Annual scientific seminar

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Maintenance planification based on imperfect condition monitoring for distributed infrastructures

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Chair Risk and Resilience of Complex Systems

Outlines

1. The maintenance problem: motivation, description and challenges
2. A quick overview of the *1-item* easy problem and results
3. A heuristic decomposition method for solving the *N-items* problem
4. Case study and encouraging results
5. Conclusion (limitations, future possible extensions, …)

1. The maintenance problem

Motivation, description and challenges

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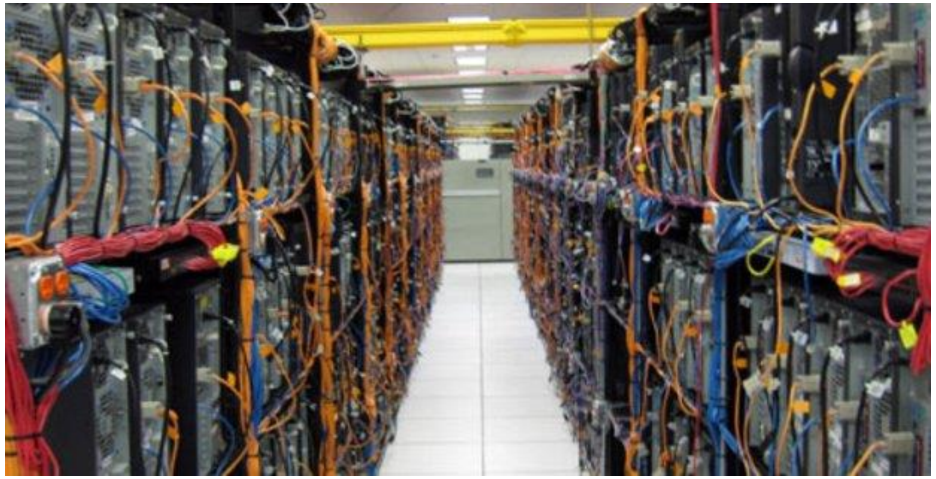
Motivation for the study of fleet systems

Definition: **fleets** are distributed systems composed of many units that function and degrade independently

Objective: optimize **condition-based maintenance (CBM)** strategies

EDF

SNCF



Orange

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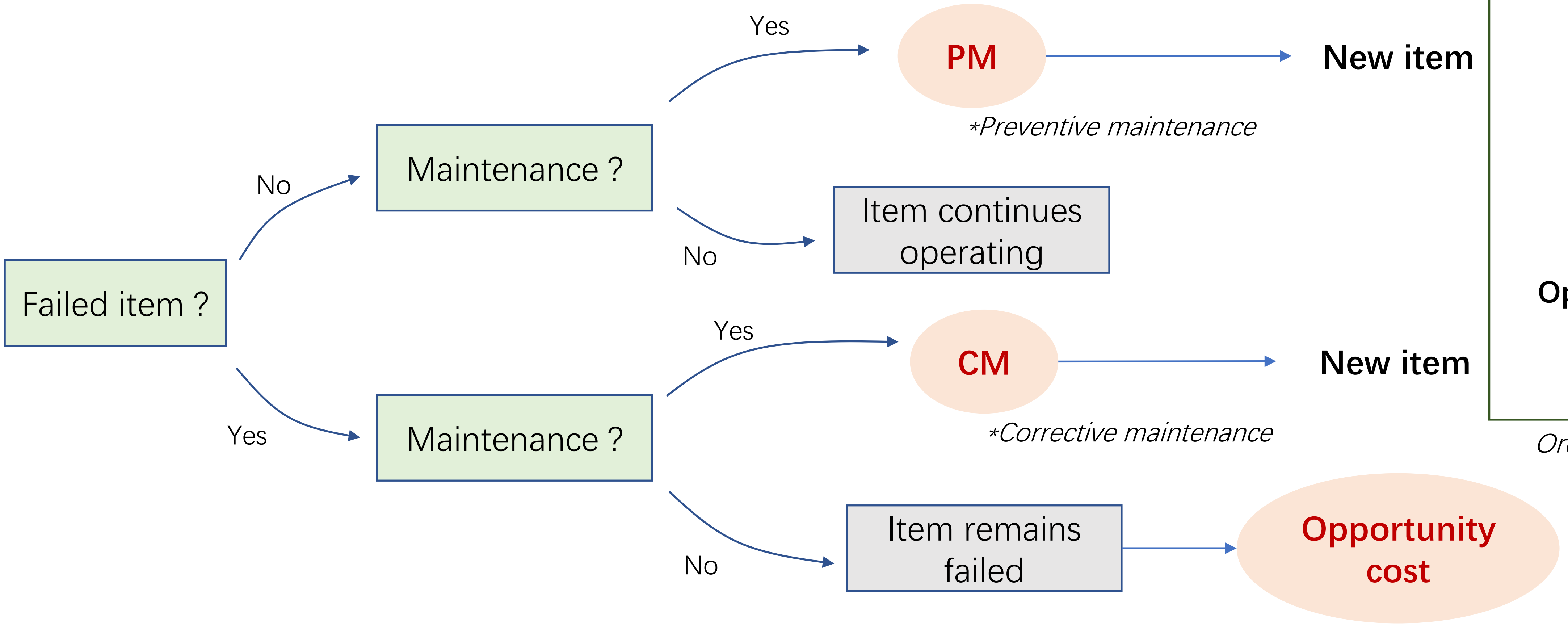
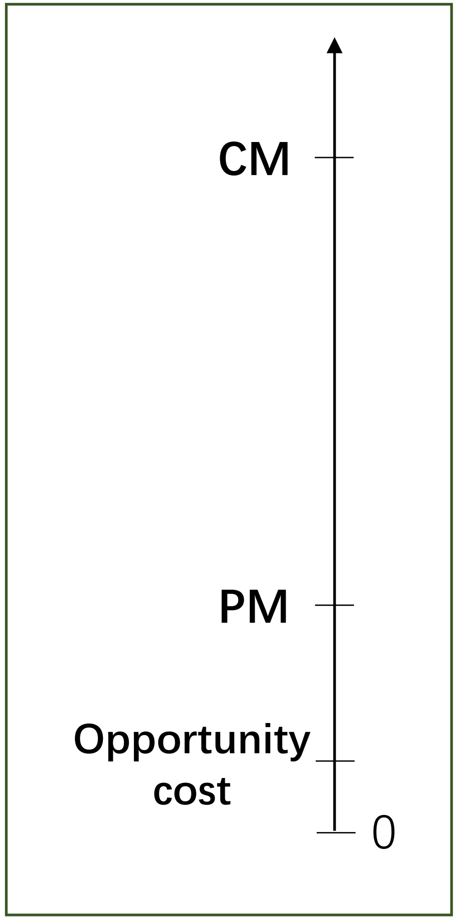
Basic maintenance decisions





Orders of magnitude

Imperfect condition monitoring

How should we adapt CBM strategies to imperfect monitoring ?

- Usually, **inspections** can be considered **perfect** (i.e., infer accurately the degradation state of the item)

- However, for different reasons, a **condition monitoring system** may inacurately estimate the state of an item
  - Failing sensors
  - Noise in the captured signal
  - Aggregation of numerous and undirect data via AI algorithms…

Imperfect condition monitoring

How should we adapt CBM strategies to imperfect monitoring ?

- ❑ Usually, **inspections** can be considered **perfect** (i.e., infer accurately the degradation state of the item)

→ Conducted by human technicians

- ❑ However, for different reasons, a **condition monitoring system** may inacurately estimate the state of an item
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Imperfect condition monitoring

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→ Information collected + analyzed by automated systems
- Remote sensors
- Interpretation

Imperfect condition monitoring

How should we adapt CBM strategies to imperfect monitoring ?

- Usually, **inspections** can be considered **perfect** (i.e., infer accurately the degradation state of the item)

Costly and **accurate**

- However, for different reasons, a **condition monitoring system** may inacurately estimate the state of an item
  - Failing sensors
  - Noise in the captured signal
  - Aggregation of numerous and undirect data via AI algorithms…

Cheap but **error-prone**

1) How to leverage efficiently this imperfect monitoring information ?

2) What is the value of information collected by the imperfect monitoring system ?

Our objective: cost minimization…

A cost-centered maintenance problem → non-critical system

3 types of cost

Individual intervention cost	Perfect inspection (**I**) Preventive maintenance (**PM**) Corrective maintenance (**CM**)
Individual opportunity cost	Cost paid when an item remains failed
System cost	E.g., deployment cost, setup cost Cost paid each time one or more interventions are performed

Individual cost: because can directly be attributed to a specific item

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...with a resource constraint

→ Because **resources are limited**, we limit the number of interventions that can be executed at each time step.

Offshore wind turbines require a specific material to be maintained (boats, helicopters, etc...)

The number of technicians is often limited

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Summary of our maintenance problem

A distributed infrastructure composed of many independent units

- Units degrade over time
- consider preventive maintenance actions

Large-scale system

Condition-based maintenance (CBM) framework

- imperfect online condition monitoring (inaccurate but « free » information)
- perfect inspections (costly + require resource)

Objective : minimize cost

- interventions costs
- opportunity costs
- system-level cost

Coupling cost

Constraint

- interventions require some amount of resource
- limited resource is available for the whole fleet at each time step

Coupling constraint

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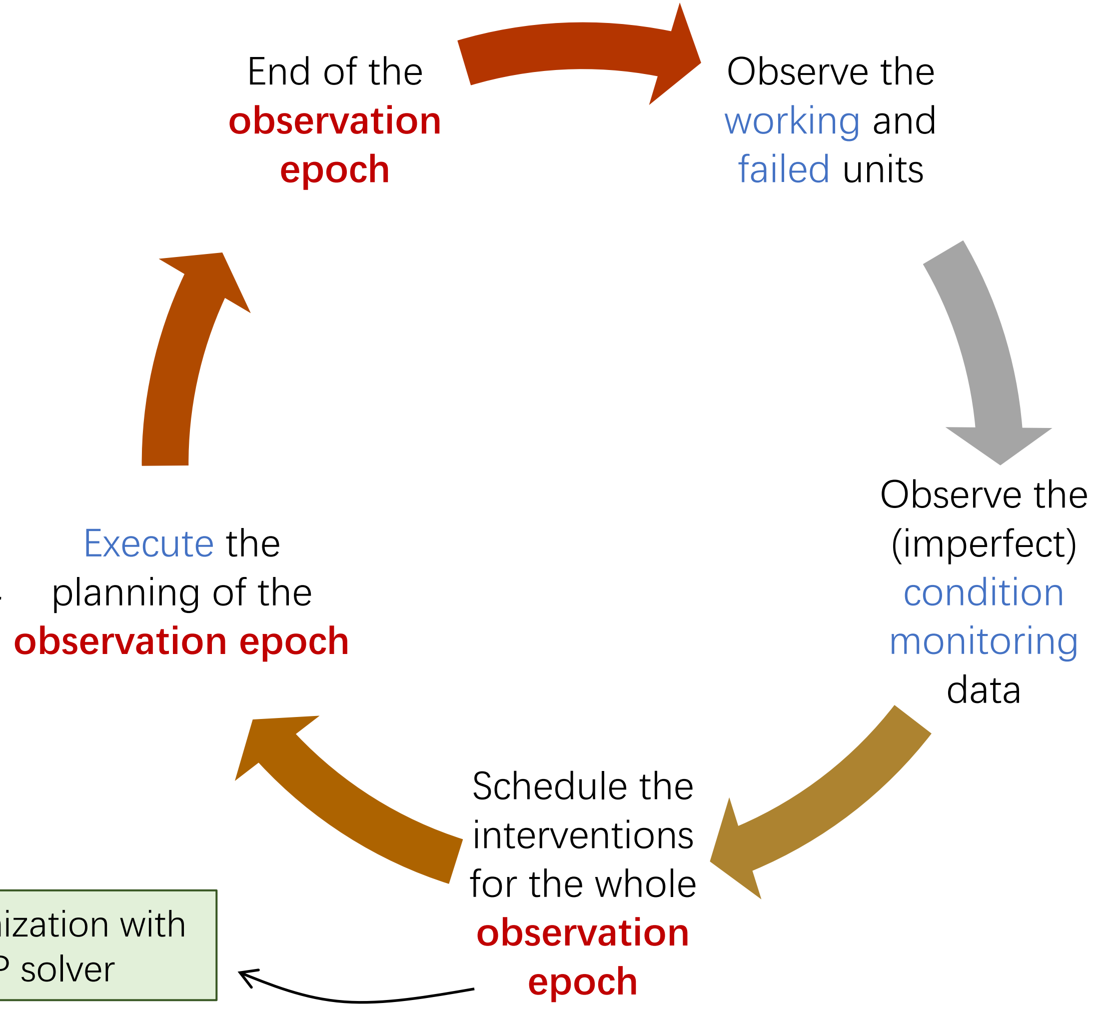
The decision process

How do we schedule interventions ?

A sequential decision-making process



Update the *belief* about each unit's state

The schedule is compute by *blocks* mainly for operational reasons

Optimization with a MILP solver

2. A quick overview of the easy 1-item problem and results

What if we only have 1 unit in the system ?

With only 1 item, the problem becomes much easier

1. No combinatorial explosion

✓ The sizes of the state and action space remain small

2. The resource is not a limitation

✓ Maintenance resource is not shared nor scarce anymore

3. No opportunistic maintenance consideration

✓ Only 1 item in the system

Such problem can be modeled as a **Partially Observable Markov Decision Process (POMDP)**, and solved efficiently via approximate dynamic programming using modern solvers.

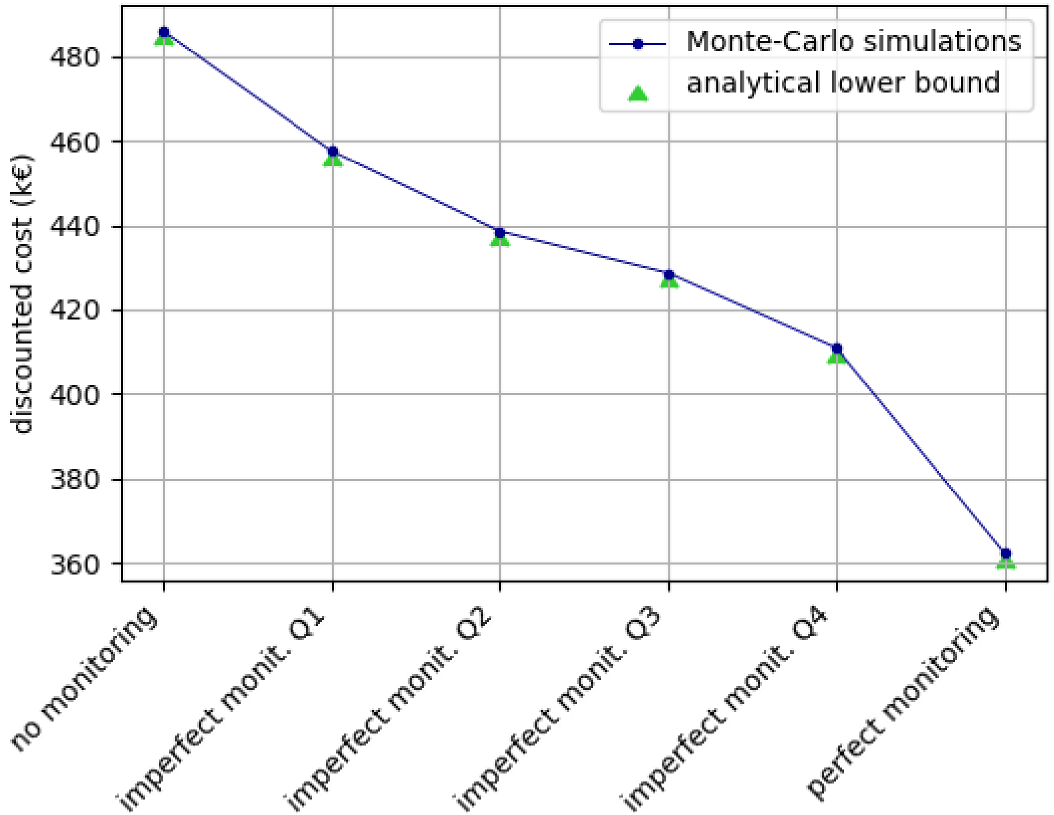
State-of-the-art point-based approximations: [1]

- Point-based value iteration
- SARSOP
- Perseus

[1] Kıvanç, İ., Özgür-Ünlüakın, D., & Bilgiç, T. (2022). Maintenance policy analysis of the regenerative air heater system using factored POMDPs. *Reliability Engineering & System Safety*, *219*, 108195.

Example on a simple case study

How much value can we expect to save ?



Definition of the VoI given by **Memarzadeh, 2016** [2]

- "*VoI is a utility-based metric related to decision making under uncertainty, and it measures the expected benefit due to the availability of a piece of information.*"
- "*The value of information is the maximum cost a decision-maker is willing to pay for getting this information*"

- **Value of information** = gap with the 'no monitoring' situation

[2] Memarzadeh, M., & Pozzi, M. (2016). Value of information in sequential decision making: Component inspection, permanent monitoring and system-level scheduling. Reliability Engineering & System Safety, 154, 137-151.

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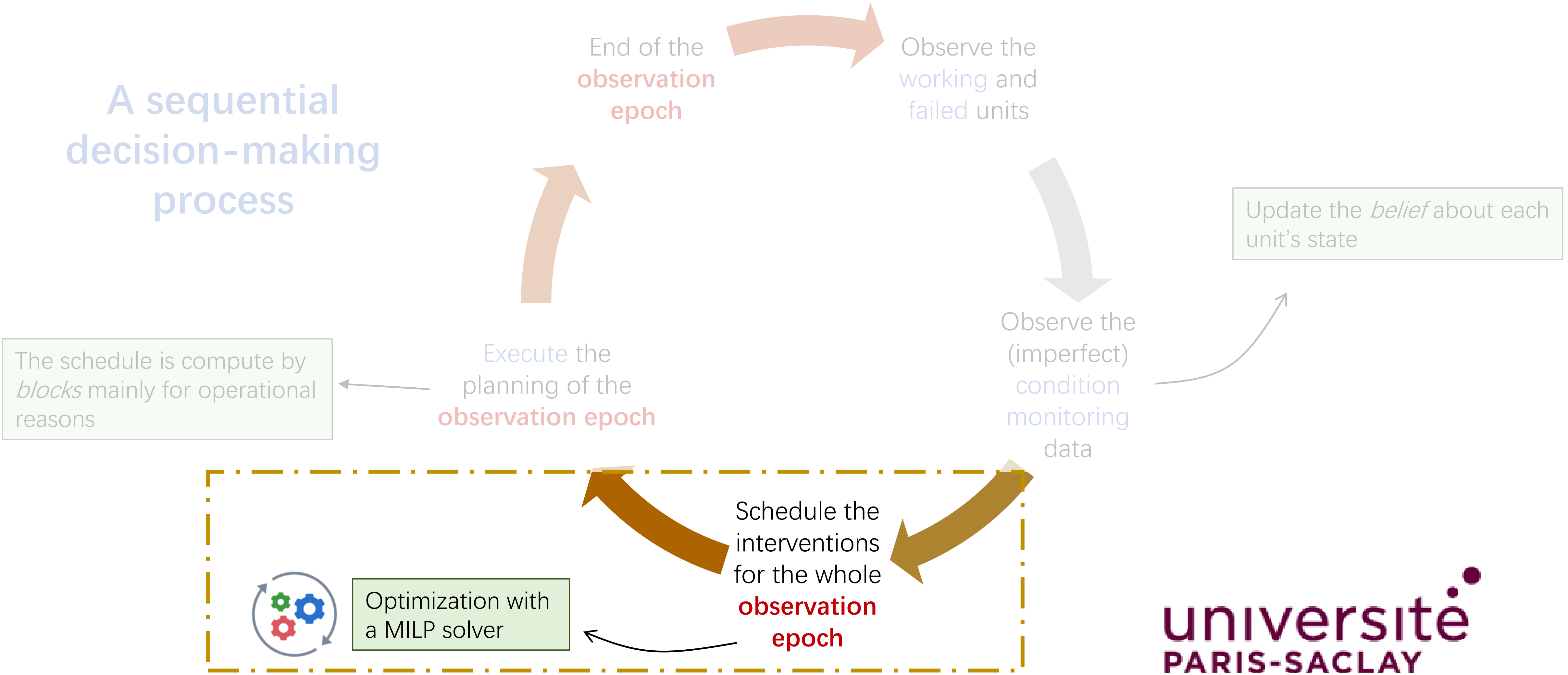
3. A heuristic decomposition method for solving the N-items problem

Impossible to generalize the POMDP solving method to large-scale systems!

Reminder of the decision process

How do we schedule interventions ?



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Optimization procedure using an (heuristic) ILP formulation

$$\min_{x,z} \sum_{t=0}^{T-1} \delta^t \cdot cost_{deploy} \cdot x_t + \sum_{i \in I_w} C_w(z_i) + \sum_{i \in I_f} C_f(z_i)$$

Immediate system costs (within the current observation epoch)

Immediate individual costs resulting from decision z + expected future costs

$$x_t \in \{0,1\}$$

$$z_{i,t}^a \in \{0,1\}$$

$$z_i^{NA} \in \{0,1\}$$

$$z_{i,t}^a \leq x_t$$

$$\sum_a \sum_i z_{i,t}^a \leq R$$

$$C_f(z_i) = \sum_{t=0}^{T-1} z_{i,t}^{CM} \cdot Q('F', t, CM) + z_i^{NA} \cdot Q('F', NA)$$

$$C_w(z_i) = \sum_{t=0}^{T-1} (z_{i,t}^{PM} \cdot Q(b_i, t, PM) + z_{i,t}^I \cdot Q(b_i, t, I)) + z_i^{NA} \cdot Q(b_i, NA)$$

Using the Q functions from the 1-item POMDP, we define
$\boldsymbol{Q(b,t,a)}$**:** expected cost of scheduling action a at time t for an item that is initially in a belief b, and then applying the 1-item optimal policy.

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How to design « good » cost functions ?

1. Use the **Q-function** of 1-item POMDP with only individual costs

2. Same but take into account the full deployment cost

3. Something else: modify the 1-item POMDP model to try to model approximately the **interaction** between *unit i* and the *rest of the fleet*

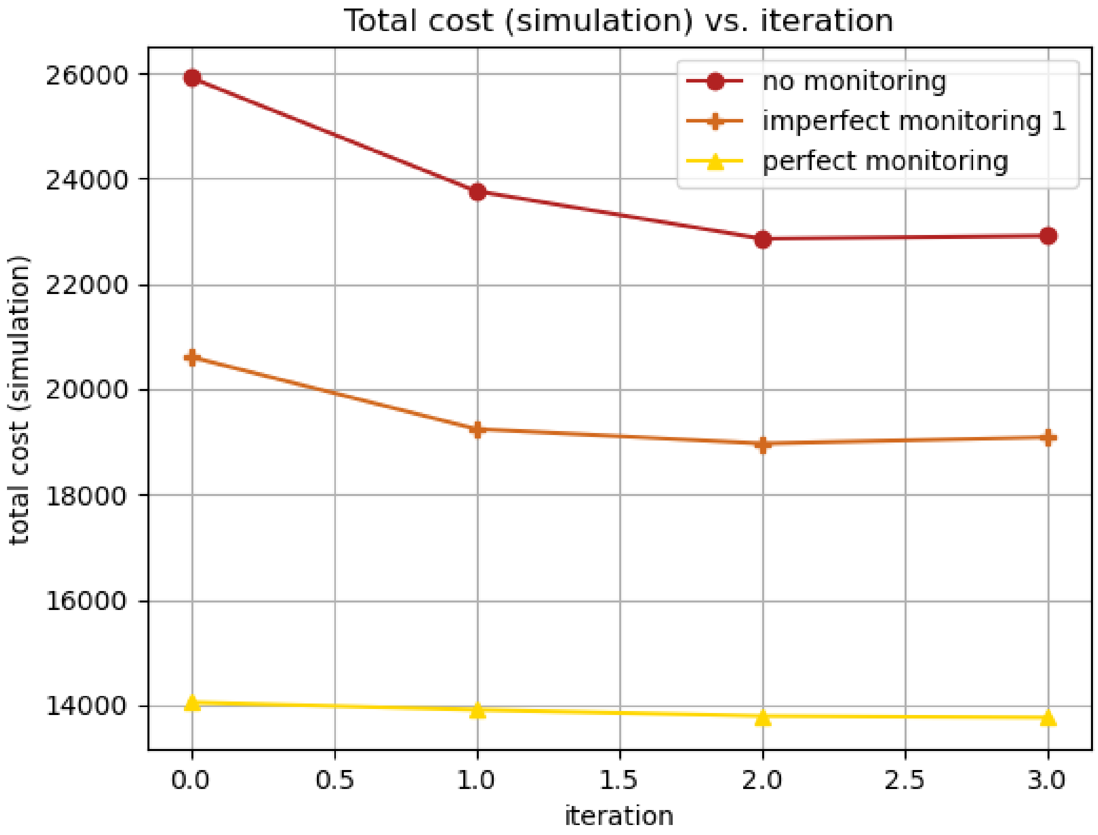
Expected future costs are very dependent on:
- The availability of the maintenance resource
- How much interventions tend to be opportunistically grouped

→ Should be included, somehow, in a **modified 1-item POMDP**

4. Case study and encouraging results

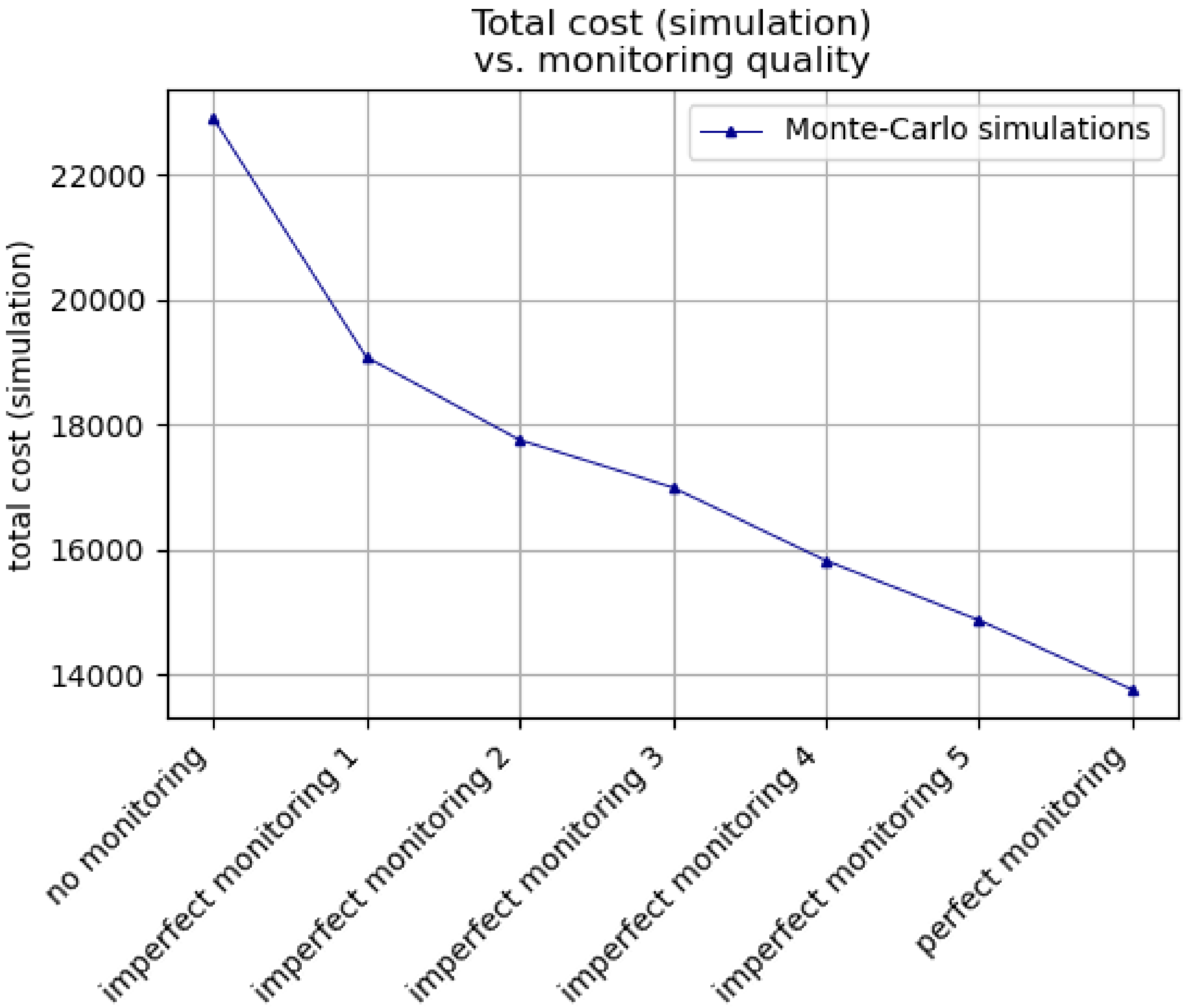
1) Our iterative procedure seems to converge

Converge towards a « low-cost » (good ?) solution



2) VoI provided by the monitoring system

Our heuristic procedure seems to capture this expected pattern: better monitoring systems lead to lower-cost solutions



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3) Comparison with simpler alternatives

Our modified 1-item POMDP seems to be relevant within this decomposition framework

	Our proposed method	Full deploy. Cost	Zero deploy. Cost
No monitoring	22,920	+10.3%	+13.9%
Imperfect monitoring 1	19,090	+8.0%	+23.3%
Imperfect monitoring 2	17,760	+7.6%	+26.6%
Imperfect monitoring 3	17,000	+6.9%	+29.5%
Imperfect monitoring 4	15,830	+4.7%	+35.2%
Imperfect monitoring 5	14,870	+3.4%	+41.4%
Perfect monitoring	13,760	+2.1%	+55.8%

5. Conclusion

Limitations and potential future extensions

Some limitations to my current work

Elements that could be incorporated for a more realistic model:

- **External factor** impacting the cost or the availability of the resource (such as the weather conditions limiting interventions)
- **Interventions duration** could be refined
- Schedule some interventions way more in advance (**delay**)
- Dynamically **adjust the planning** to any unexpected situation
- **Heterogeneous fleet**
- Consider the **sub-components** of each unit (fleet as a system of systems)