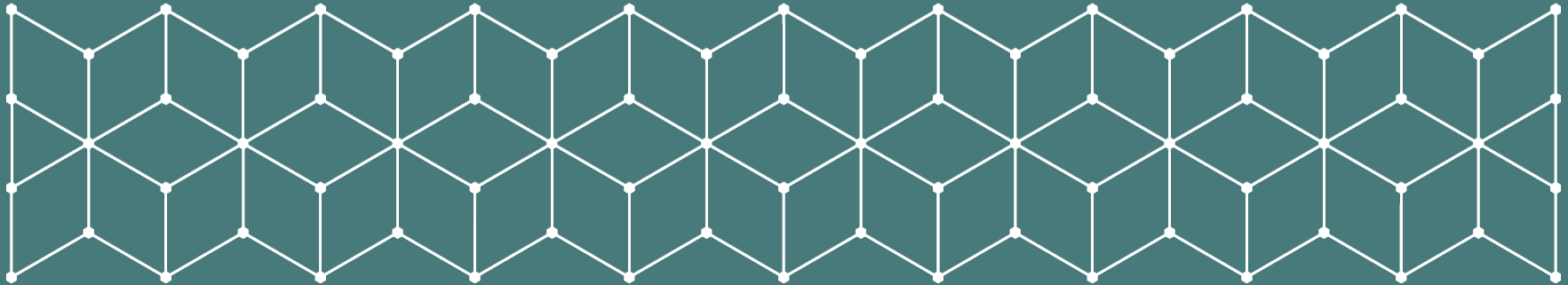


Digital Twins: models everywhere

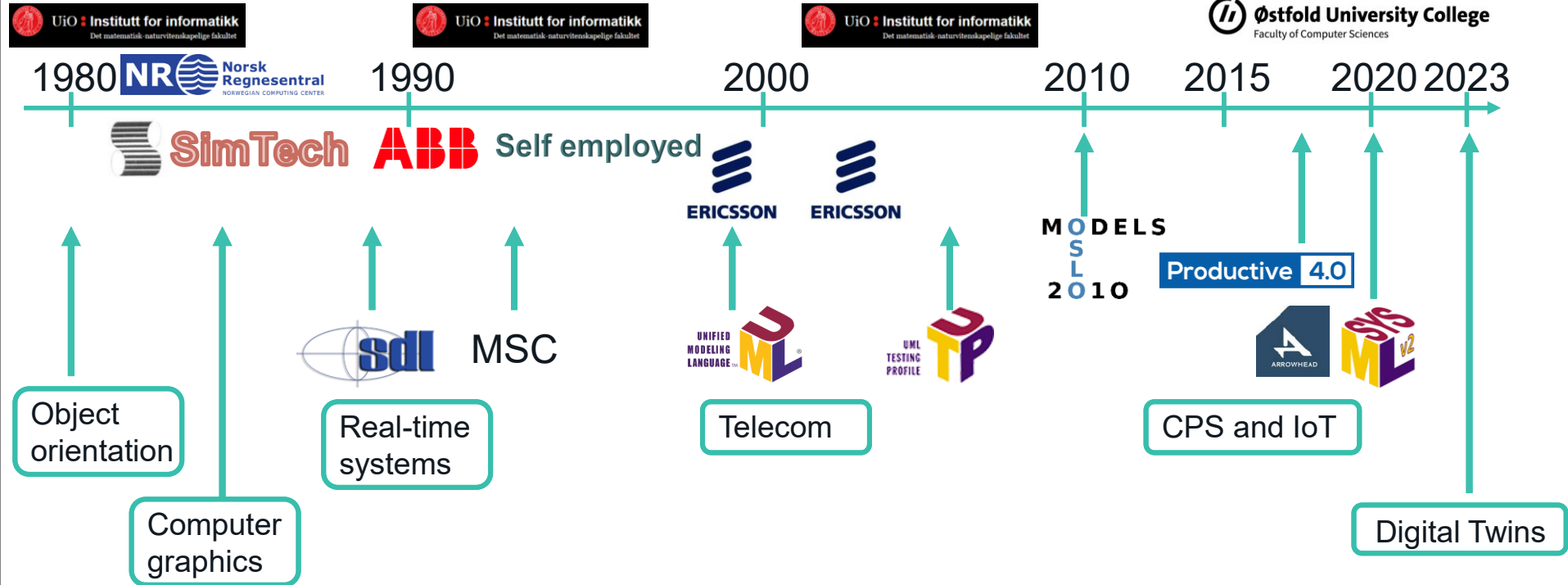
Øystein Haugen



Øystein Haugen – Professor@ Østfold University College



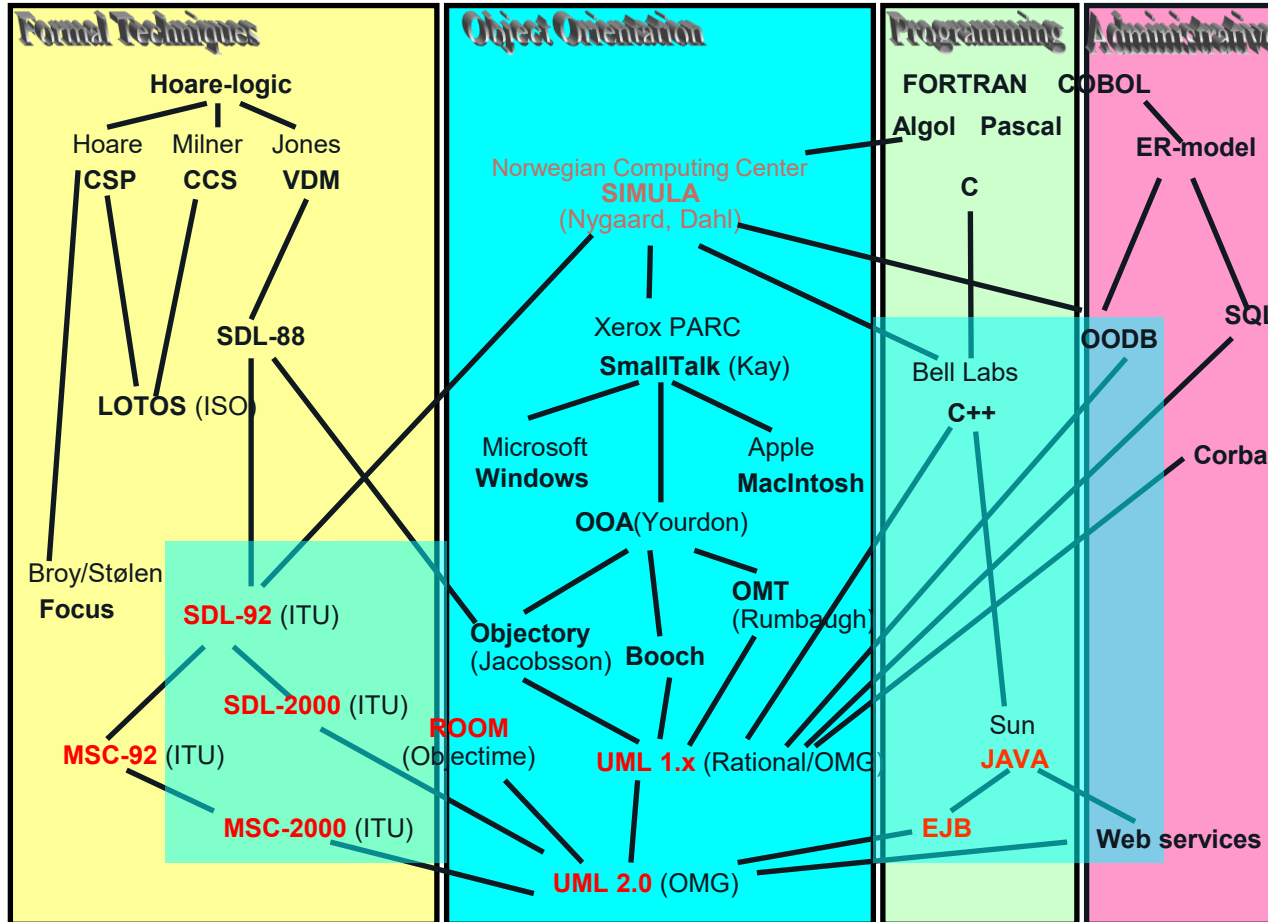
 Østfold University College
Faculty of Computer Sciences



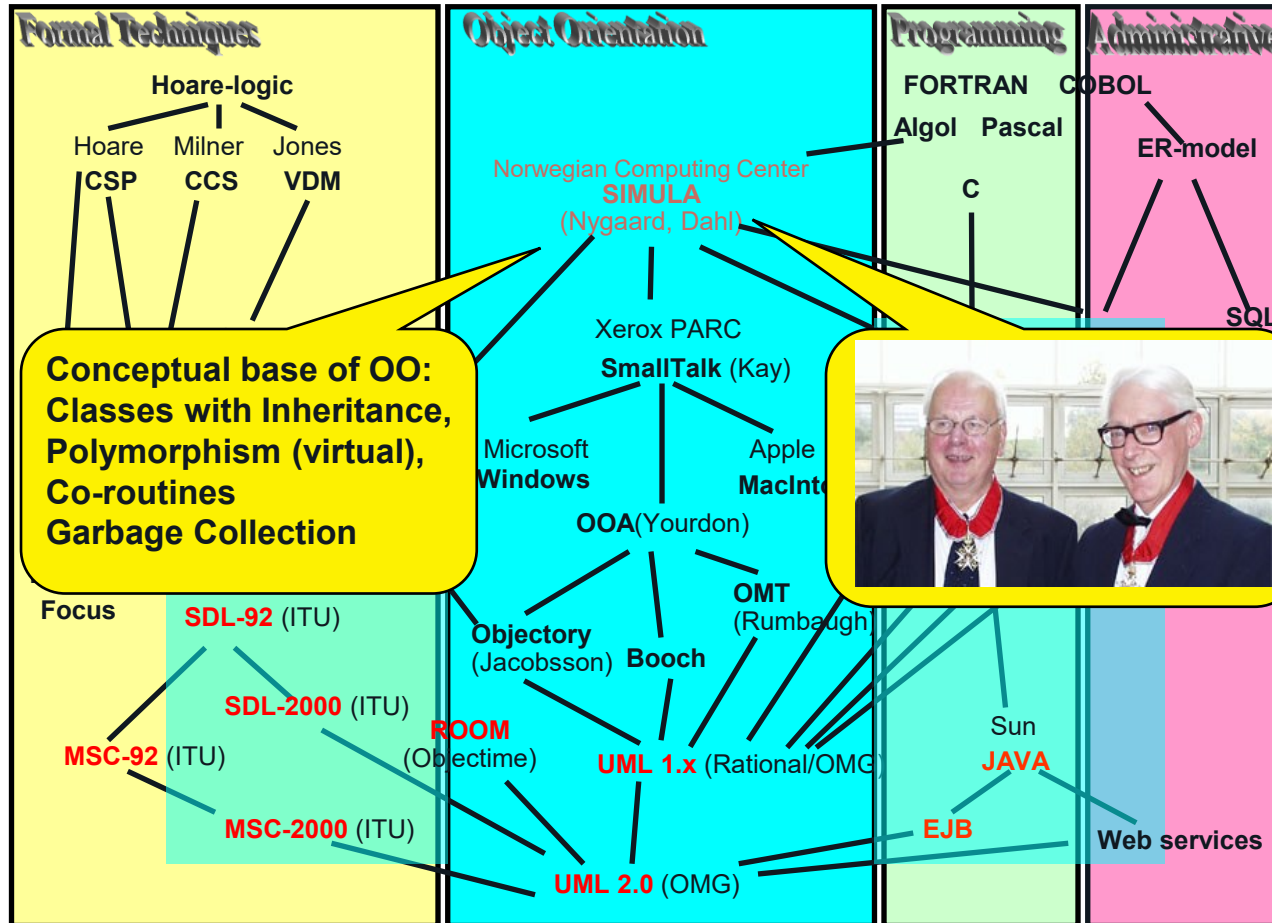
A History of Modeling Languages



A history of modeling languages



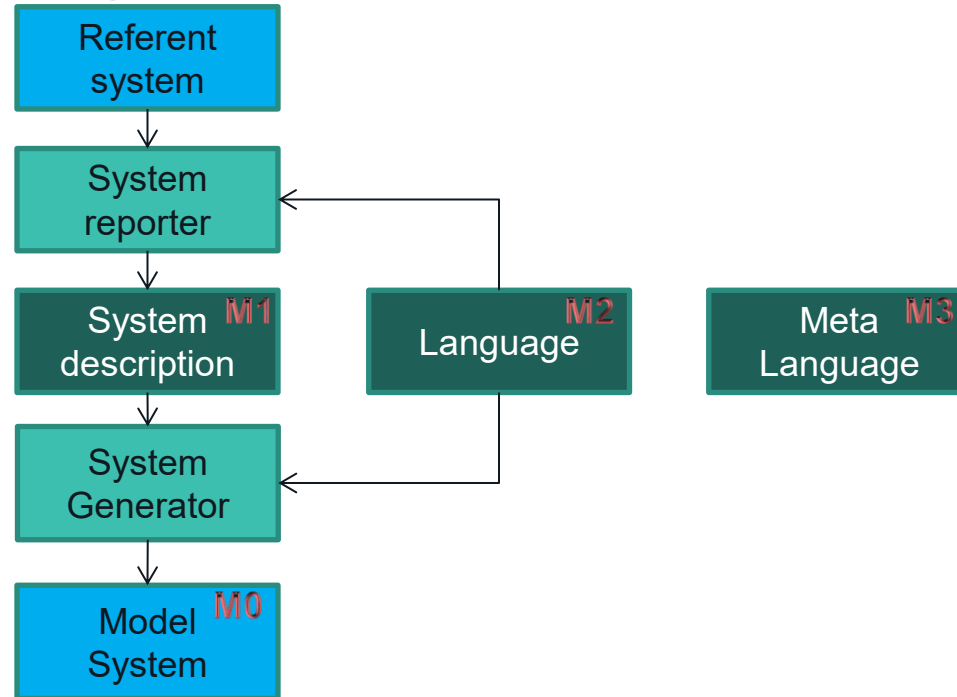
The founding fathers



Modeling a system

- A system is a part of the world
 - which *we choose to regard as a whole*, separated from the rest of the world *during some period of consideration*, a whole which we choose to consider as *containing a collection of components*, each characterized by a selected set of associated *data items and patterns*, and by actions which may involve itself and other components
- Mental systems
 - Systems existing in the human mind, physically materialized as states of the cells of our brains
- Mental and manifest models
 - when a *limited set of properties* is selected from a system
- These definitions are from K. Nygaard and his DELTA team (in 1975)

A Model of Modeling



Modeling is abstraction

- By making a model you distinguish between
 - what is **important** and what is not important
 - for a given **purpose**
- There may be **several fruitful models** of the same reality
- Modeling is an act of **conscious thinking**
 - but it may be assisted by automatic means and tooling

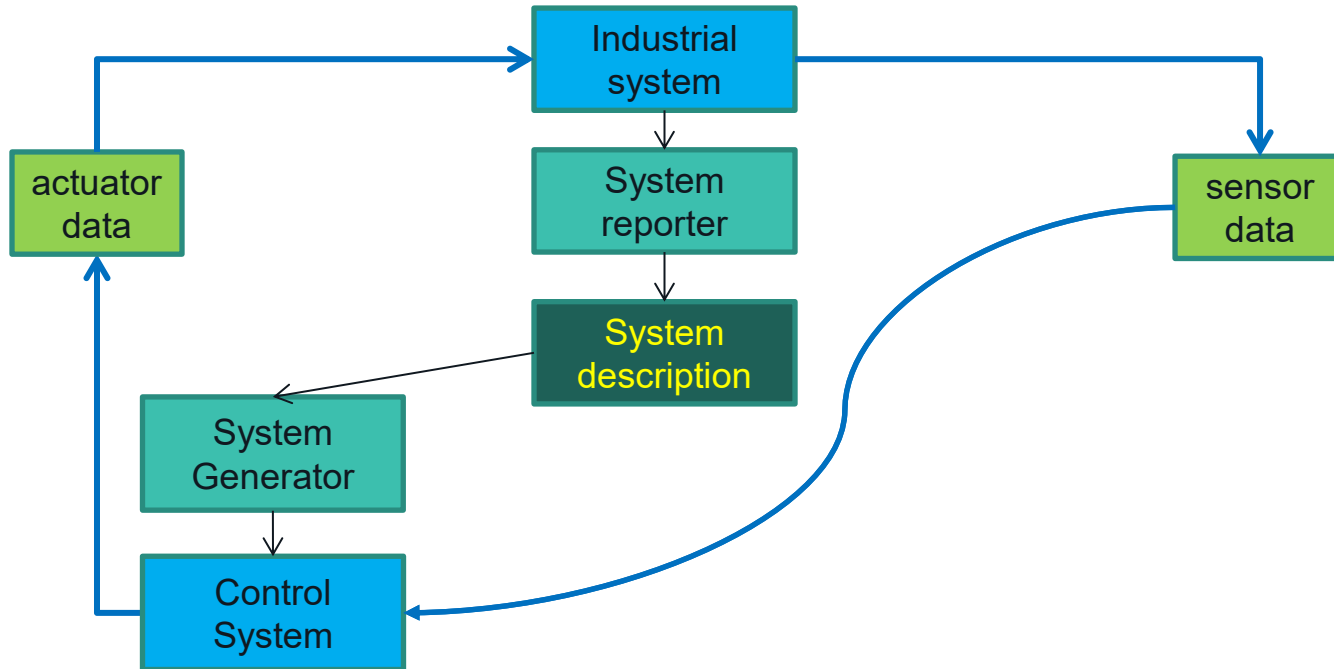
Digital Twins



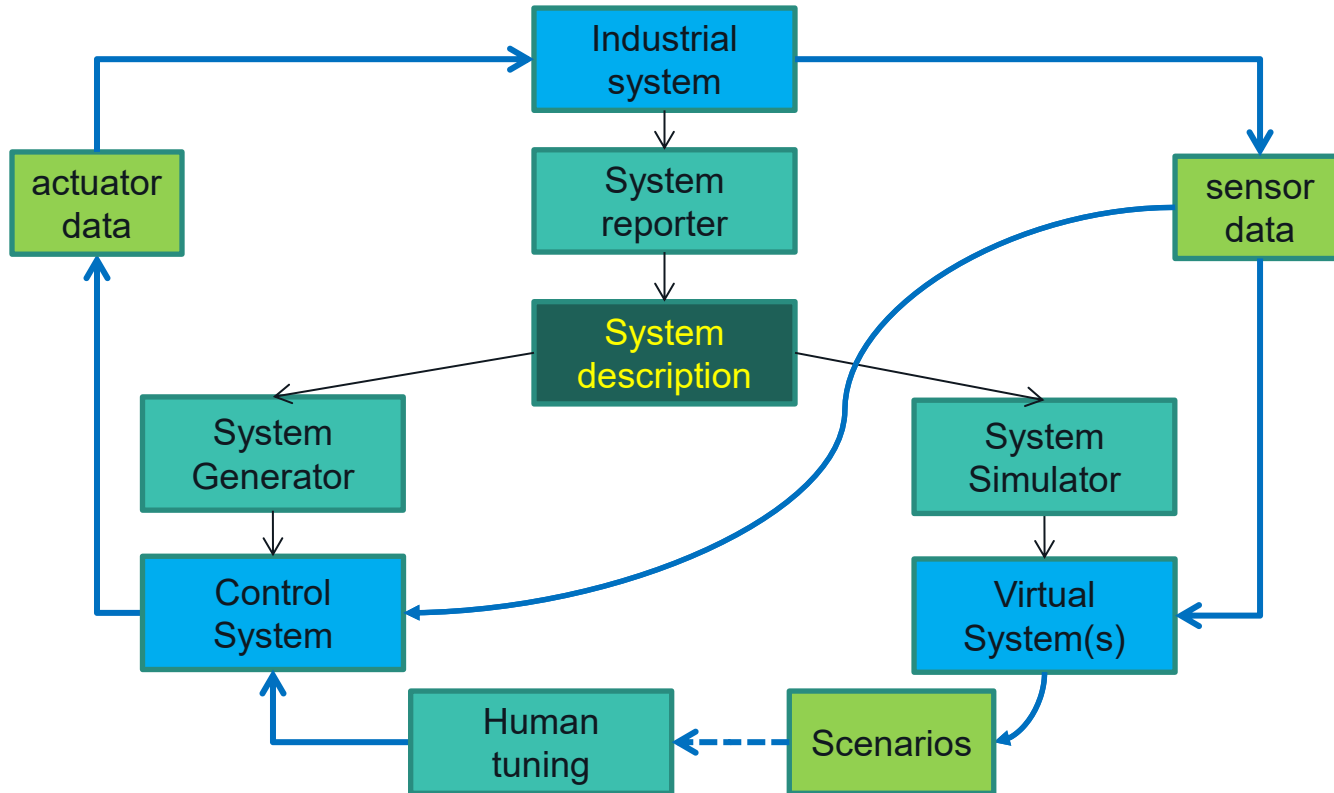
Google Trend on net search of Digital Twins



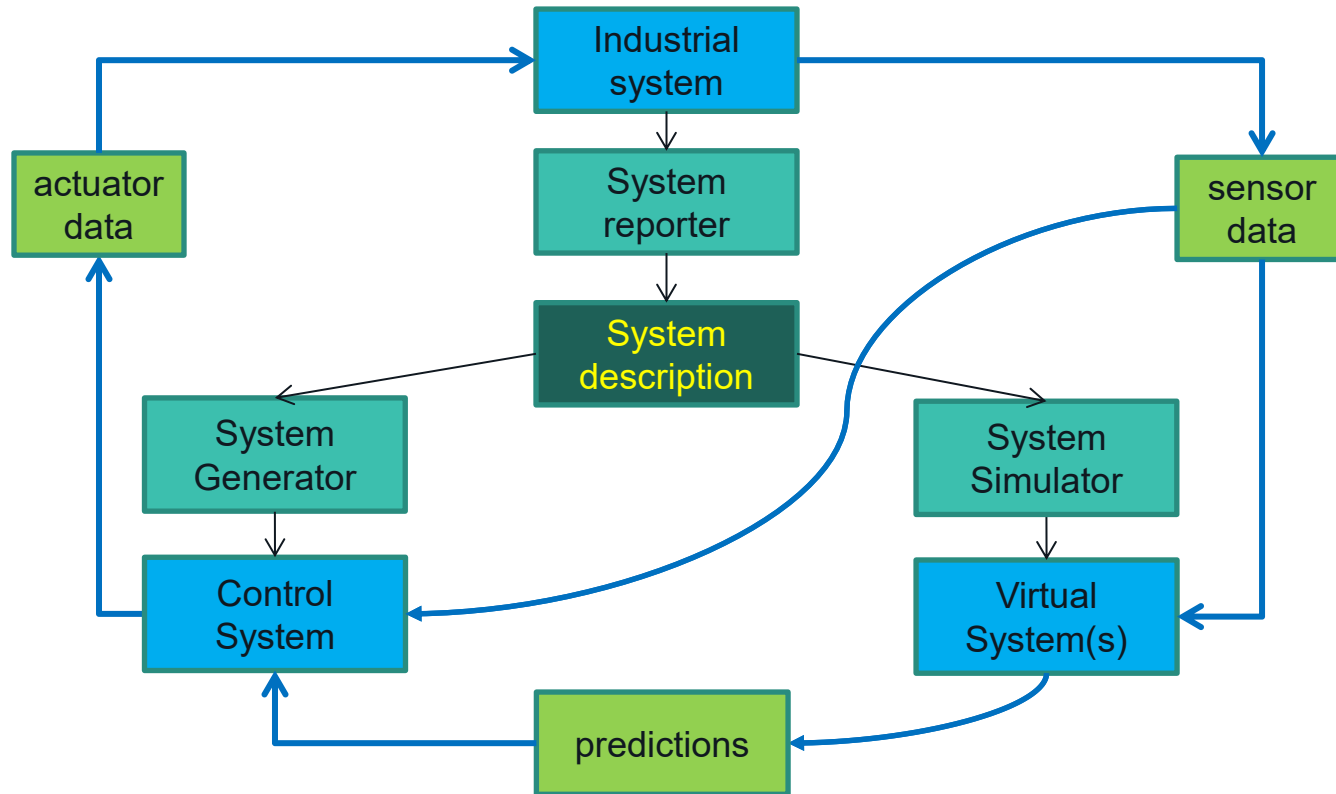
Once upon a time ...



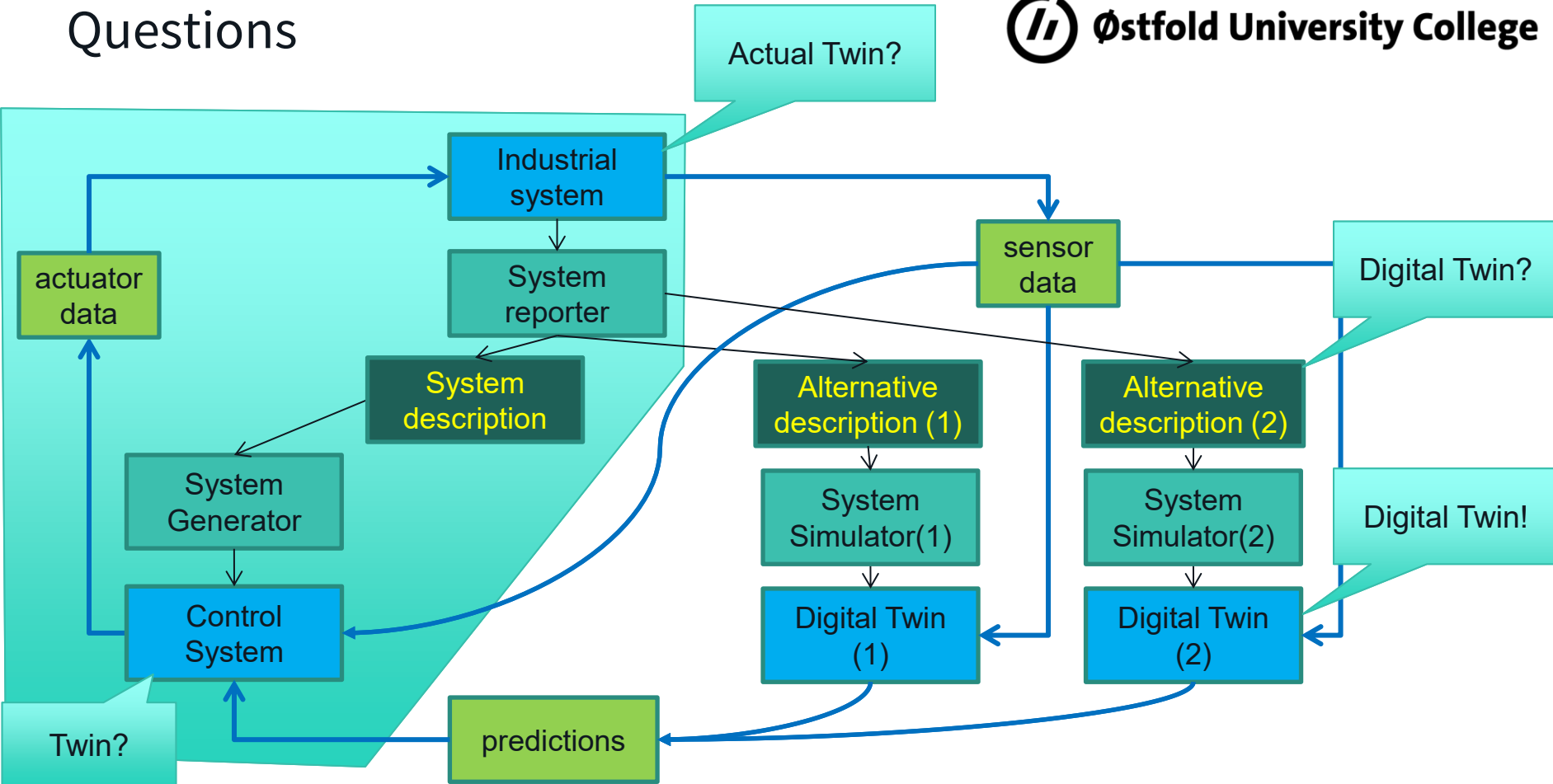
... then we created Digital Simulation



Or the more advanced Digital Twin



Questions



Definition: Digital Twin and Actual Twin

- A Digital Twin (DT) is a digital representation of an actual system, referred to as the actual twin (AT), that is dynamically updated with AT data and that can interact with and influence the AT
 - From SoSyM paper: Continuous Evolution of Digital Twins using the DarTwin Notation
- Digital Twin seems to be a fruitful approach to understanding and manipulating systems with different stakeholders

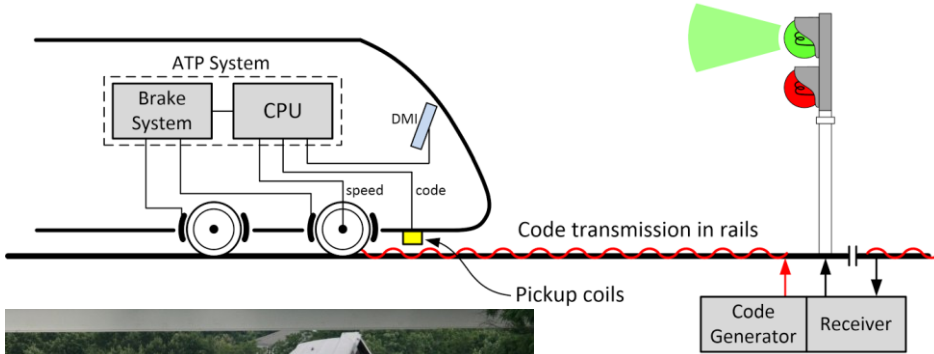
Why are Digital Twins popular for Industry 4.0?

- Modern systems are dynamic
 - Behavior is important
- Modern systems should work 24/7
 - Adaptivity and evolution are important
 - Simulation is important
- Modern systems are often cyber-physical
 - Concurrency and real-time are important
 - Physical wear and tear are important

The thing with CPS:
“It is physical, stupid!”

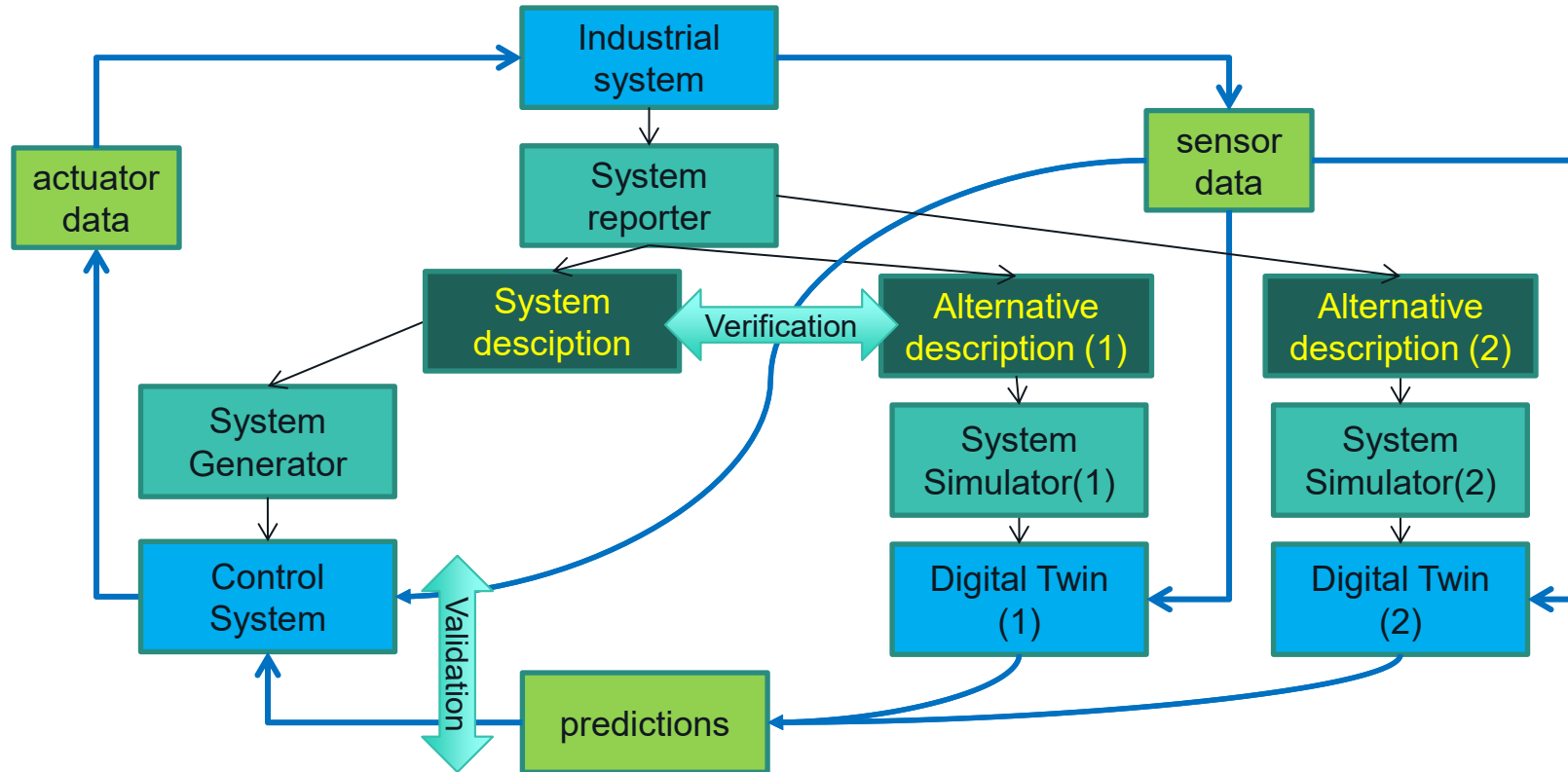


Automatic Train Control (for ABB ca 1990)

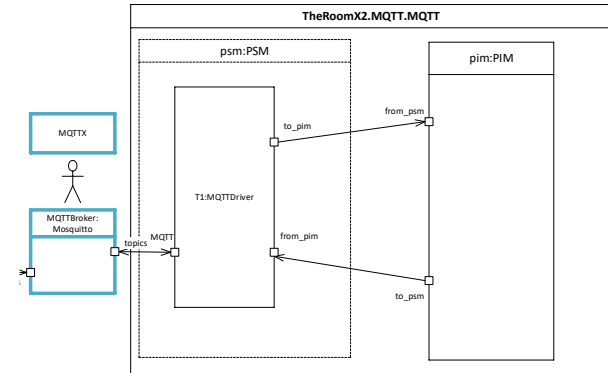
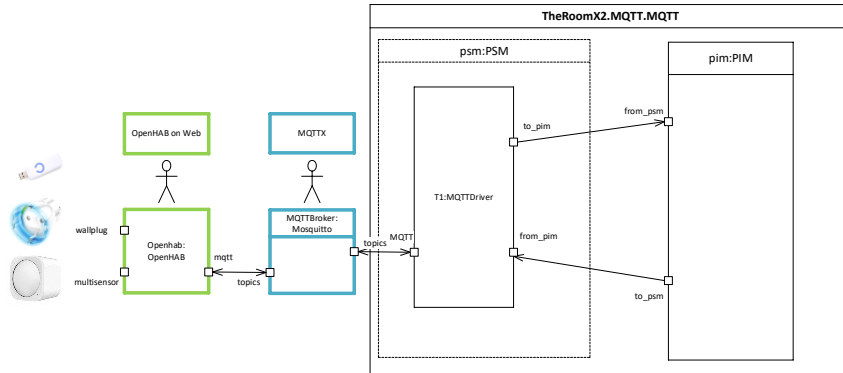
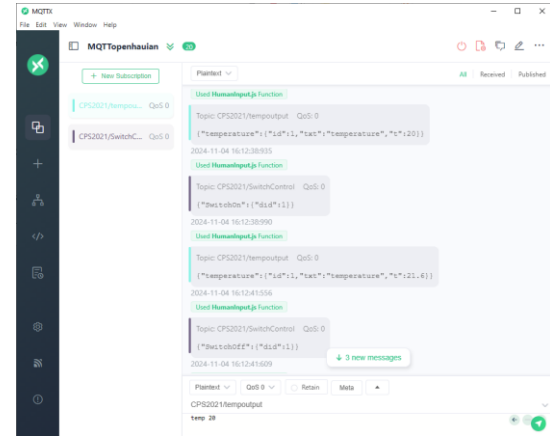
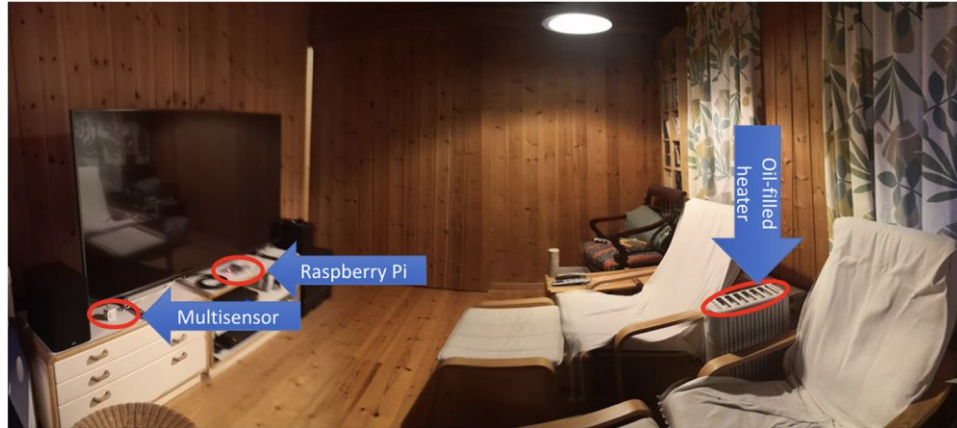


(illustration photos from Internet)

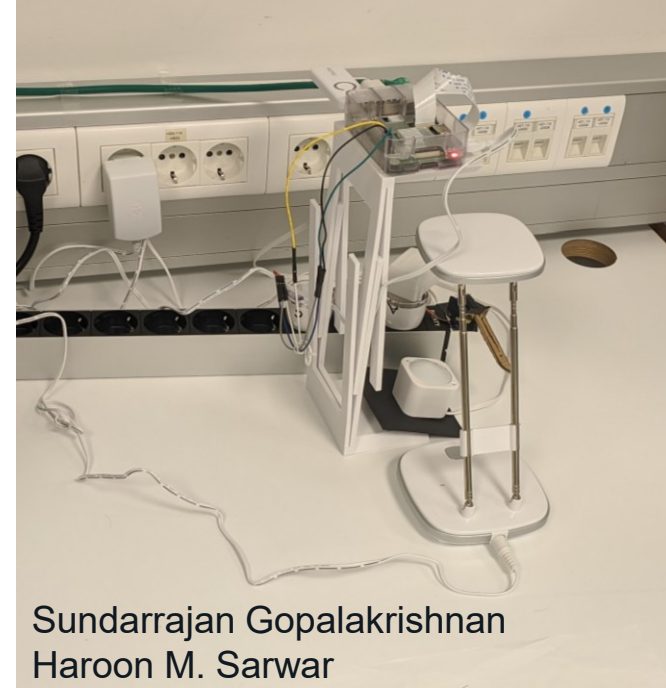
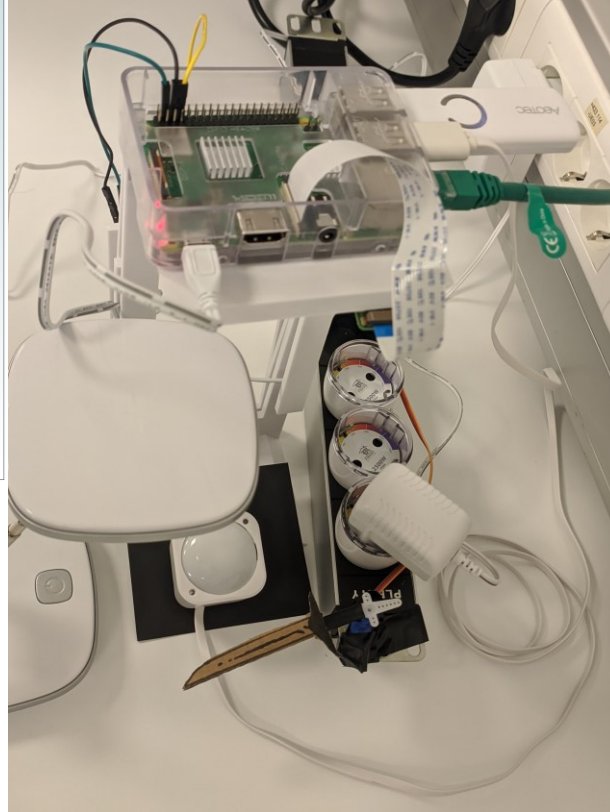
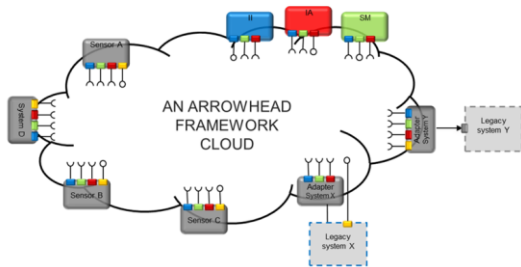
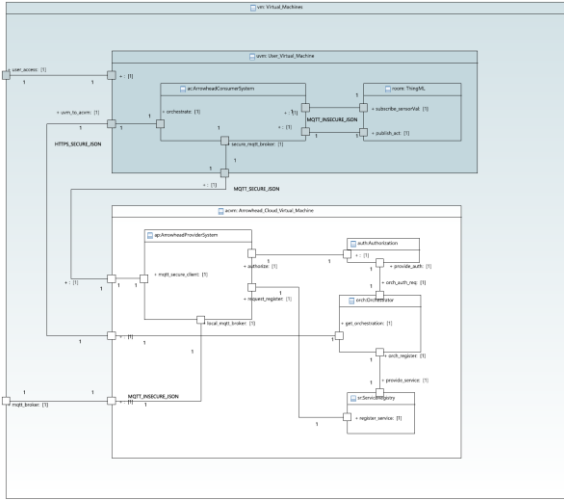
- Trains are physical
- Trains are heavy and move fast
 - 400 km/h
 - Braking takes kilometers
- Train Control means full brake if red light is passed
- How would you test this?
- How can you be sure it works the day you need it?
- Necessary technology: simulation
- Related IoT technology:
 - Self-driving cars



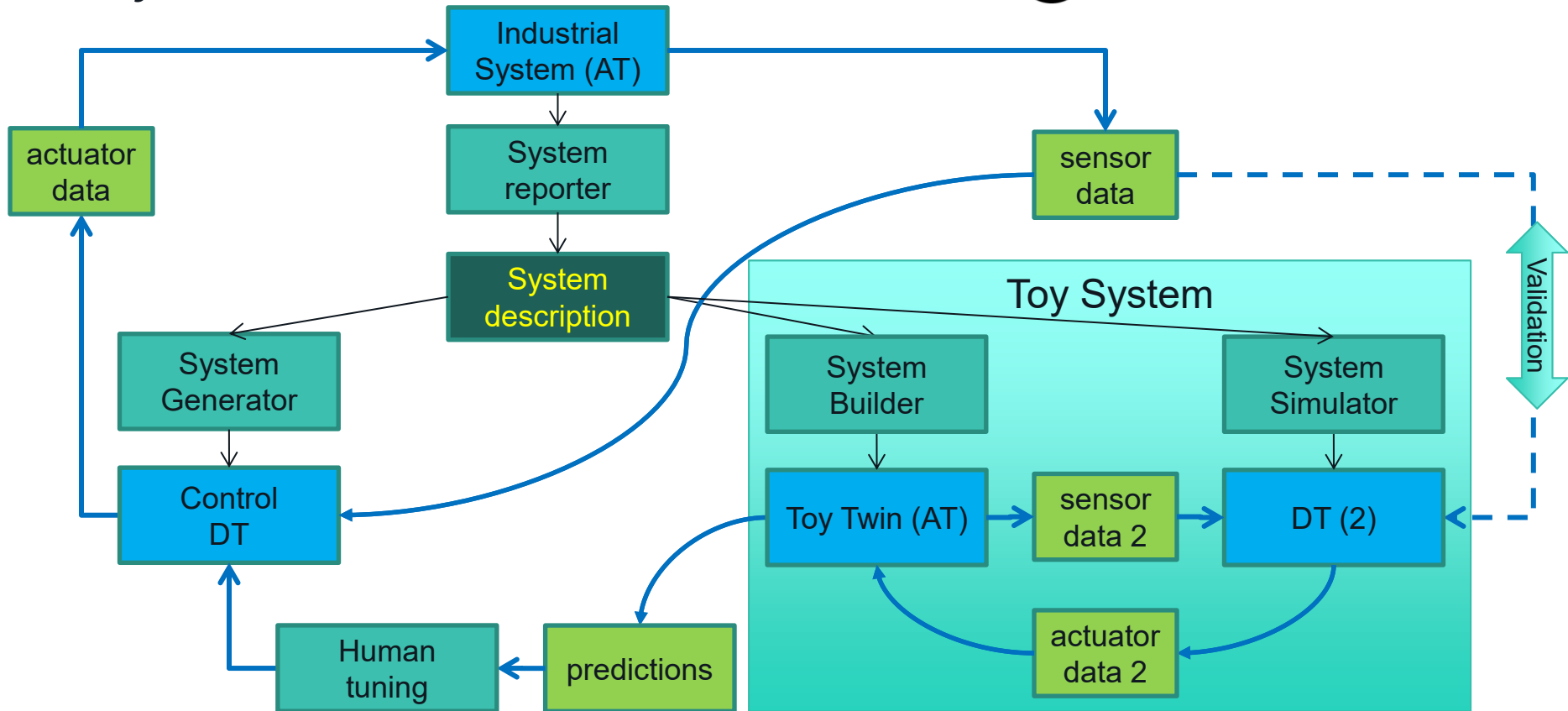
The room and its simulation



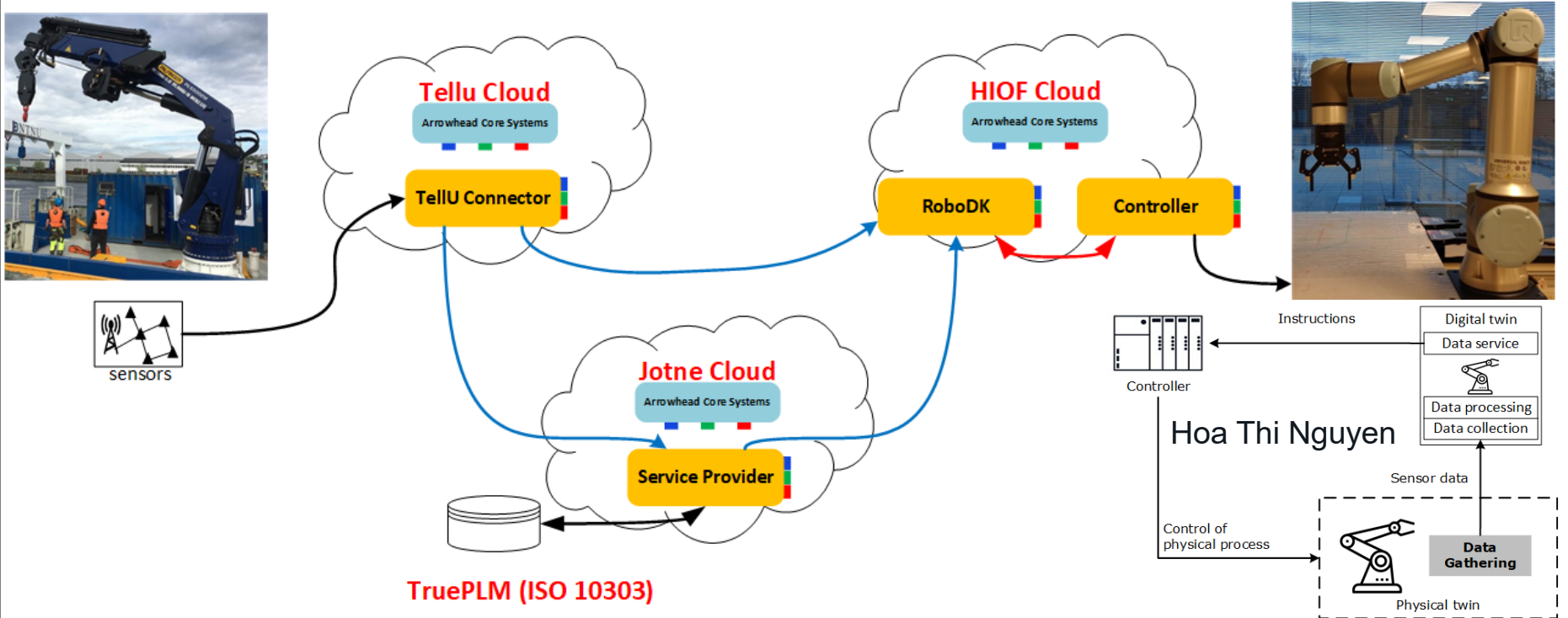
Covid-time: The Arrowhead Remote Virtual Physical Lab



Toy Twin



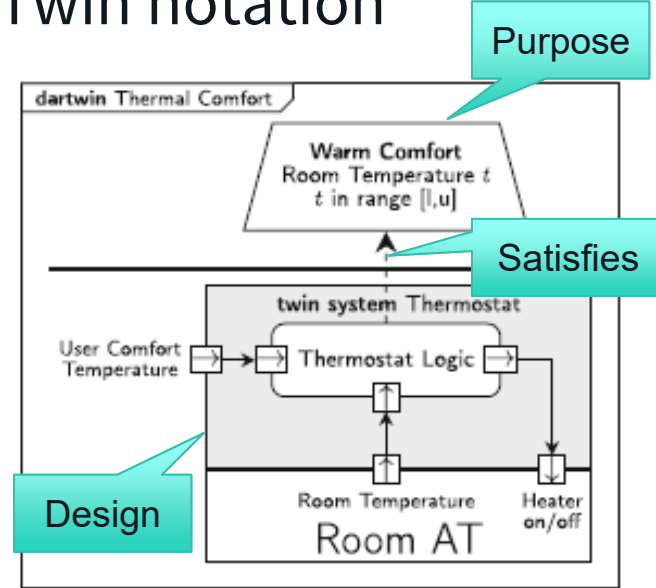
Arrowhead: Physical crane; Lab robot arm; Digital Twin



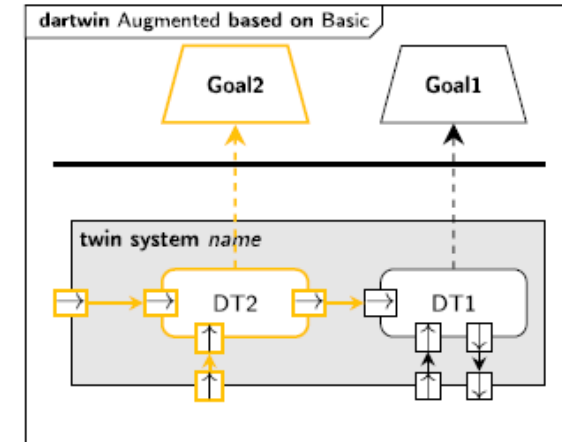
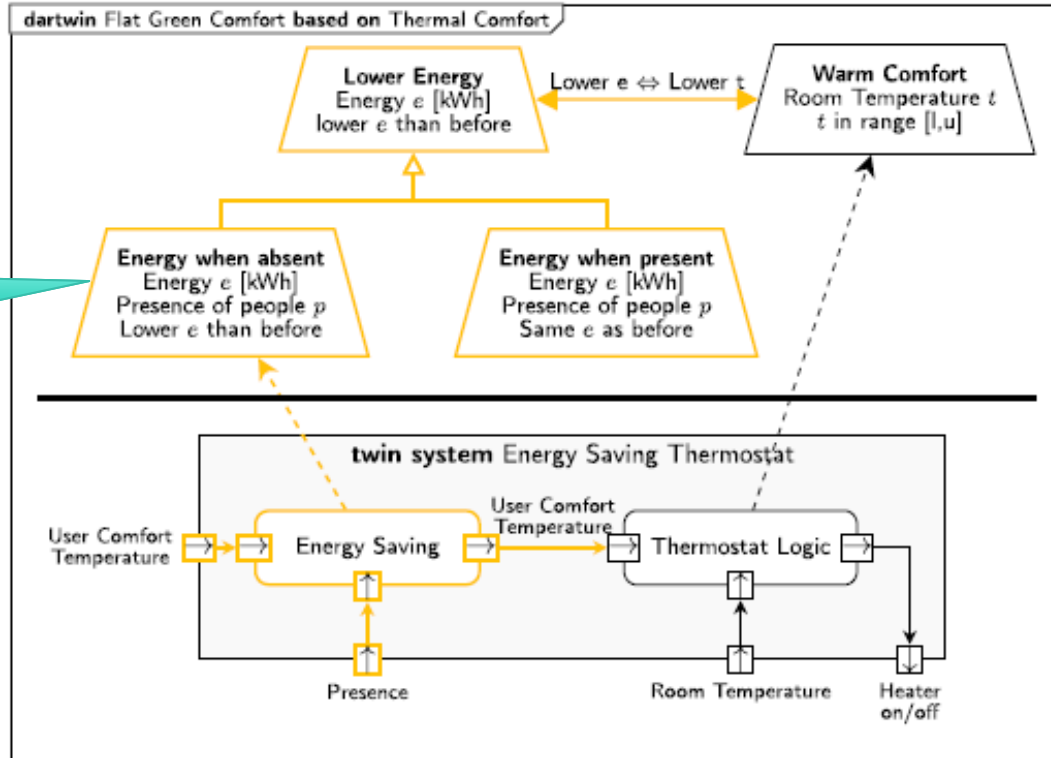
Adapting and Evolving Digital Twins



Evolving my room – a true story – the DarTwin notation

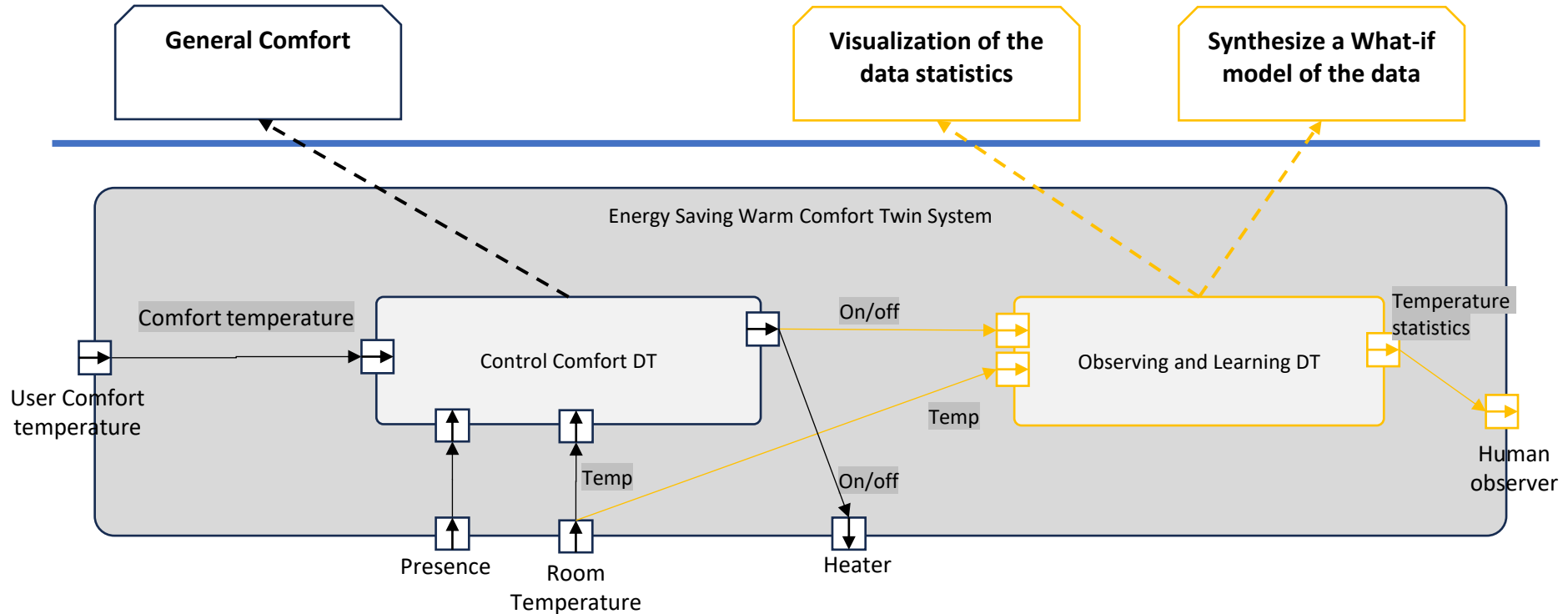


Evolution 1: Green comfort – saving some energy

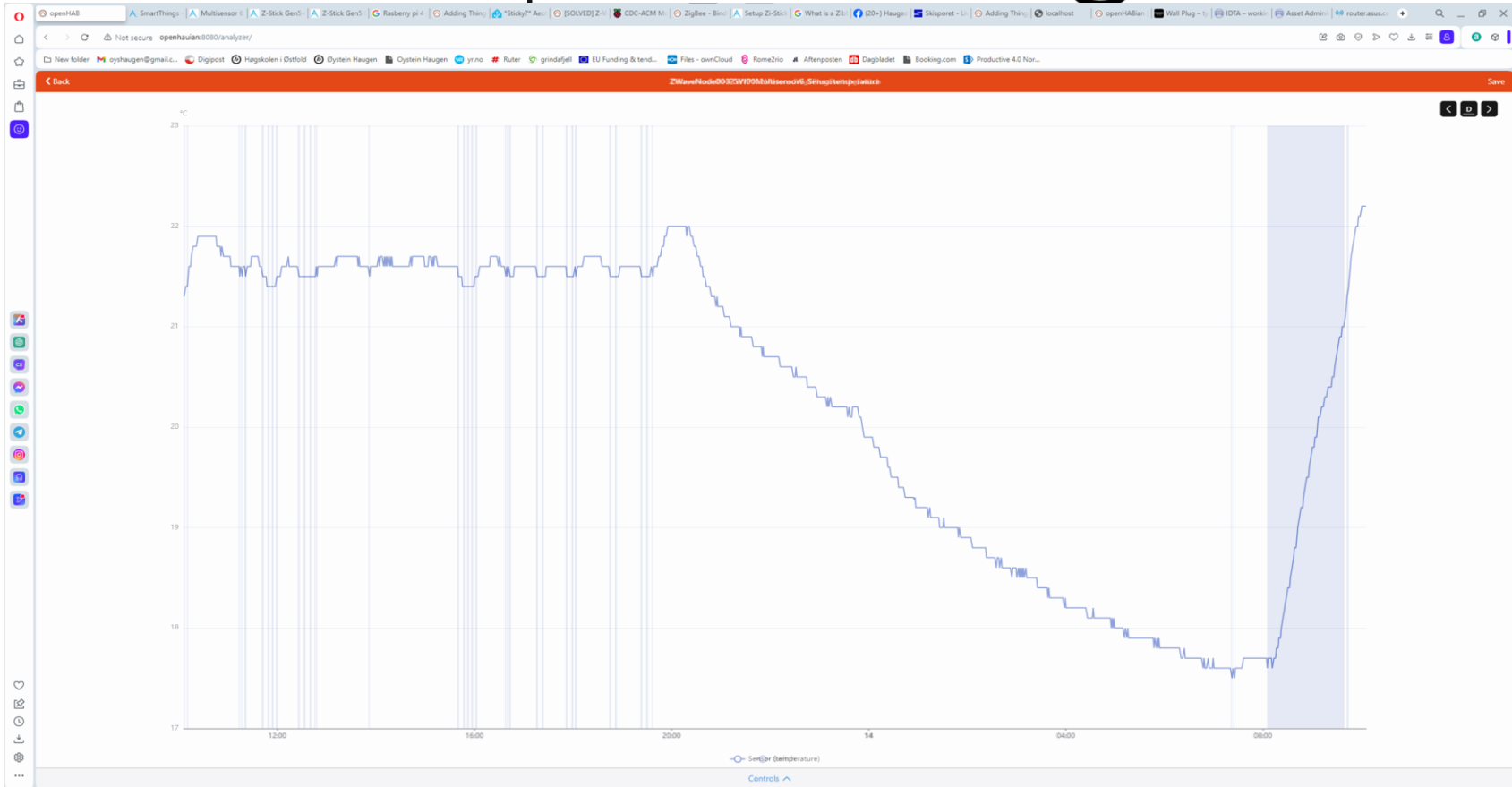


New changes

First DT Stage: Dashboard



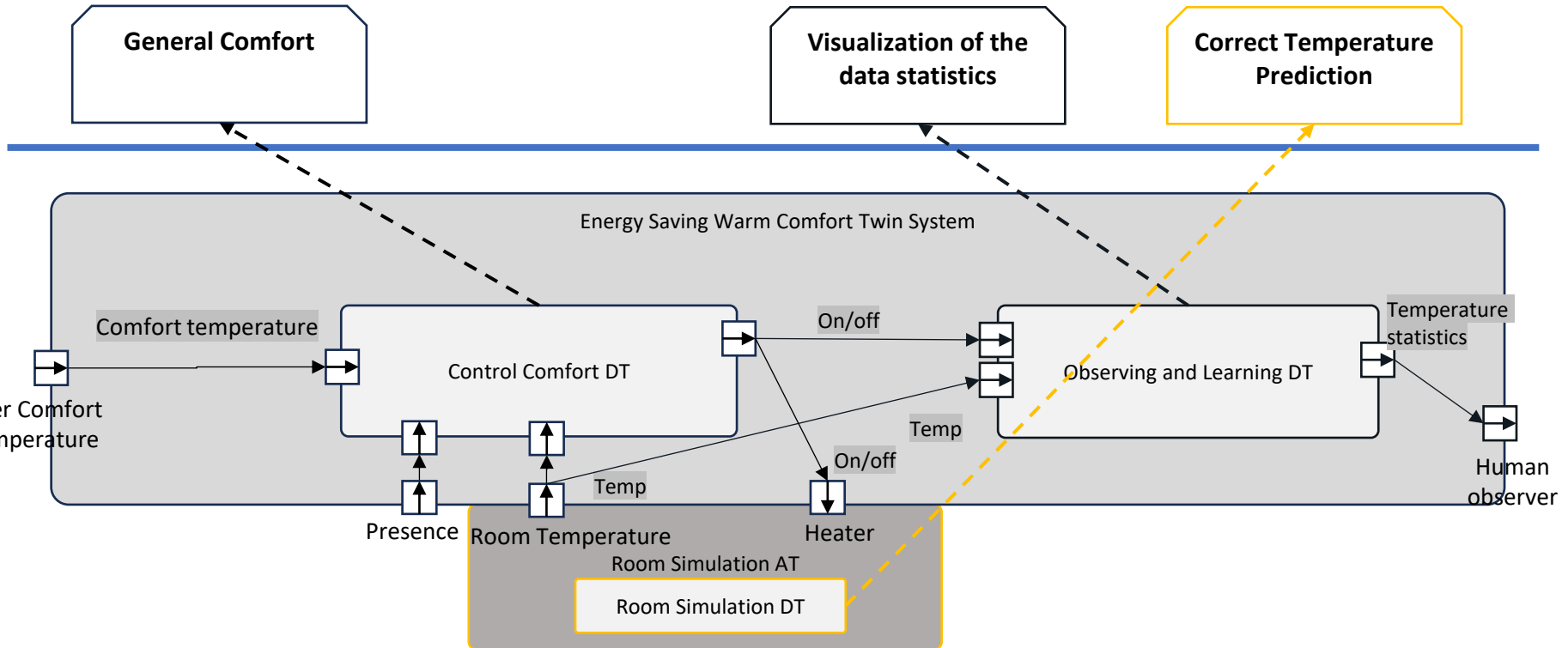
Observations via OpenHAB



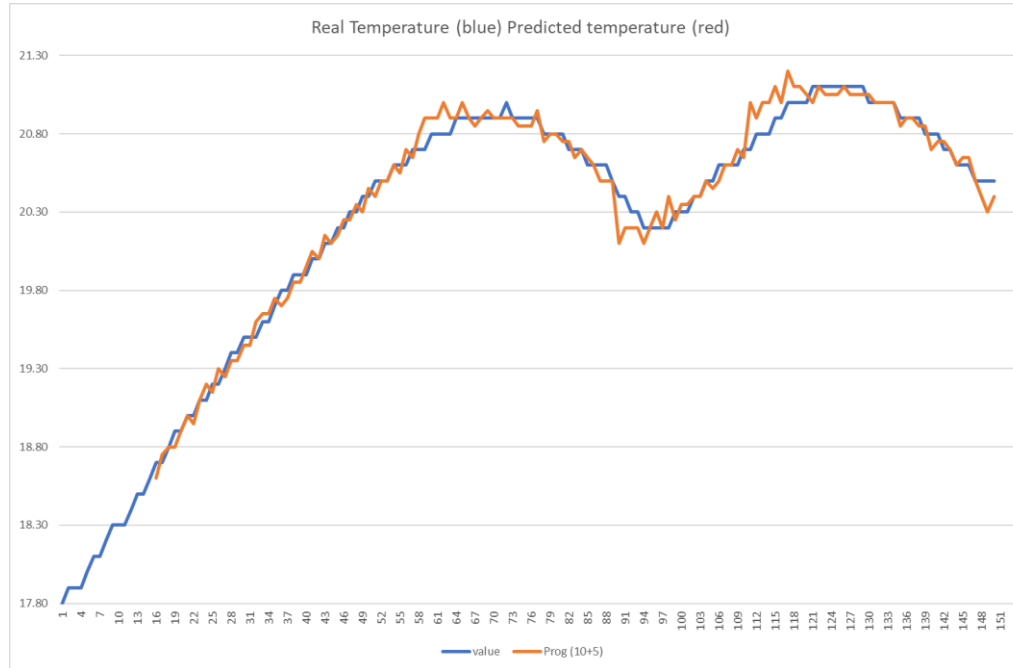
DT for Monitoring

- Prepare for human decisions
- Dashboards for overview
- Augmented reality for combining reality with information

Second DT Stage: What-if Simulation



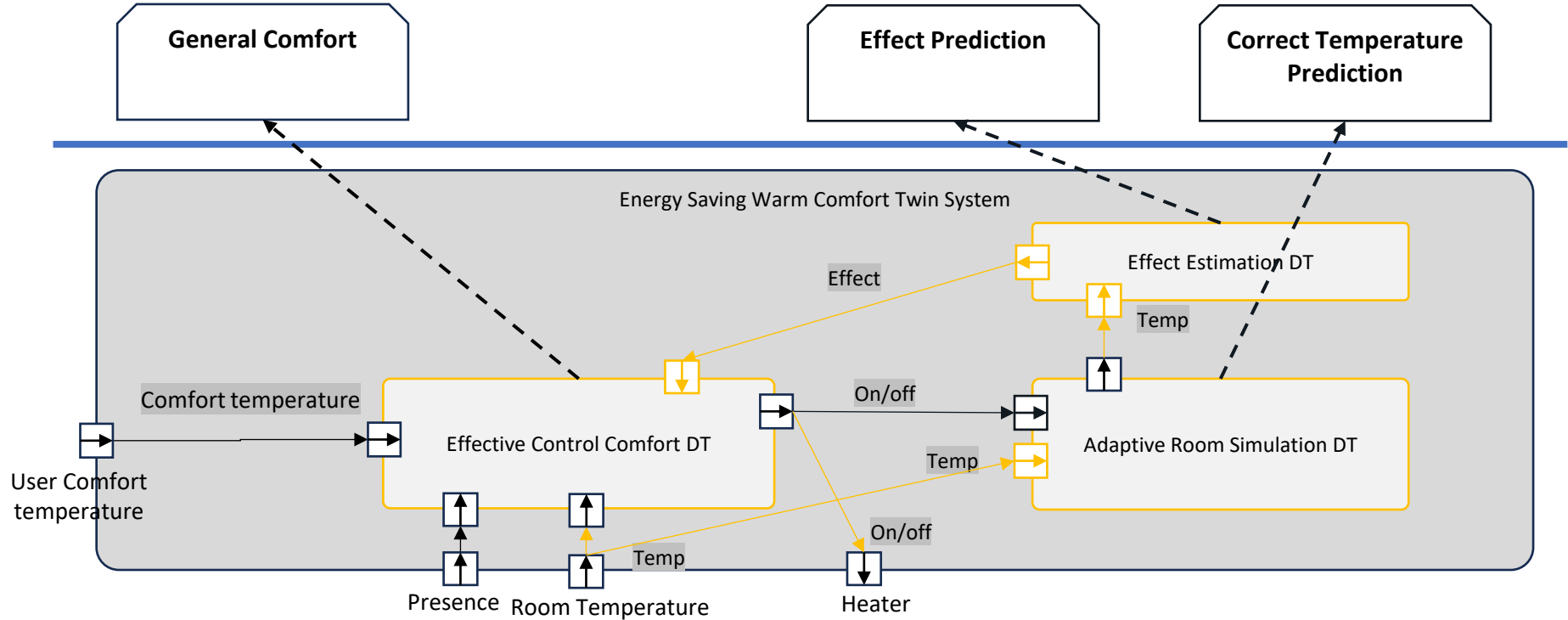
Simulation validation by comparing with historic data



DT for Prediction

- Simulation
- What-if scenarios
- Gamification
- Interdisciplinary exploration and understanding through risk-free execution of DT

Third DT Stage: Prediction-driven control



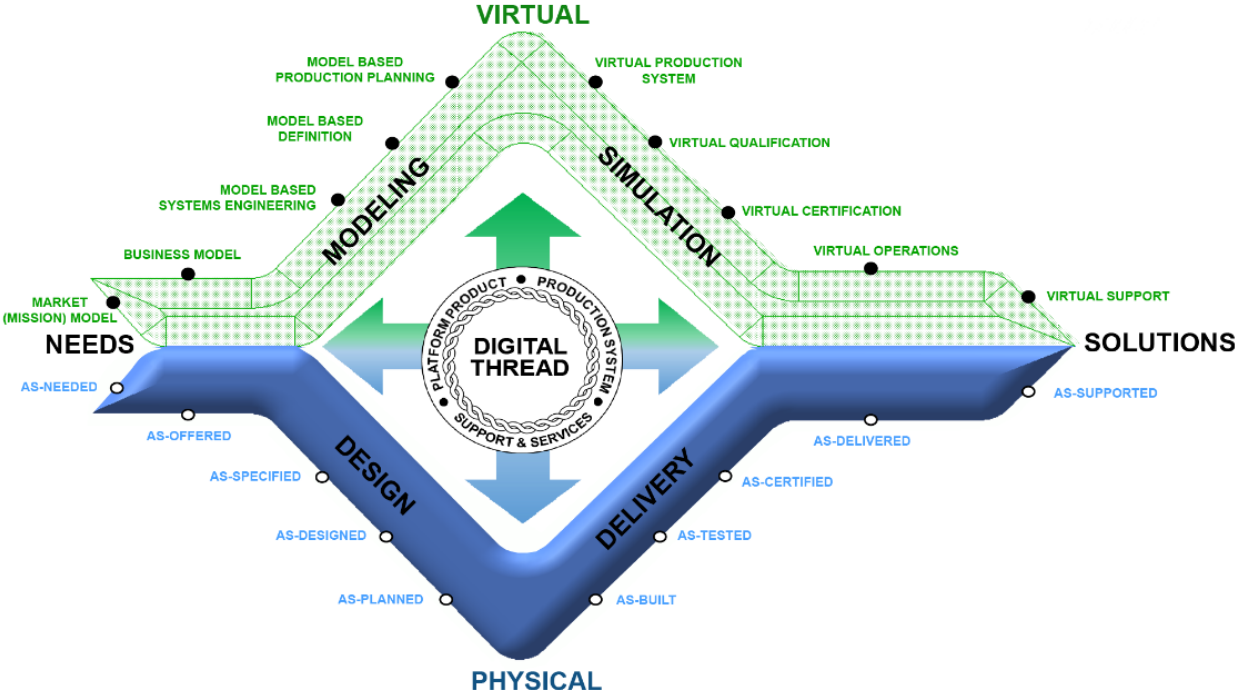
DT for Control

- Automation
- Data must be consumed in time
- Updates must preferably be done while executing
- Should apply redundancy
 - Several DTs for the same purpose
 - Federated DTs with different principles
 - Include some human in the loop at least for validation

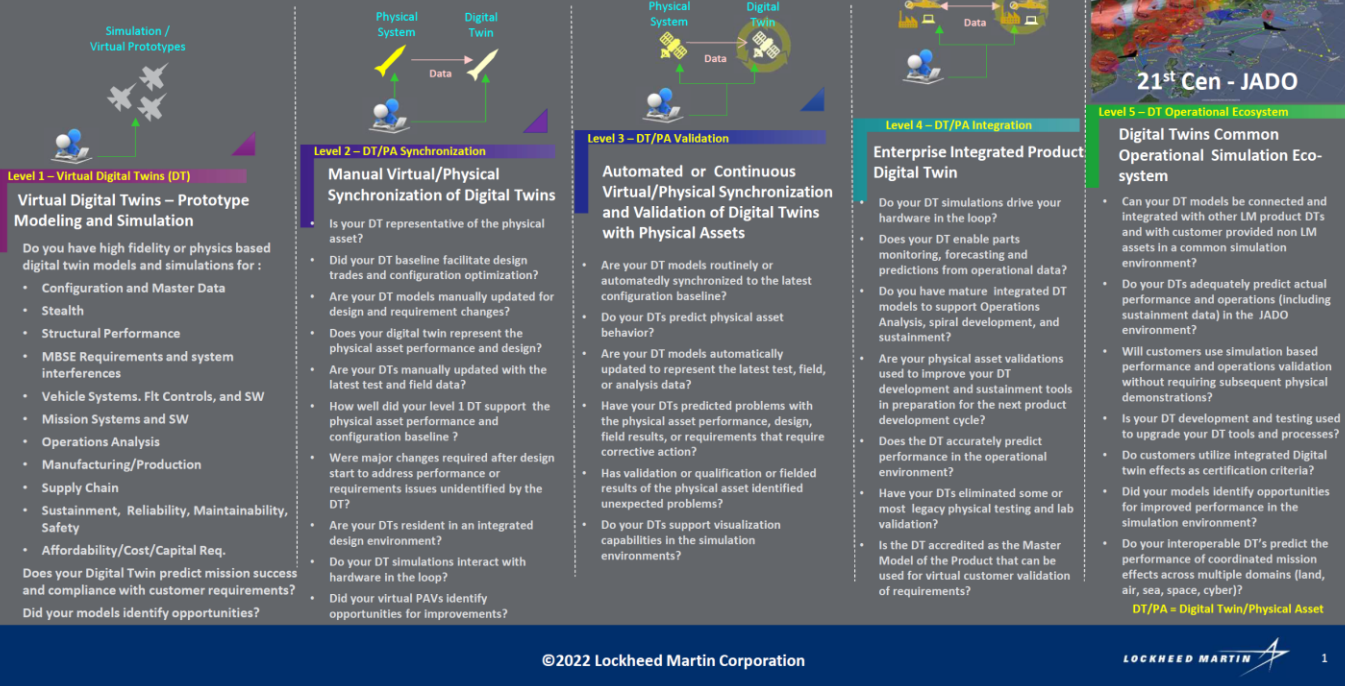
Digital Twins for collaboration



Evolution of System Engineering (SE) to Model Based Engineering (MBE)



LM DIGITAL TWIN MATURITY MODEL



Simulation / Virtual Prototypes

Level 1 – Virtual Digital Twins (DT)
Virtual Digital Twins – Prototype Modeling and Simulation

Do you have high fidelity or physics based digital twin models and simulations for :

- Configuration and Master Data
- Stealth
- Structural Performance
- MBSE Requirements and system interferences
- Vehicle Systems, Fit Controls, and SW
- Mission Systems and SW
- Operations Analysis
- Manufacturing/Production
- Supply Chain
- Sustainment, Reliability, Maintainability, Safety
- Affordability/Cost/Capital Req.

Does your Digital Twin predict mission success and compliance with customer requirements?
 Did your models identify opportunities?

Level 2 – DT/PA Synchronization
Manual Virtual/Physical Synchronization of Digital Twins

- Is your DT representative of the physical asset?
- Did your DT baseline facilitate design trades and configuration optimization?
- Are your DT models manually updated for design and requirement changes?
- Does your digital twin represent the physical asset performance and design?
- Are your DTs manually updated with the latest test and field data?
- How well did your level 1 DT support the physical asset performance and configuration baseline ?
- Were major changes required after design start to address performance or requirements issues unidentified by the DT?
- Are your DTs resident in an integrated design environment?
- Do your DT simulations interact with hardware in the loop?
- Did your virtual PAVs identify opportunities for improvements?

Level 3 – DT/PA Validation
Automated or Continuous Virtual/Physical Synchronization and Validation of Digital Twins with Physical Assets

- Are your DT models routinely or automatically synchronized to the latest configuration baseline?
- Do your DTs predict physical asset behavior?
- Are your DT models automatically updated to represent the latest test, field, or analysis data?
- Have your DTs predicted problems with the physical asset performance, design, field results, or requirements that require corrective action?
- Has validation or qualification or fielded results of the physical asset identified unexpected problems?
- Do your DTs support visualization capabilities in the simulation environments?

Level 4 – DT/PA Integration
Enterprise Integrated Product Digital Twin

- Do your DT simulations drive your hardware in the loop?
- Does your DT enable parts monitoring, forecasting and predictions from operational data?
- Do you have mature integrated DT models to support Operations Analysis, spiral development, and sustainment?
- Are your physical asset validations used to improve your DT development and sustainment tools in preparation for the next product development cycle?
- Does the DT accurately predict performance in the operational environment?
- Have your DTs eliminated some or most legacy physical testing and lab validation?
- Is the DT accredited as the Master Model of the Product that can be used for virtual customer validation of requirements?

Level 5 – DT Operational Ecosystem
Digital Twins Common Operational Simulation Ecosystem

- Can your DT models be connected and integrated with other LM product DTs and with customer provided non LM assets in a common simulation environment?
- Do your DTs adequately predict actual performance and operations (including sustainment data) in the JADO environment?
- Will customers use simulation based performance and operations validation without requiring subsequent physical demonstrations?
- Is your DT development and testing used to upgrade your DT tools and processes?
- Do customers utilize integrated Digital twin effects as certification criteria?
- Did your models identify opportunities for improved performance in the simulation environment?
- Do your interoperable DT's predict the performance of coordinated mission effects across multiple domains (land, air, sea, space, cyber)?

DT/PA = Digital Twin/Physical Asset

21st Cen - JADO

LOCKHEED MARTIN 1

©2022 Lockheed Martin Corporation

Mirror Image: The Power of Digital Twins at Lockheed Martin

https://www.lockheedmartin.com/content/dam/lockheed-martin/space/documents/digitaltwin/Lockheed%20Martin%20Digital%20Twin%20Maturity%20Model_2021.pdf

CNC production (Mekanisk Service Halden)

- Carving materials to create desired shapes
- Guided by machine programs
- High speed, high precision

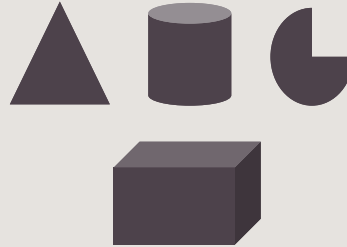


Enhance automation for the operation (Hoa Nguyen)

Imitation learning



Environment



"Imitation"

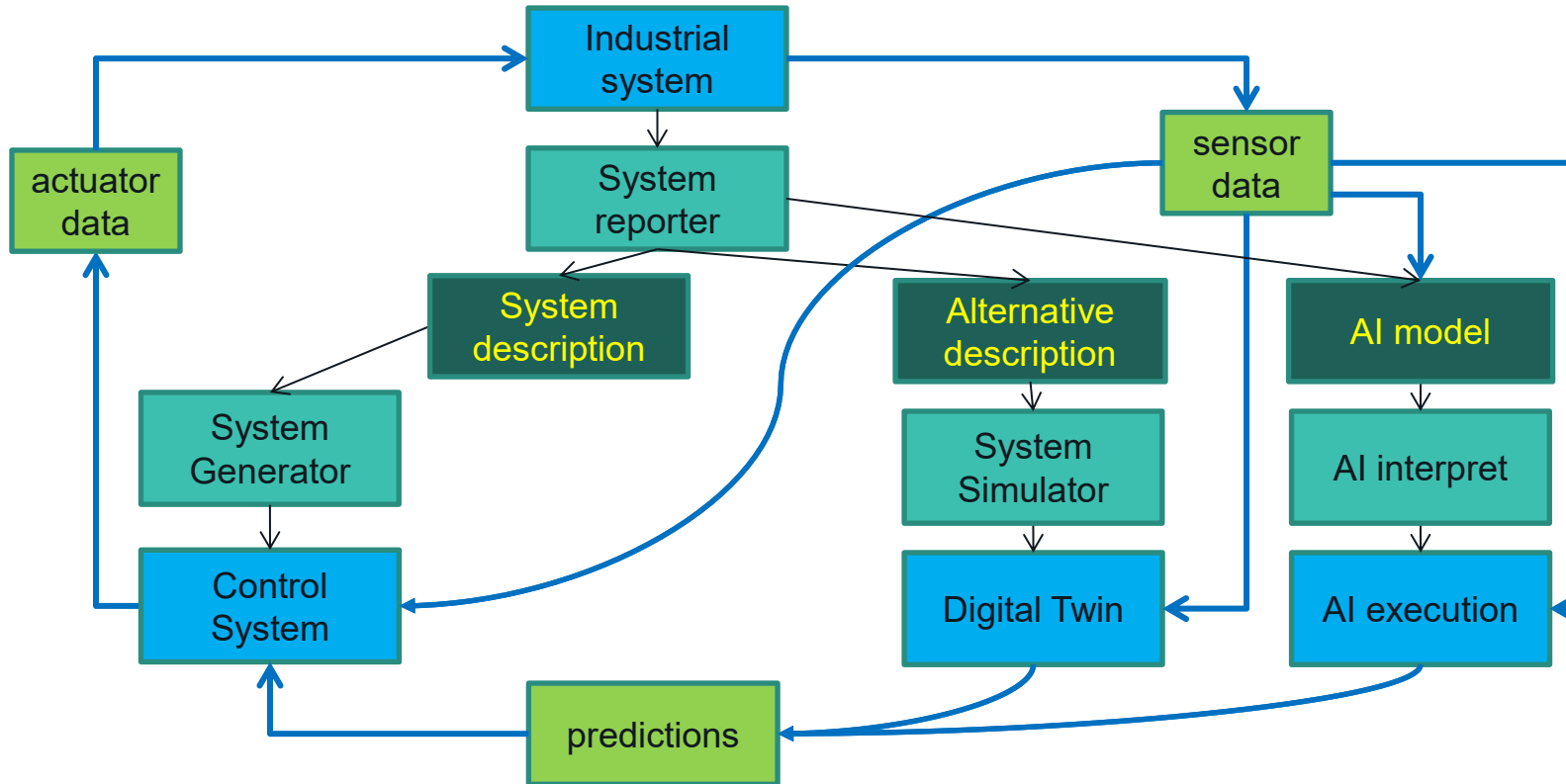


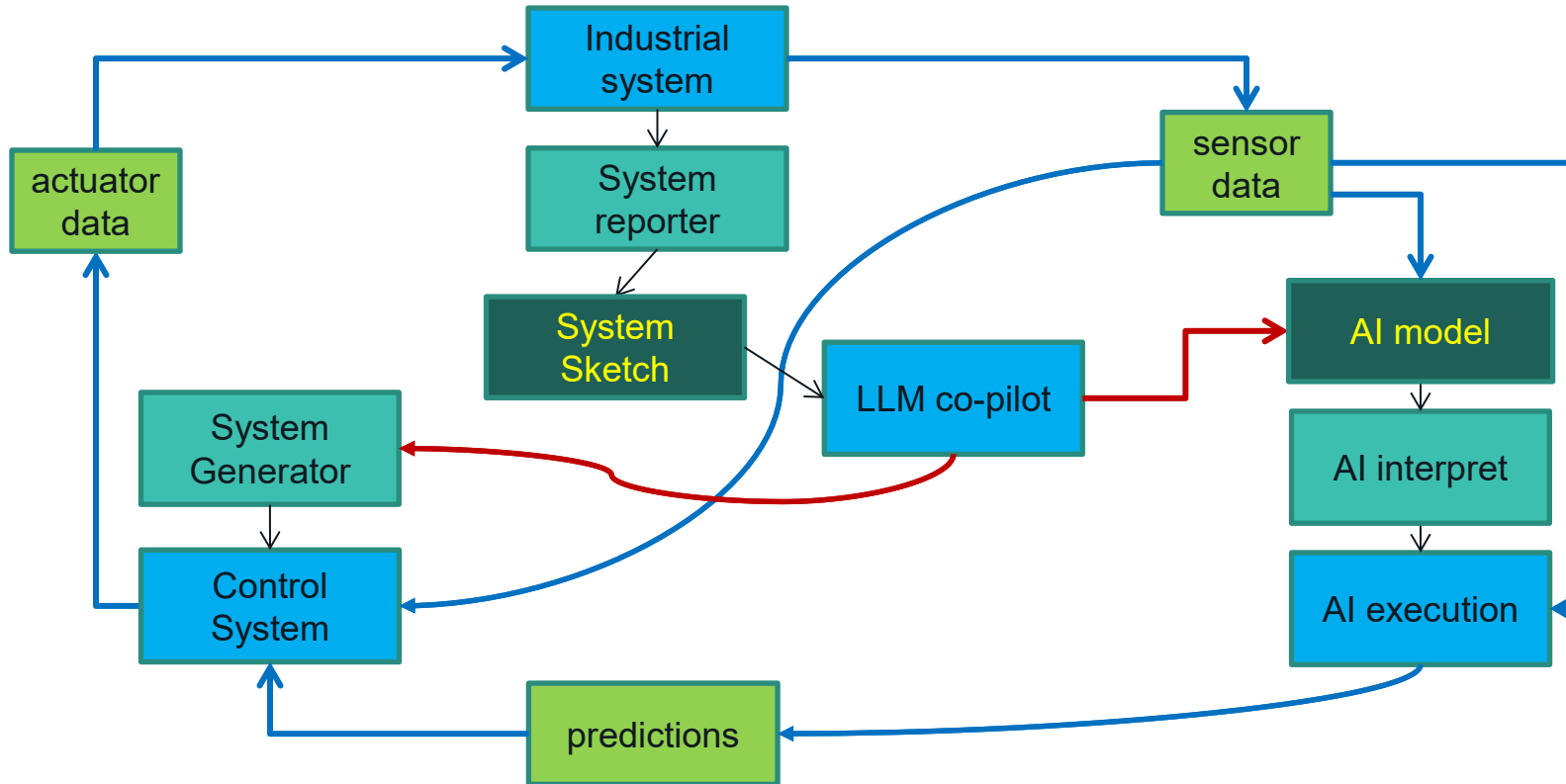
Using **the same information** that operators get while monitoring, the AI algorithm can learn the operators' **control patterns** from historical loggings

the eleph**Ant** In the room

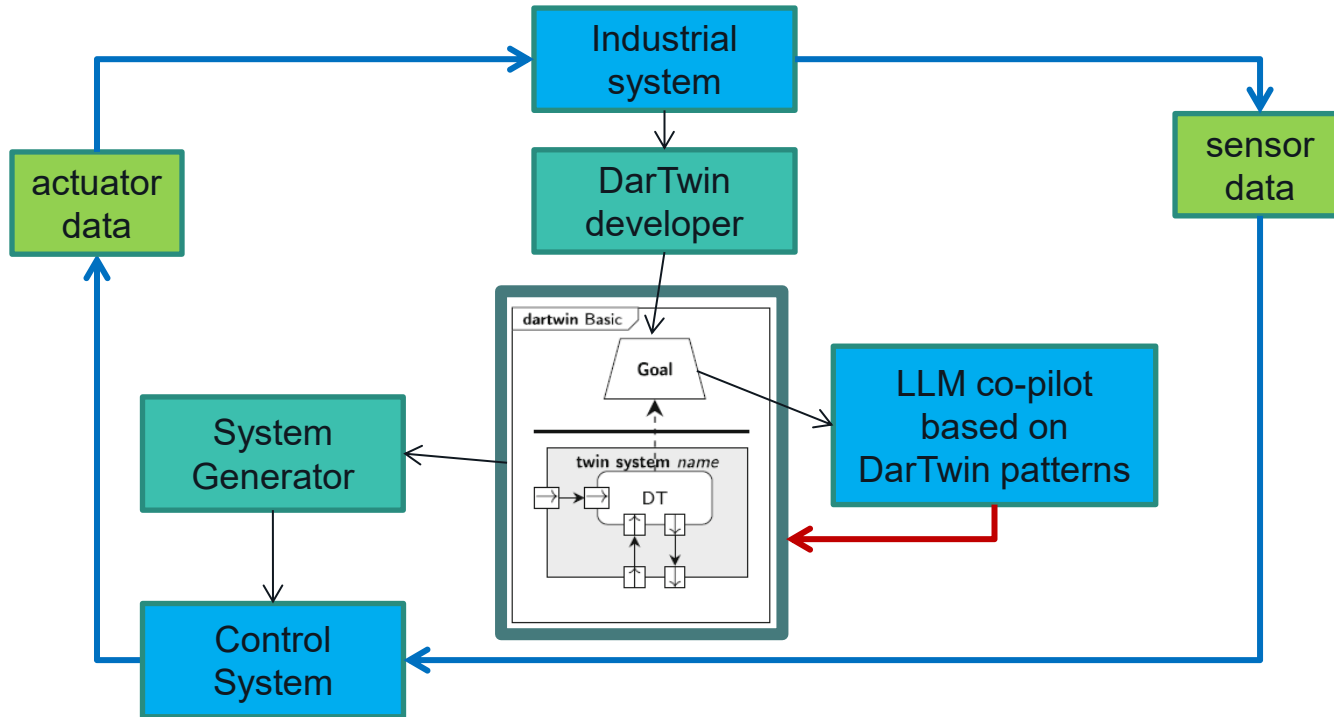


Digital Twins with Artificial Intelligence





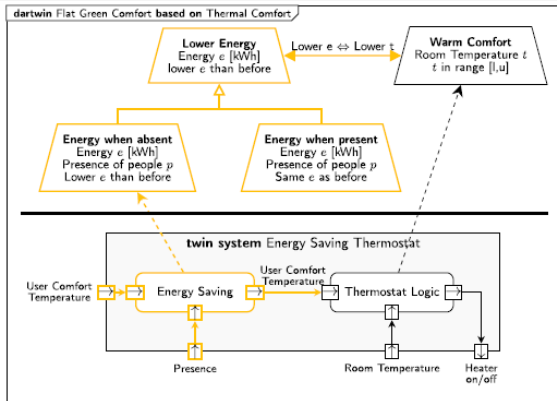
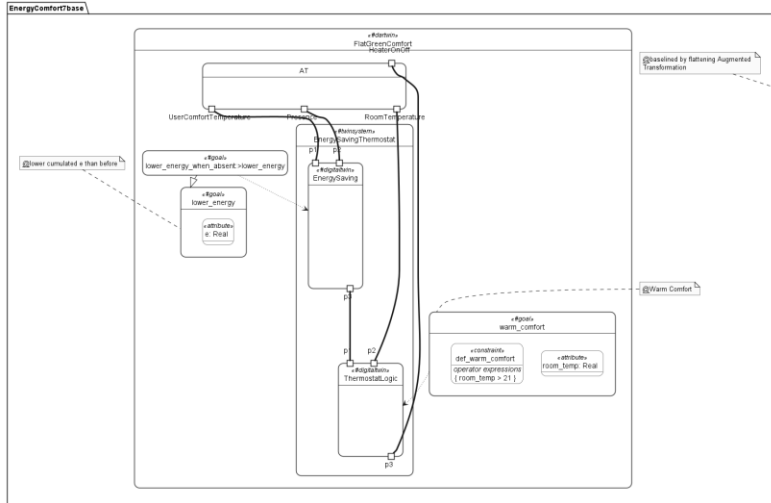
Digital Twins **by** Artificial Intelligence **and** a DarTwin developer



Formalizing DarTwin in SysML v2



Flat Green Comfort in SysML v2 DarTwin Østfold University College



```
#dartwin FlatGreenComfort {
#twinsystem EnergySavingThermostat {
    connect FlatGreenComfort.AT.UserComfortTemperature to EnergySaving.p1;
    connect FlatGreenComfort.AT.RoomTemperature to ThermostatLogic.p2;
    connect ThermostatLogic.p3 to FlatGreenComfort.AT.HeaterOnOff;

#digitaltwin ThermostatLogic {
    port p1;
    port p2;
    port p3;
}

#digitaltwin EnergySaving {
    port p1;
    port p2;
    port p3;
}

connect FlatGreenComfort.AT.Presence to EnergySaving.p2;
connect EnergySaving.p3 to ThermostatLogic.p1;

} // EnergySavingThermostat

part AT {
    port UserComfortTemperature;
    port Presence;
    port RoomTemperature;
    port HeaterOnOff;
}

#goal warm_comfort {
    doc /* Warm Comfort */
    attribute room_temp:Real;
    constraint def_warm_comfort { room_temp > 21}
}

#goal lower_energy {
    attribute e:Real; // Energy kWh
    doc /* lower cumulated e than before */
}

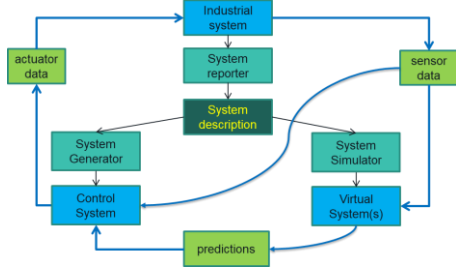
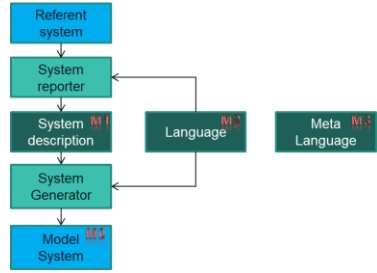
#goal lower_energy_when_absent :> lower_energy;

allocate warm_comfort to EnergySavingThermostat.ThermostatLogic;
allocate lower_energy_when_absent to EnergySavingThermostat.EnergySaving;

} // FlatGreenComfort
```

Related References

- › E. Holbæk-Hanssen, P. Håndlykken, K. Nygaard. System description and the DELTA language, 1975 (https://www.nb.no/items/URN:NBN:no-nb_digibok_2015041408024?page=31)
- › Bræk, Rolv; Haugen, Øystein. Engineering real time systems : an object-oriented methodology using SDL. Prentice-Hall 1993 (ISBN 0-13-034448-6)
- › Joost Mertens, Stefan Klikovits, Francis Bordeleau, Joachim Denil and Øystein Haugen. Continuous Evolution of Digital Twins using the DarTwin Notation. Software and Systems Modeling (SoSyM) 2024 <http://dx.doi.org/10.1007/s10270-024-01216-7>
- › Nguyen, Hoa Thi; Haugen, Øystein. Building Experimental Laboratory for Digital Twin in Service Oriented Architecture. I: 2022 IEEE 5th International Conference on Industrial Cyber-Physical Systems - ICPS
- › Delsing, Jerker; Kulcsár, Géza; Haugen, Øystein. SysML modeling of service-oriented system-of-systems. Innovations in Systems and Software Engineering 2022 <http://dx.doi.org/10.1007/s11334-022-00455-5>
- › Nguyen, Hoa Thi; Haugen, Øystein; Olsson, Roland. Imitation Learning from Operator Experiences for a Real time CNC Machine Controller. IEEE Conference on Industrial Informatics 2023
- › SysML v2: the official document <https://www.omg.org/spec/SysML>
- › SysML v2: the GitHub repository <https://github.com/Systems-Modeling/SysML-v2-Release>
- › Seidewitz., E.: On a metasemantic protocol for modeling language extension. In: Proceedings of the 8th International Conference on Model-Driven Engineering and Software Development - Volume 1: MODELWARD, pp. 465{472. INSTICC, SciTePress (2020). <https://doi.org/10.5220/0009181604650472>

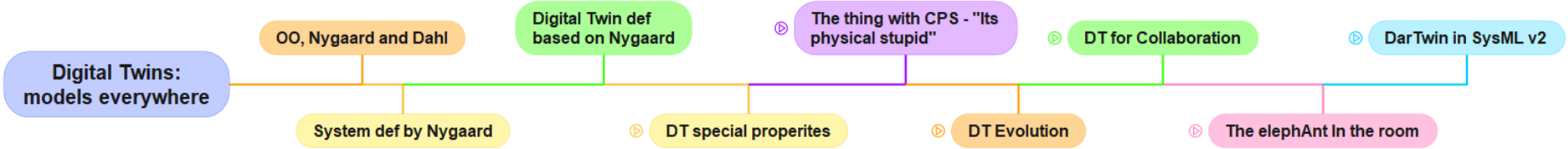


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  port p3;
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  port p2;
  port p3;
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