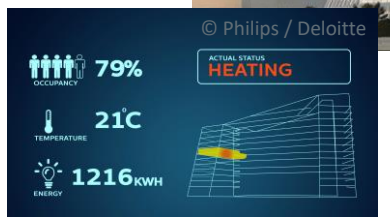


Digital Twin Strategies for SoS

4 Challenges and 4 Architecture Setups for Digital Twins

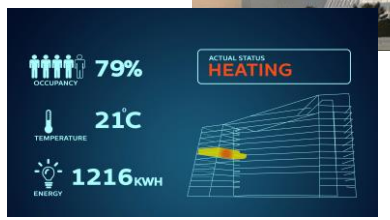
Michael Borth
Jacques Verriet
Gerrit Muller

ESI

ESI looks back at more than a decade of research in cyber physical systems.

System of systems

are key for our industry partners.



© Philips / Signify / Deloitte
The Edge in Amsterdam
most sustainable office building

Digital Twin Strategies for SoS

4 Challenges and 4 Architecture Setups for Digital Twins

ESI

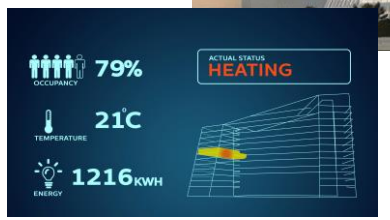
ESI looks back at more than a decade of research in cyber physical systems.

System of systems

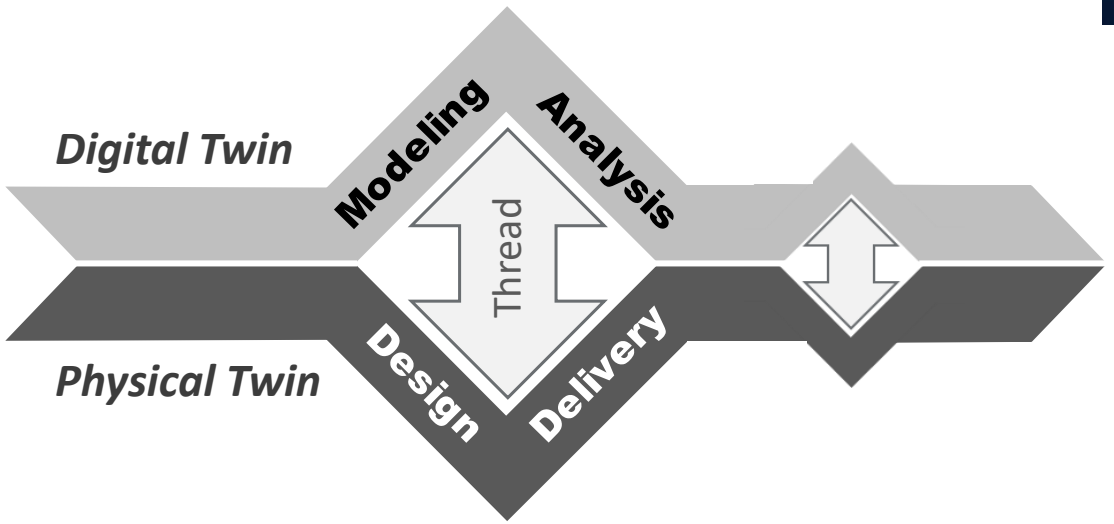
are key for our industry partners.

But they pose special challenges towards the realization and use of

digital twins.



© Philips / Signify / Deloitte
The Edge in Amsterdam
most sustainable office building



ESI

ESI looks back at more than a decade of research in cyber physical systems.

System of systems
are key for our industry partners.

But they pose special challenges towards the realization and use of
digital twins.

- **Long lifetime of infrastructure SoS**
- **Goals and conflicts on coalition of systems**
- **No sharing due to organizational independence**
- **Dynamic nature of cyber physical SoS**

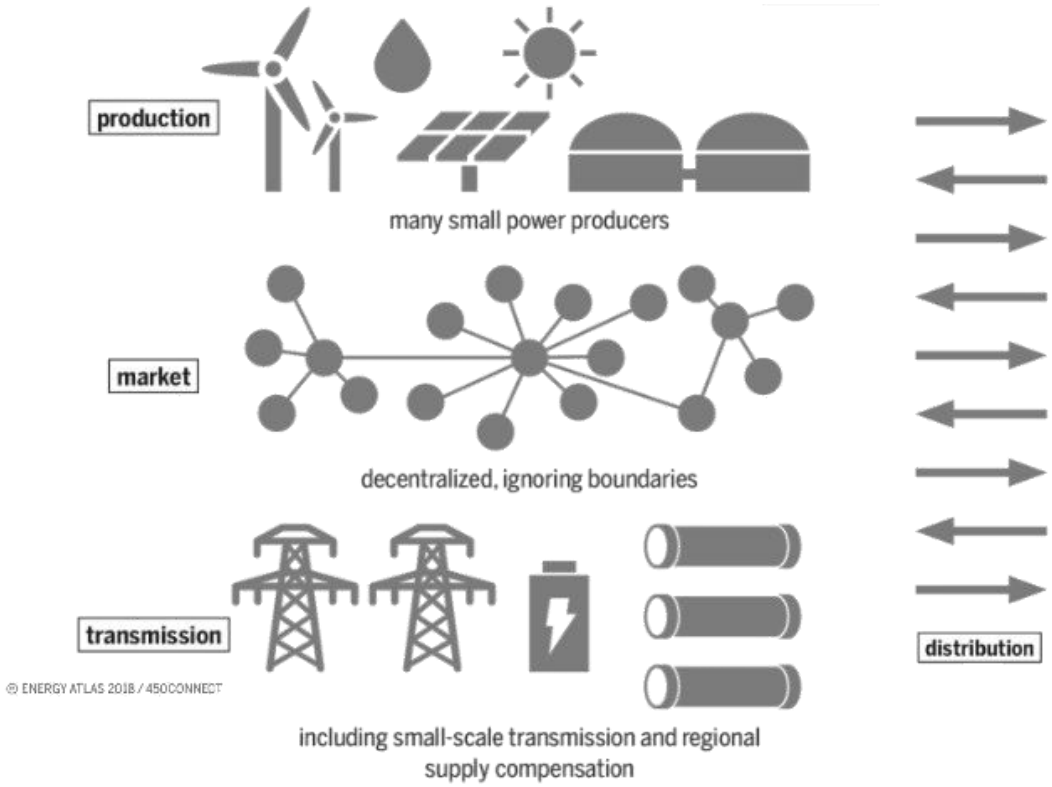
require a dedicated strategy.

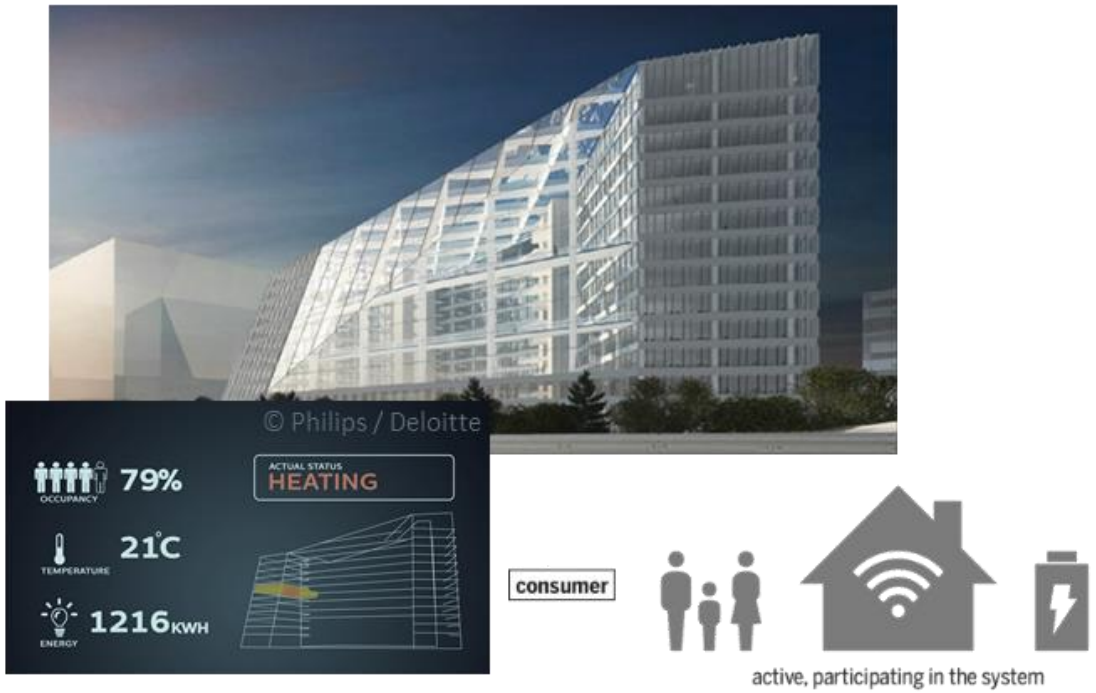
Digital Twin Strategies for SoS

4 Challenges and 4 Architecture Setups for Digital Twins

ESI

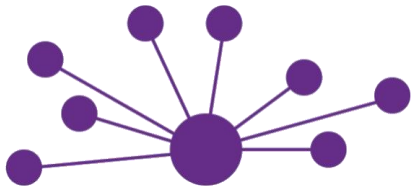
Illustrated in the Energy Domain





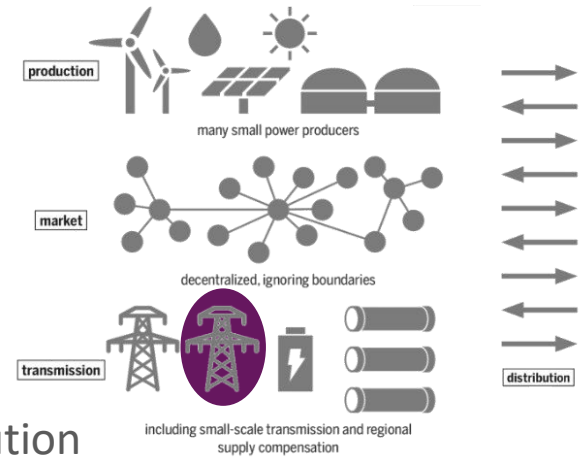
Long Lifetime of (Infrastructure) SoS

Legacy tech not realized
for digital twin access
→ no data / interfaces



Partial updates
→ constant evolution

Producer and consumer tech age → changing characteristics



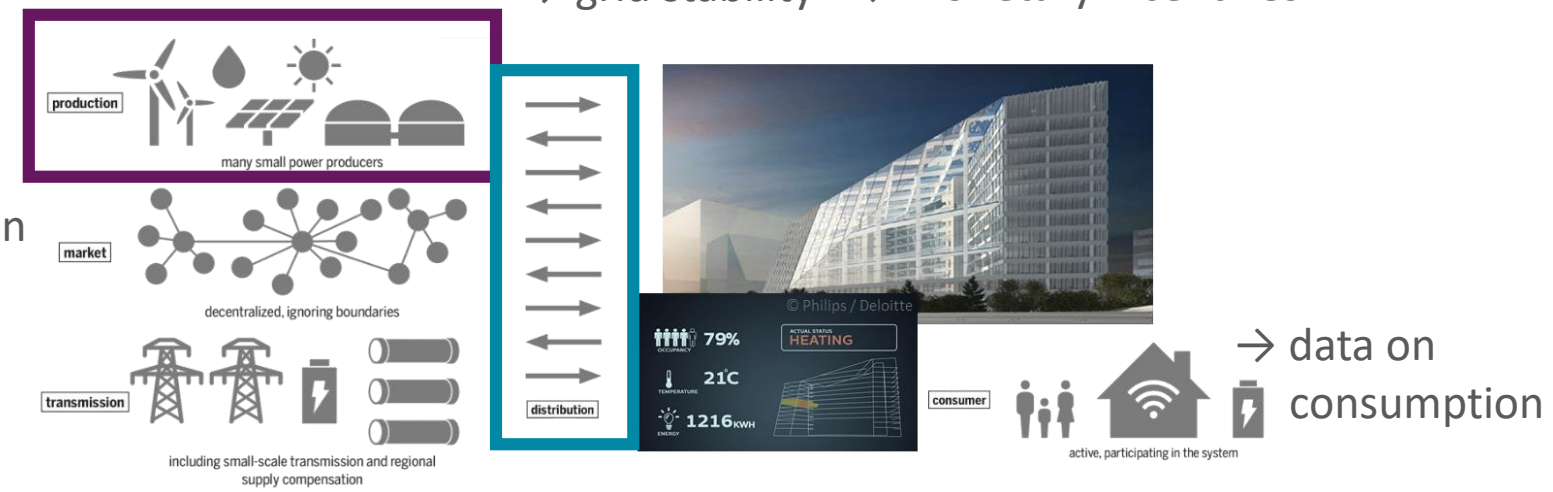
Digitalization techniques update faster
→ infrastructure lacks behind

Reasons to update the digital twin clash with lack of knowledge / people / resources.

Goals and Conflicts in Coalitions (Organizational Independence)

Goals are not (always) aligned and can conflict.

Goal: individual benefit
→ highest compensation
→ fraud possible



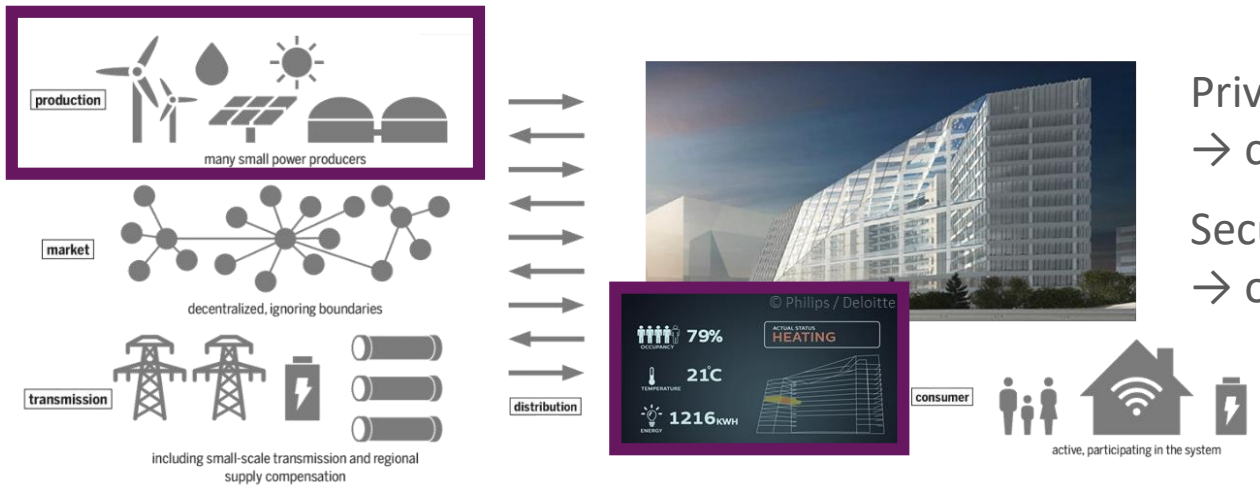
Goal: global benefit
→ grid stability → monetary incentives

→ data on consumption

Contribution to SoS goals is often ill-defined / hard to determine, as sensor data, incentive mechanisms, and goal definitions do not mesh.

No Information Sharing (Organizational Independence)

Information hiding
→ IP protection
→ fraud possible



Privacy concerns for
→ consumption data

Security concerns for
→ occupancy data

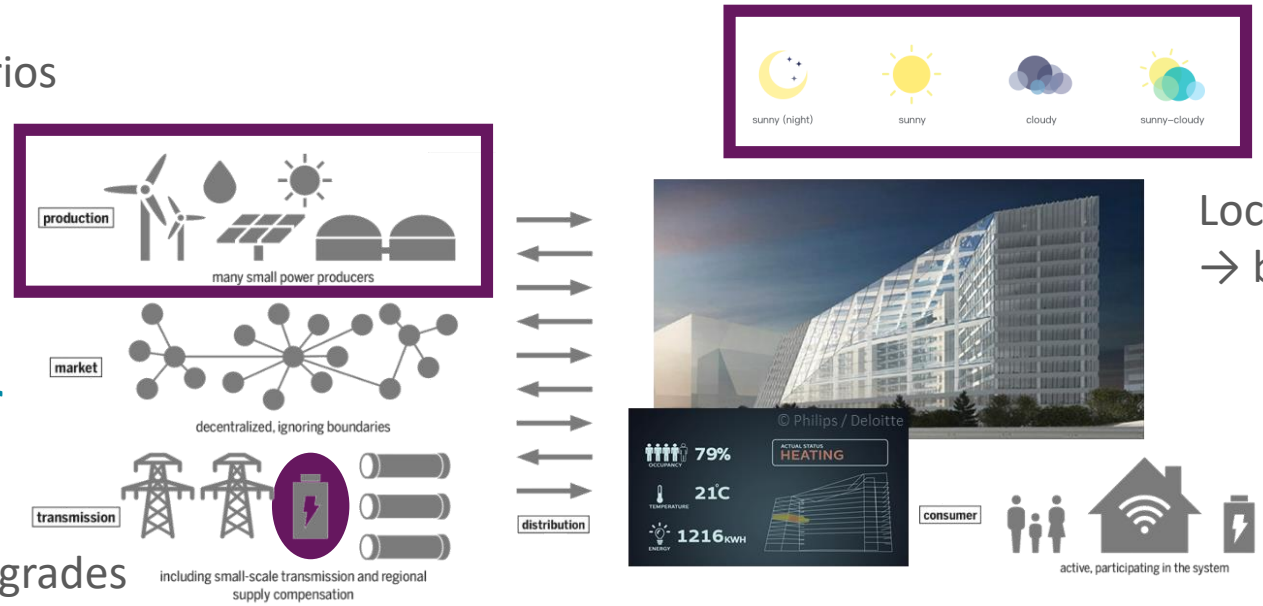
Lack of data and information sharing hampers or prevents the realization and use of digital twins, but happens often for good reasons or lack of trust.

Dynamic Nature of Cyber Physical SoS

Join-and-leave scenarios
→ SoS configuration
in constant flux

Coupling hampers divide and conquer

Evolution by upgrades



Local adaptations
→ behavior change

Digital twins must have the ability to be changed or reconfigured with little effort. Their setup and goals must account for unforeseen emerging effects.

Systems of systems pose challenges towards the realization and use of digital twins.

ESI approaches these challenges with **architecture concepts**.

- **Focus on upper echelons**
- **Ensure modularity with causality**
- **Safeguard digital twin and SoS with reflection**
- **Digital twin accesses loose coupling of SoS**

together form a dedicated strategy.

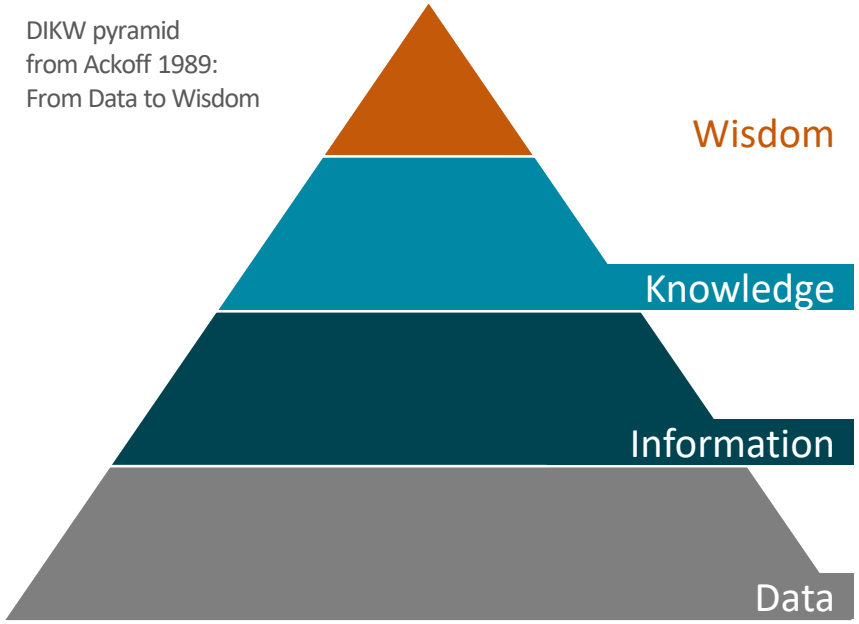
Digital Twin Strategies for SoS

4 Challenges and 4 Architecture Setups for Digital Twins

ESI

Focus on Upper Echelons

DIKW pyramid
from Ackoff 1989:
From Data to Wisdom



Alignment to SoS purpose

Higher value due to processing, less sensitive

Fidelity and efforts of detailed approach

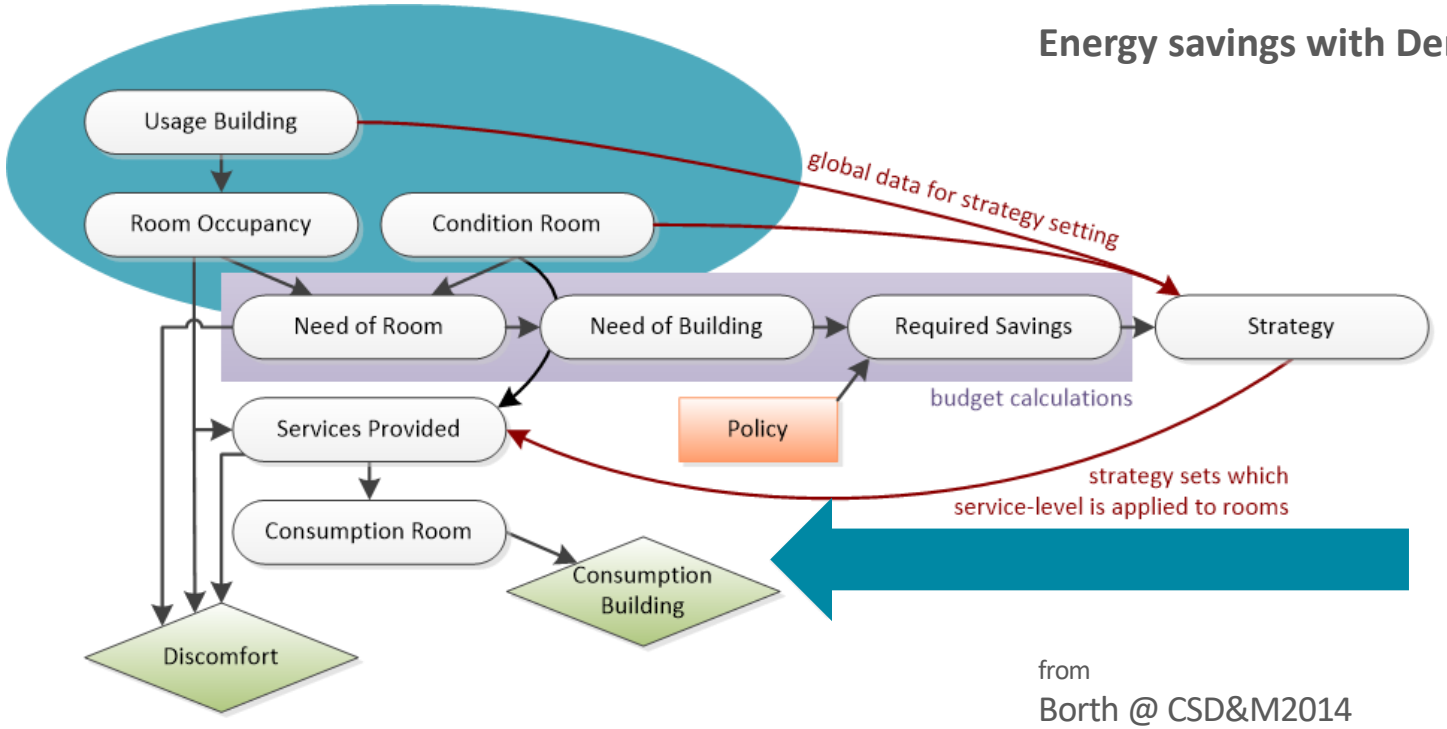
Situation awareness:
SoS goal achievement and mechanisms

Analysis:
System capabilities, consistency, prognosis

Local Analysis:
System control, technical diagnosis and CBM

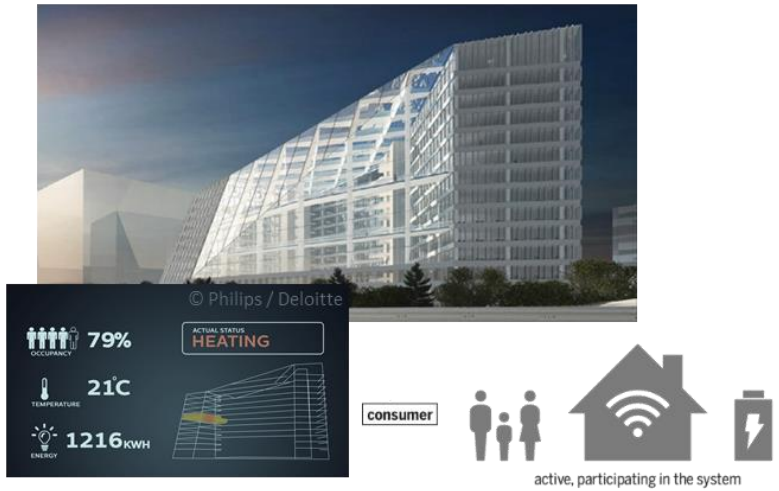
We focus digital twins on higher-order system of systems information processing, but mimic a DIK hierarchy within their structure to realize different tasks.

Focus on Upper Echelons



Energy savings with Demand-Response

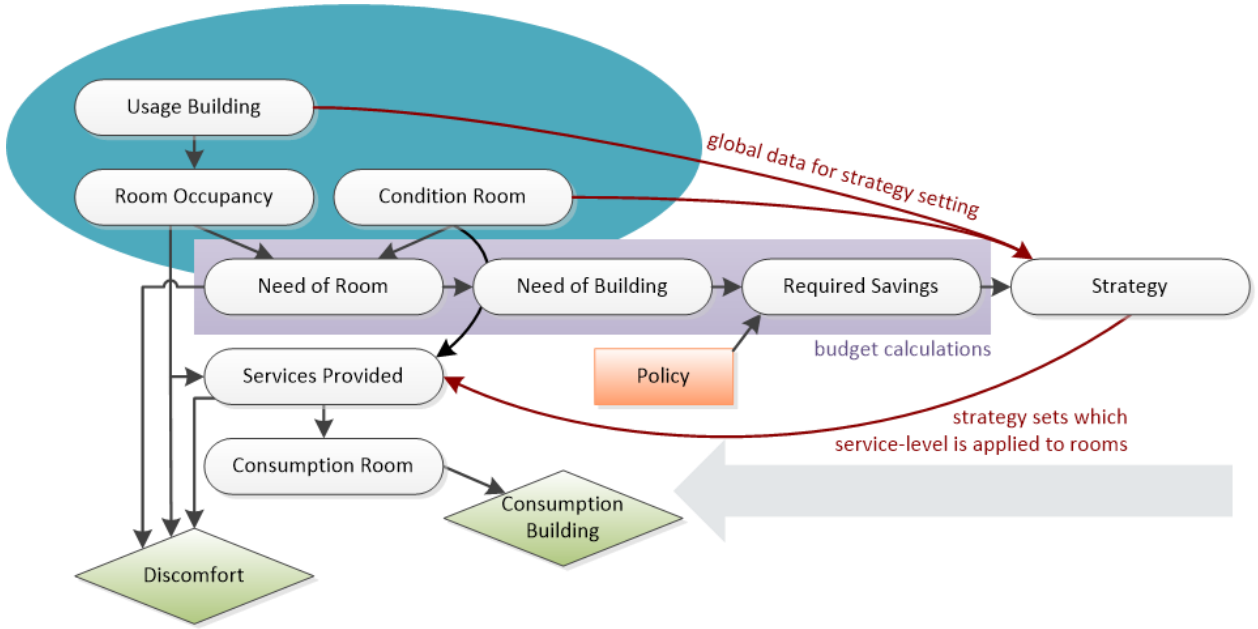
Situation awareness
SoS goal achievement
and mechanisms



from
Borth @ CSD&M2014
Probabilistic System Summaries

Top-level calculations or approximations summarize over details.

Ensure Modularity with Causality



Probabilistic Causation

Probability of a hypothesis given evidence

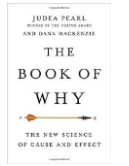
$$P(H|e) = \frac{P(e|H) * P(H)}{P(e)}$$

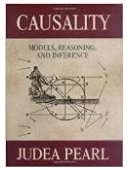
is proportional to
its likelihood * its prior

Rev. Thomas Bayes
probably him. or not.

cause → effect

Efficient inference in networks
(Judea Pearl)





Causality ensures conceptional and computational composability, especially for probabilistic models that excel in digital twins.

Ensure Modularity with Causality

MITRE

You have seconds left.
Only one approach succeeded.

Probabilistic inference in Bayesian networks is best in class in computing joint probability distributions.

That cracks a NP-hard task by exploiting independencies.

Digital twins benefit from the real-time capabilities of probabilistic models.
(and from their reasoning under uncertainty even on incomplete observations, …)

Ensure Modularity with Causality

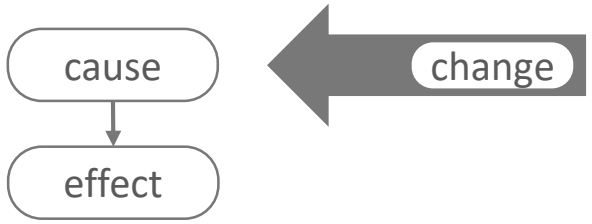
Outlier detection, diagnosis, prognosis, what-if

"Causal questions can never be answered from data alone."

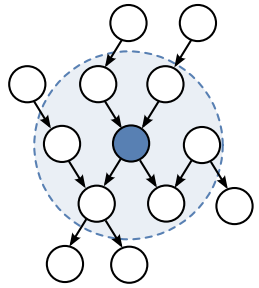
Diagnosis
reasoning from observed effects

Prognosis
reasoning from belief in cause

Outlier detection
estimates the probability of findings



What-if
evaluates a change



Probabilistic Causation

Causally sufficient structures

Faithfulness

unshielded collider

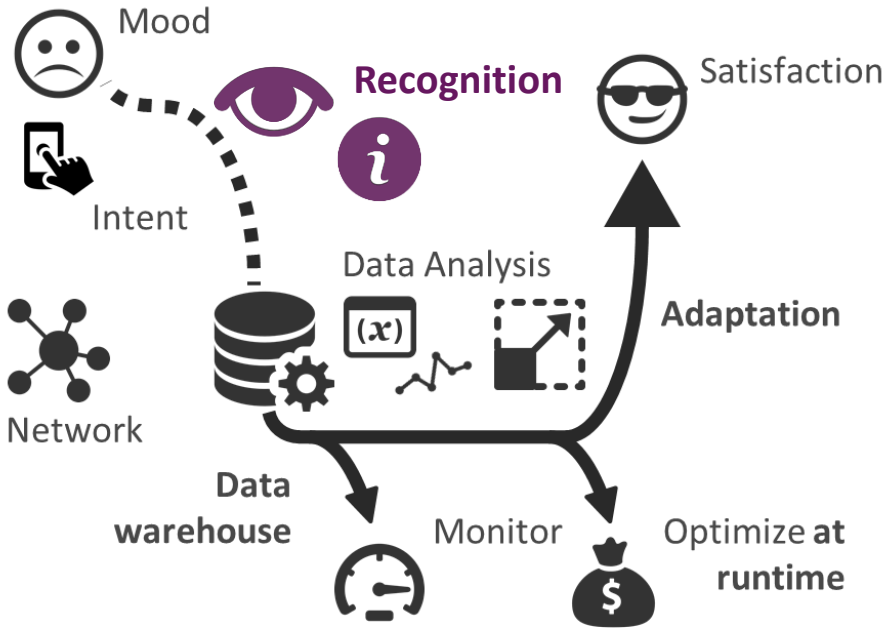
alternate pathway can cancel effect

Causality helps to handle a wide range of applications and helps to build models – due to the modularity, but also as one can merge data and knowledge.

Safeguard Digital Twin and SoS with Reflection

Smart buildings and smart grid include recognition and data analysis steps.

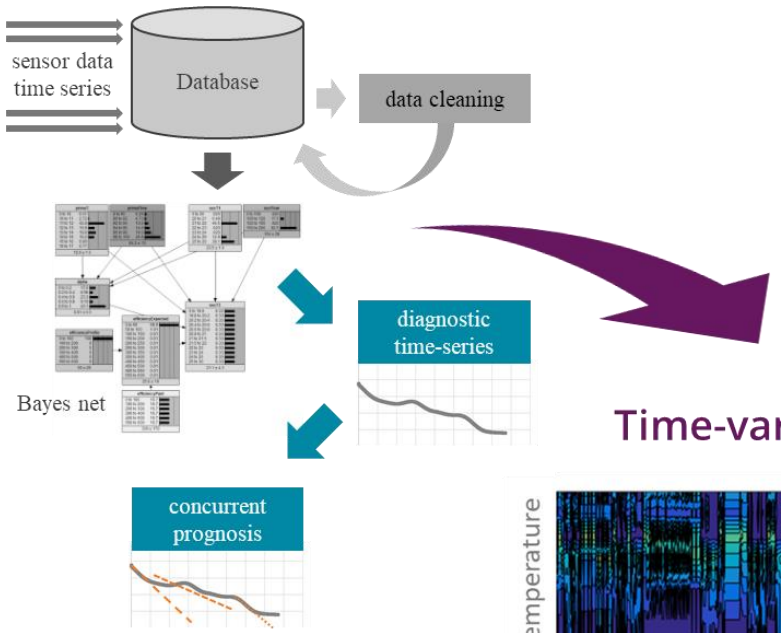
They are typically geared towards adaptations to user behavior or the environment.



We extend their scope towards the quality of information streams (timeliness and uncertainty) and its impact on capabilities.

Reflection or inner awareness: ability to reason about own state and performance. Digital twins look at information health and the capability to perform their function.

Safeguard Digital Twin and SoS with Reflection



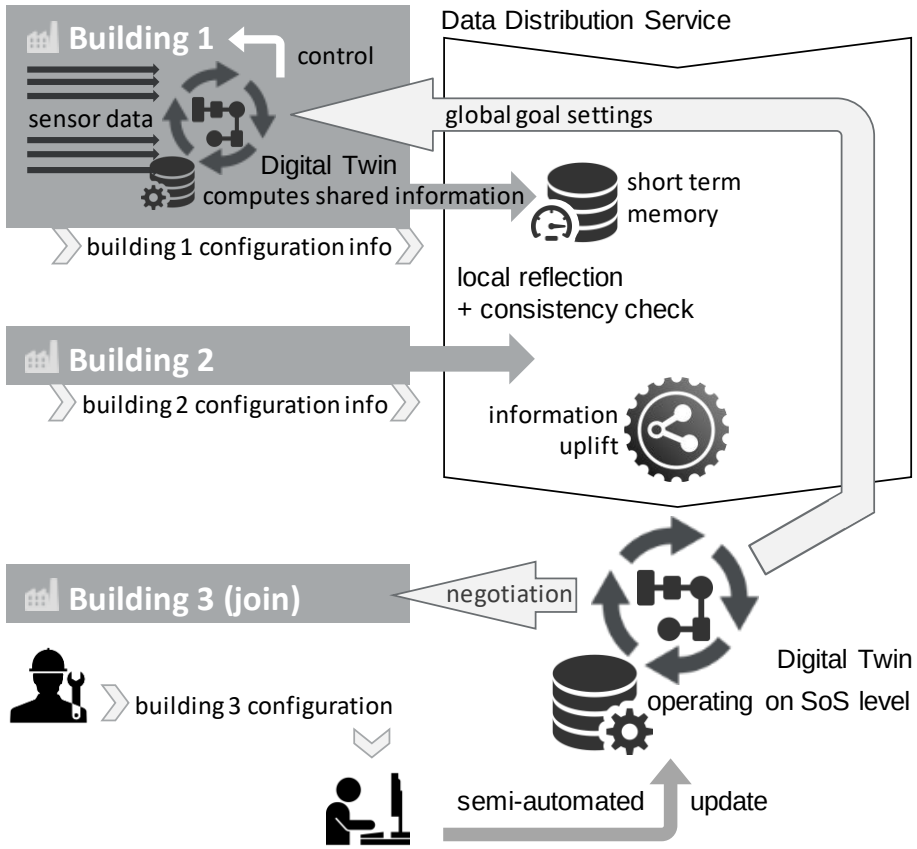
Awareness on the uncertainty within a Digital Twin's conclusions allows to safeguard decision making.

Same line of reasoning as in mission readiness estimations.

Time-varying probability distribution field

from
Borth & Barbini @ PHM Society 2019
Probabilistic Health and Mission
Readiness Assessment at System-Level

Realization: Digital Twin Accesses Loose Coupling Points of SoS



It all comes together in SoS architecture pattern

- Raw data remains within the buildings where it is available for local digital twins
- Reflection mechanisms run consistency checks over aggregated behavior data.
- Overarching SoS goals are maintained via communication of high-level concepts.
- Modularity provides the means to have new prosumers join the grid.
- Causal reasoning allows the digital twin to forecast the effects of the new situation.

Systems of systems pose challenges towards the realization and use of digital twins.

ESI approaches these challenges with

architecture concepts

embedded in the right processes:

- **Digital thread for lifecycle management**
- **Update automation without twinning the twins**

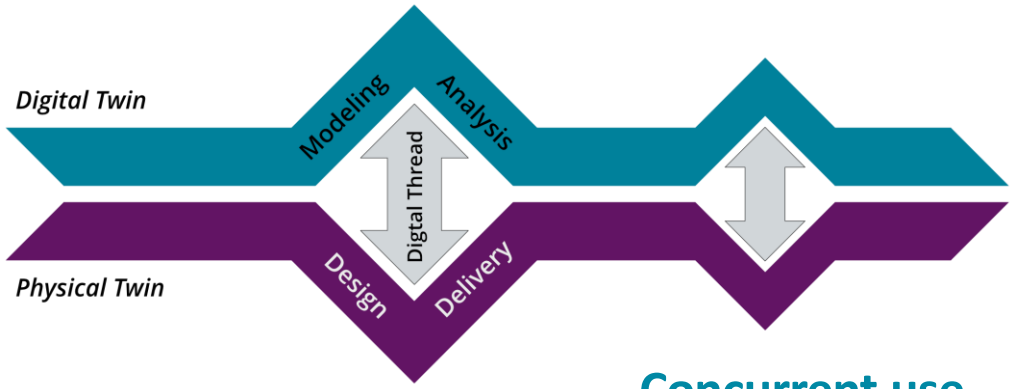
Digital Twin Strategies for SoS

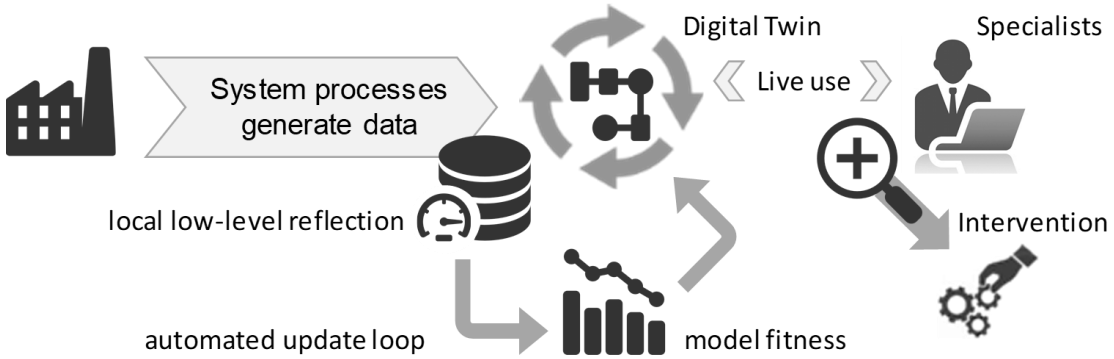
4 Challenges and 4 Architecture Setups for Digital Twins

ESI

Processes and Operations

Digital thread for lifecycle management





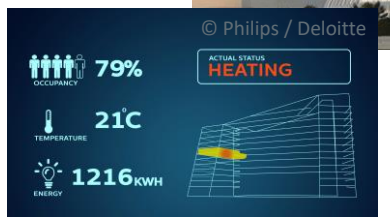
Concurrent use and updates → **Update automation without twinning the twins**

Digital Twin and Thread: extension of MBE Diamond from
S. J. Hatakeyama, D. W. Seal, D. Farr, S. C. Haase (2019)

see also
Borth & van Gerwen @ CSD&M2018
Tracking Dynamics in Concurrent Digital Twins

Digital twins address hard consequences of Maier's criteria:

- managerial pitfalls due to independence
- knowledge / version management issues
- emerging effects due to dynamics
- upgrade costs and challenges



Building them for SoS is not easy.
It requires thought and the best processes.

But it is worth it!

Digital Twin Strategies for SoS

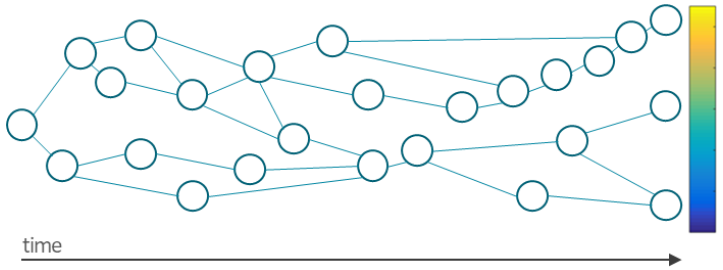
Gerrit Muller Jacques Verriet Michael Borth

Smart Systems Research

Michael.Borth@tno.nl

ESI

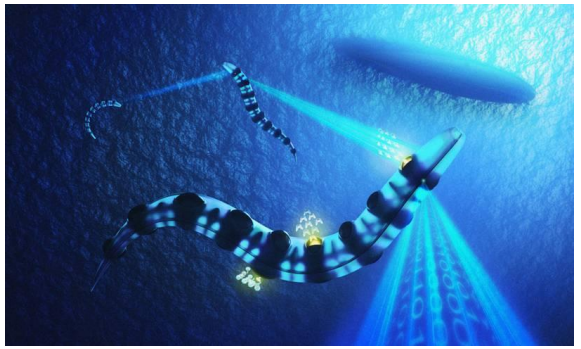
Adaptive Intelligent Systems



Intelligence as a thermodynamic force

$F = T \nabla S\tau$

Wissner-Gross & Freer @ Phys. Rev. Lett. 110, 2013
Causal Entropic Forces



Maximizing future freedom of action
leads to intelligent behavior.

Here there be Dragons

Smart Systems Research @ ESI
Michael.Borth@tno.nl

ESI

Here there be Dragons

Learning induces change. Change invalidates knowledge.

If yesterday insights mean little, cause and effect are only obvious in hindsight. Diagnosis, prognosis, control, etc. become wicked problems.

Emergent control is both our boon and our bane.

It is needed to realize the behavior fitting to the unknown, but learning needs positive feedback cycles – while control favors the opposite.

Ignorance regarding both limits and stability.

The performance of recognition and optimization follows an unknown shape under unknown factors and exhibits tipping points.

3 Focus Areas to Discover Terra Incognita

energy savings

The Edge – Deloitte | Signify

Smart Industry - ASML

Naval Forces - Thales
capability sustainment

awareness

Port of Rotterdam
critical infrastructures

Resilience

Predictive digital twins
offering a direct ROI

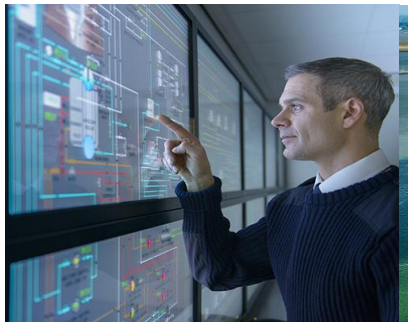
needs & gives live data

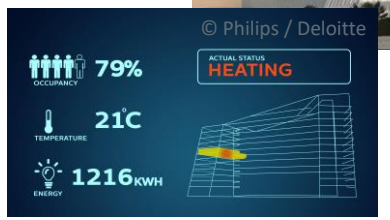
models & numbers

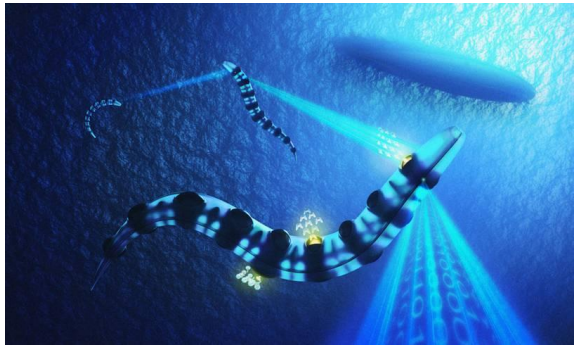
causality

needs

Machine Learning Engineering | Engineering Machine Learning







Welcome to the Journey

Dr. Michael Borth

Smart Systems Research

Michael.Borth@tno.nl

ESI