Eumεtry sas

DIGITAL TWINS FOR ASSET MANAGEMENT OF SYSTEMS, AND SYSTEMS OF SYSTEMS

PIERRE DERSIN

June 13, 2022

AGENDA

1. Introduction
2. Asset Management
3. Digital Twins
4. Digital Twins for System Asset Management
5. Digital Twins for Systems of Systems
6. Conclusions and Way forward
7. References

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Pierre Dersin

Ph.D. Electrical Engineering and M.S. Operations Research MIT

EE/Math: ULB (Brussels University)

Since January 2022: President, EUMETRY sas (Louveciennes, France)

Since 2019: Adjunct Professor, Luleå University of Technology (LTU), Sweden,

Operations & Maintenance Division

1990- 2021 : ALSTOM (St-Ouen, France)

- **PHM (Prognostics & Health Management) Director, « Digital & Integrated Systems ».Initiated and led predictive maintenance activity (railway rolling stock and signaling)**
- **RAM (Reliability, Availability, Maintainability) Director (set up 'RAM Center of Excellence')**
- **Also, co-director of joint Alstom-Inria Lab on Digital Mobility (2014-2018)**

Before 1990:

-- Factory Automation/ Industrial Diagnostics (Fabricom: Belgium and USA)

-- Large scale Electric Power Grid Reliability (MIT, Systems Control)

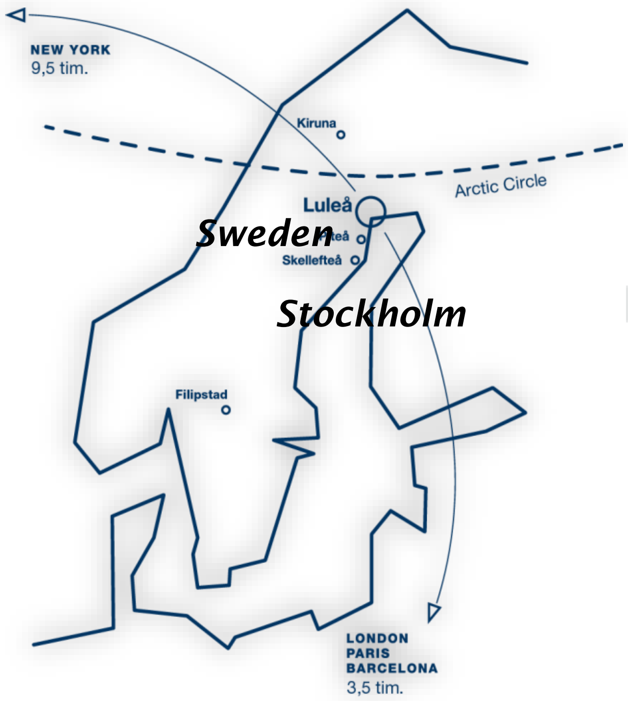
Publications: RAMS, ESREL ALT, MMR symposia; IEEE Transactions (Automatc Control , Power Apparatus & Systems). Four chapters in ' Handbook of RAMS in Railways: Theory & Practice ', Ed. Zio, Mahboob, CRC, 2018. Member of IEEE-RS AdCom and DRI. Leader of TC on Systems of Systems. **Alan O.Plait Award for best tutorial at RAMS Symposium (2020**)

Eumetry sas : " the good measure"

From Greek 'eu' », good ,
and 'metron' , measure

Consulting in RAMS, PHM, AI, Probability and Statistics for Industry– Louveciennes, France

Luleå University of Technology (Luleå tekniska universitet, LTU)



Division of Operation & Maintenance Engineering

Luleå Railway Research Center JVT

Focus on
RAMS
In Railway
Systems

Center for Maintenance and Industrial services CMIS

University – Technology COOPERATION

Asset Management Concept

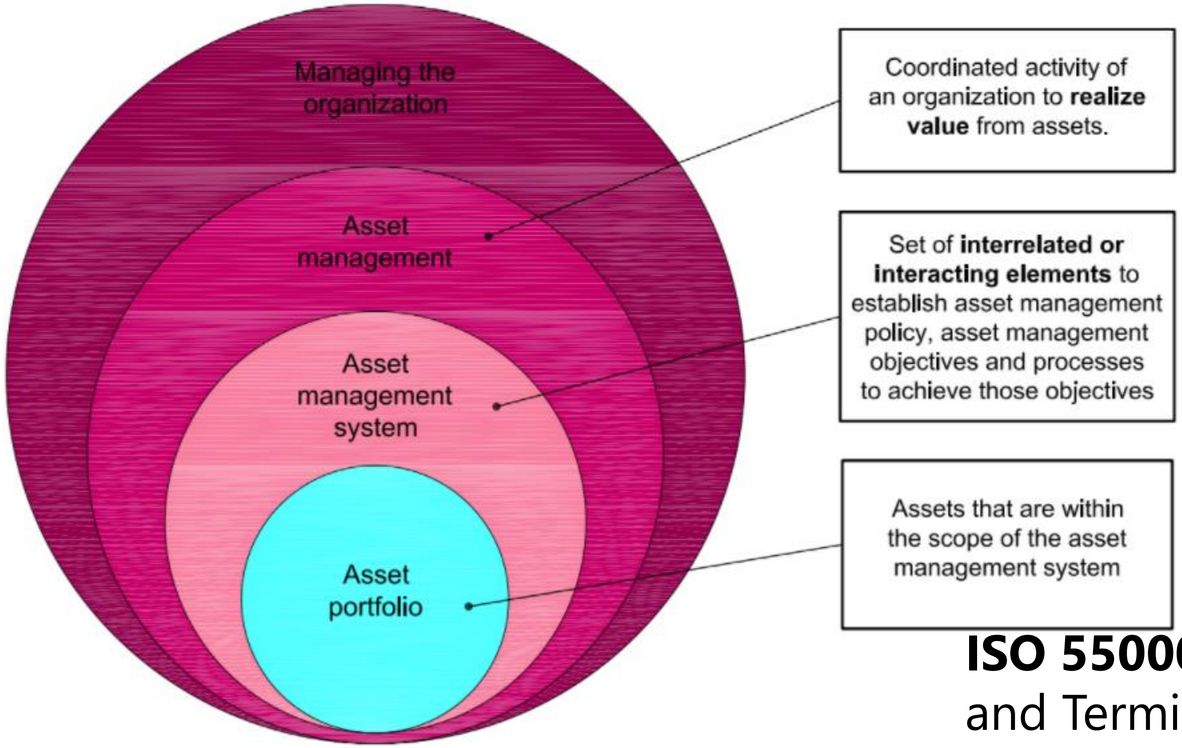


Figure 1 — Relationships between key terms

- Key : what matters is the <u>Value</u> which the organization generates from its assets
- Management throughout life cycle
- Decision Process> Asset Management

<u>Standards of Reference:</u>

ISO 55000 Asset Management – Overview, Principles and Terminology - **ISO 55001** Asset Management – Management Systems – Requirements **- ISO 55002** Asset Management – Management Systems – Guidelines for the Application of ISO 55001

Short- term and long- term Views

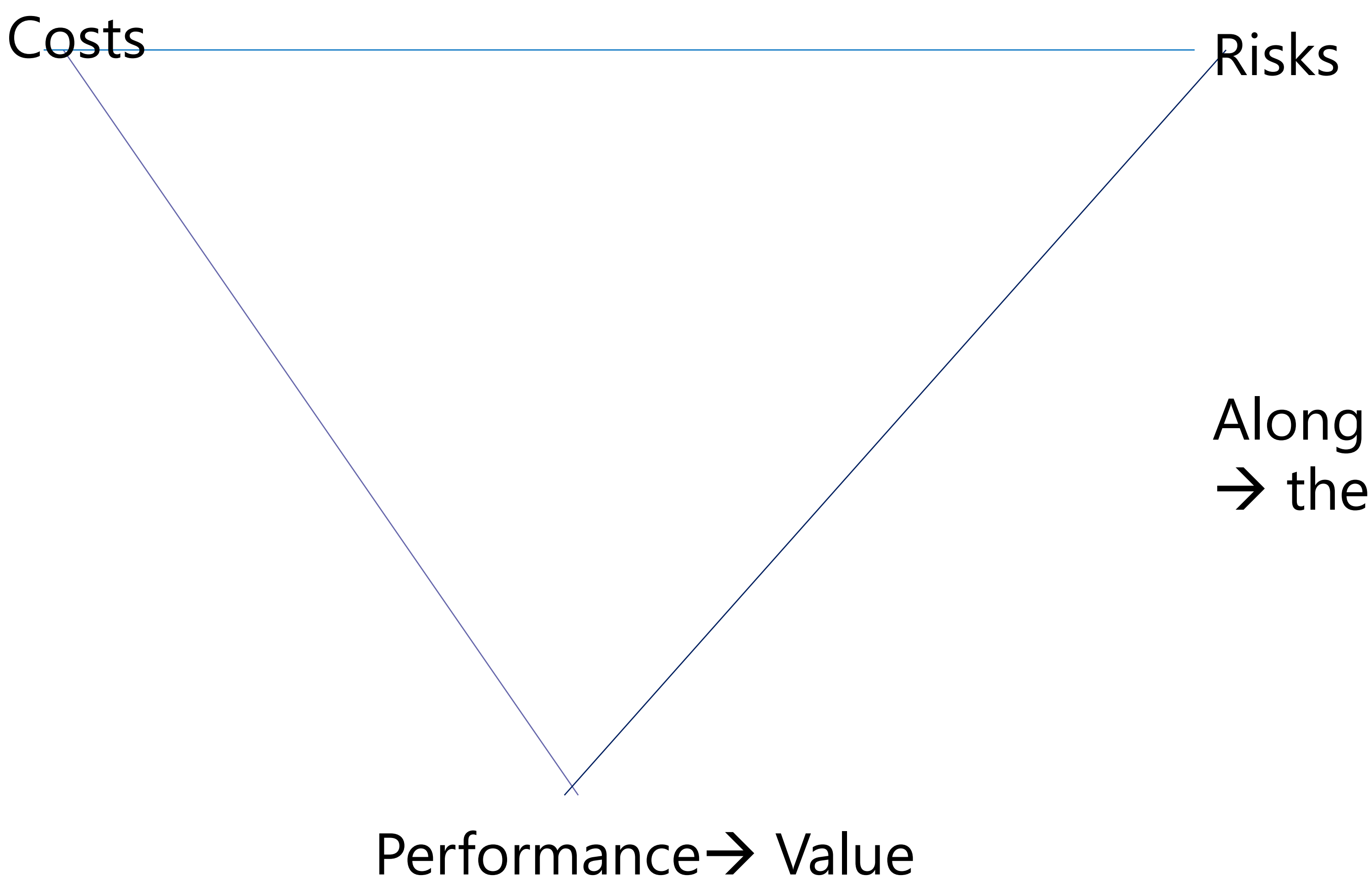
Short term / Long term

Managing Assets	Asset Management
Your **colleagues** are focused on: • Asset data, location and condition assessment • Current KPIs • Department budget	Your **colleagues** are focused on: • Information supported decisions (strategic context and related to customer needs) • Strategies to select and exploit assets over their lifecycles to support business aims • Collaboration across departments to optimise resources allocated and activities
Your **stakeholders** are focused on: • Costs • Current performance • Response to failures / maintaining function	Your **stakeholders** are focused on: • Triple bottom line and value • Clarity of purpose of the organization • Focus on impact of activities on organization's objectives
Your **top management** is focused on: • Short term gain / loss • Departmental / individual performance • Savings, especially OPEX	Your **top management** is focused on: • Long term value for the organization • Developing competence and capability across workforce • Business risks understood and mitigated
Your **suppliers** are focused on: • Short term contracts and performance • Service level agreements are focused on contract specifications	Your **suppliers** are focused on: • Long term contracts and/or partnering relationships in support of client value and objectives • Understanding client strategy and needs in 5-10 years

(ISO/TC251, 2017)

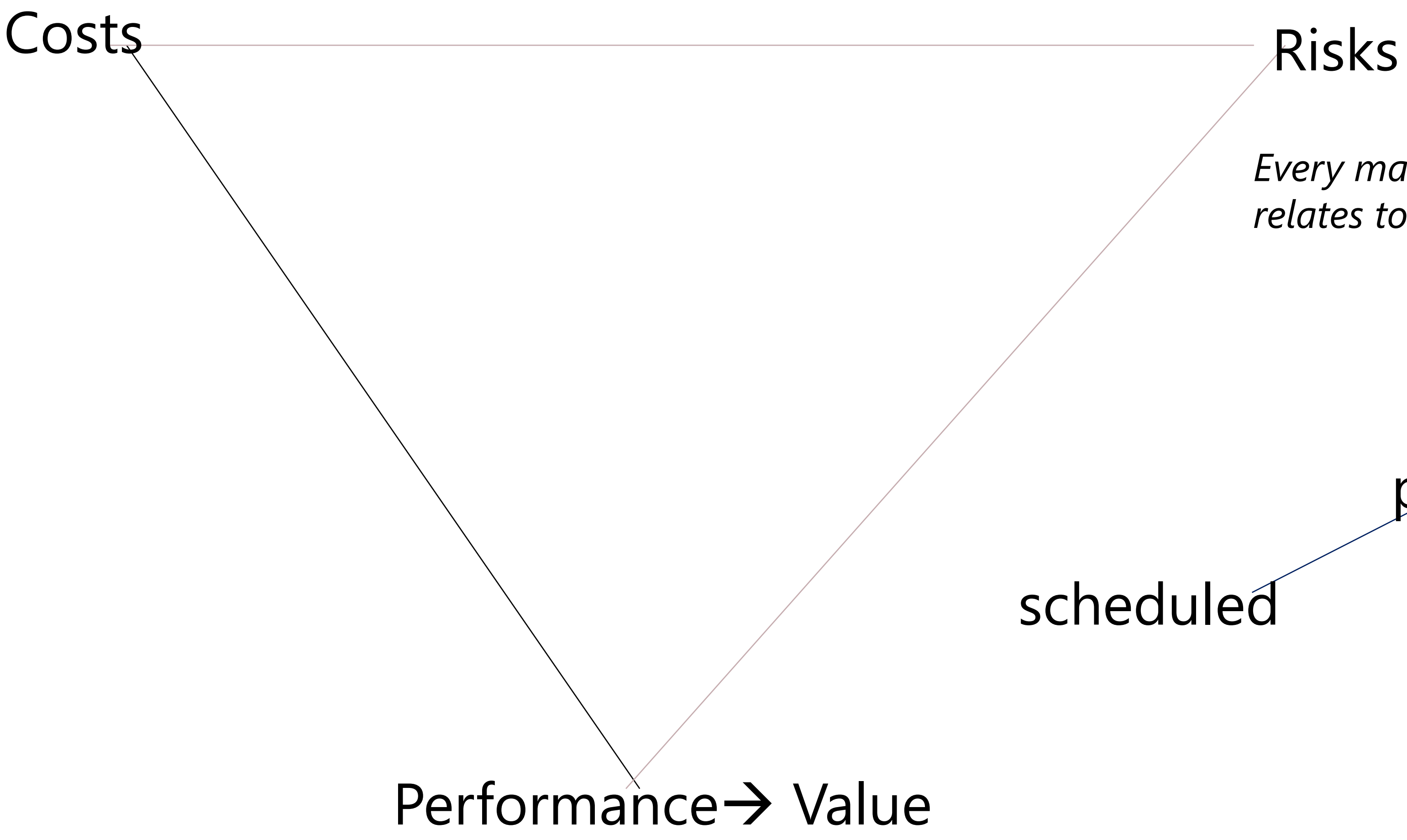
from" Industrial AI",
R.Karim et al. (Luleå University of Technology)
Springer, to appear

Asset Management– the 'magic triangle'

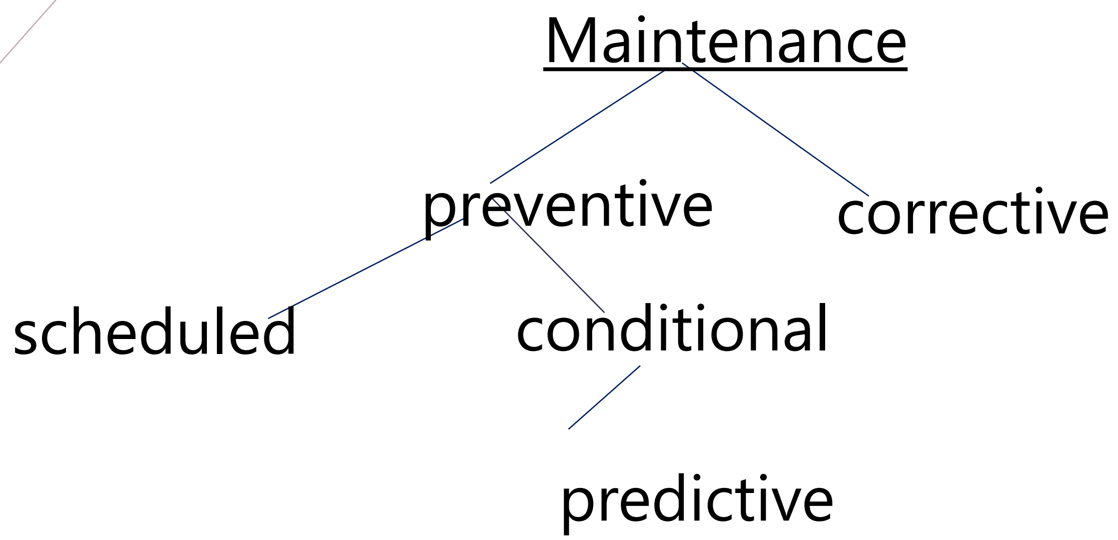


Along the life cycle
→ the "triangle" evolves

Maintenance→ actions necessary to keep an asset in, a restore it to, a state in which it can fulfill its function (IEC-60030-3-14)



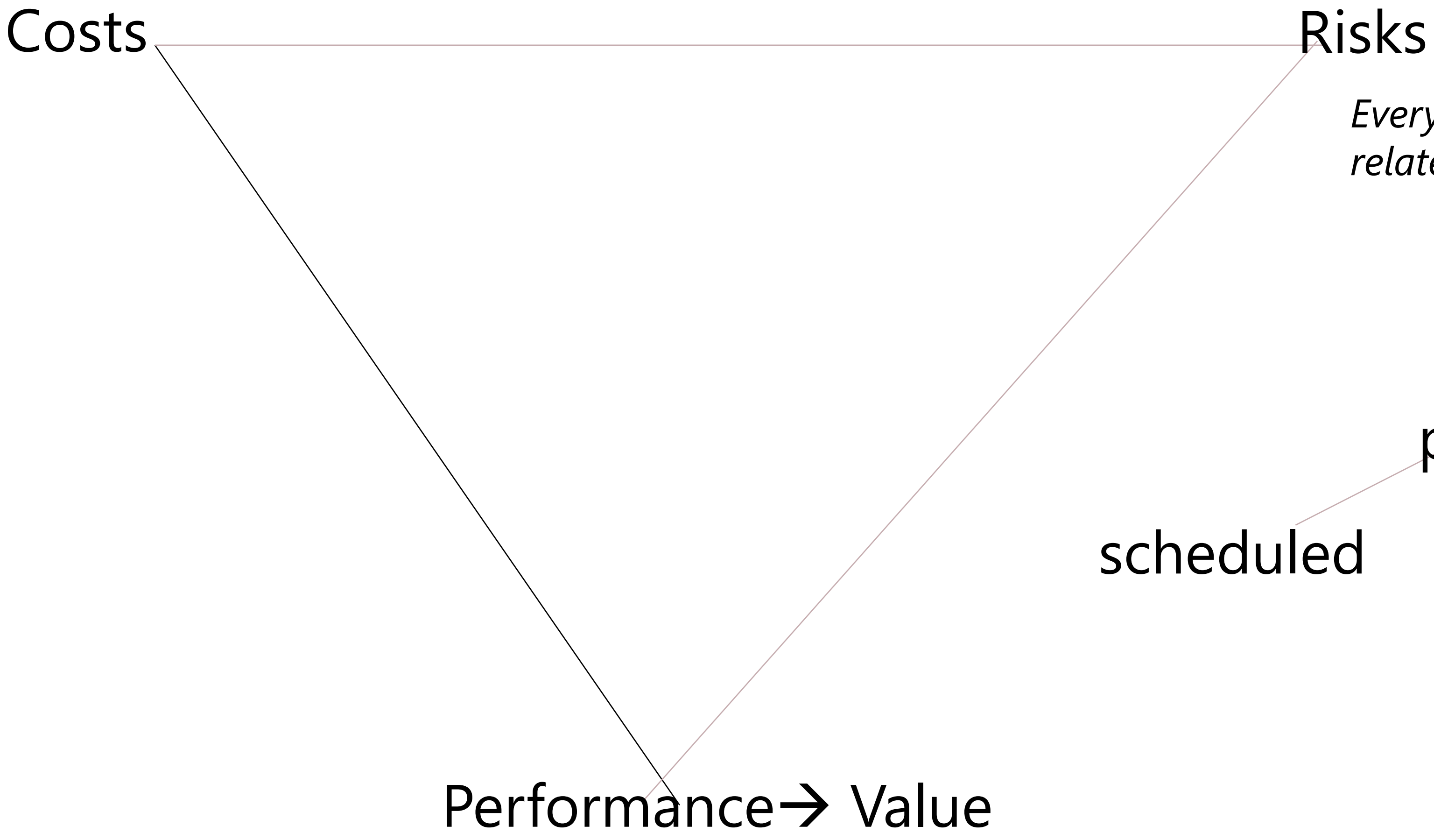
Every maintenance policy is characterized by how it relates to the summits of the triangle



Maintenance along life cycle

For an optimal asset management throughout the life cycle, maintenance policy will generally evolve over time. For instance, end of life→ wear-out (increasing failure rate)

→ Conditional maintenance / rejuvenation actions



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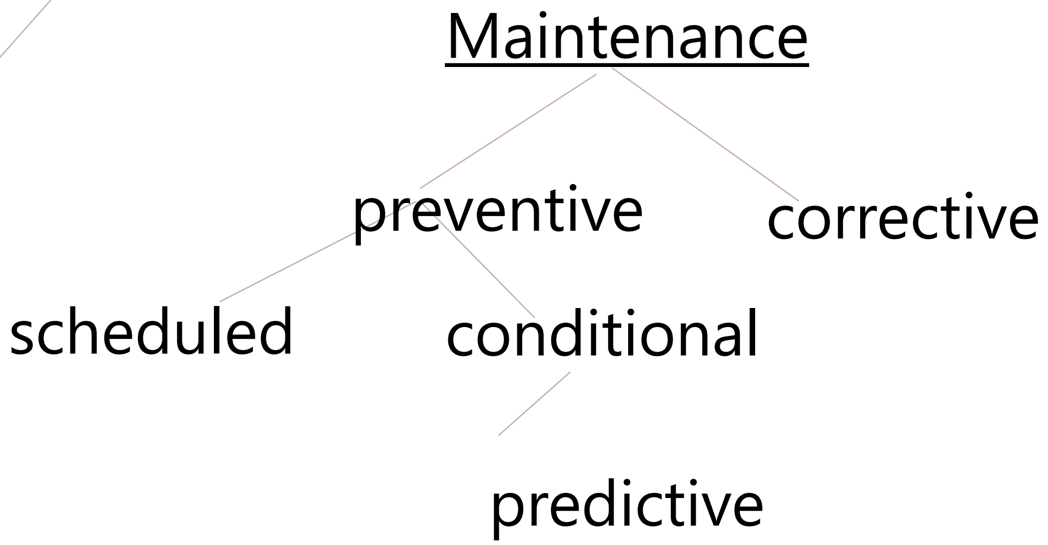

Maintenance along life cycle

For an optimal asset management throughout the life cycle, maintenance policy will generally evolve. For instance, end of life→ wear-out (increasing failure rate)

→ Conditional maintenance / rejuvenation actions

Costs

Investment
Maintenance
Operations
Obsolescence
Retirement
(LCC)

Risks

Every maintenance policy is characterized by how it relates to the summits of the triangle

Maintenance

preventive

corrective

scheduled

conditional

predictive

Performance→ Value

Availability, Sustainability,etc.
Production Capacity (passenger-km, MWh)

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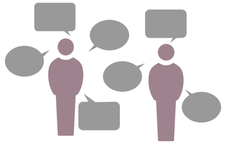
Digitalization is changing the world of maintenance and operation

FROM

Communication

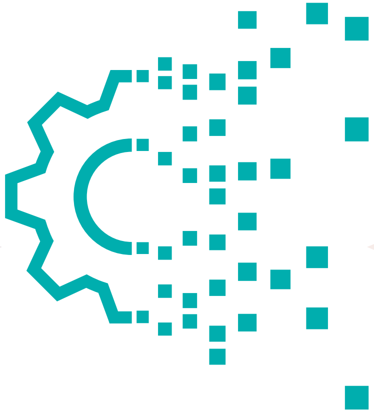


Silos

Information accessibility

No Added value

Digitalisation



Accessibility of data
Management of information
Interface with other systems
Maintainer feedback

TO:

Availability needs, operation load, KPIs

Assets Health notifications

Depot resources in real time

Optimisation of global productivity

Digitalization favors interaction between different maintenance and operations players

Impacts of Digitalization

- Another aspect of digitalization is the blurring of borders between real and virtual.
- Software content of products is increasing constantly→ cyber-physical systems

  Examples: Railway Signaling and Control; Electric Power Transmission; Aircraft operation (fly by wire)

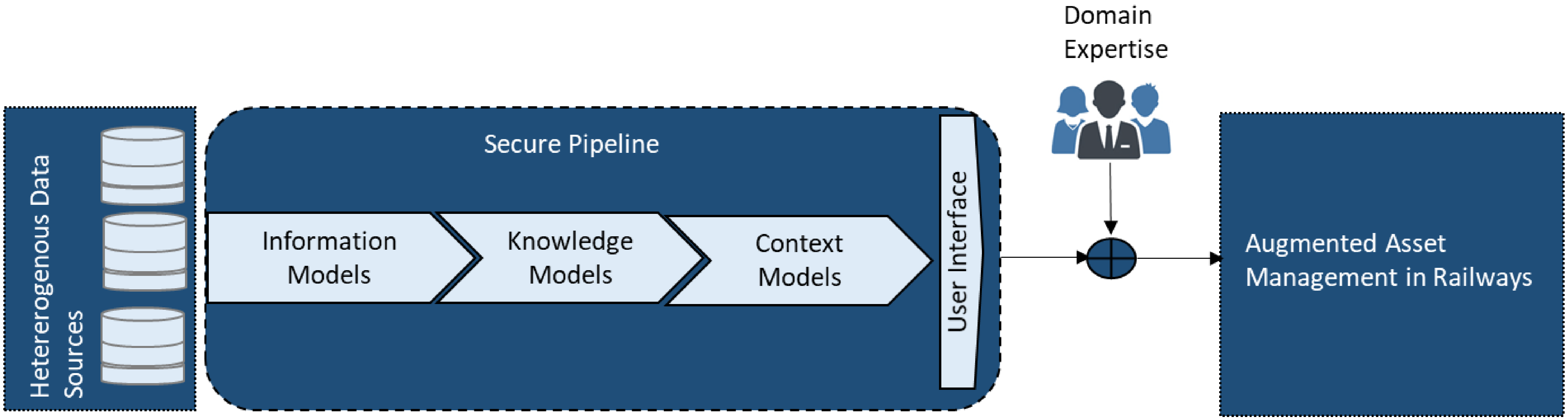
→ Hardware testing increasingly replaced by software simulation.

→ Digital Transformation implies that vast volumes of data are collected over lifecycle and need to be processed and transformed into actionable information.

→ This is where digital twins come in.

THE AUGMENTED ASSET MANAGEMENT CONCEPT FOR RAILWAY SYSTEM

Augmented Asset Management: concept of augmenting the decision-making related to asset management processes with the use of Industrial AI and digitalization.



From: " Augmented Asset Management of Railway System empowered by Industrial AI", Jaya Kumari, Licentiate thesis, Luleå University of Technology, June 2022

Main Properties of a Digital Twin

- A "Digital Twin" is an abstract representation of a physical object : representation must be accurate enough to support the goals that have been identified and that are being pursued

- Note that a digital twin can also, and usually does, contain more data than its real counterpart.

Example: history of design changes, suppliers, history of maintenance operations performed on an asset, even minute-to-minute monitoring of aircraft engine data.

→A digital twin is also a historical repository of its physical counterpart.

- All these data sets can be used for real-time analyses and simulation. They can also be used collectively to identify patterns and meanings

- In a true digital twin, changes in the physical object impact its twin and conversely

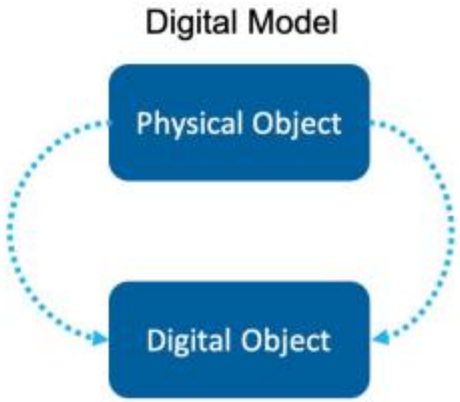
Source : Draft paper from IEEE Digital Reality Initiative on " symbiotic autonomous systems'

'Digital Twin' Stage 1 : only a Digital Model

Characteristics of the physical object are replicated (manually) in the digital model

If the physical object changes, the digital model remains identical (unless modified manually).

No changes to the digital object impacts the physical object.

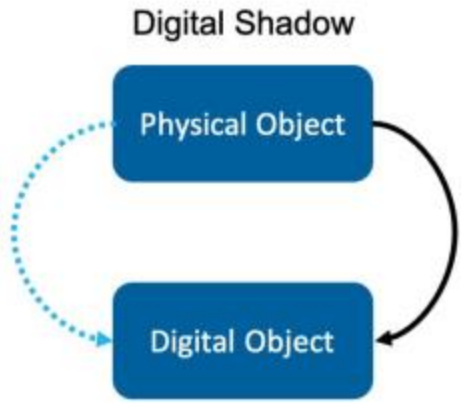


Source: « Digital Twins :Enabling Technologies, Challenges and Open Research », A.Fuller et al., IEEE Access, July 2020

‘Digital Twin’ Stage 2 : a Digital Shadow

Characteristics of the physical object are replicated automatically in the digital model

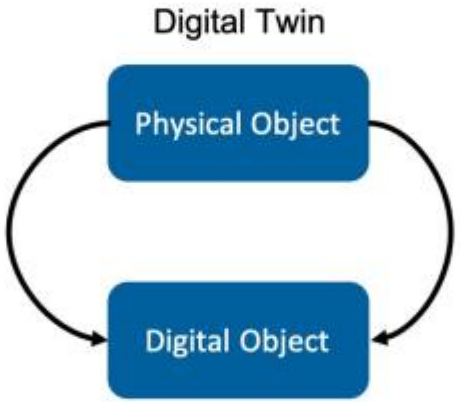
A change to the physical model will automatically modify the ‘digital shadow’, but not conversely.



‘Digital Twin’ Stage 3 : true Digital Twin. All functions in the physical object.

Characteristics of the physical object are replicated automaticall in the digital model

A change to the digital model wil modify the physical object.‘

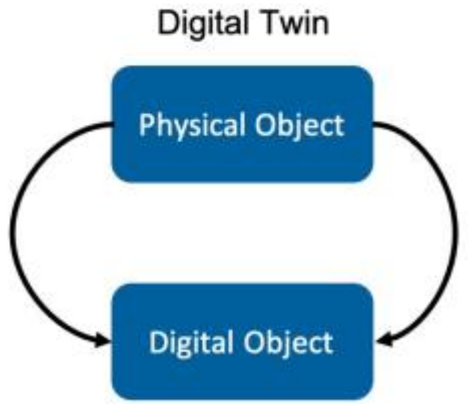


In Stage 3 all functions are residing and performed in the physical object.
The digital twin has a copy of those functions and, based on internal/external processing , may evaluate the effects of changing the execution of some of them and request the physical twin the change. (IEEE DRI= Digital Reality Initiative).

‘Digital Twin’ Stage 4 : true Digital Twin. Functions shared between the two twins.

Characteristics of the physical object are replicated automatically in the digital model

A change to the digital model will automatically modify the physical object.‘



At Stage 4, bi-directional influence as in Stage 3.
In addition, functions are shared between physical object and digital twin.
Some of the functionalities are performed in the digital twin and result in a behavior change in the physical twin
Therefore if connection between the two is interrupted, some functions are lost (R. Saracco, IEEE DRI)

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Digital Twin for System Asset Management

Combining Degradation Models (physics of failures) with data-driven approaches for predictive maintenance

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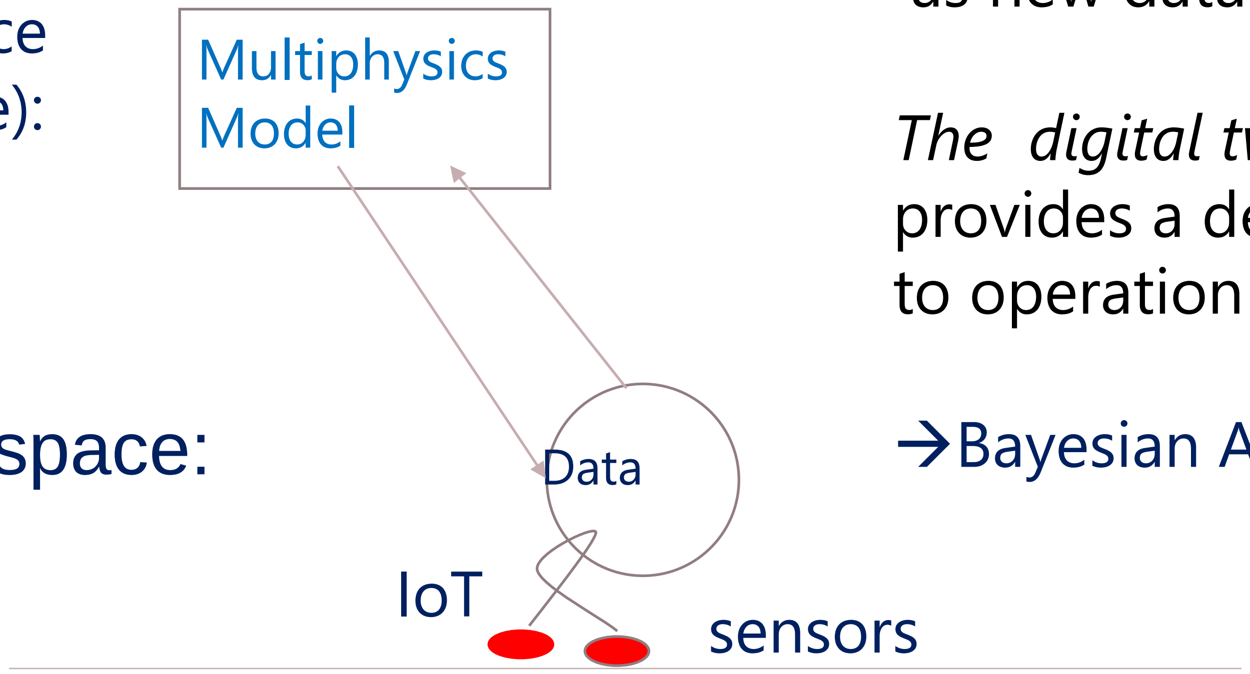
Virtual Space
(cyberspace):
Digital twin

Physical space:
Asset



A priori models are enriched progressively as new data are acquired.

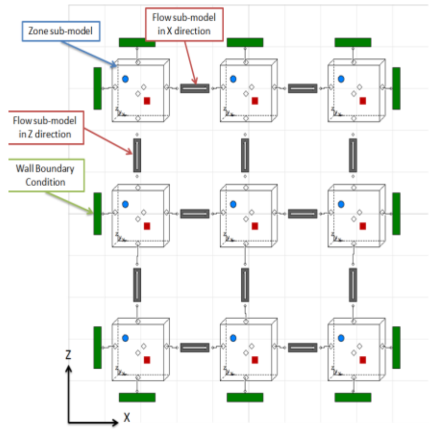
The digital twin
provides a decision support
to operation and maintenance

→Bayesian Approach

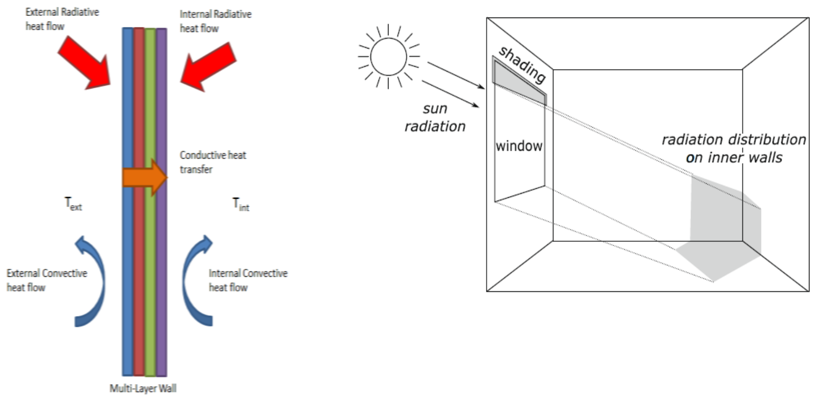
Example: Digital twin of tramway HVAC (Alstom)

- HVAC system physical model :

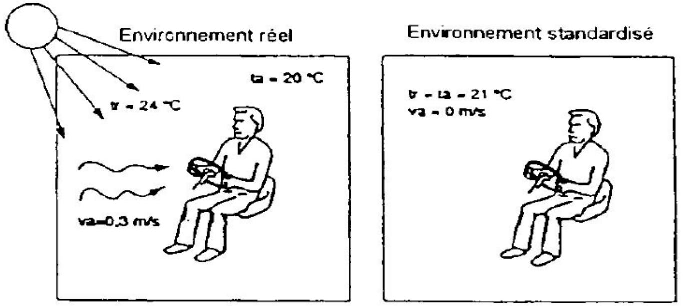
Air flow



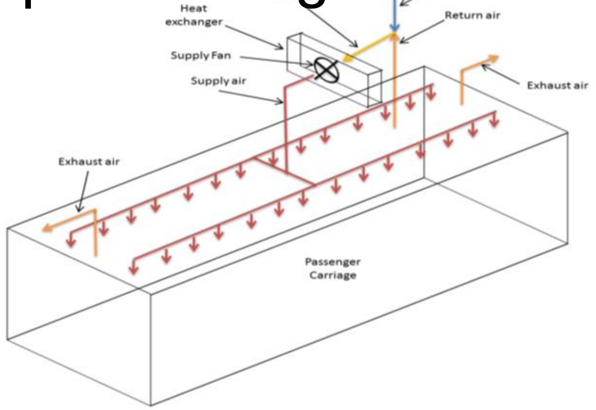
Walls and Windows



Seat Occupancy rate



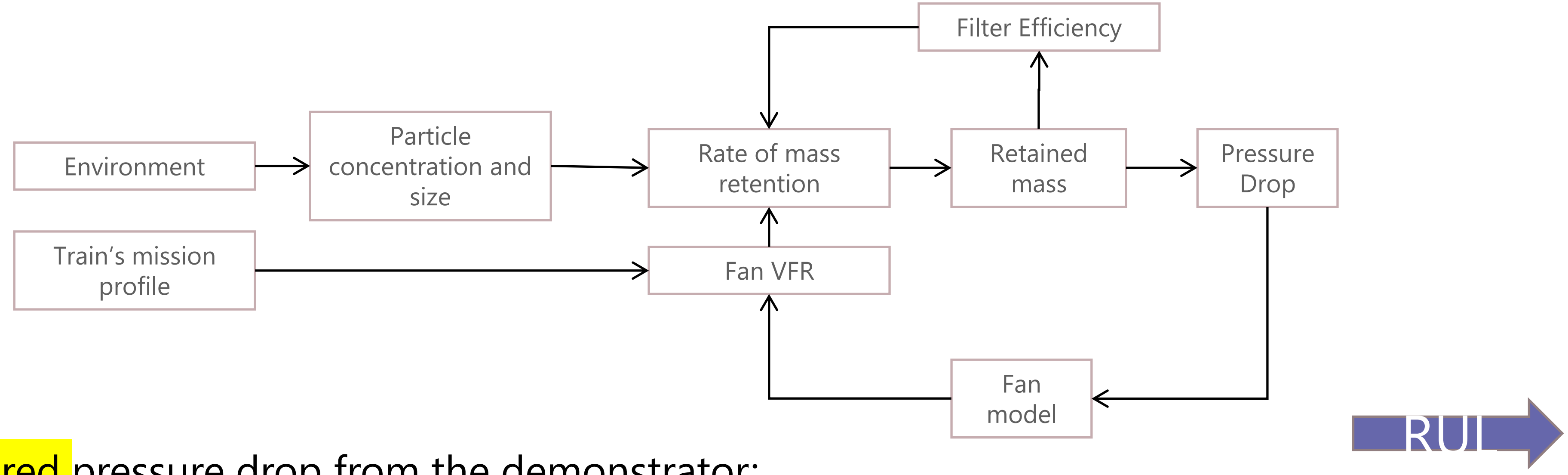
Air ducts and air processing units



Alstom 's Train HVAC Filter Digital Twin

MODEL

- Filter is modelled as a porous medium where the increase in pressure arising out of clogging is calculated using Darcy's law.
- The porosity of the filter decreases as particle mass is retained.

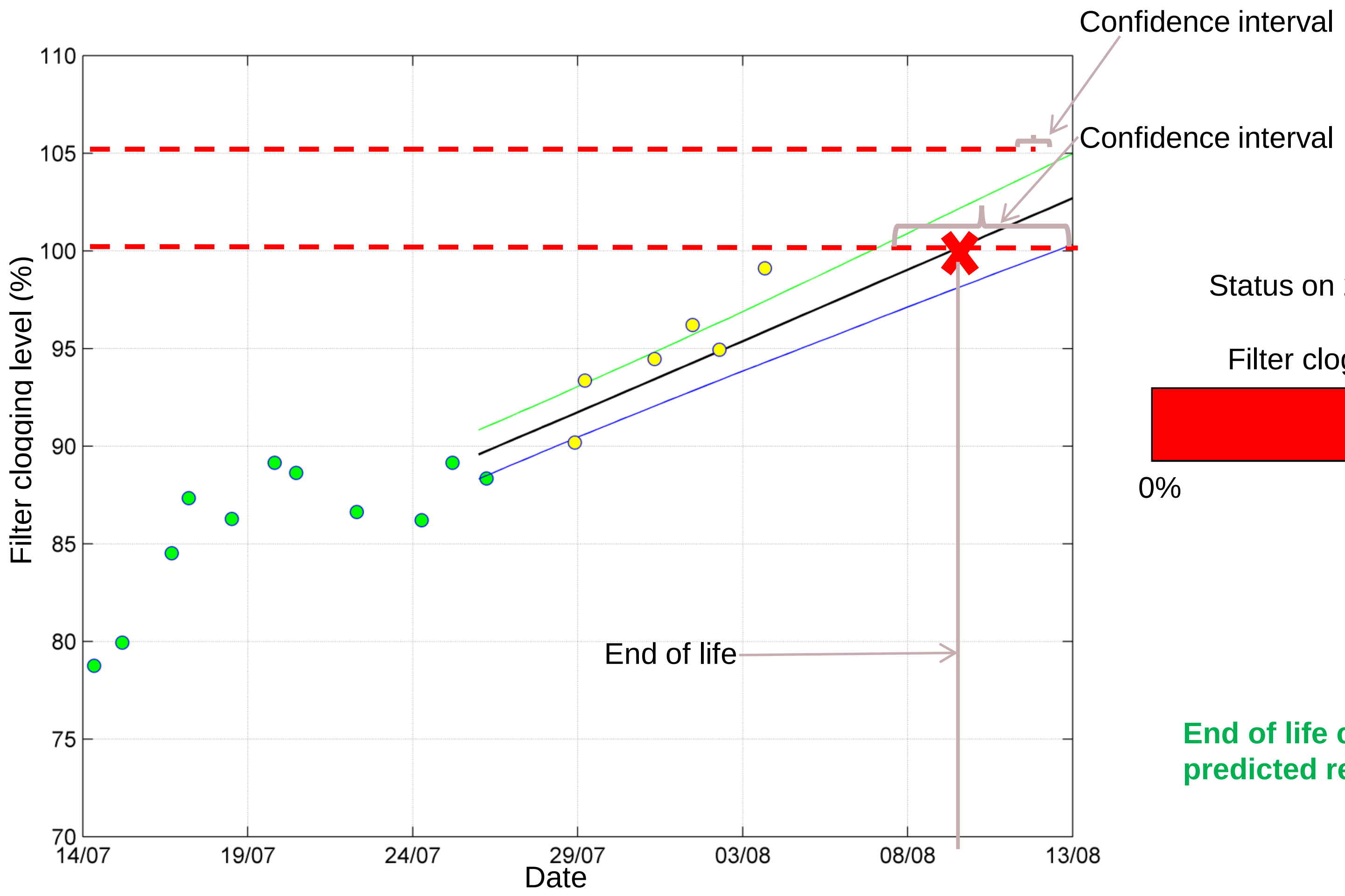


DATA

- Using measured pressure drop from the demonstrator:
  - Parameters of the physical model have been calibrated to match measured values;
  - the rate of mass retention can be estimated using optimization algorithms.

Source : "A Monte-Carlo Approach for Prognostics of clogging Process in HVAC filters using a hybrid strategy " A. Staino, R. Abou-Eïd, P.Dersin, iEEE PHM 2018

HVAC Filter: Prognostics with Digital Twin



Status on 26th July 2017.

Filter clogging indicator

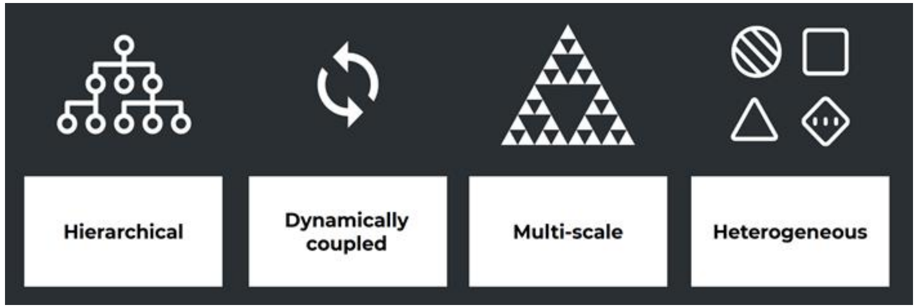
89%

14 days remaining

End of life coincides with predicted remaining useful life.

Hierarchy of Digital Twins: Example of Electrical Power Systems

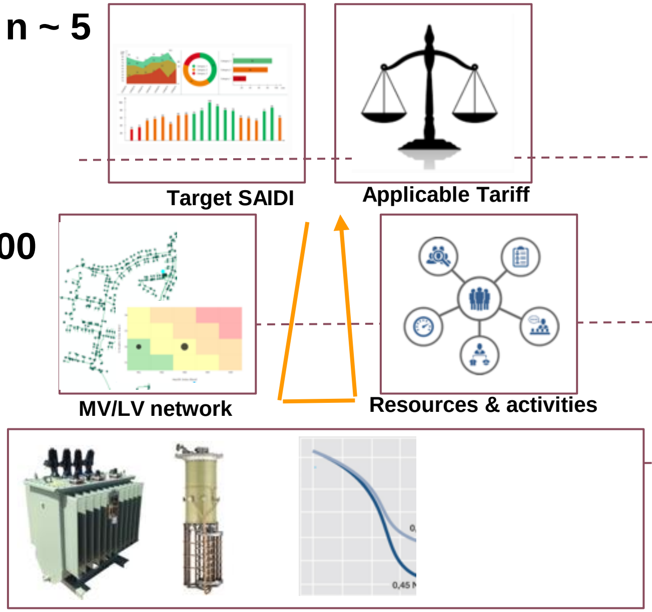
Characteristics of Electrical Systems



n ~ 5

n ~ 100

n ~ 1 000 000



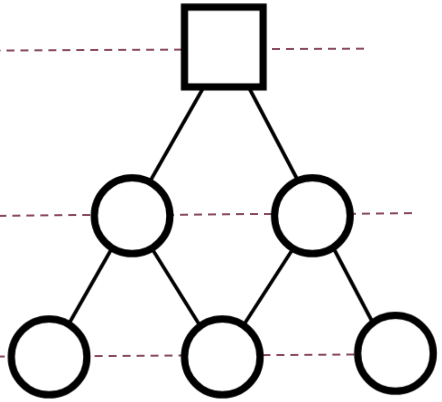
Target SAIDI

Applicable Tariff

MV/LV network

Resources & activities

Reliability of LV transformer and its Tap changers



Digital Twin of an Organization

Business Plan

Composite Digital Twin

Processes & resources

Discrete Digital Twin

Assets & Actions

What to Expect When You're Expecting Digital Twins, Gartner, 2019. Benoit Lheureux, W. Roy Schulte, Alfonso Velosa, Marc Kerremans

Gartner

Management of a Fleet of Assets

In a number of applications, the problem at hand is managing, not an individual asset, but a fleet of assets.

Examples:

-- Fleet of aircraft

-- Fleet of trains , or point machines

→ Question: How to utilize information acquired at fleet level to manage one asset? Or conversely.

The assets may be identical but have

-- different mission profiles

-- difference maintenance histories

→ How to take advantage of similarities while taking differences into account?

➡ Fleet-level Digital Twin vs asset- level Digital Twins

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What is a System of Systems ?

Field of study since the 1980s (defense industry) . Reliability, Safety, Maintenance implications still insufficiently understood

- Geographical distribution
- Operational and managerial independence
- Heterogeneity
- Evolutionary Development
- Emergent Behavior

Implications for Reliability Engineering ? – more generally, RAMS

Examples of Systems of Systems

- Complex Electrical Power transmission grid (with telecommunication)
- Multi-modal Transportation (train + bus +…)
- Health Care Systems
- Fleet of autonomous vehicles

→ Pose special challenges for RAMS and Asset Management

,

- Critical infrastructure (CI) as Complex Adaptive System of Systems (**CASoS**)

- ***types of links:*** geospatial, logistic, technologies, operational and management rules, exchange of information, energy and other resources, etc.;

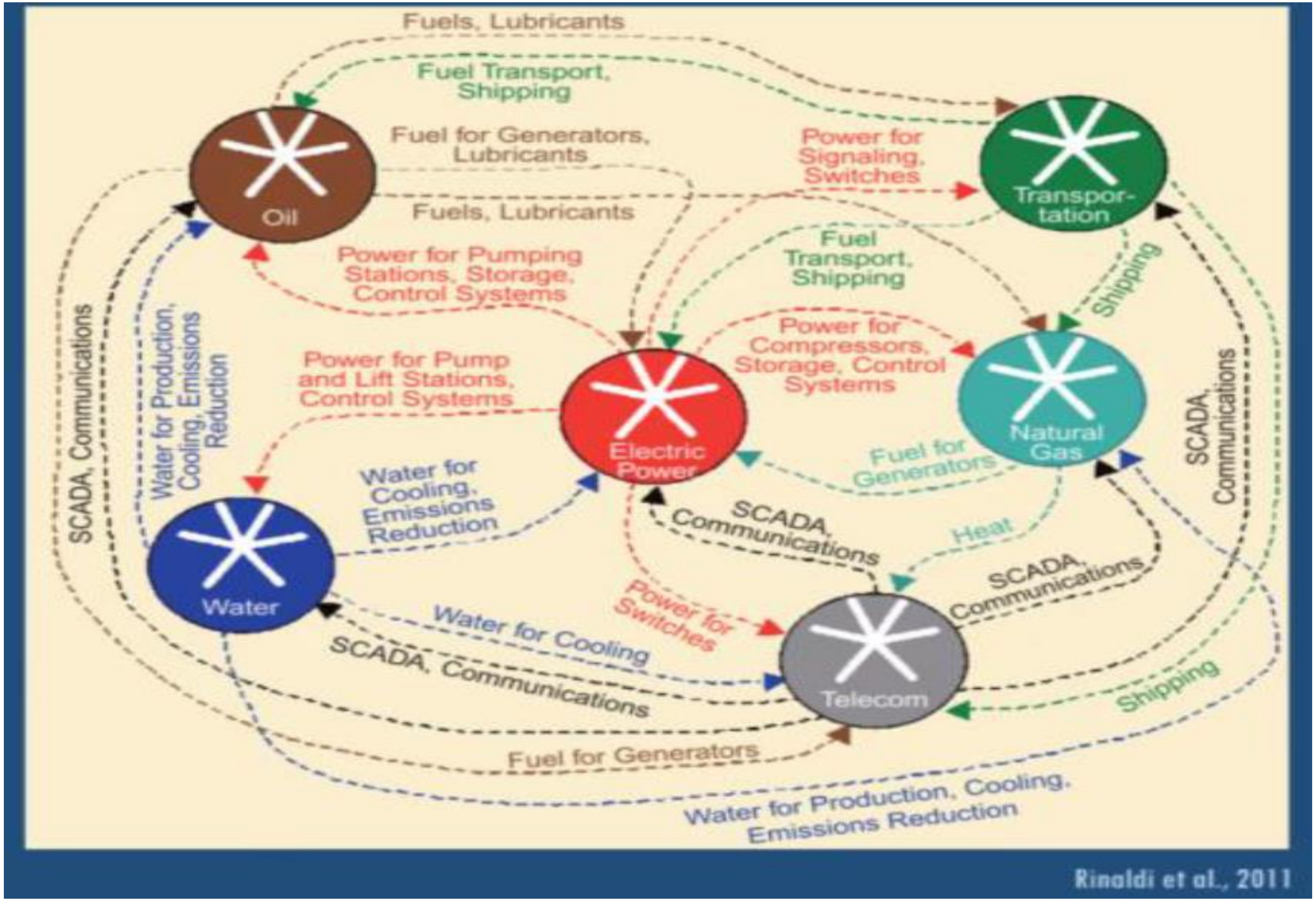
- Organizations managing CI are *capital-intensive and fairly complex* themselves (internal structure, operations and deployed technologies);

- *Business and operational environment is increasingly complex* characterized by deep uncertainties (natural, weather, human);

Increasing complexity and interdependencies→ CI become more vulnerable (fragile) creating conditions for *cascading, system-level failures;*

- *Techniques and tools* based on traditional methods show limits in effectively modeling complexities and uncertainties; new modeling approaches are needed.

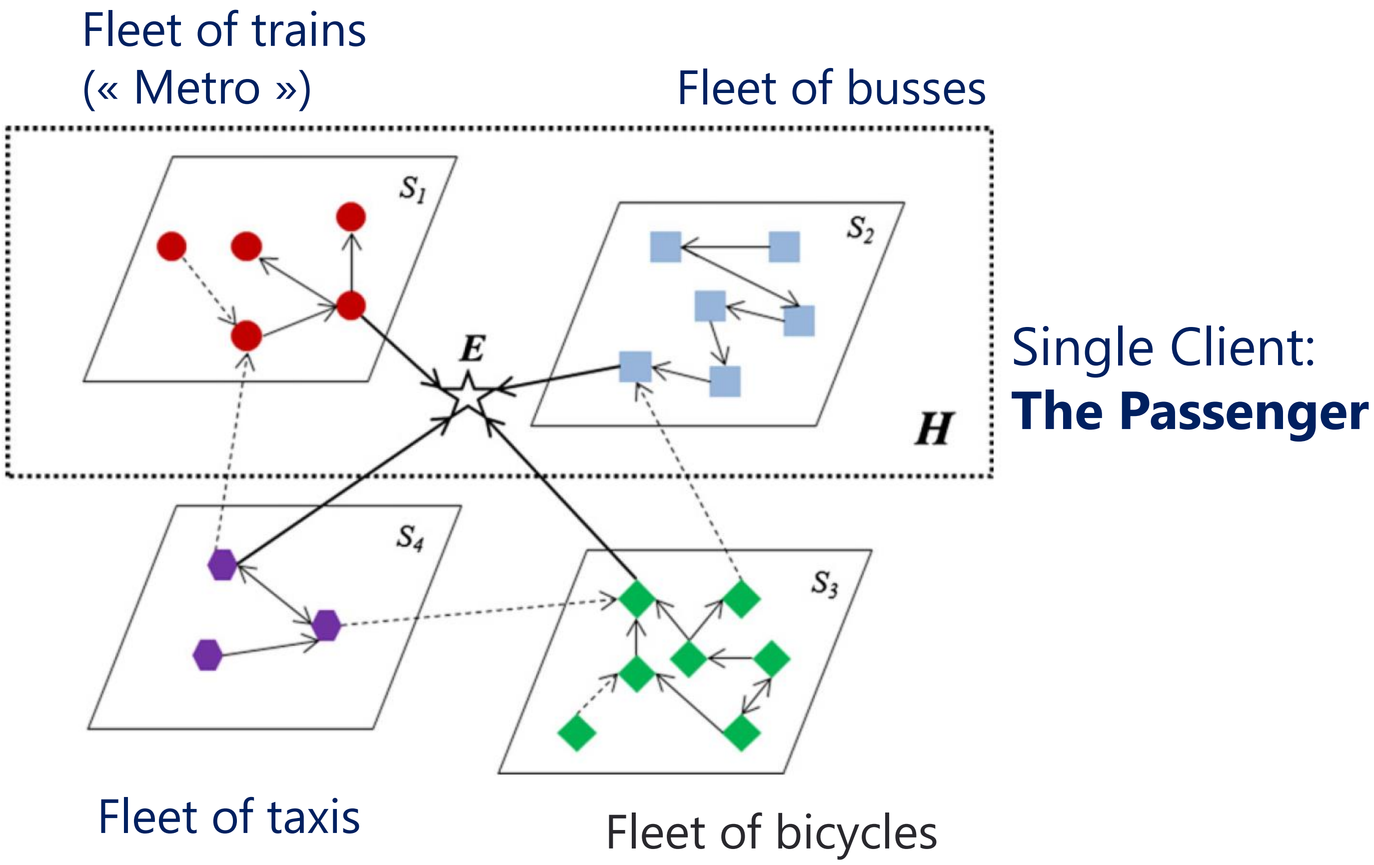
Critical Insfrastructure Interdependencies



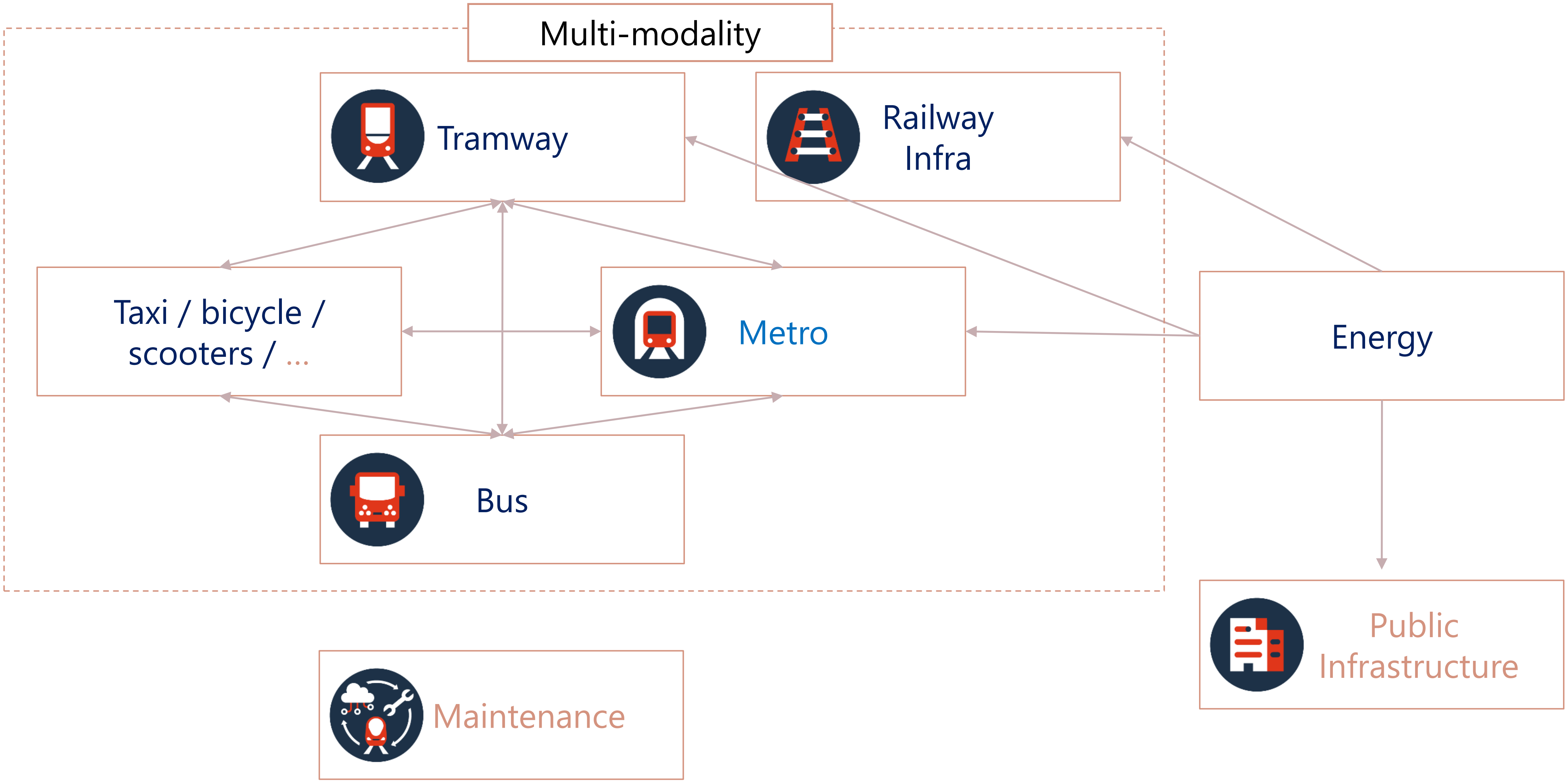
Source : H.Baroud ESREL 2020

Example of SoS :Multi-Modal Transportation

- Different systems are managed independently but must (or should) coordinate
- Electrical Power Supply and Telecommunication System are essential to Functional Fulfillment



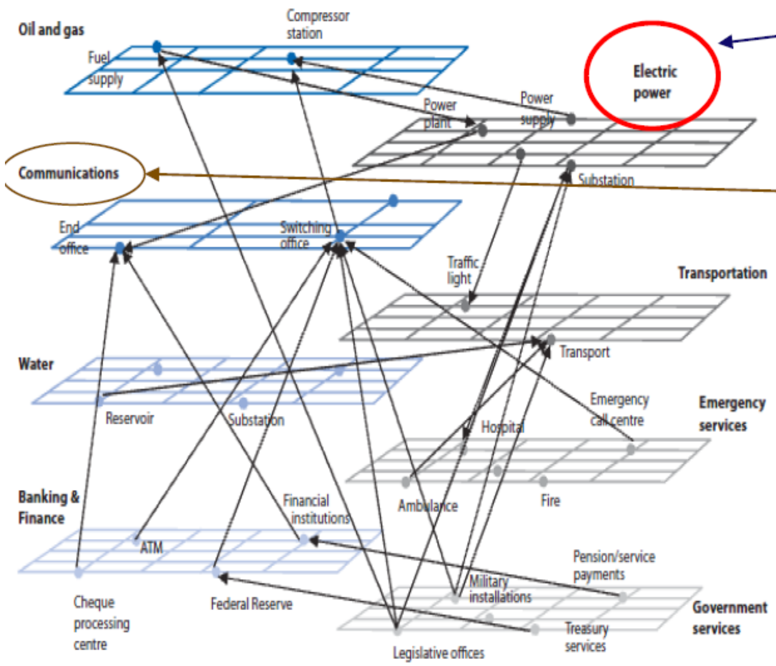
Multimodal Transportation: players and Interactions

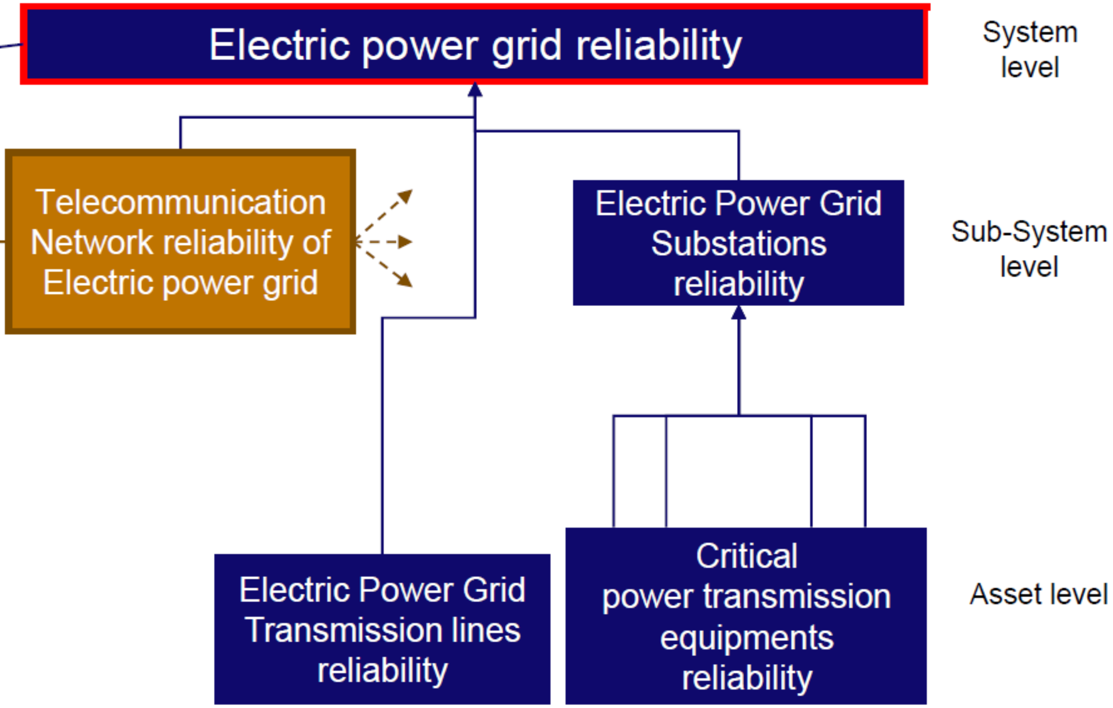


Example of SoS :Electric Power Grid

Hydroquebec
Electric Power Grid

Critical infrastructure interdependencies





Source: OECD
http://www.oecd.org/governance/48256382.pdf

Use of Digital Twins for SoS Asset Management

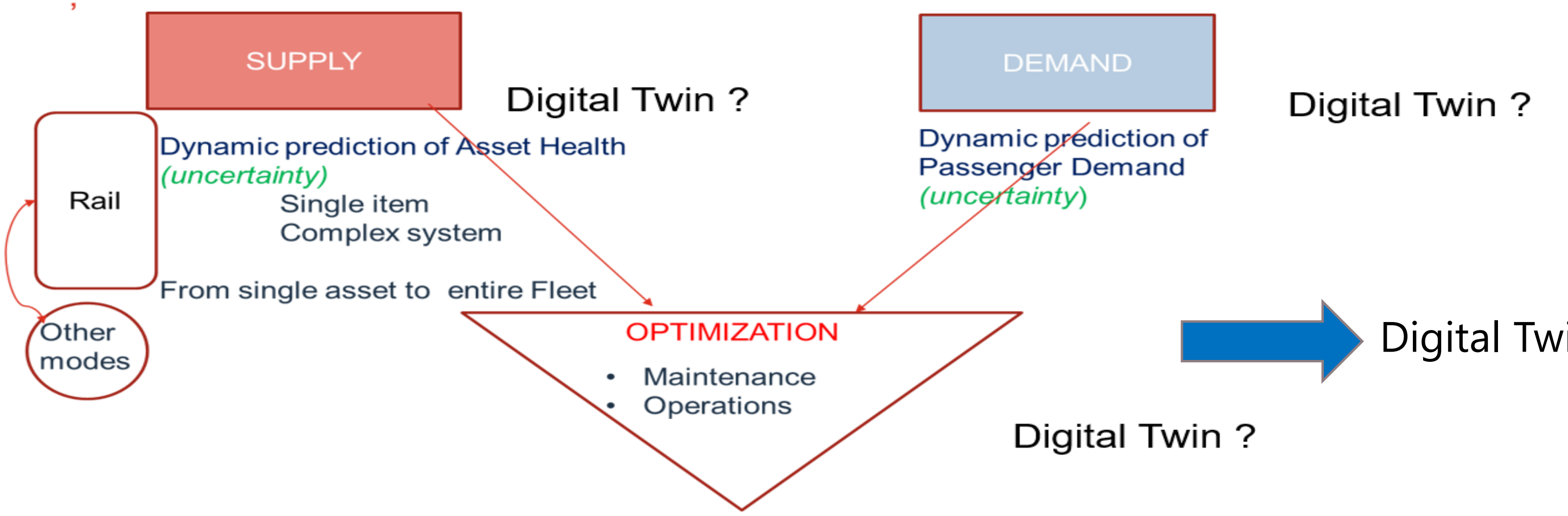
- Each System can be modelled by a Digital Twin (DT)
- Then the System of Systems can be modelled by the dynamic interaction between digital twins
- The human decision maker can even be modelled as a '*cognitive digital twin*'
- Digital twins can/ should be updated throughout life cycle

→IEEE Digital Reality Initiative/ Reliability Society Project (SoS TC)

Joint Maintenance and Operation Optimization

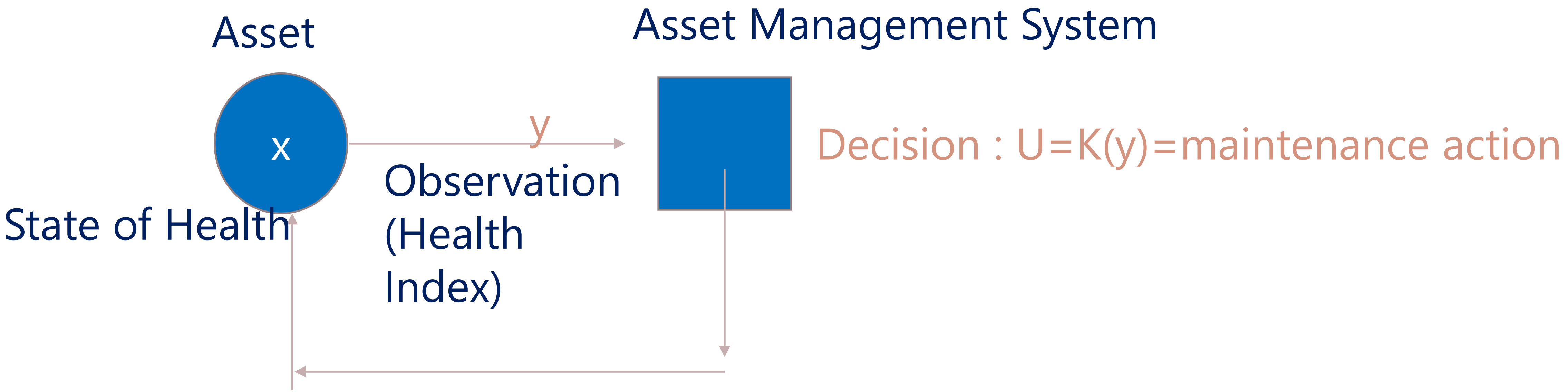
Multimodal SoS Maintenance/Operation Optimization

1) Performance Assessment
2) Decision Making



Digital Twins at Stages 4, 5

Closing the Maintenance/Operation Loop



Observability : to what extent can one estimate the true health state x from the health index y ?

Controllability : how certain can one be of insuring system normal operation through maintenance policy U ?

Note: maintenance is often imperfect. And the effect of a maintenance action is not observed immediately.

At the fleet level: same problem but multi-dimensional : $\underline{x} = (x_1, \ x_n)$, $\underline{U} =(U_1,\ldots U_n)$

AGENDA

Conclusions

- Asset Management is about value creation throughout Life Cycle
- The magic triangle : costs, risk, performance, throughout lifecycle
- Digital twins-updated throughout lifecycle, are a powerful enabler for asset management in the era of digitalisation
- Digital twins can exist at several levels : components, systems, systems of systems

Perspectives and challenges (non exhaustive)

PERSPECTIVES	CHALLENGES
The Digital Twin throughout Life Cycle	Coexistence of Assets of different ages
Asset Management for Systems, and Systems of Systems	
Self-Learning, Self-repairing Systems	Not enough Data
	Too many Data
	Change Management
Integrate 'Resilience Analysis' and asset management (critical infrastructures)	Proactive Cybersecurity
Deep Learning for Predictive Maintenance	Algorithm Interpretability Integration of data-driven algorithms and physical models
Quantum Machine Learning	Certification

Acknowledgement

The author is grateful for the numerous enriching discussions with colleagues at Luleå University of Technology , former colleagues at Alstom, and IEEE partners at Hydroquébec, Cosmo Tech and Vanderbilt University.

Some Bibliographical References

- R.Karim, P.Dersin, D. Galar, H. Jarl, “ AI Factory: a Framework for Digital Asset Management”, Proc. 31st ESREL Conference, 2021
- Ramin Karim, Diego Galar, Uday Kumar, “ AI Factory: Theory, Applications, Case Studies, Springer (to appear)
- A. Staino , R. Abou-Eïd, P. Dersin, “ a Monte-Carlo Approach for Prognostics of clogging Process in HVAC Filters using a hybrid Strategy: a real Case Study in Railway Systems”, Proc. IEEE PHM Conf., June 2018
- Kumari, J., Karim, R., Thaduri, A., & Dersin, P. (2022). A Framework for Now-Casting and Forecasting in Augmented Asset Management. International Journal of System Assurance Engineering and Management.
- IEEE Future Directions Committee- DigitalTwins eBook, R. Saracco, 2017

AN OCEAN OF OPPORTUNITIES

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