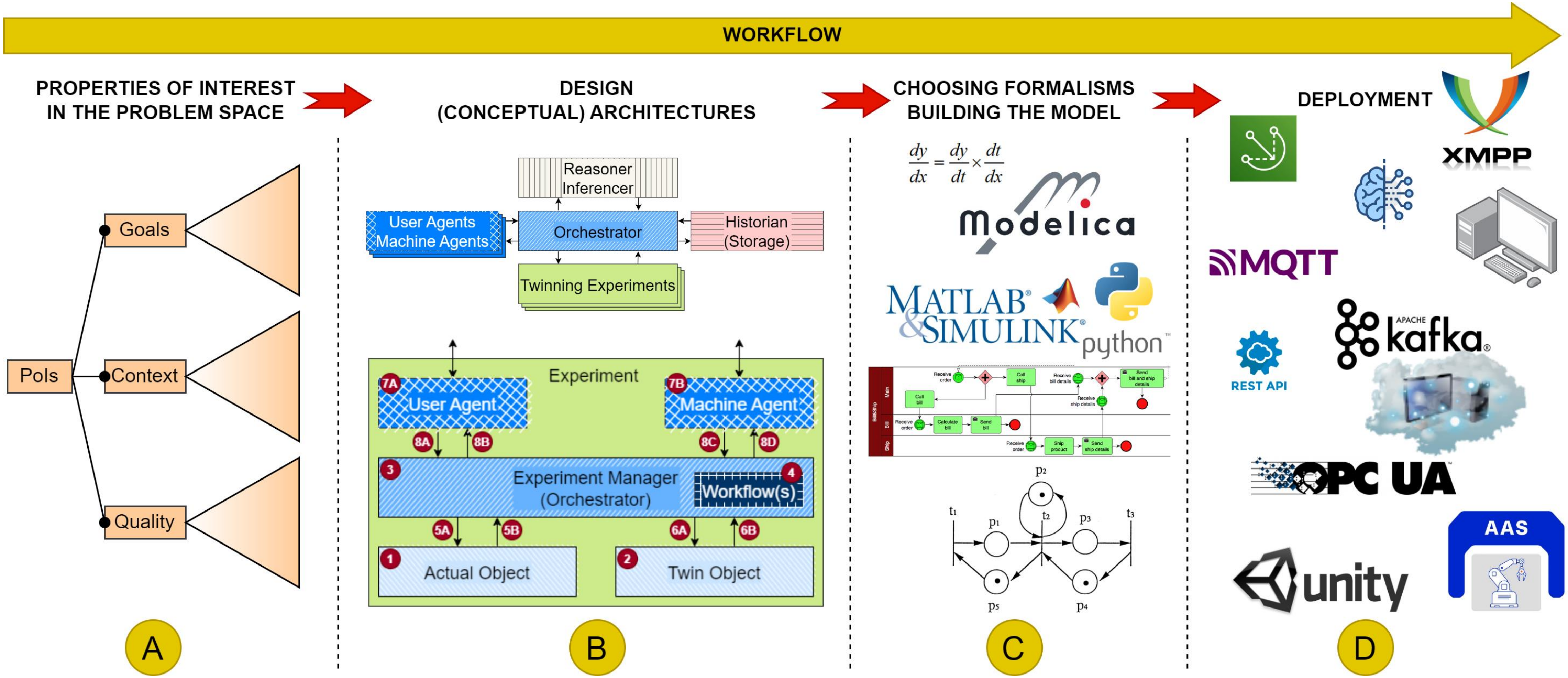
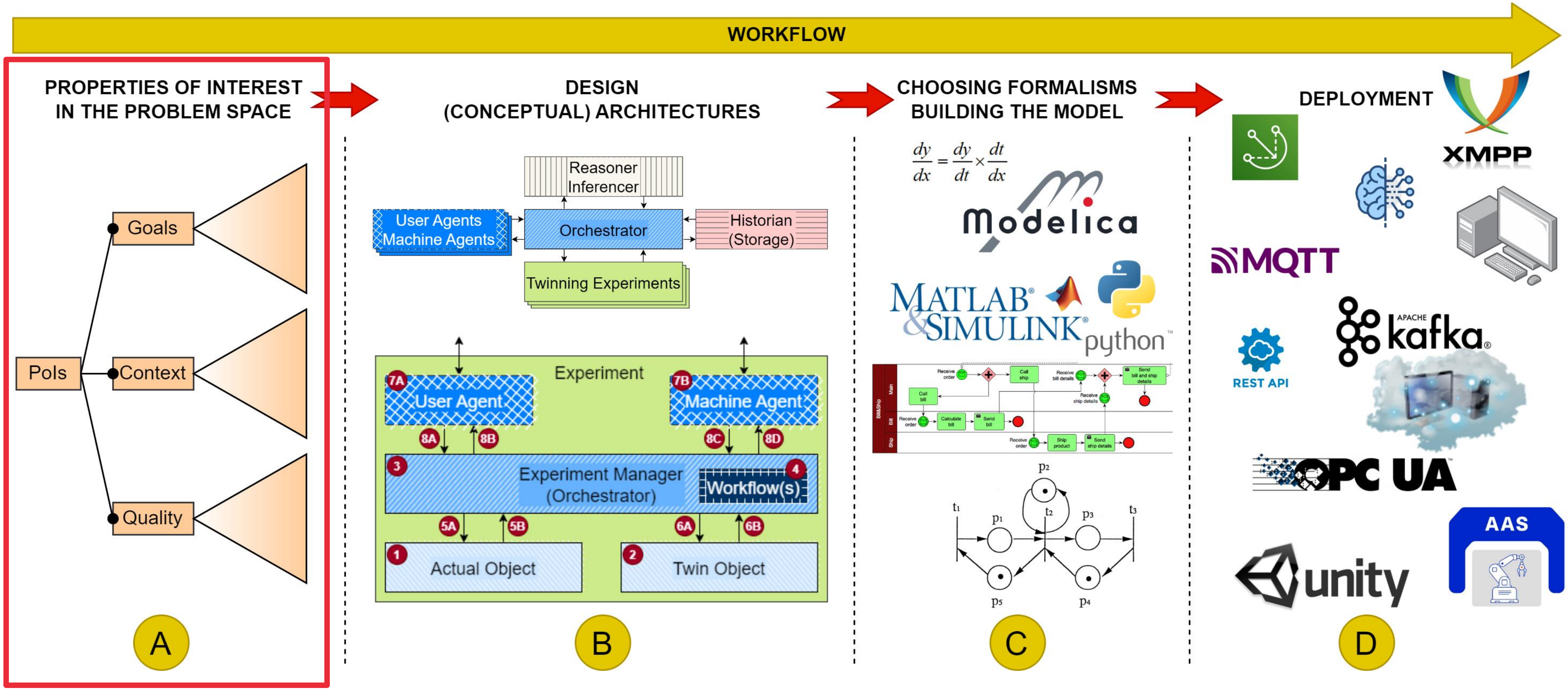
Stages of Twinning Variability (main contribution)



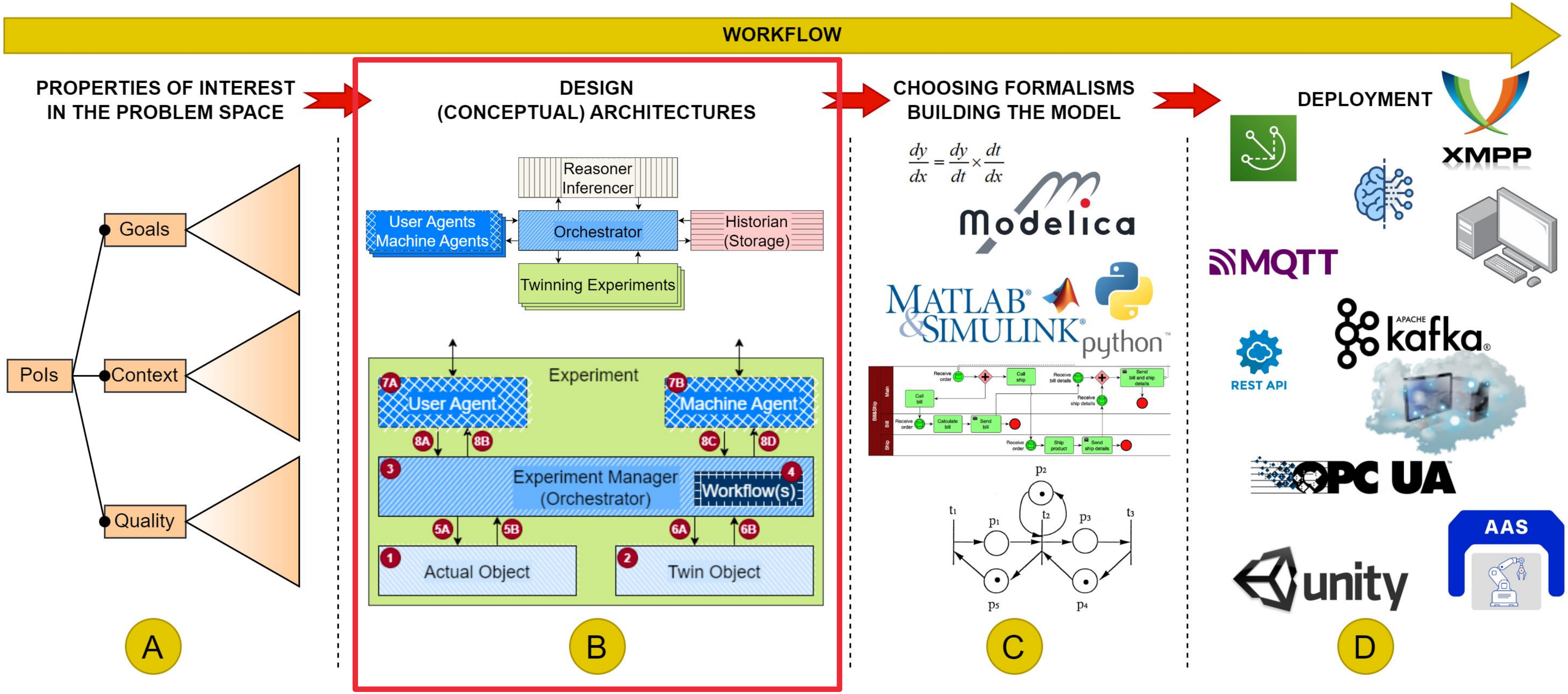
R. Paredis and H.Vangheluwe. 2024. "*Modelling and Simulation-Based Evaluation of Twinning Architectures and Their Deployment*". In Proceedings of SIMULTECH 2024, pp. 170-182.

Stages of Twinning Variability – The Problem Space



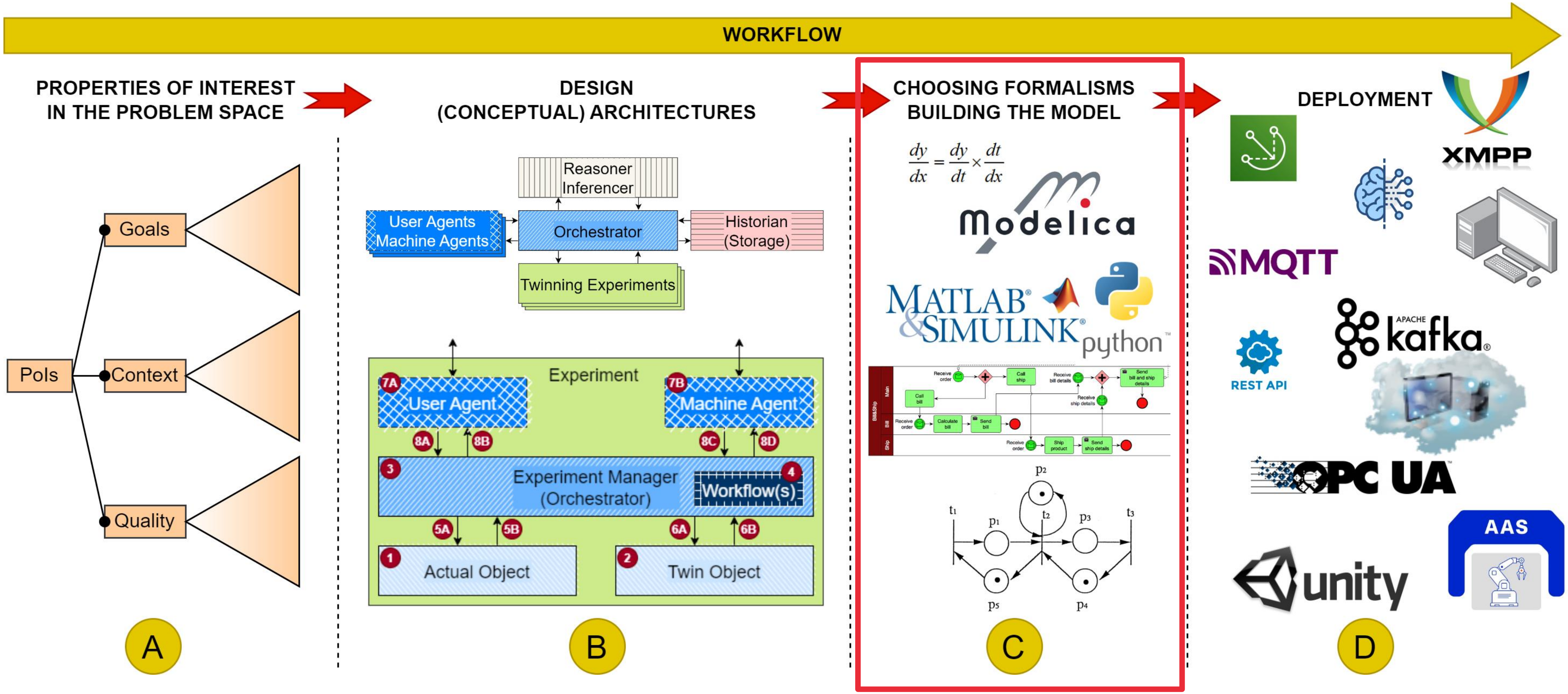
R. Paredis and H.Vangheluwe. 2024. "*Modelling and Simulation-Based Evaluation of Twinning Architectures and Their Deployment*". In Proceedings of SIMULTECH 2024, pp. 170-182.

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



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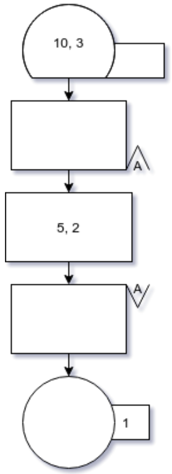
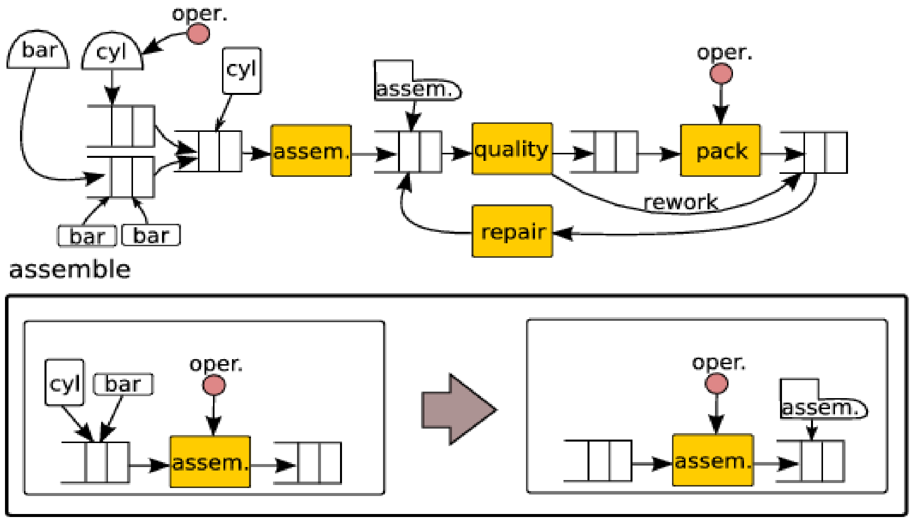
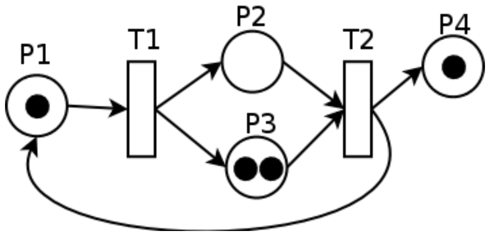
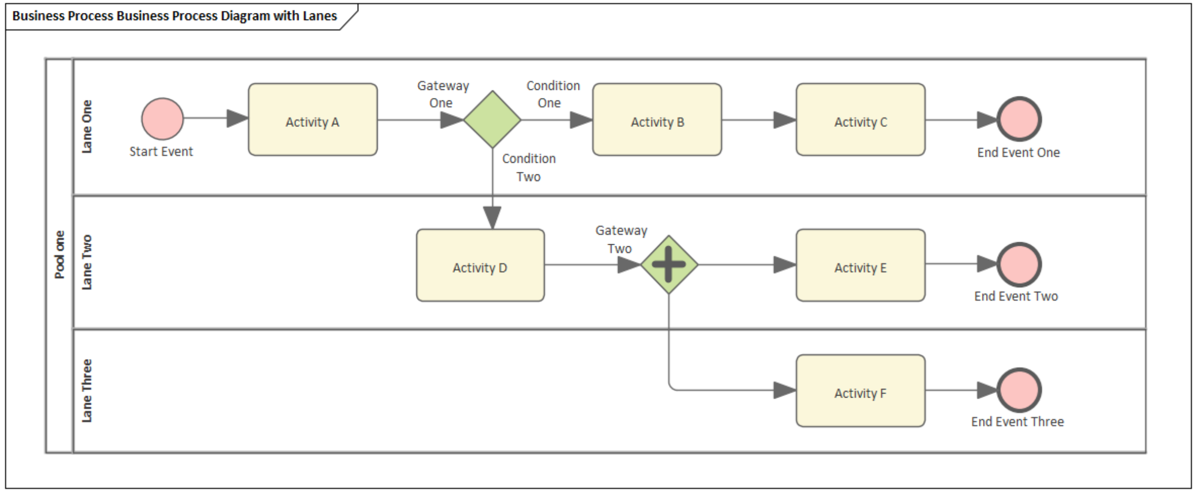
R. Paredis and H.Vangheluwe. 2024. “*Modelling and Simulation-Based Evaluation of Twinning Architectures and Their Deployment*”. In Proceedings of SIMULTECH 2024, pp. 170-182.

MPM: Using the most appropriate…









1. for $\{0 \le z \le z_f - \sigma\}$:

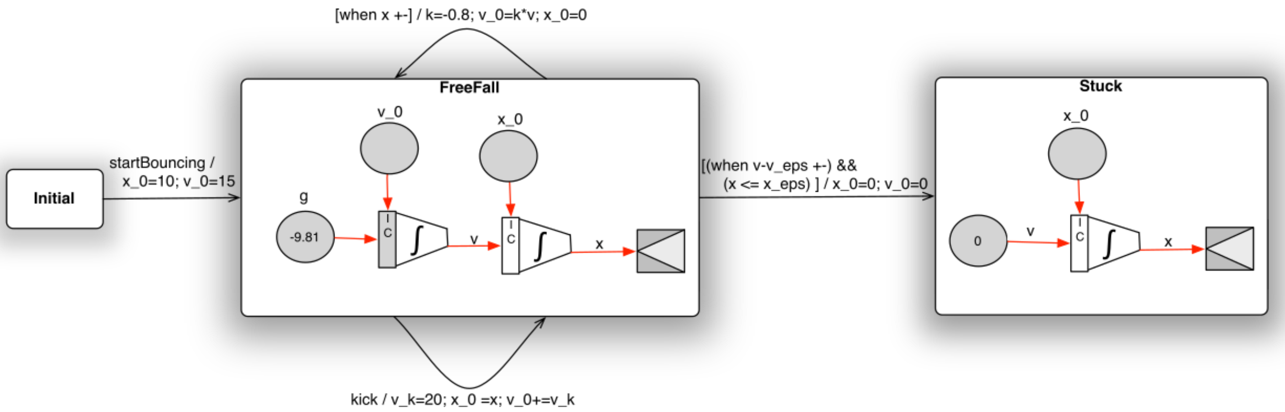
$$\frac{\partial X(z,t)}{\partial t} = -\left[(1 - nX(z,t))\ v_0\ e^{-nX(z,t)} + \frac{Q_u(t)}{A}\right]\frac{\partial X(z,t)}{\partial z} + D_0\frac{\partial^2 X(z,t)}{\partial z^2};$$

2. for $\{z_f - \sigma < z < z_f + \sigma\}$:

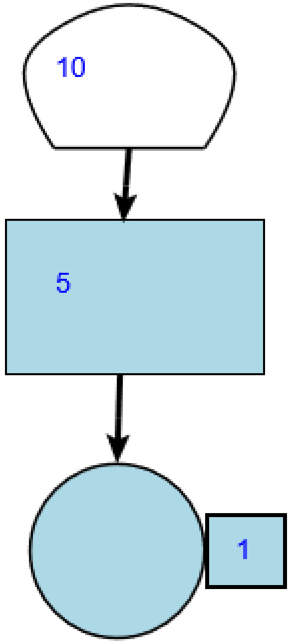
$$\frac{\partial X(z,t)}{\partial t} = -\left[(1 - nX(z,t))\ v_0\ e^{-nX(z,t)} + \frac{Q_u(t)}{A}\right]\frac{\partial X(z,t)}{\partial z} + X_f(t)\frac{Q_f(t)}{A}\frac{1}{2\sigma} + D_0\frac{\partial^2 X(z,t)}{\partial z^2};$$

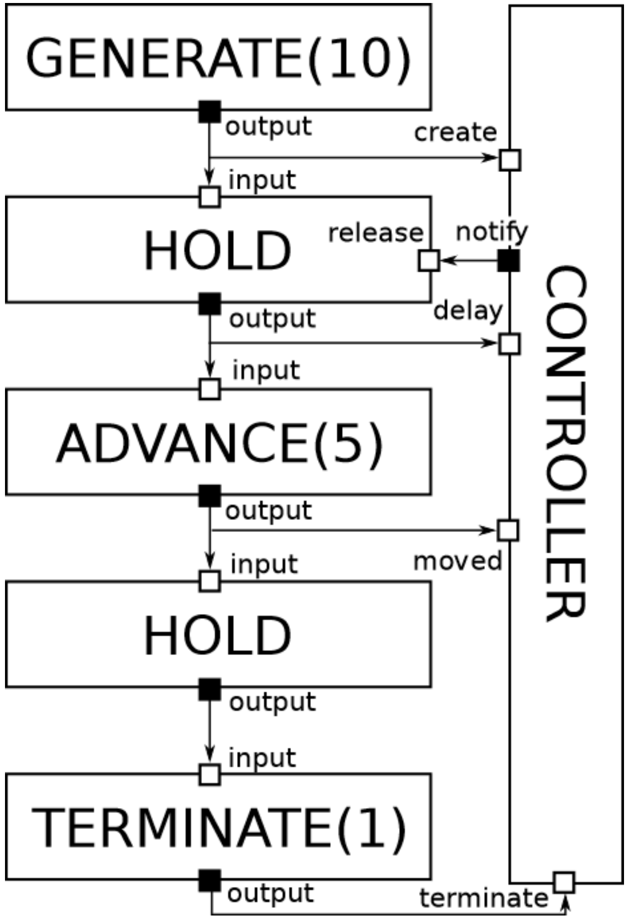
3. for $\{z_f + \sigma \le z \le L\}$:

$$\frac{\partial X(z,t)}{\partial t} = -\left[(1 - nX(z,t))\ v_0\ e^{-nX(z,t)} + \frac{Q_u(t)}{A}\right]\frac{\partial X(z,t)}{\partial z} + D_0\frac{\partial^2 X(z,t)}{\partial z^2}.$$



MPM: sGPSS to Python(P)DEVS (master's thesis)

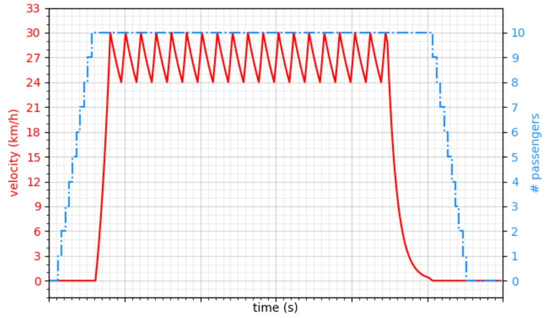


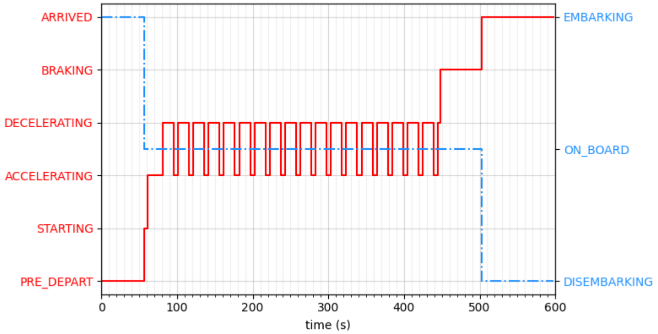


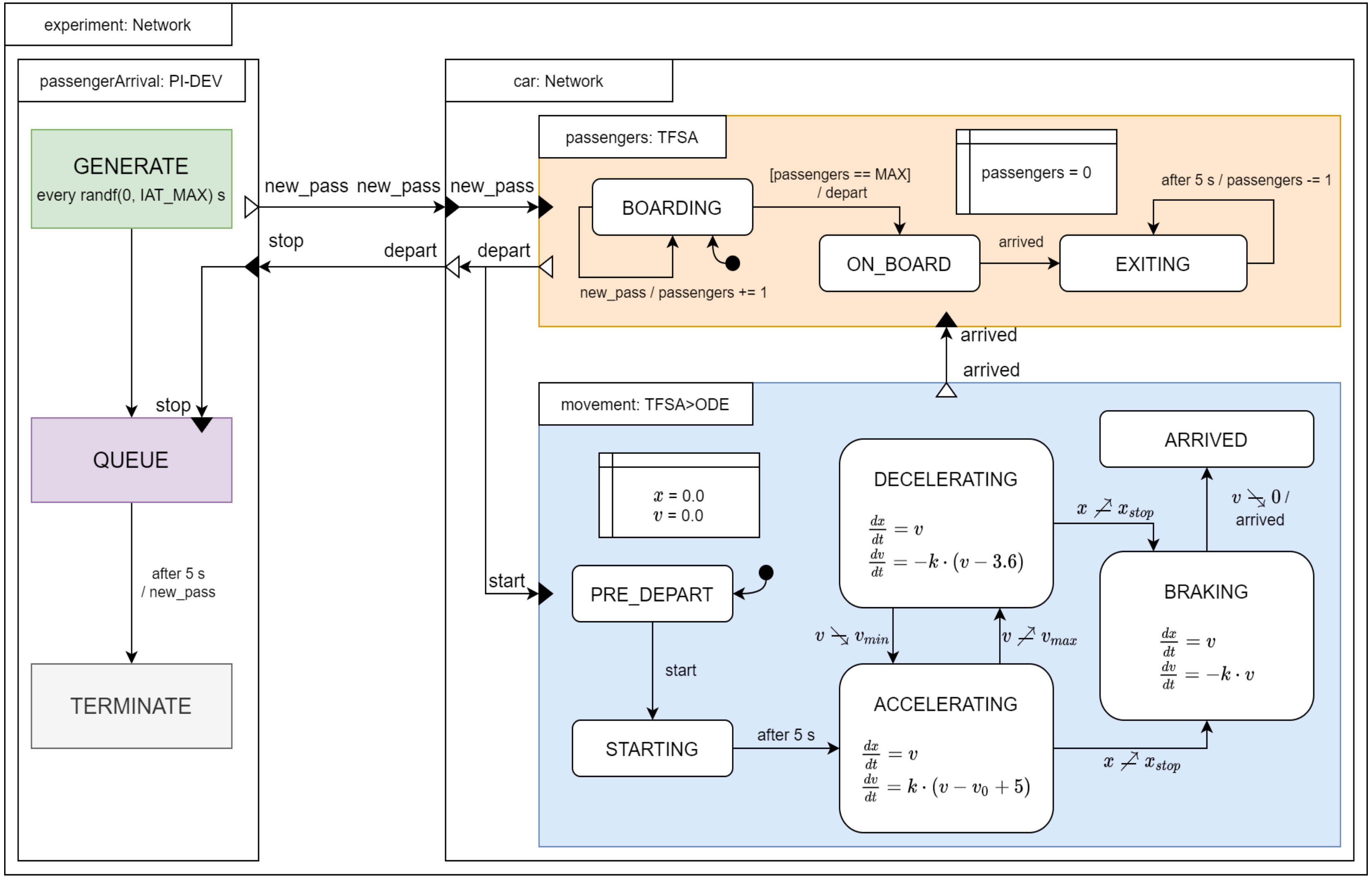

```python
from pypdevs.DEVS import CoupledDEVS
from pypdevsbbl.domain.gpss import Transaction, Hold, Controller, dist
from pypdevsbbl.domain.gpss import ADVANCE, TERMINATE
from pypdevsbbl.generic.generators import RandomDelayGenerator as GENERATE

class Model(CoupledDEVS):
    def __init__(self):
        super().__init__("Model")

        self.GPSS2DEVS_2_Controller = self.addSubModel(Controller("GPSS2DEVS_2_Controller"))


        self.GPSS2DEVS_0_L0 = self.addSubModel(GENERATE("GPSS2DEVS_0_L0", dist=dist, args=(10,),
                                                        func=lambda x, t: Transaction(x, t), dt=None))
            self.GPSS2DEVS_4_L0 = self.addSubModel(Hold("GPSS2DEVS_4_L0"))
            self.connectPorts(self.GPSS2DEVS_0_L0.output, self.GPSS2DEVS_4_L0.input)
            self.connectPorts(self.GPSS2DEVS_0_L0.output, self.GPSS2DEVS_2_Controller.create)
            self.connectPorts(self.GPSS2DEVS_2_Controller.broadcast, self.GPSS2DEVS_4_L0.release)

            self.GPSS2DEVS_1_L1 = self.addSubModel(ADVANCE("GPSS2DEVS_1_L1", dist=dist, args=(5,)))
        self.GPSS2DEVS_4_L1 = self.addSubModel(Hold("GPSS2DEVS_4_L1"))
        self.connectPorts(self.GPSS2DEVS_1_L1.output, self.GPSS2DEVS_4_L1.input)
        self.connectPorts(self.GPSS2DEVS_4_L0.output, self.GPSS2DEVS_2_Controller.delay)
        self.connectPorts(self.GPSS2DEVS_4_L1.output, self.GPSS2DEVS_2_Controller.moved)
        self.connectPorts(self.GPSS2DEVS_2_Controller.pause, self.GPSS2DEVS_1_L1.pause)
        self.connectPorts(self.GPSS2DEVS_2_Controller.broadcast, self.GPSS2DEVS_4_L1.release)

        self.GPSS2DEVS_5_L2 = self.addSubModel(TERMINATE("GPSS2DEVS_5_L2", '1'))
        self.connectPorts(self.GPSS2DEVS_5_L2.output, self.GPSS2DEVS_2_Controller.terminate)


        self.connectPorts(self.GPSS2DEVS_4_L0.output, self.GPSS2DEVS_1_L1.input)
        self.connectPorts(self.GPSS2DEVS_4_L1.output, self.GPSS2DEVS_5_L2.input)
```


R. Paredis, S. Van Mierlo and H.Vangheluwe. 2020. "*Translating Process Interaction World View Models To DEVS: GPSS To (Python(P))DEVS*". In Proceedings of WSC 2020, pp. 2221-2232.

MPM: PI-DEV+TFSA>(ODE+StEL) to DEVS







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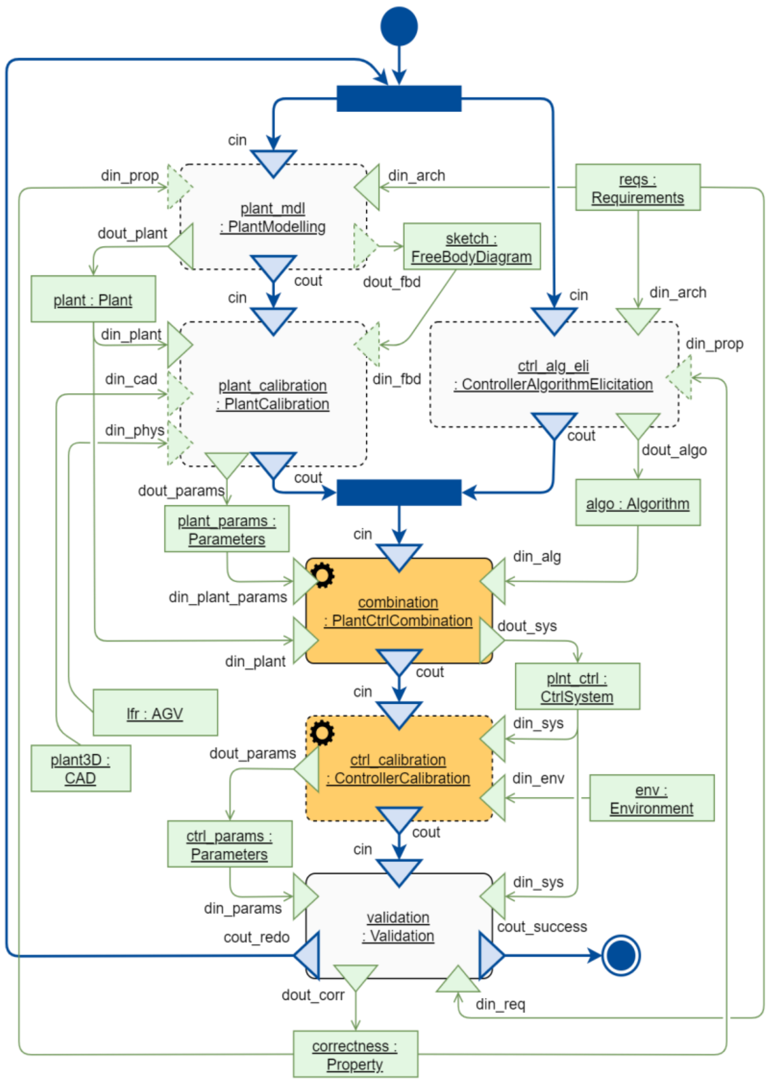
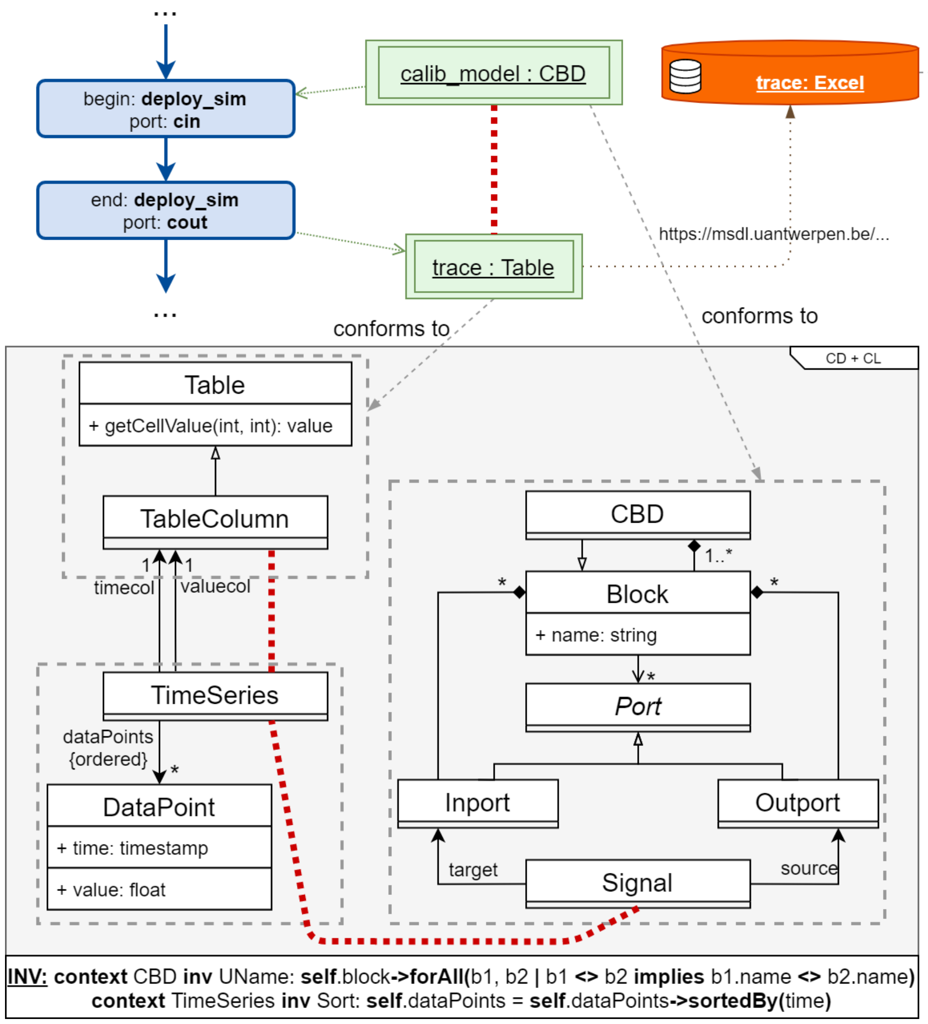
R. Paredis, J. Denil, and H.Vangheluwe. 2021. “*Specifying and Executing the Combination of Timed Finite State Automata and Causal-Block Diagrams by Mapping onto DEVS*”. In Proceedings of WSC 2021.

MPM: Extending the FTG+PM

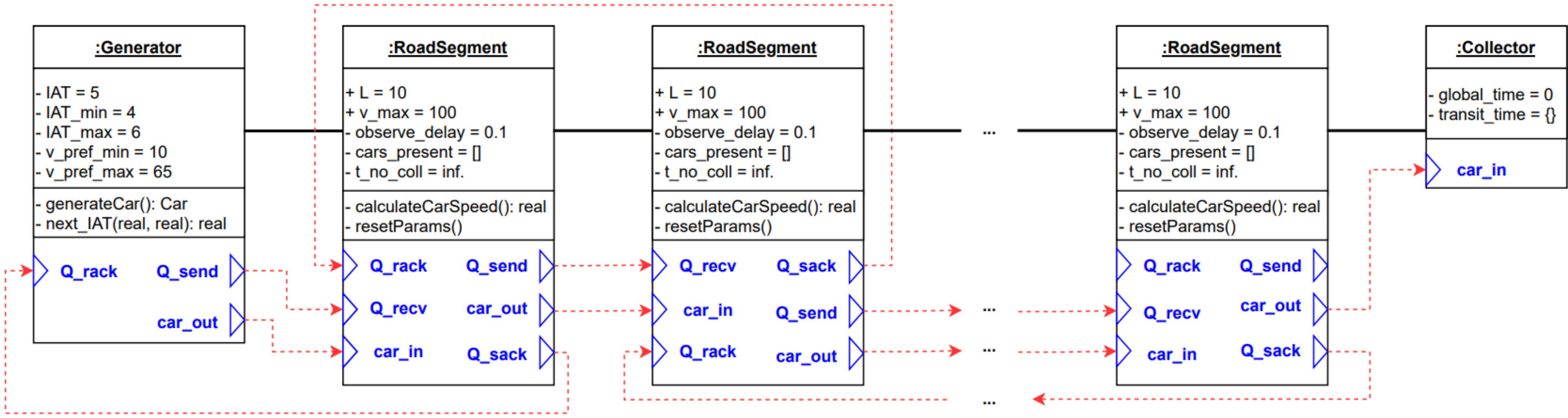


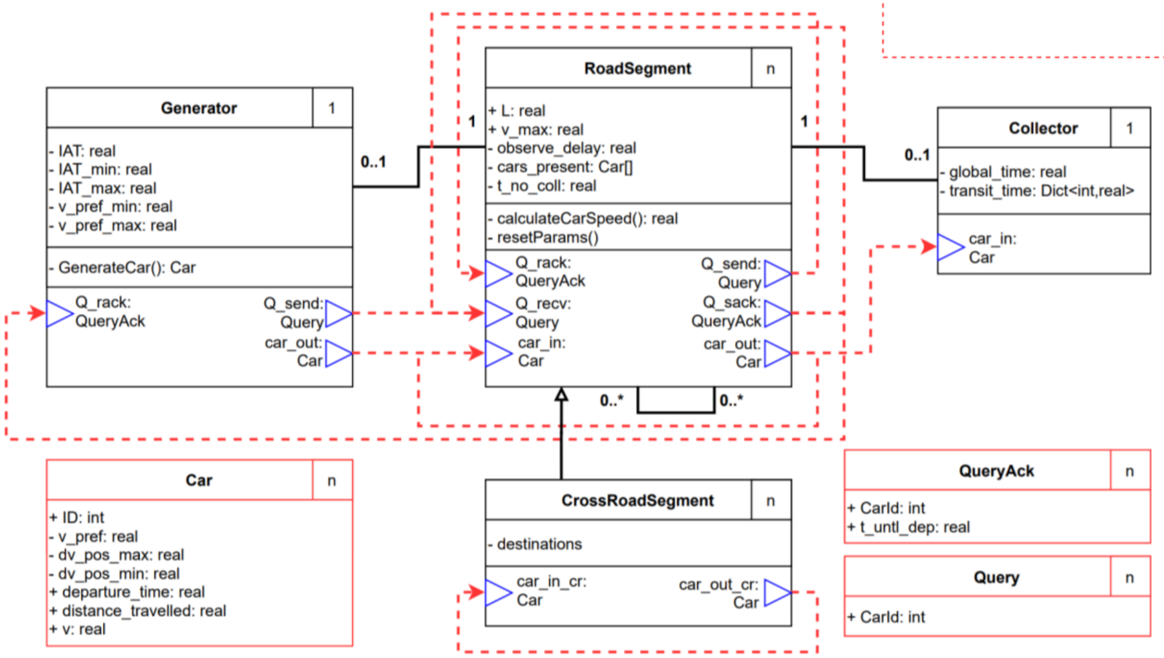


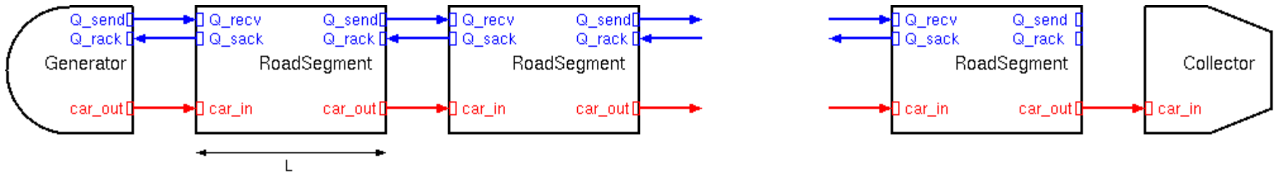
	A	B	C	D
1	time	x	y	heading
596	118.8	0.215843	-0.29999	0.677788
597	119	0.216126	-0.29976	1.302247
598	119.2	0.216222	-0.29941	1.599066
599	119.4	0.216212	-0.29904	1.46084
600	119.6	0.216252	-0.29868	1.124072
601	119.8	0.216409	-0.29836	0.877111
602	120	0.216641	-0.29808	0.865045
603	120.2	0.216877	-0.2978	1.027622
604	120.4	0.217065	-0.29749	1.198563
605	120.6	0.217197	-0.29715	1.255207
606	120.8	0.21731	-0.2968	1.190118
607	121	0.217445	-0.29647	1.084936
608	121.2	0.217614	-0.29615	1.025846
609	121.4	0.217803	-0.29583	1.041682
610	121.6	0.217986	-0.29552	1.099589
611	121.8	0.218151	-0.2952	1.146234
612	122	0.218301	-0.29487	1.151624
613	122.2	0.218449	-0.29453	1.123763
614	122.4	0.218606	-0.29421	1.092062
615	122.6	0.218773	-0.29388	1.080216
616	122.8	0.218944	-0.29356	1.090973

R. Paredis, J. Exelmans, and H.Vangheluwe. 2022. “*Multi-Paradigm Modelling For Model Based Systems Engineering: Extending The FTG+PM*”. In Proceedings of ANNSIM 2022.

MPM: CLAVS/ODVS

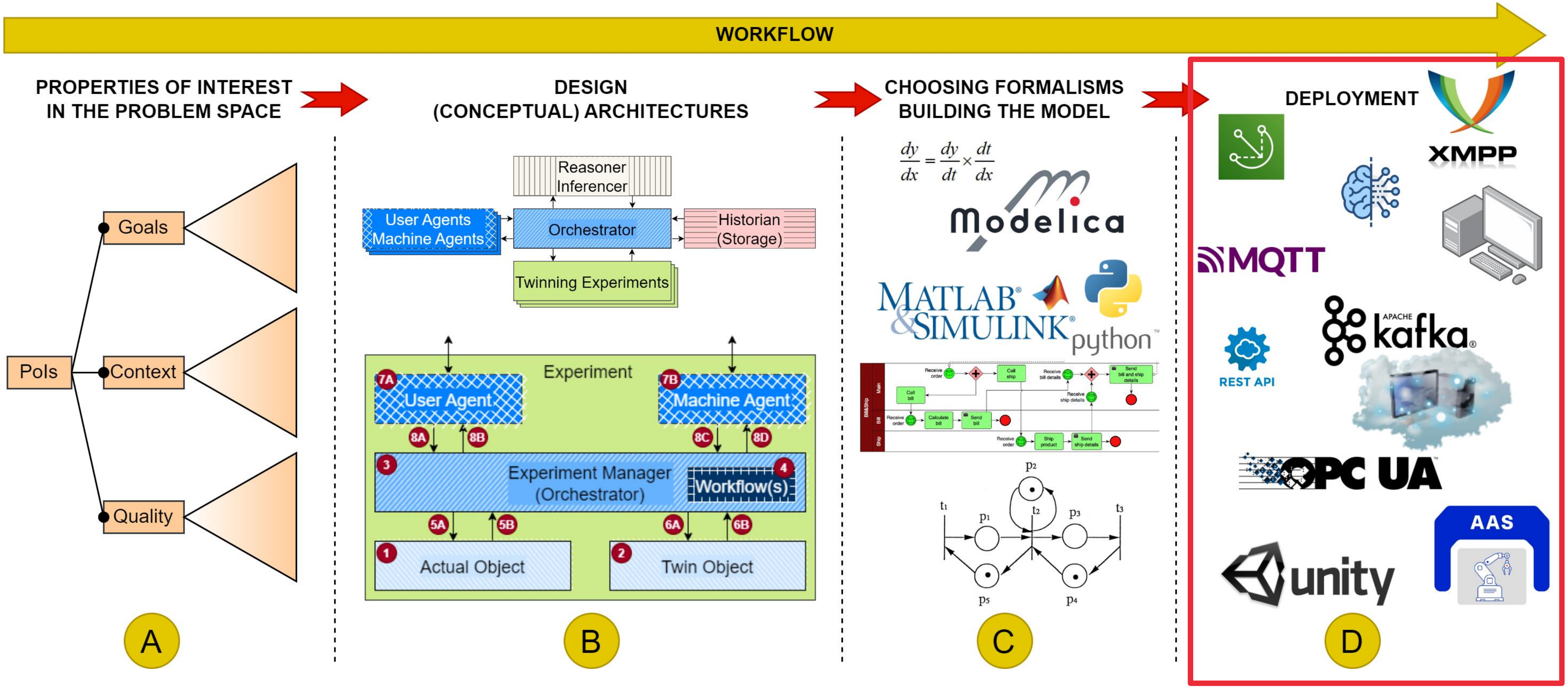






J. Parezys, R. Paredis, and H.Vangheluwe. 2023. "*CLAVS/ODVS: Combining Class/Object Diagrams and DEVS*". In Proceedings of WSC 2023.

Stages of Twinning Variability – Deployment



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.

Research Questions

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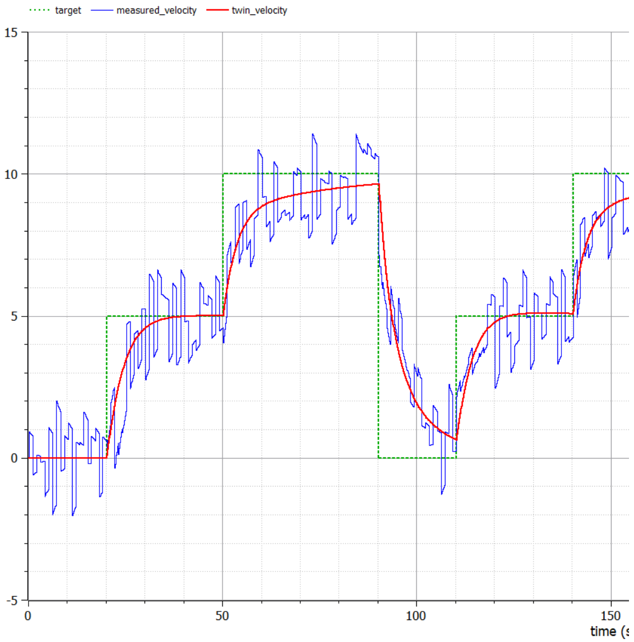
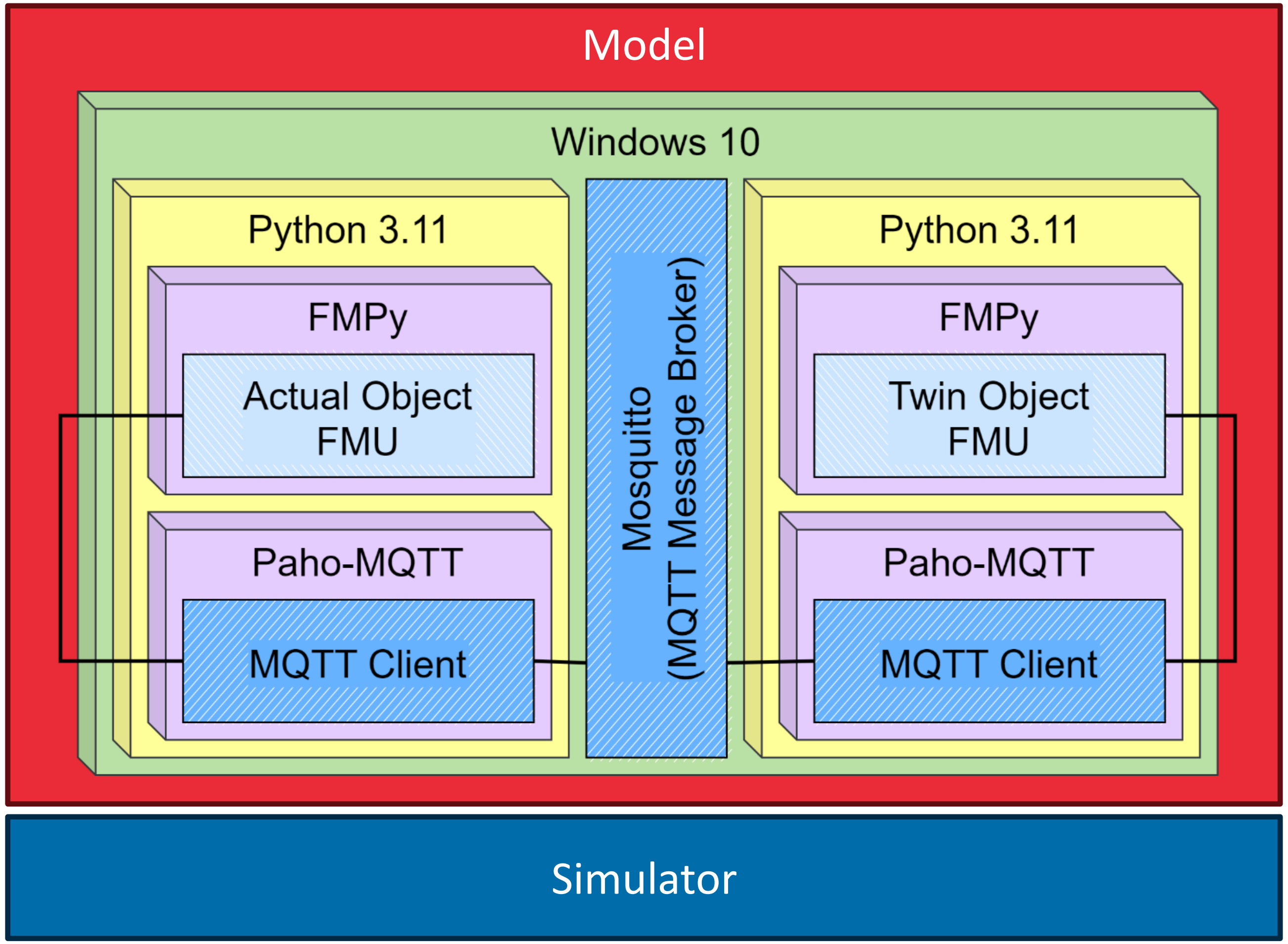
- RQ5: *How can we conveniently combine multiple DTs into a larger system?*

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



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



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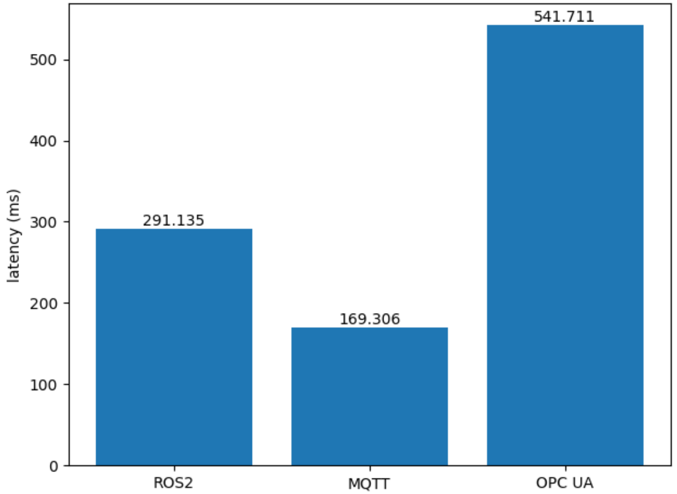
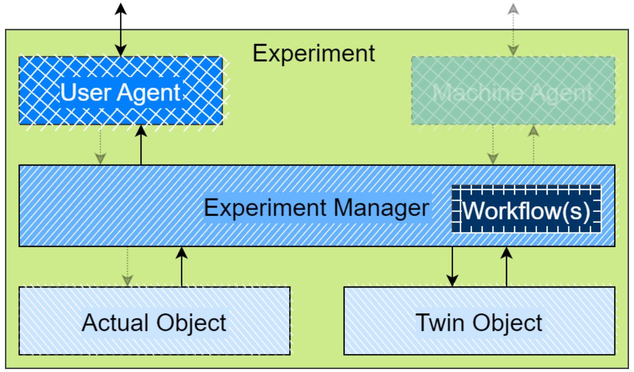
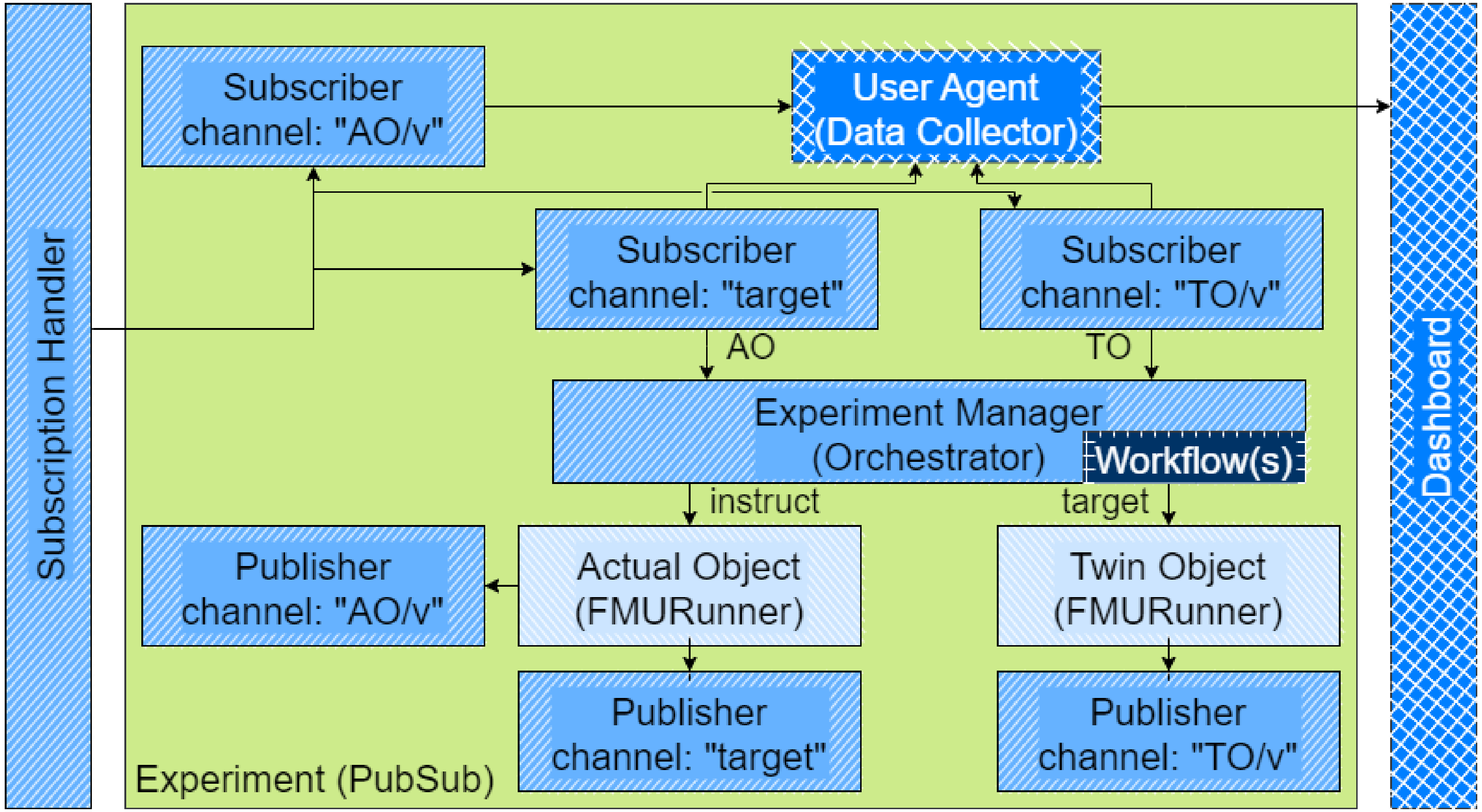
Proof-of-Concept: 1D Behaviour of a Ship







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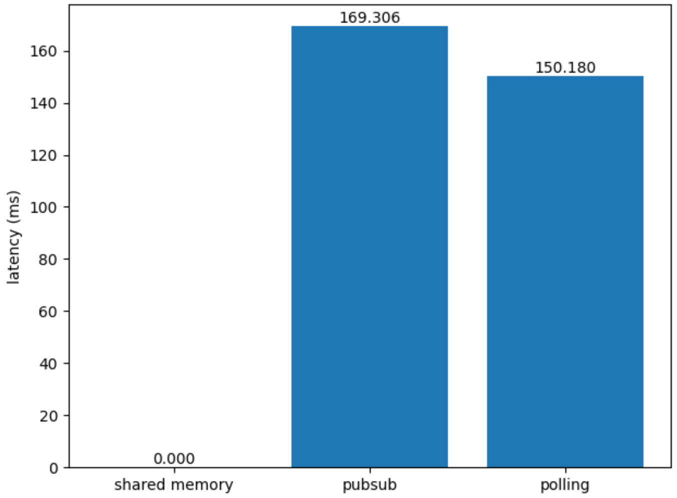
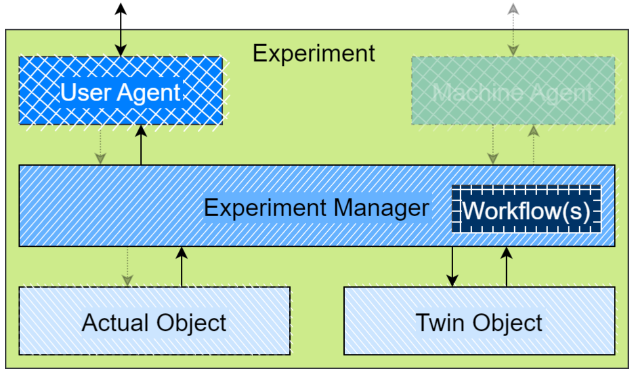
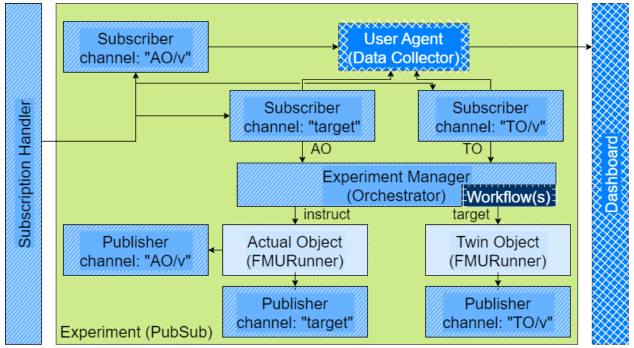
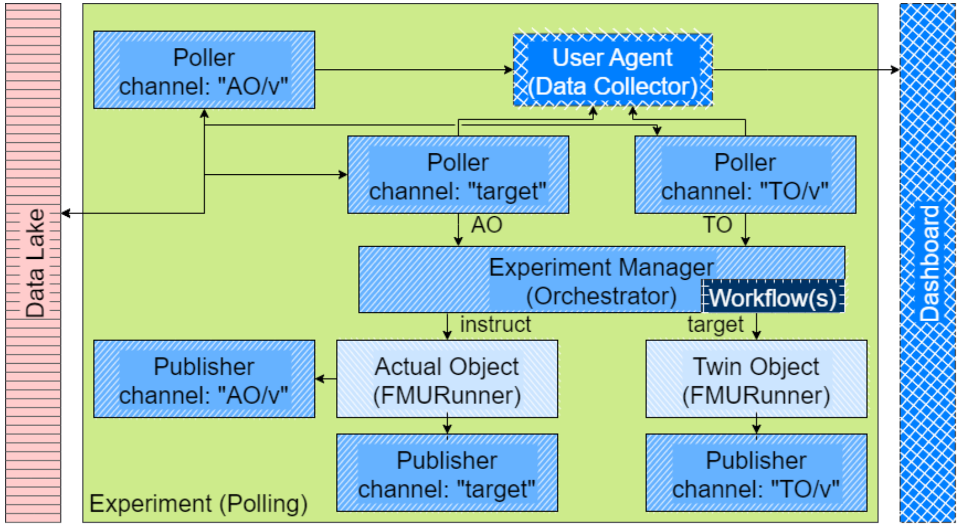
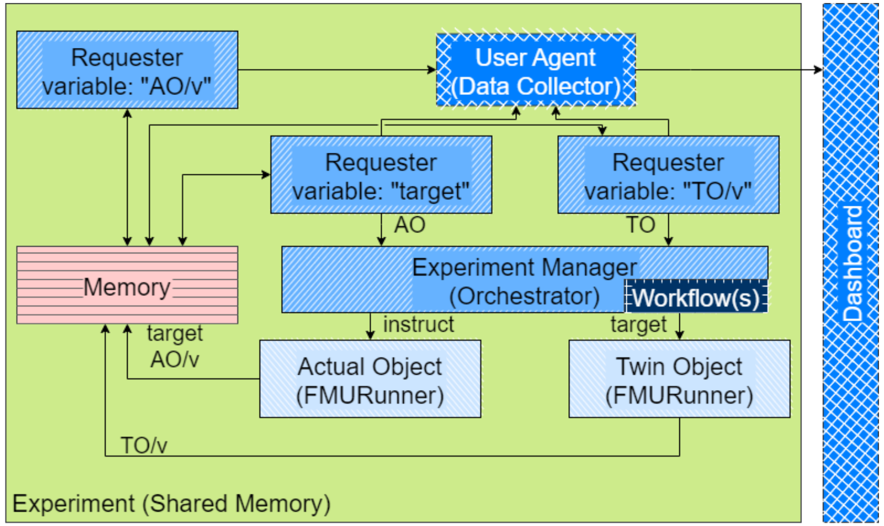
1D Behaviour of a Ship











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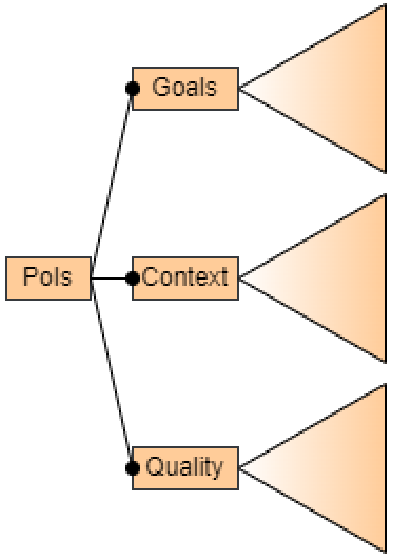
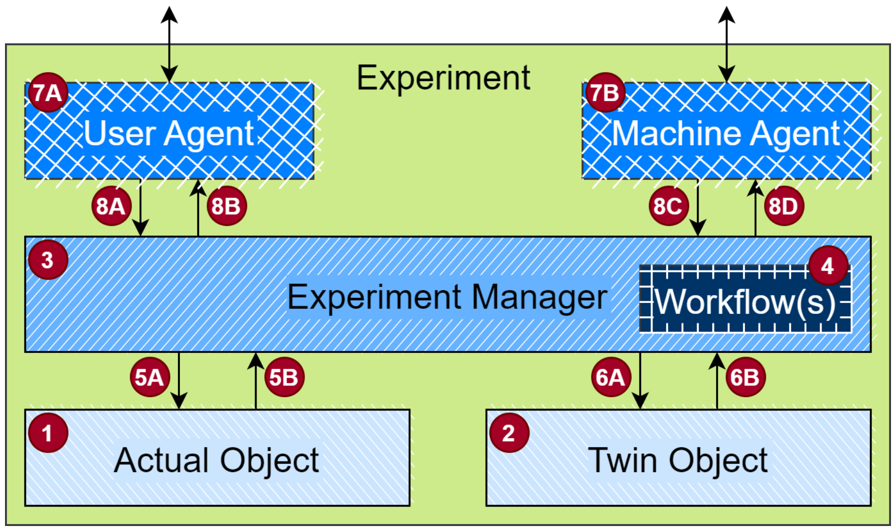
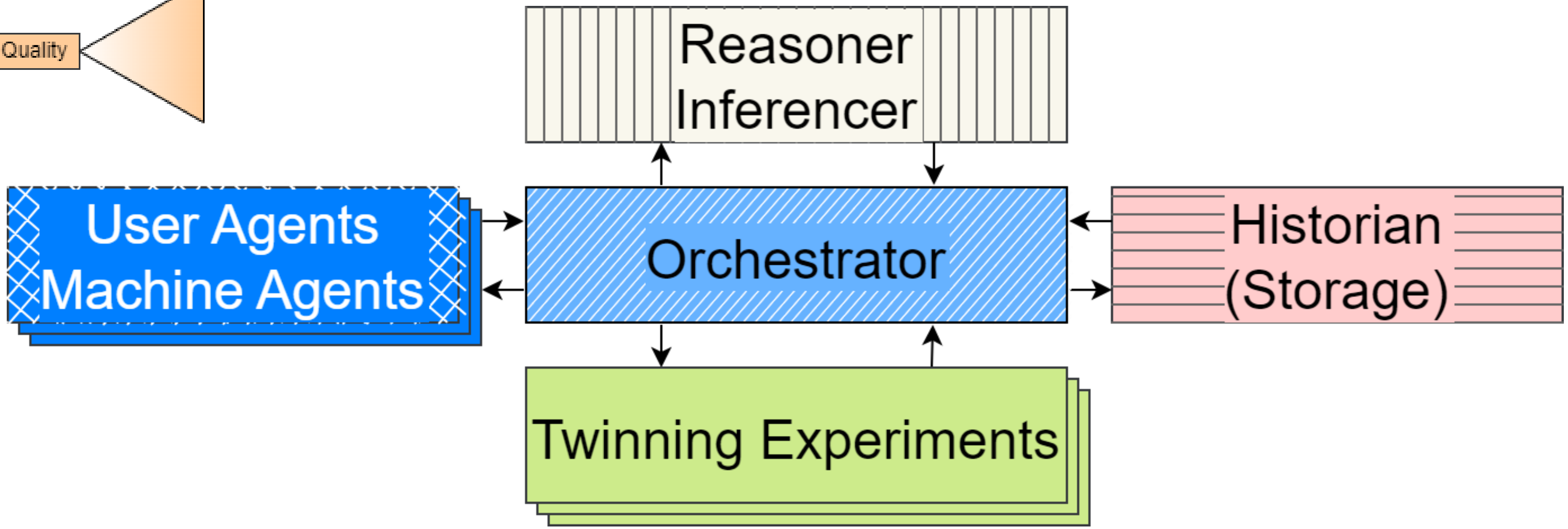
Conceptual Architecture(s)







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R. Paredis, and H.Vangheluwe. 2022. “*Towards a Digital Z Framework Based on a Family of Architectures and a Virtual Knowledge Graph*”. In Proceedings of MoDELS 2022.
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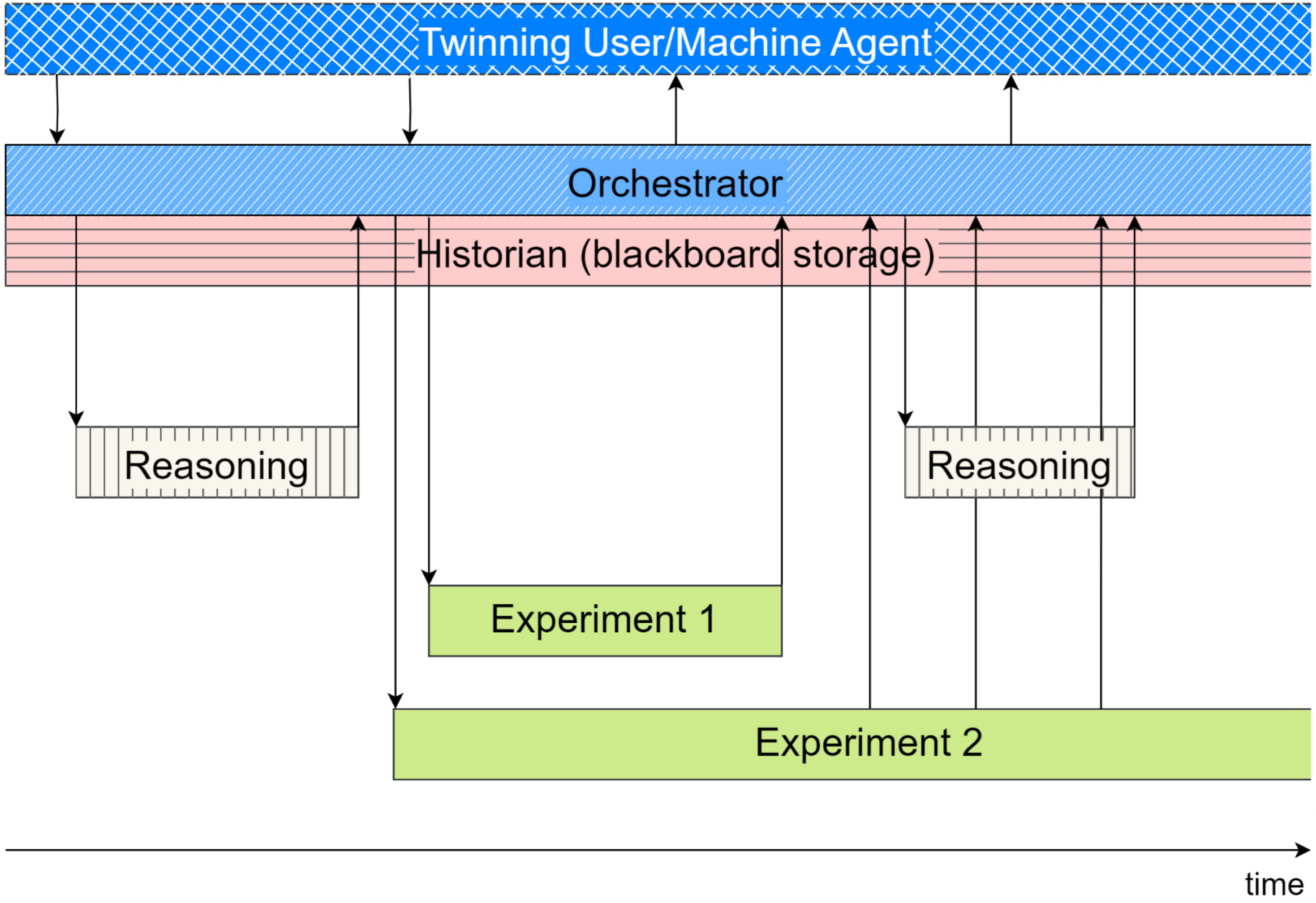
Conceptual Architecture(s)



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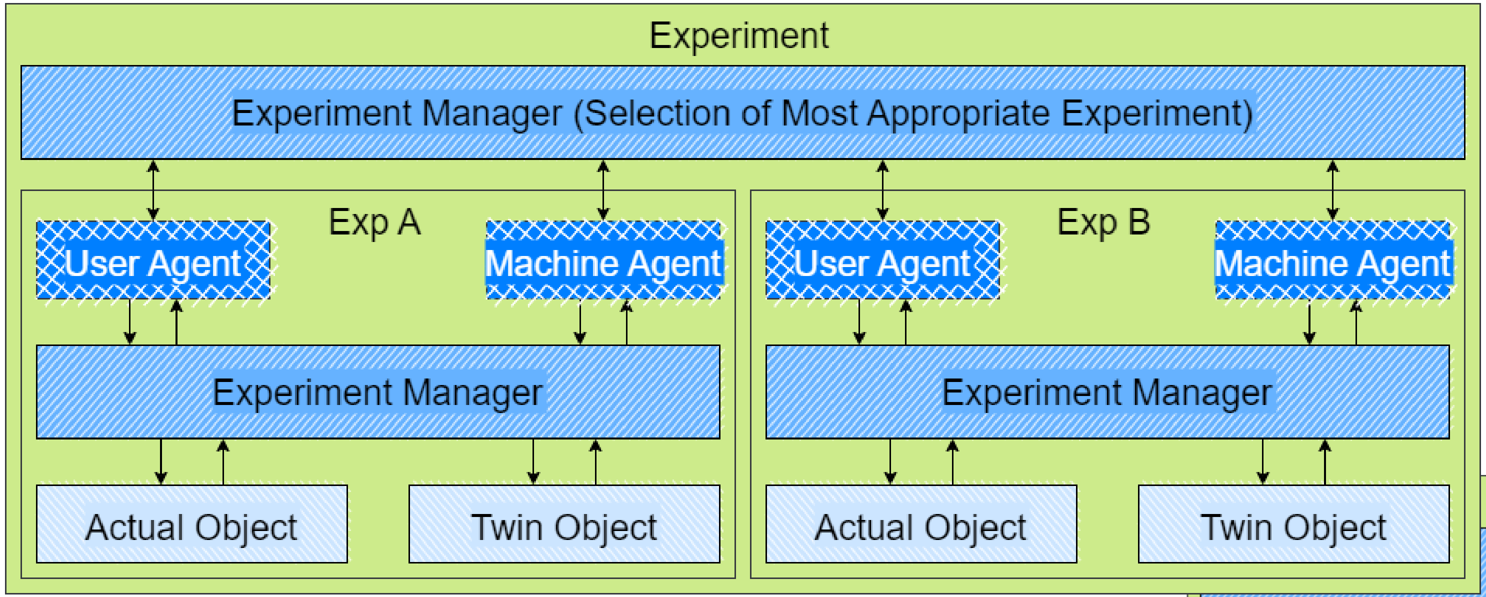
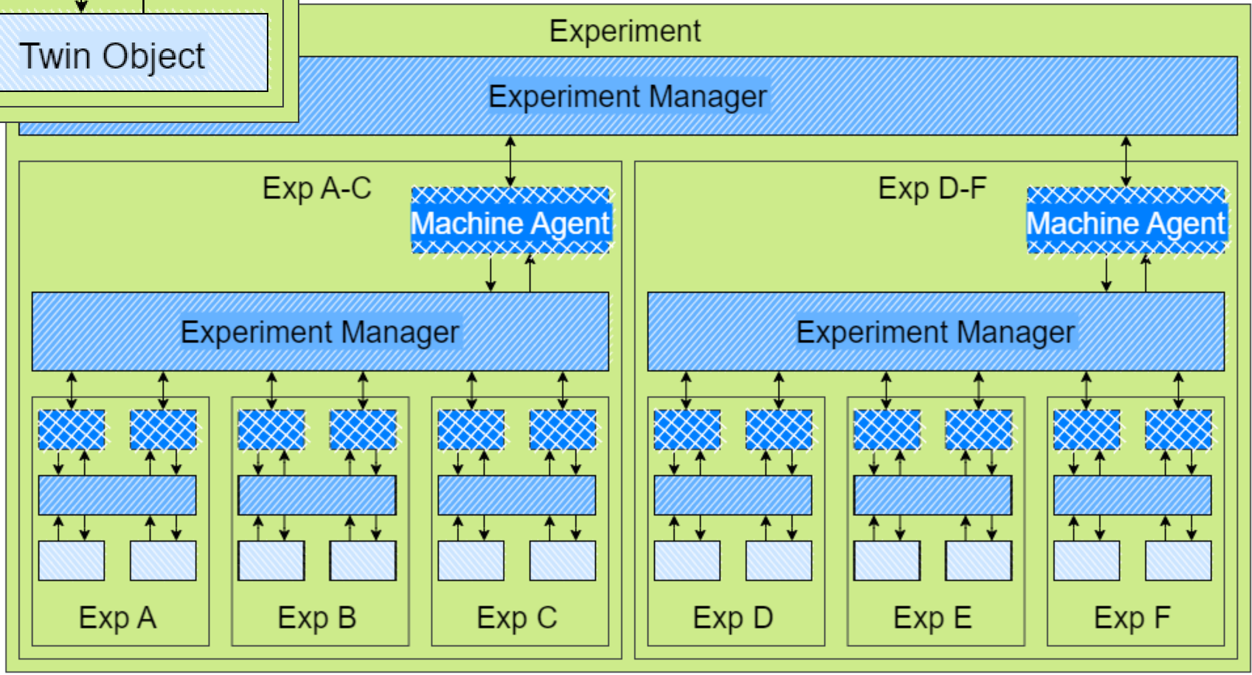
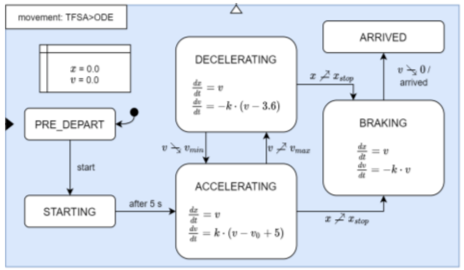
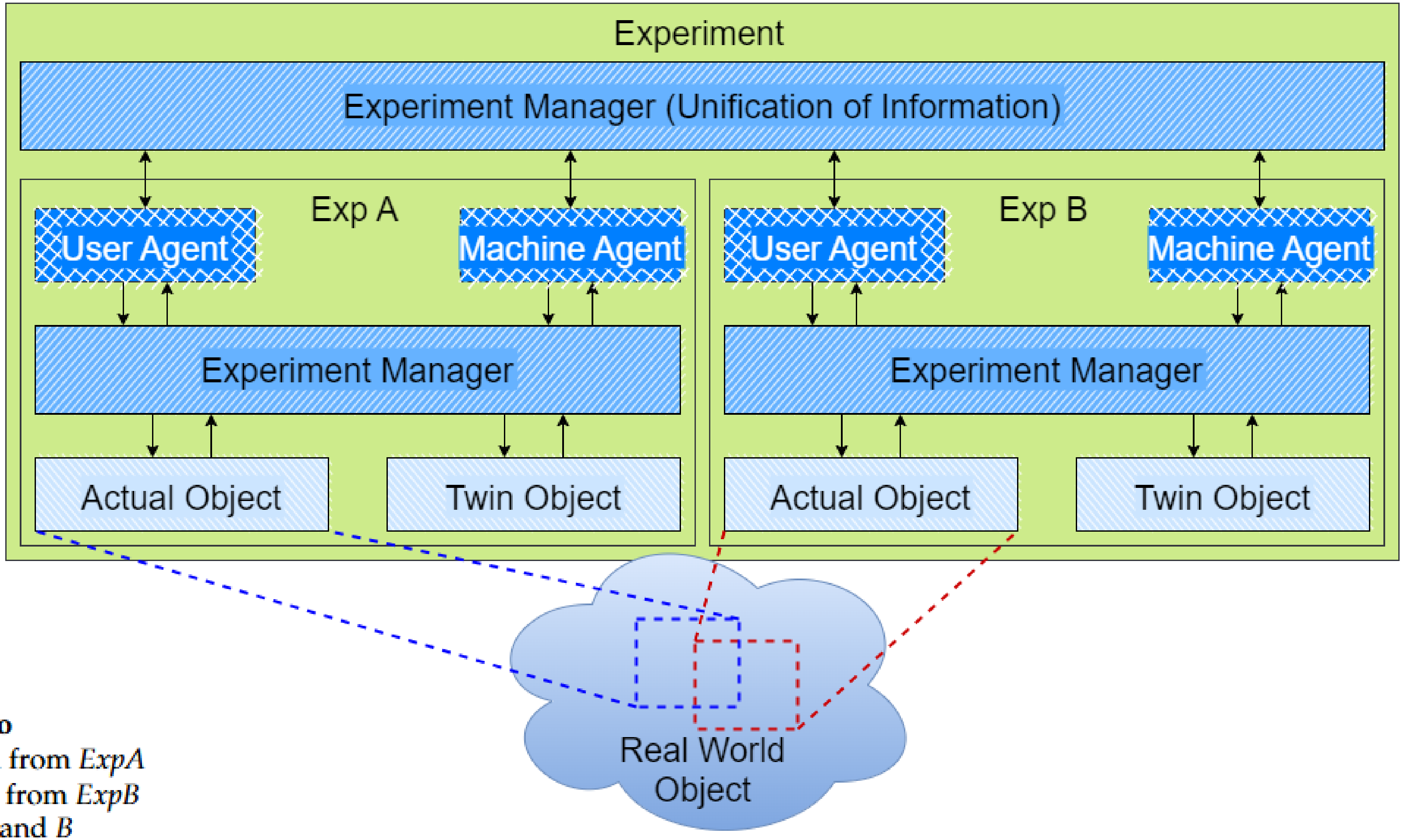
Combining Twinning Experiments (TEs)

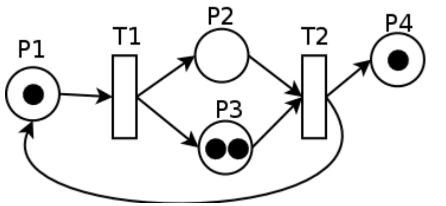




Combining TEs – Multiple PoIs

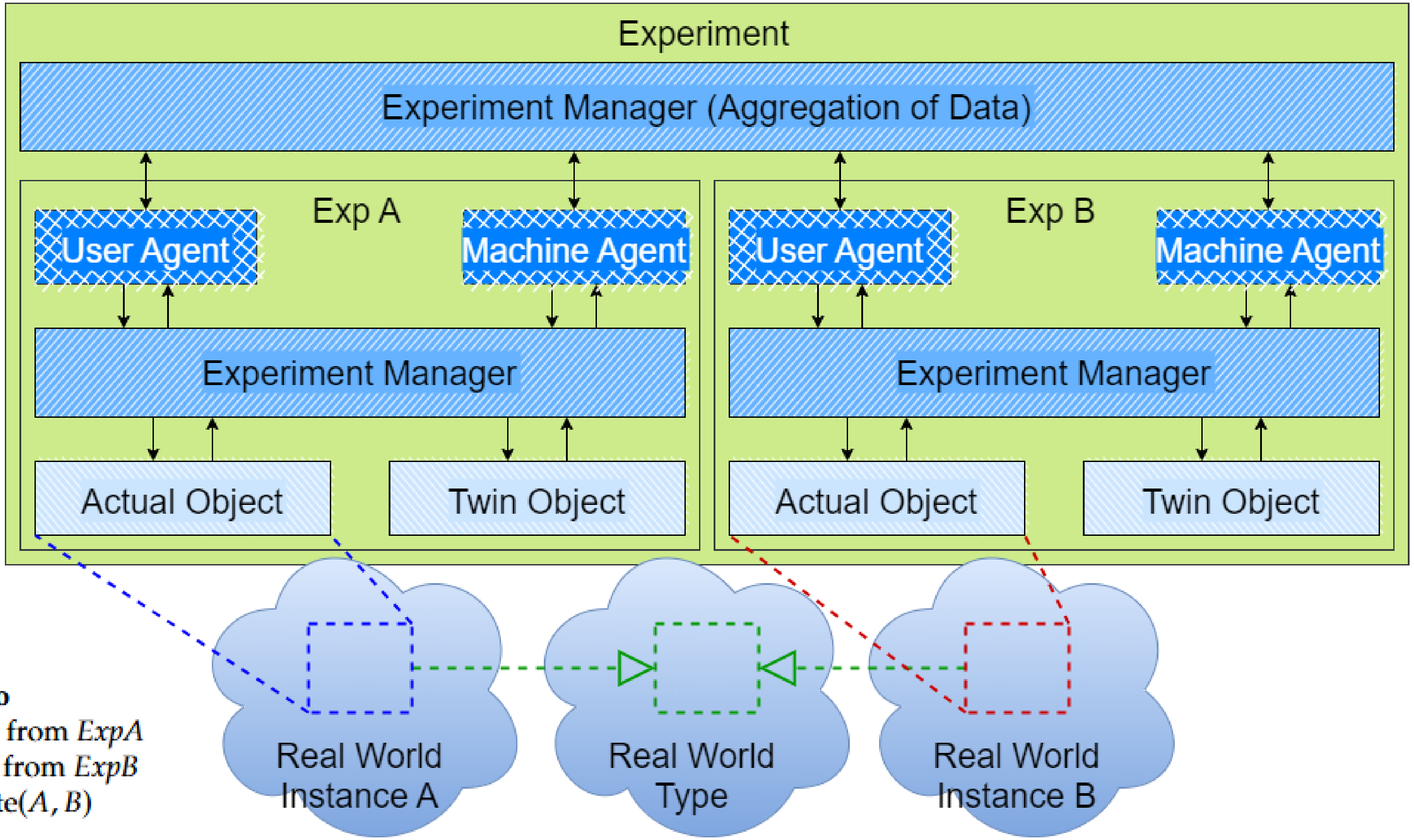






start *ExpA* and *ExpB*
while not finished **do**
    $A \leftarrow$ Collect data from *ExpA*
    $B \leftarrow$ Collect data from *ExpB*
    yield union of A and B
end while

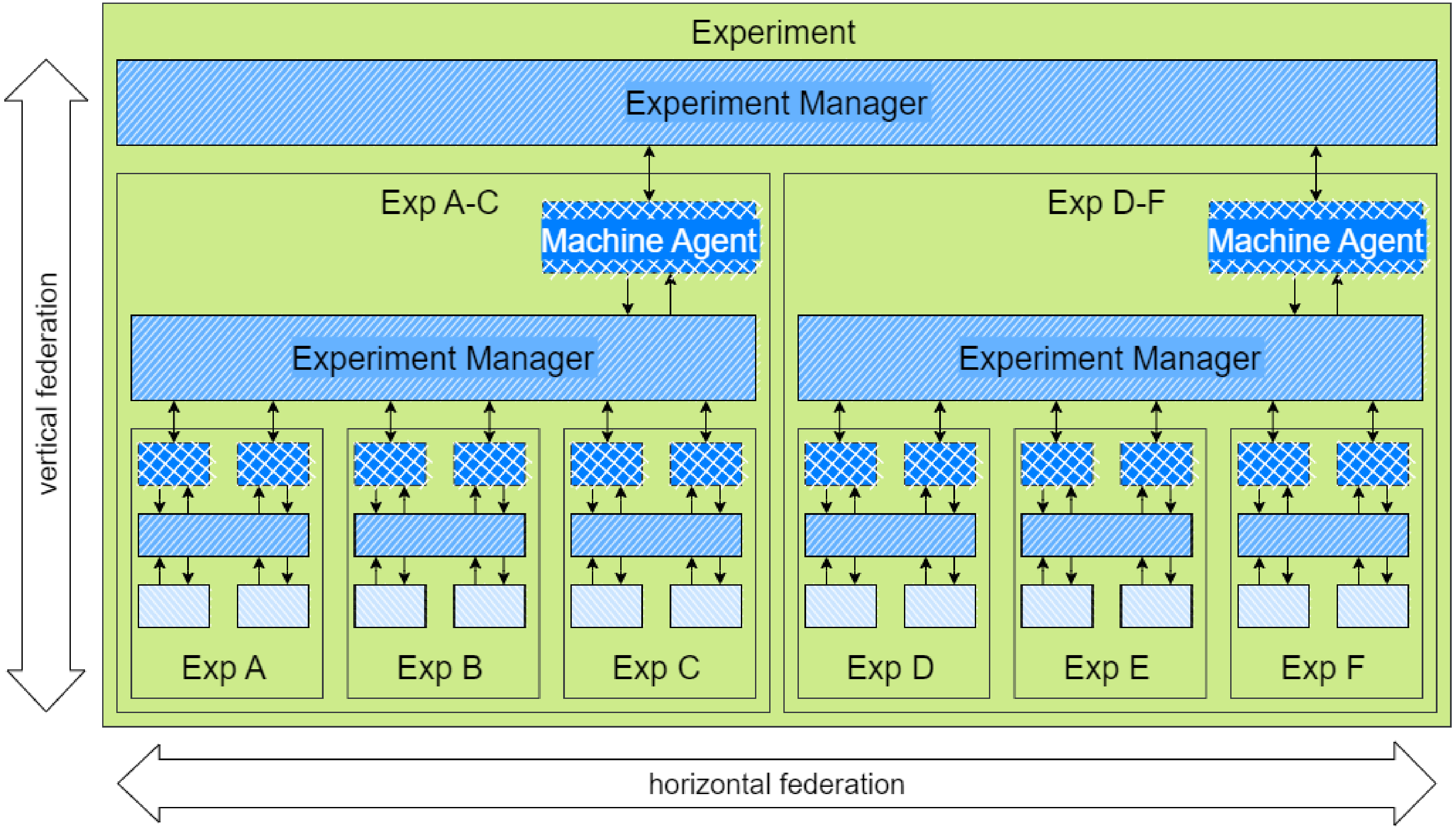
Combining TEs – Multiple Instances vs Types



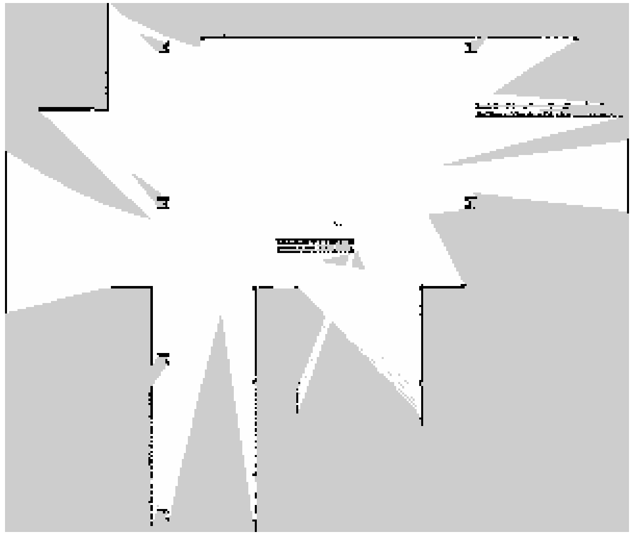
start $ExpA$ and $ExpB$
while not finished **do**
  $A \leftarrow$ Collect data from $ExpA$
  $B \leftarrow$ Collect data from $ExpB$
  $Type \leftarrow$ aggregate(A, B)
  yield $Type$
end while

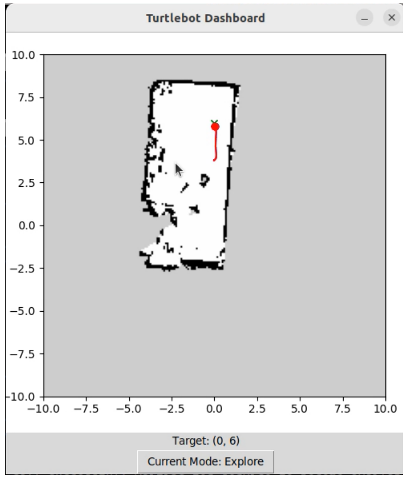


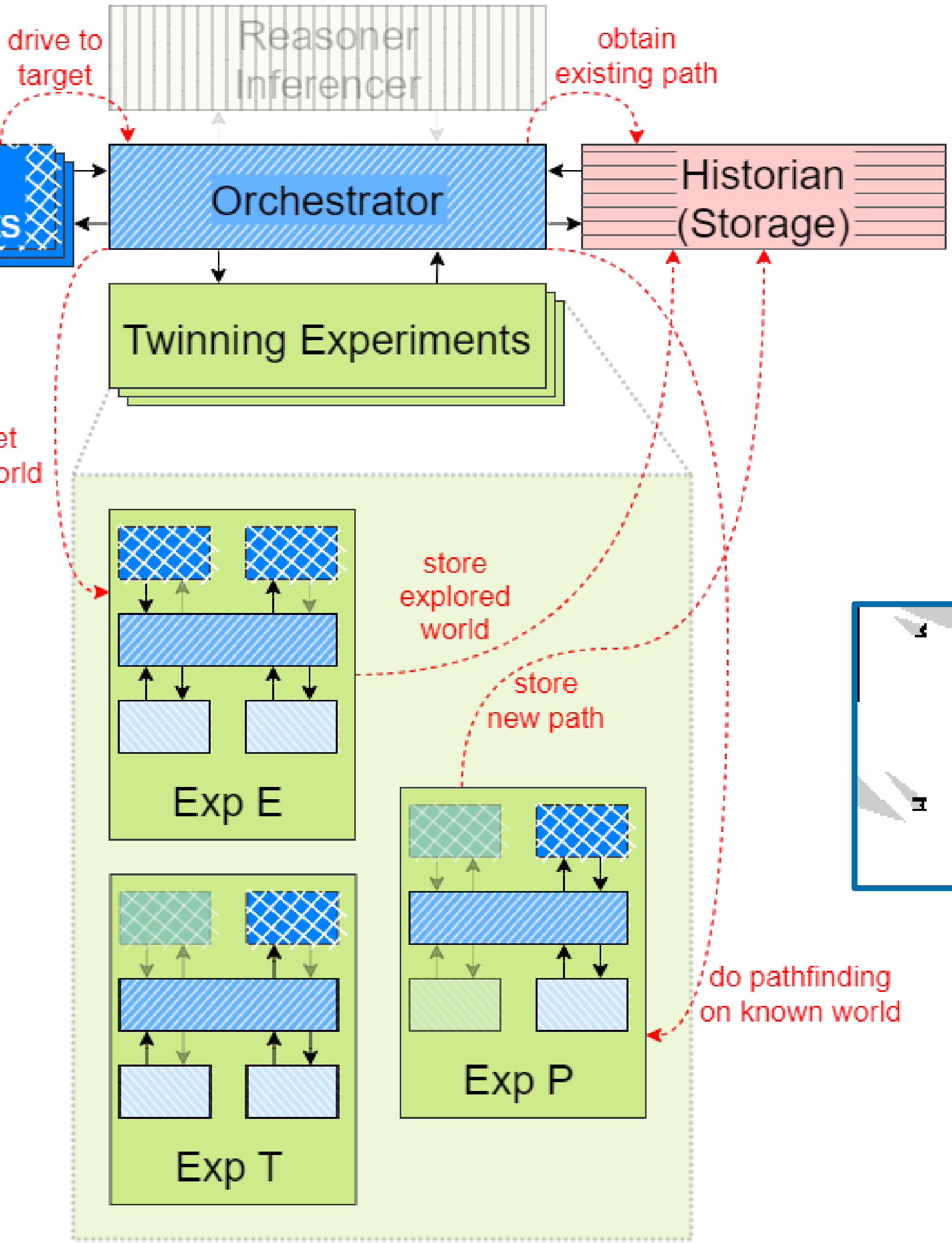
Combining TEs – Multiple Combinations

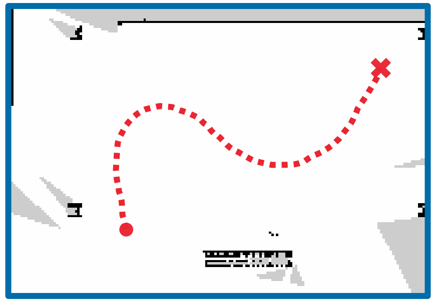


Proof-of-Concept: Turtlebot









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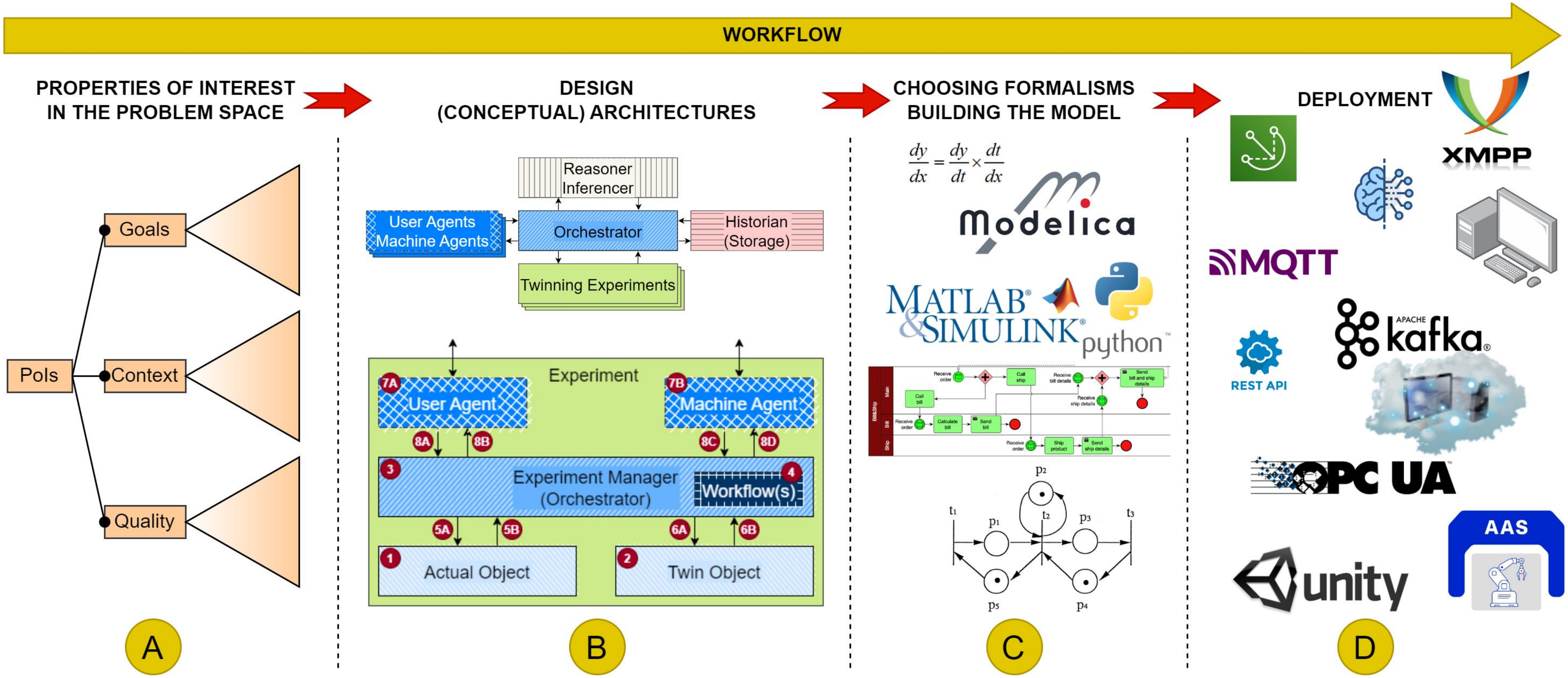
- RQ5: *How can we conveniently combine multiple DTs into a larger system?*

Stages of Twinning Variability (main contribution)



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.

Future Work

- **RQ2: *Given the large number of existing DTs in the literature, can we unify?***
  - The literature needs to be re-studied and this unification needs to be shown
- **RQ3: *Is there a relationship between specific DT requirements, the system architecture, the used models, and the eventual deployment?***
  - Interaction between these stages still needs to be analyzed
- **RQ5: *How can we conveniently combine multiple DTs into a larger system?***
  - These combinations need to be verified against the literature