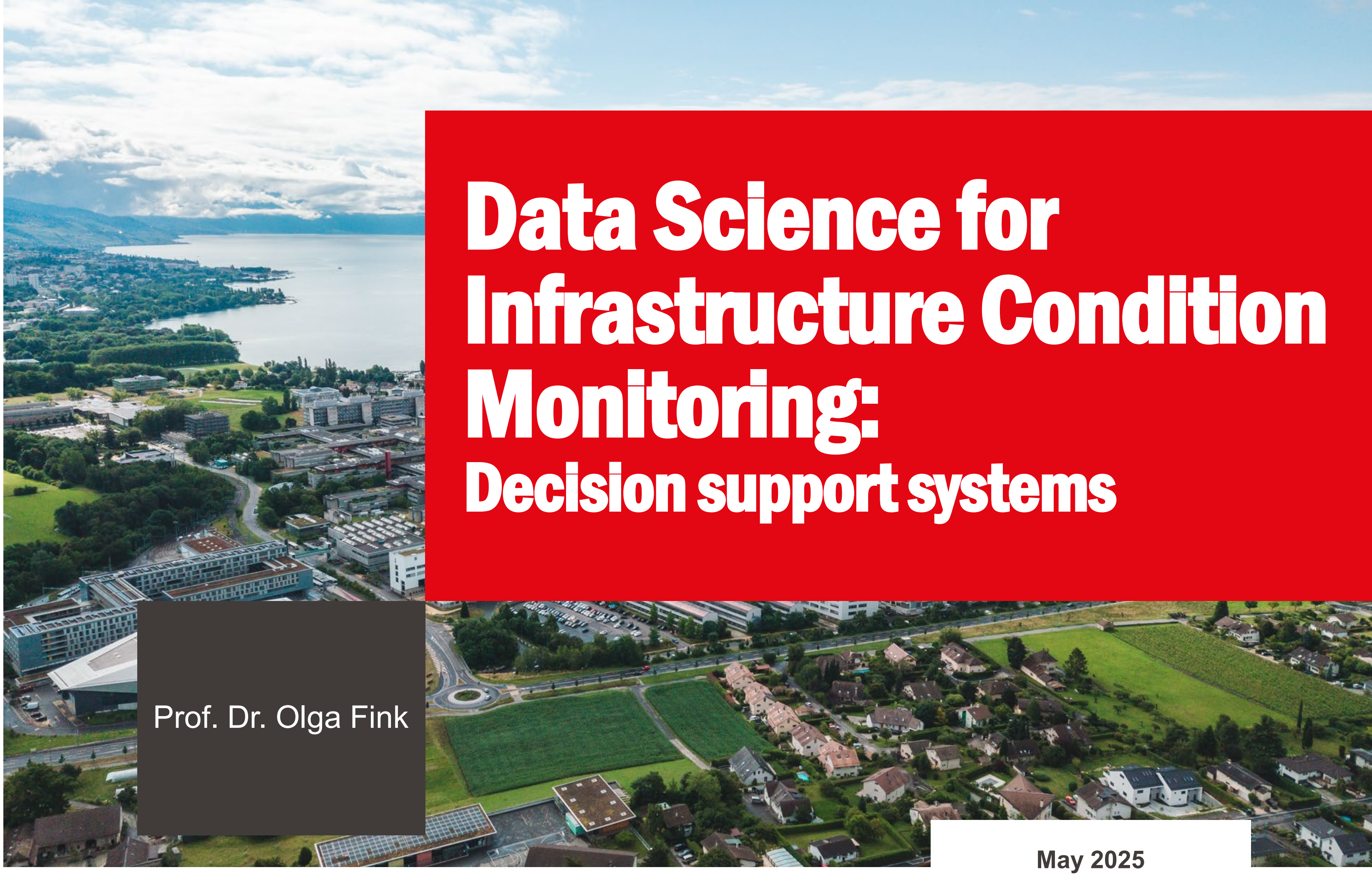

Data Science for Infrastructure Condition Monitoring:

Decision support systems

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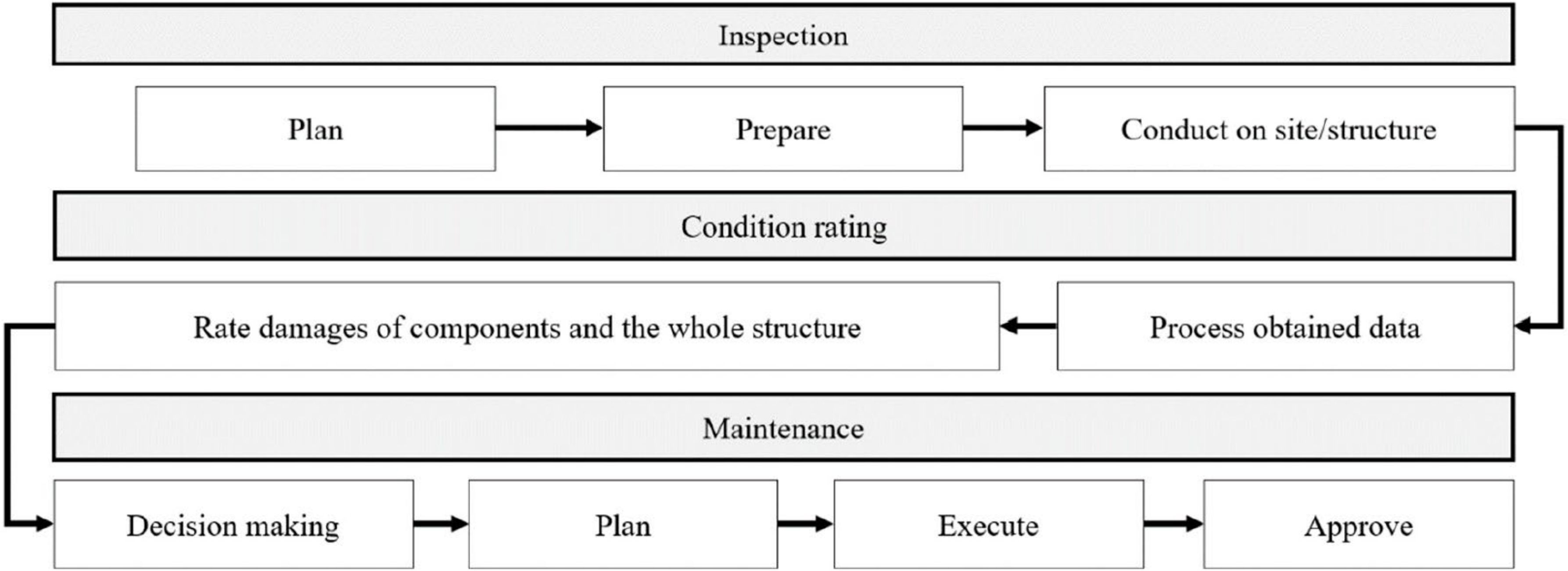
May 2025

École
polytechnique
fédérale
de Lausanne

Process of Structural Health Monitoring

Overview of current maintenance processes



Sun, Zhiyan, et al. "Optimal Sensor Placement for Structural Health Monitoring: A Comprehensive Review." *Journal of Sensor and Actuator Networks* 14.2 (2025): 22.

The SHM Process – Overview

- Sensing
- Data Acquisition
- Data Processing
- Feature Extraction
- Damage Detection, Diagnosis, Prognosis
- Decision Making

Condition monitoring methods (repetition)

- Measurement technology
- Accuracy of the monitored parameters
- Feasibility of monitoring
- Operating conditions during measurement
- Measuring interval
- Data acquisition rate
- Registration of the monitored parameters
- Measuring points
- Preliminary warning and alarm criteria
- Reference values

Considerations in the selection of measuring points (repetition)

- Safety,
- Selection of the transducers,
- Signal conditioning,
- High sensitivity to error changes,
- Low sensitivity to other influencing variables,
- Repeatability of the measurements,
- Attenuation or signal loss,
- Accessibility,
- Ambient conditions,
- Costs

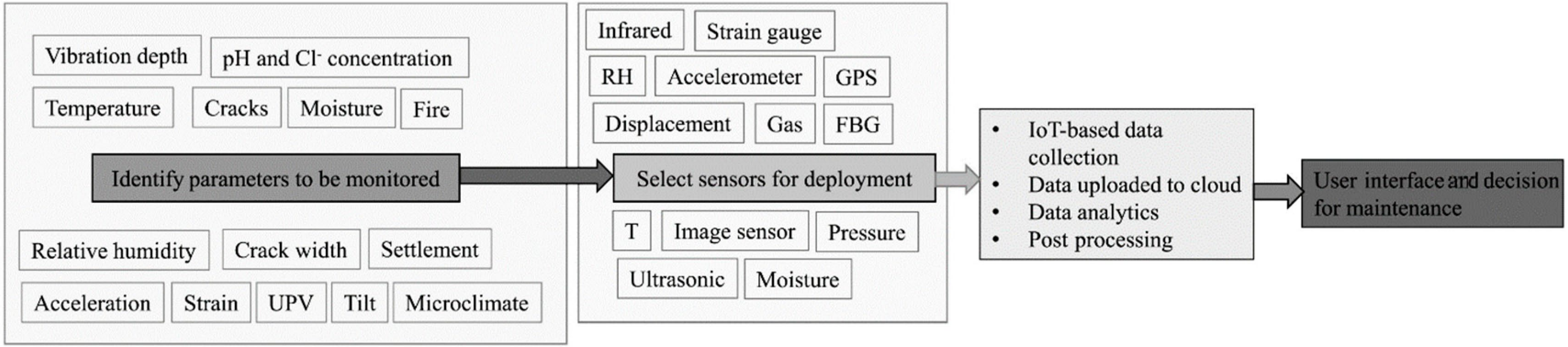
Data acquisition and analysis

- Measurement and trend analysis
- Quality of the measurement
- Comparison of the measurement results with the warning and alarm criteria
- Diagnostics and prognosis
- Improving the reliability of diagnoses and/or forecasts

Data Processing

- Noise filtering and normalization
- Data fusion from multiple sources
- Managing missing or corrupted data

SHM approach to infrastructure assessment and decision-making.



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Non-Destructive Evaluation method categories

NDE Category	Approach
Visual Inspection	Dye Penetrate
Acoustic Wave-based	Ultrasonic Testing
Optical Techniques	Thermal Barrier Coatings Based on Infrared Thermography
Imaging Techniques	Digital Radiograph
Electromagnetic Fields	Eddy Current Testing

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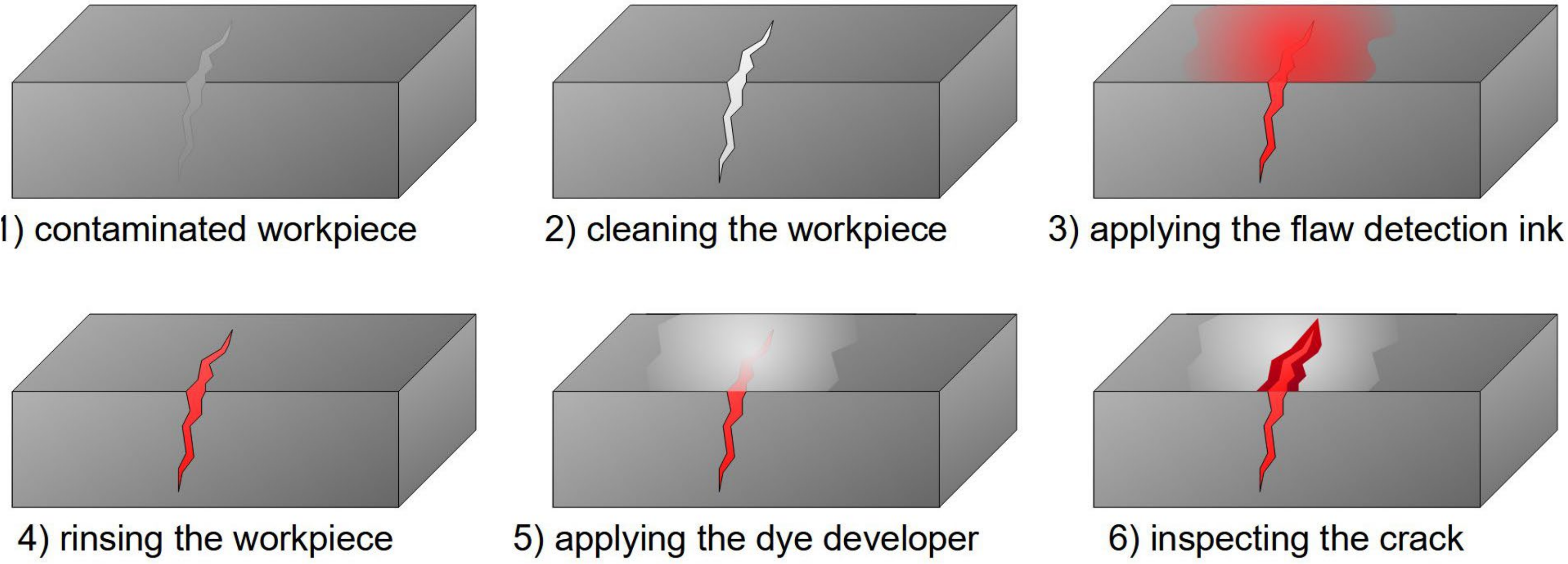
Dye pentrant inspection



Sensor placement

What Is the Sensor Placement Problem?

- The Sensor Placement Problem involves determining:
- How many sensors to use, and
- Where to place them on a structure
- to maximize monitoring effectiveness while minimizing cost and redundancy.

Why Is Sensor Placement Critical?

- Poor placement → missed faults or false positives.
- Good placement → better signal coverage, earlier fault detection, lower cost.
- Especially critical in **large-scale systems** (e.g., bridges, aircraft, wind turbines).

Goals of Sensor Placement

- Maximize fault detectability
- Enable damage localization
- Capture key dynamic behaviors (e.g., mode shapes)
- Minimize information redundancy
- Maintain robustness to sensor failure
- Optimize cost-performance tradeoff

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Types of Sensor Placement Strategies

- **Heuristic Methods**
  - Greedy algorithms, expert rules, trial-and-error.
  - **Fast but suboptimal**.
- Optimization-Based Approaches

$$\max_{x \in \{0,1\}^n} J(x) \quad \text{subject to:} \quad \sum x_i \leq k$$

- Where x_i indicates sensor at location *i*, and *J(x)* is an objective like:
  - Fisher Information Matrix (FIM)
  - Mutual information
  - System observability/controllability

Sensor Placement via Mutual Information

- Mutual Information (MI) quantifies the amount of information that one random variable (sensor measurements) contains about another (system state or damage state).

$$I(X;Y) = H(X) - H(X|Y)$$

- Where:
- X: Random variable representing the system state (e.g., damage location, severity).
- Y: Sensor measurements.
- H(X): Entropy (uncertainty) of the system state.
- H(X|Y): Remaining uncertainty in the system state after observing the sensors.

Goal

Select a set of sensor locations $S \subset \mathcal{L}$ (possible locations) such that:

$$\max_{S, |S| \leq k} I(X; Y_S)$$

where Y_S is the measurement vector from the selected sensor locations.

Why Use MI for Sensor Placement?

- Data-driven and model-agnostic.
- Can naturally handle nonlinear, high-dimensional systems.
- Accounts for redundancy: avoids placing sensors that provide overlapping information.
- Robust in probabilistic settings (e.g., under uncertainty in system state or noise).

Digital Twins

1. Definition: Digital twins

- A digital twin is defined as "a living model of the physical asset or system, which continually adapts to operational changes based on the collected online data and information, and can forecast the future of the corresponding physical counterpart".

M. Grieves and J. Vickers, "Digital twin: Mitigating unpredictable, undesirable emergent behavior in complex systems," in *Transdisciplinary Perspectives on Complex Systems: New Findings and Approaches*, Springer International Publishing, 2016, pp. 85–113.

2. Definition: Digital twins

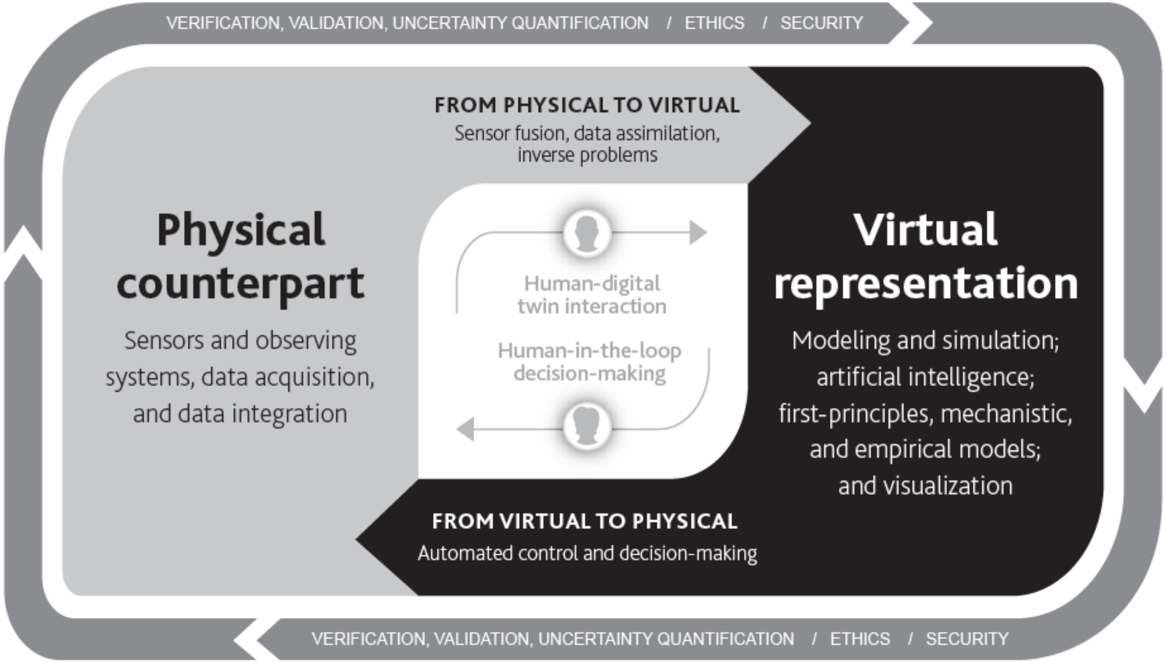
- *A digital twin is a set of virtual information constructs that mimics the structure, context, and behavior of a natural, engineered, or social system (or system-of-systems), is dynamically updated with data from its physical twin, has a predictive capability, and informs decisions that realize value. The bidirectional interaction between the virtual and the physical is central to the digital twin.*

National Academies 2023: Foundational Research Gaps and Future Directions for Digital Twins

Digital Twin integration

R. Stark, C. Fresemann, and K. Lindow, “Development and operation of Digital Twins for technical systems and services,” *CIRP Ann.*, vol. 68, no. 1, pp. 129–132, Jan. 2019.

Elements of a digital twin



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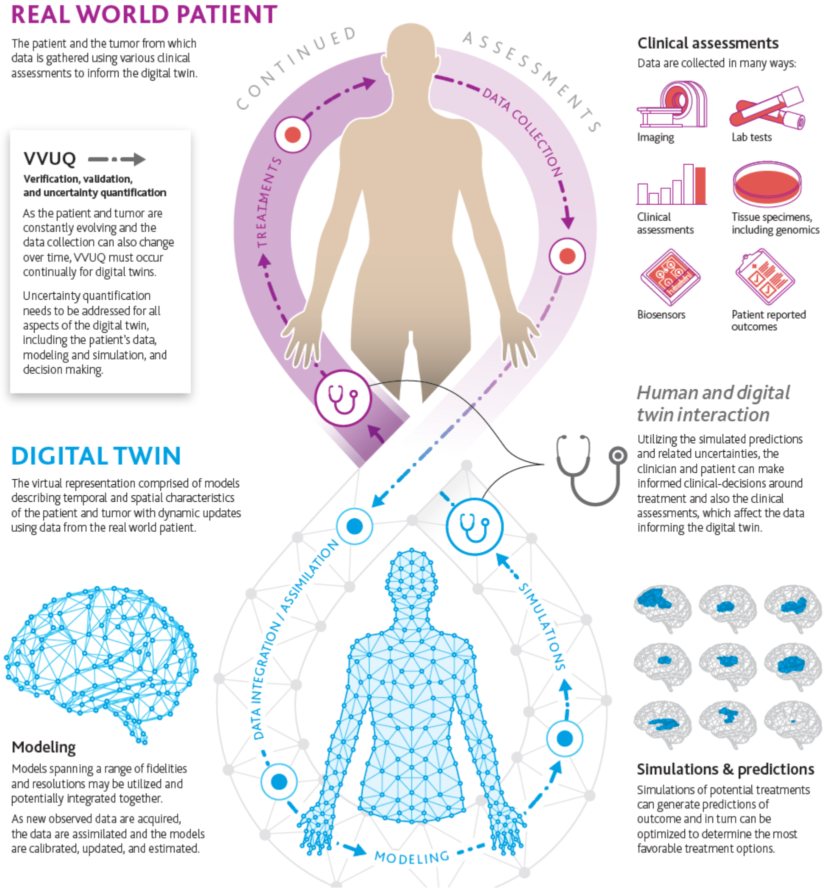
Digital twin of a patient



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Verification, Validation, Uncertainty Quantification

- **Verification:** Does a computer program correctly solve the equations of the mathematical model?
- **Validation:** To what degree is a model an accurate representation of the real world, from the perspective of the intended model uses?
- **Uncertainty Quantification:** What are uncertainties in model calculations of quantities of interest?

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Application cases of DT in SHM

- Real-Time Structural Monitoring
- Predictive Maintenance
- Damage Localization & Assessment
- Scenario Simulation (e.g. simulates "what-if" stress, load, or disaster scenarios)
- Post-Event Assessment
- Life-Cycle Performance Prediction
- Decision Support for Asset Management

A Digital Twin should be Fit for Purpose

- **Balancing required fidelity for prediction, available resources, and acceptable costs**
- Different digital twin purposes drive different fitness requirements related to modeling fidelity, data availability, visualization, time-to-solution, etc.
- For many potential use cases, achieving fitness-for-purpose is currently intractable

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Decision support

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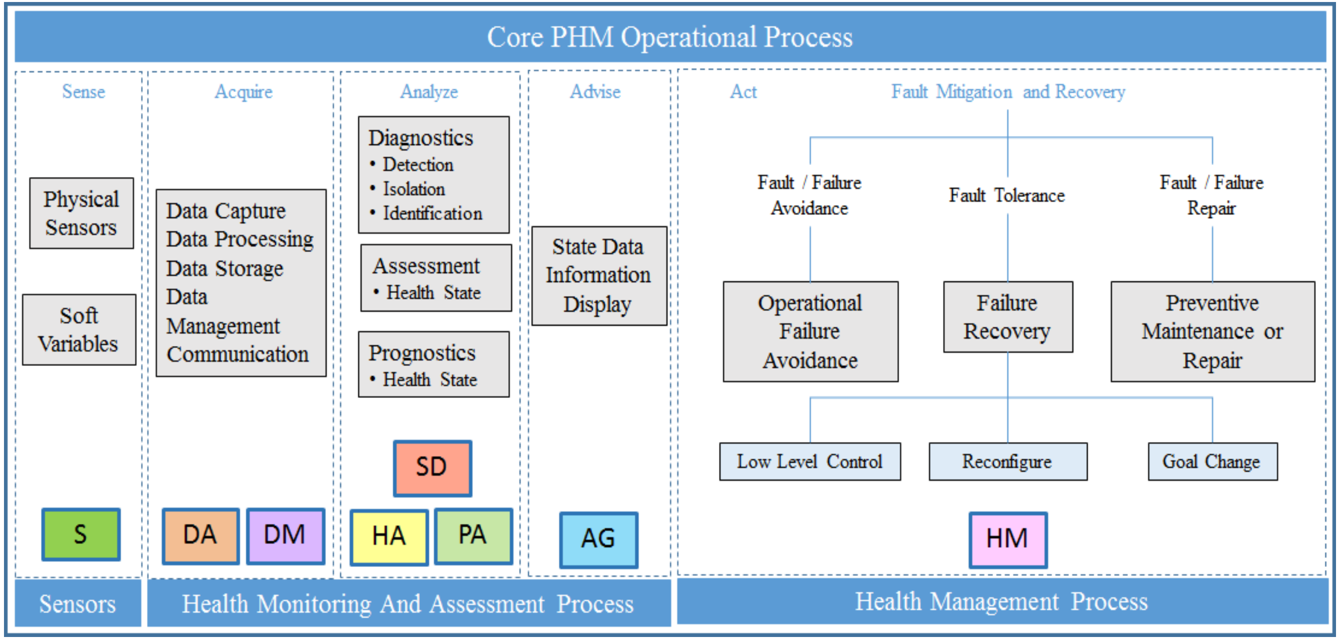
Reminder: PHM system operational view



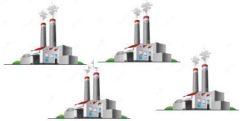
Source: P1856™/D31 Standard

Five levels of condition-based and predictive maintenance

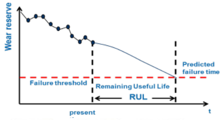
V. Prescriptive Level
- Prolong the component's lifetime
- Self configuration, optimization and adjustment

IV. Decision support Level
- Prioritize and optimize maintenance decisions
- Remote visualization

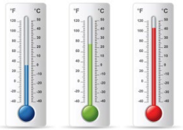
III. Fleet Level
- Fleets of machines
- Cyber-physical systems
- Peer-to-peer Monitoring
- Components under different operating conditions



II. PHM Level
- Fault detection, diagnostics and prediction of the remaining useful life
- Degradation and performance prediction



I. Condition Monitoring Level
- Effective sensor selection
- Connection + data aggregation
- Internet of things infrastructure



Why decision support systems for PHM required?

- Required recommendation at system, fleet and enterprise level:
  - Optimal specific action (what needs to be done)
  - Optimal point in time
  - Required ressource usage (including personel, tools and material)
  - Under the given constraints from the ressource availability and operational requirements

(Prognostics and) Health Management

- Health management utilizes prognostic information to make **decisions** related to safety, condition-based maintenance, ensuring adequate inventory, and product life extension.
- Health management goes beyond the predictions of failure times

→supports optimal maintenance and logistics decisions

→by considering the available resources +

→the operating context +

→the economic consequences of different faults.

- Health management process of taking timely and optimal maintenance actions based on outputs from diagnostics and prognostics, available resources and operational demand

Types of decisions

- Aggregate information at the system level (taking boundary conditions into consideration)
- Health-aware control → operation
- Adjustment of operations with respect to the equipment’s health state
- Optimization of maintenance scheduling
- Take decision at fleet level (e.g. mission scheduling)
- …

Decision making frameworks

- **Rule-Based Systems**: Simple thresholds, decision logics
- **Probabilistic Models**: e.g. Bayesian networks
- **Optimization-Based Decision Support**: Maintenance scheduling, resource allocation.
- **Learning-based Systems:** Reinforcement learning for maintenance optimization
- **Multi-Criteria Decision Analysis (MCDA)**
  - Trade-offs between safety, cost, downtime.

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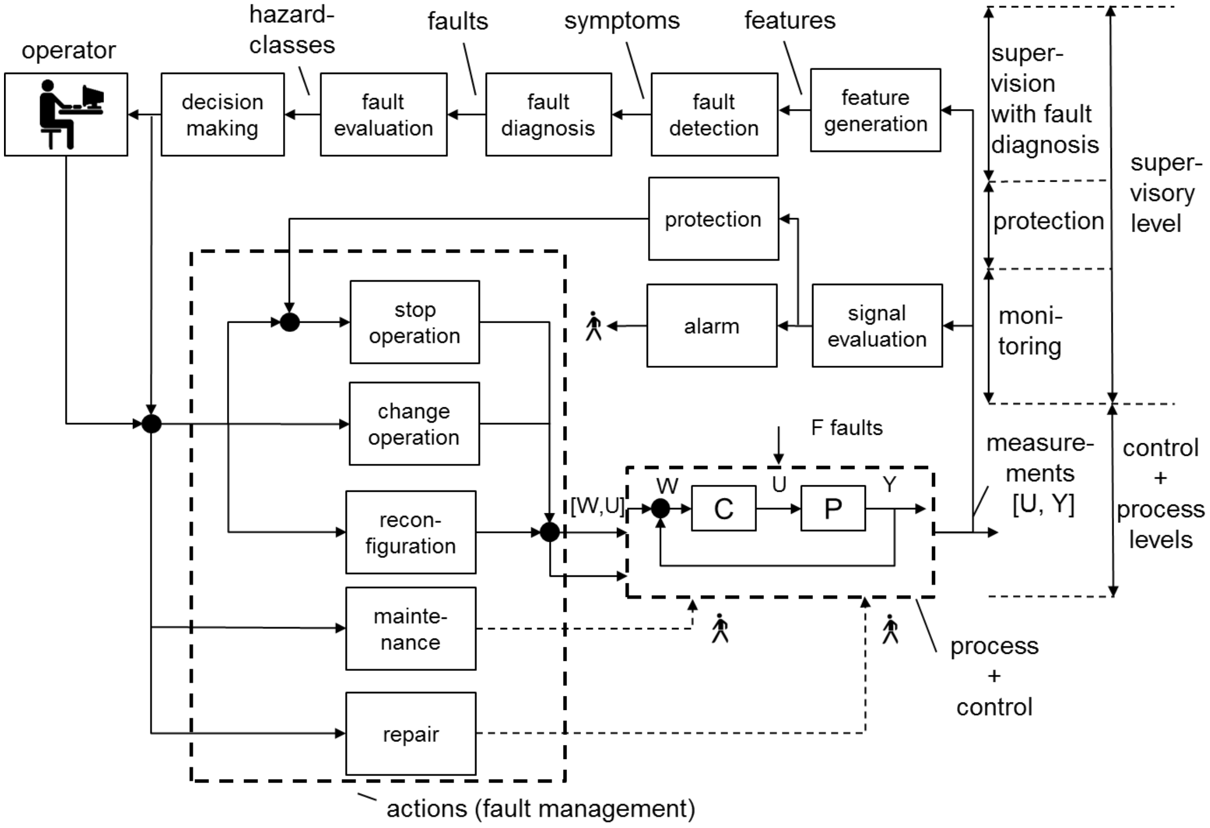
Decision-Making Tools

- **Optimization Algorithms:** Determining the most cost-effective maintenance schedules and resource allocations.
- **Scenario Analysis:** Evaluating the impact of different maintenance strategies or operational changes.
- **Risk Assessment:** Assessing the likelihood and consequences of potential failures to prioritize actions.

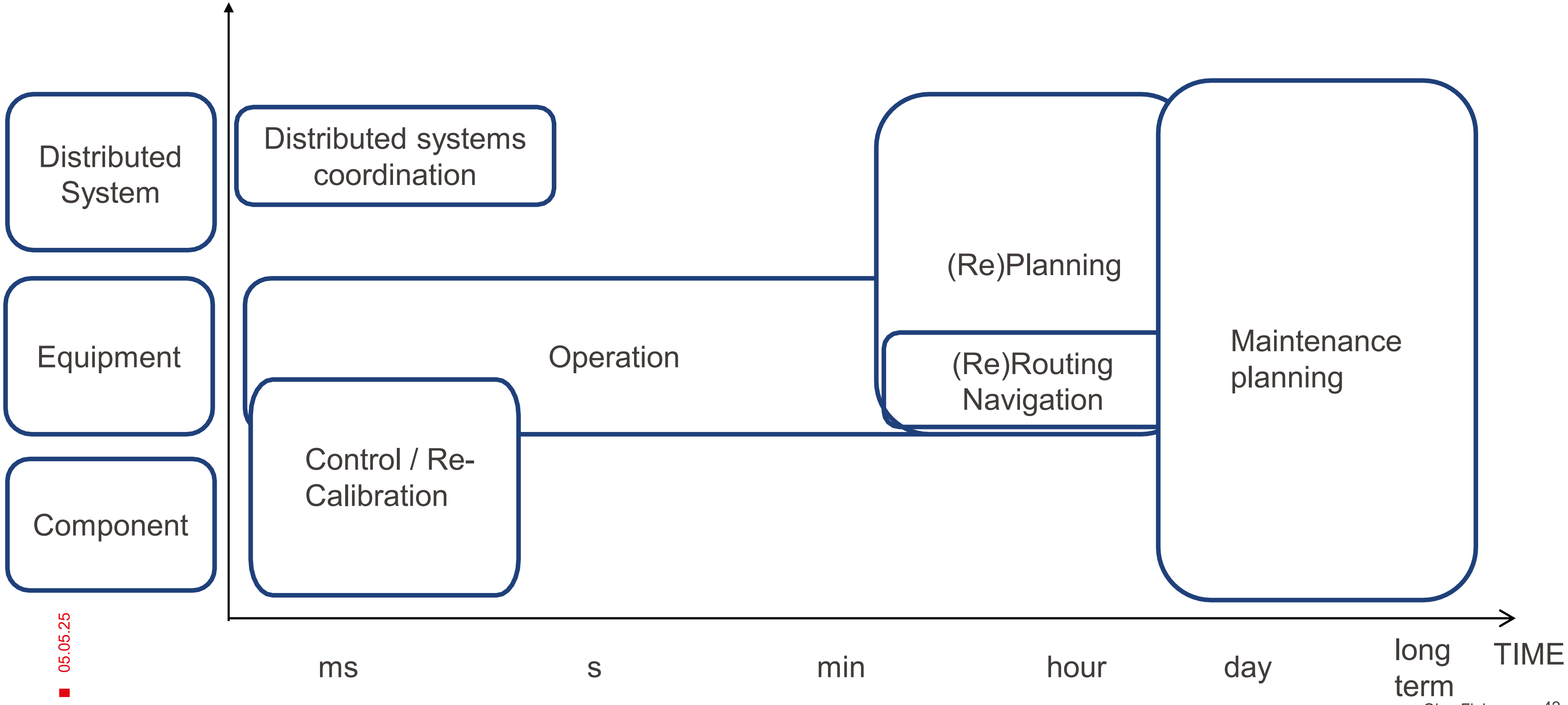
Optimization-Based Decision Support

- Formulate maintenance and inspection as an optimization problem.
- **Cost-Based Optimization**
  - **Objective**: Minimize total life-cycle cost (inspection + repair + downtime + risk).
  - **Constraints**: Safety, regulatory limits, resource availability.
  - **Techniques**: Linear/nonlinear programming, mixed-integer programming.
- **Partially Observable Markov Decision Processes (POMDPs)**
  - **Context**: Damage is not directly observable.
  - **Advantage**: Balances cost of monitoring vs. cost of failure.
  - **Example**: Decide whether to inspect, repair, or wait based on belief states updated from sensor data.

Health management



Decision making in complex systems



Steps to perform

- Establish objectives (e.g. availability, reliability, safety, performance and energy consumption), constraints (e.g. ressources), decision variables
- Incorporate operational and maintenance requirements on single system and on the fleet level (plus possible flexibility)
- Establish priorities and decision variables
- Quantify critical metrics
- Perform trade-off study incl. risk

Elements of decision support systems

Fleets of different assets (being composed of different components) incl. their criticality

Health indicators or RULs, detection alarms (ideally including the uncertainty level)

Scheduled maintenance + inspections (e.g. due to safety requirements)

Maintenance ressources (maintenance infrastructure, tools, spare parts, logistics)

Human ressources (incl. qualification)

Missions / operational requirements

Decision support system

Performance objectives (availability, cost targets, efficiency …)

Operational schedules

Maintenance planning + schedule (grouping of several components / systems)

Personnel planning

Requirements for spare parts /logistics

Occupation of maintenance infrastructure

Performance indicators (costs, operational availability, efficiency, product quality, quality of service, etc.)

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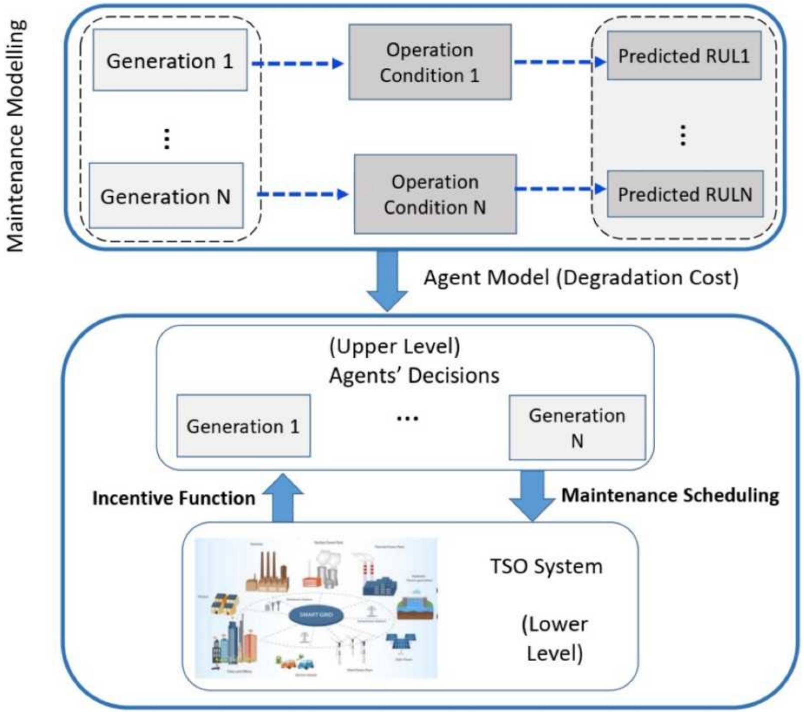
Multi-agent predictive maintenance scheduling in an electricity market



Rokhforoz, P., Gjorgiev, B., Sansavini, G., & Fink, O. (2021). Multi-agent maintenance scheduling based on the coordination between central operator and decentralized producers in an electricity market. *Reliability Engineering & System Safety*, *210*, 107495.

Business models

Possible business models in predictive maintenance

- Sensors a service
- Subscription
- Performance based contracting
- Pay per use
- Guaranteed availability
- Freemium
- Add-on
- Solution provider