Estimating Maintenance Cost of Offshore Electrical Substations

IFORS 2026

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13/07/26

Le réseau de transport d'électricité

CERMICS
École nationale des ponts et chaussées

IFORS 2026
The 24th Conference of the International Federation of Operational Research Societies
12-17 JULY
VIENNA, AUSTRIA

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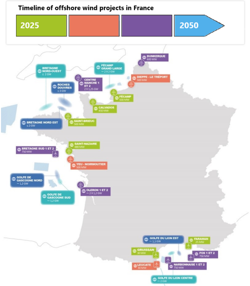
Context

Offshore wind is growing.



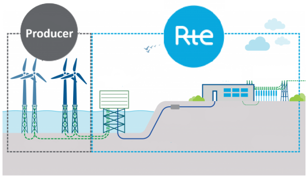
Source: RTE - 2024

France wants to promote offshore wind farms.

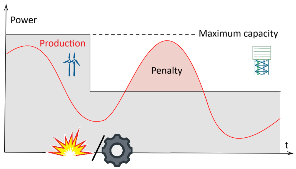
- Attractive conditions for producers.

From the TSO perspective:

- Penalties apply to curtailed energy exceeding the contractual maintenance days quota.



Source: RTE



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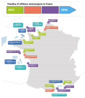

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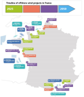
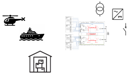


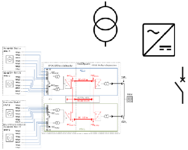
Estimating maintenance cost to make informed strategic choices now.



Estimating maintenance cost to make informed strategic choices now.

transport

storage



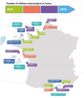
Source: TenneT

substation design

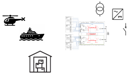
- Strategic choices must account for 40-year maintenance costs.

Context

Offshore wind is growing.



Estimating maintenance cost to make informed strategic choices now.



Estimating maintenance cost is challenging.

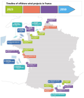
Estimating maintenance cost is challenging.

Source: RTE - PSEM Calvados

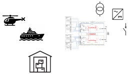
- Substations are 50/100 miles offshore.
- Logistics and ancillary tasks take a lot of time.

Context

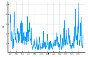
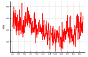
Offshore wind is growing.



Estimating maintenance cost to make informed strategic choices now.



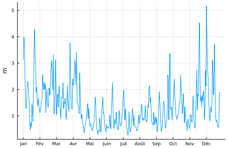
Estimating maintenance cost is challenging.

Estimating maintenance cost is challenging.

Two weather-related uncertainties:

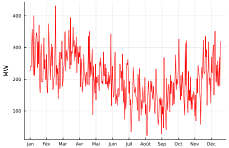
Accessibility



Source: Copernicus

Daily average **wave height**
(Baie de Saint-Brieuc - 2023)

Production



Source: RTE

Daily average offshore wind farm **production**
(Baie de Saint-Brieuc - 2023)

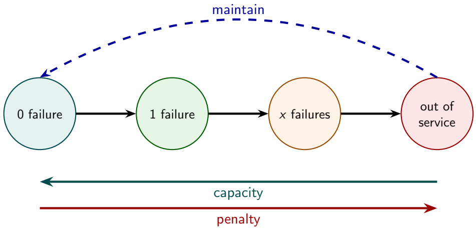
- Accessibility depends on wave height.
- Penalties are proportional to curtailed energy.

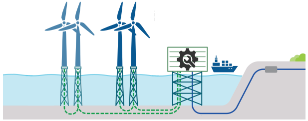
Objective

Estimate the maintenance cost resulting from offshore substation design choices by optimizing maintenance operations under uncertainty.

Offshore maintenance cost estimation is new to RTE

- This problem is new to RTE and, to our knowledge, new to the literature.
- A Markov Decision Process (MDP) formulation is natural: states represent different levels of capacity loss, and thus different penalty levels.
- In this talk, we focus on the maintenance of a single substation.





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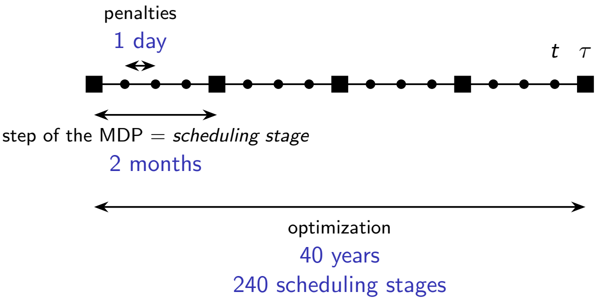
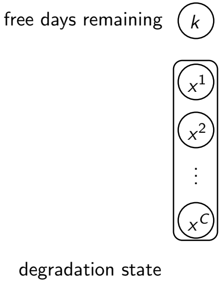
Temporal structure

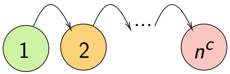
- Decisions are taken every two months.
- The penalties are computed at a daily time step.



MDP: state

The station consists of C components.





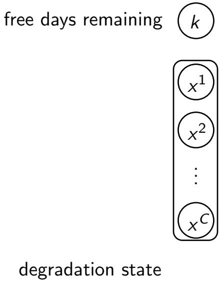
Global degradation state

$$x = (x^c)_{c \in [1:C]} \in \bigotimes_{c \in [1:C]} [1 : n^c].$$

$\prod_{[1:C]} n^c$ possible degradation states.

➥ Curse of dimensionality.

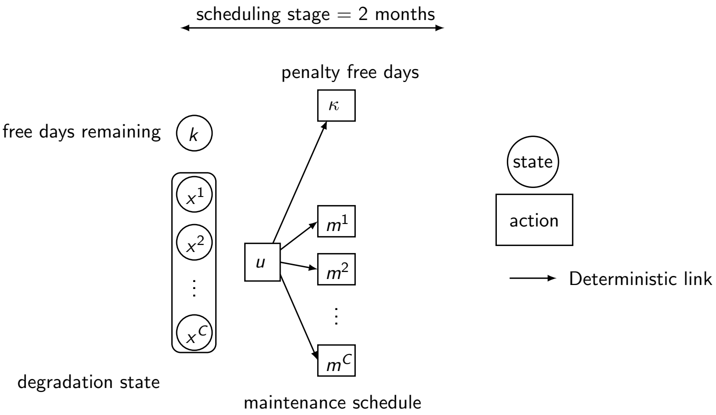
MDP: state



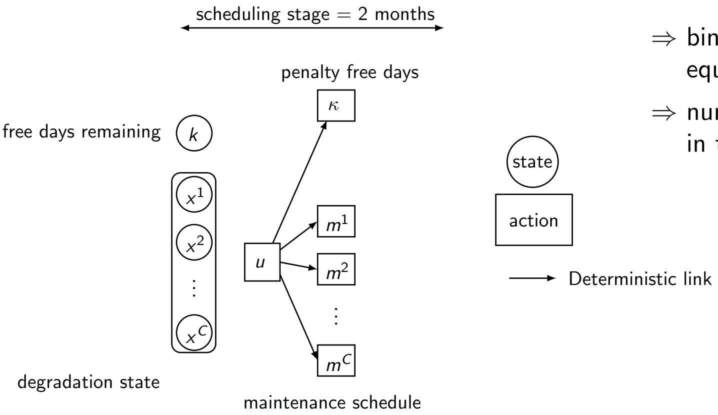
MDP: actions

Global maintenance schedule u

➥ Combinatorial object.



MDP: actions



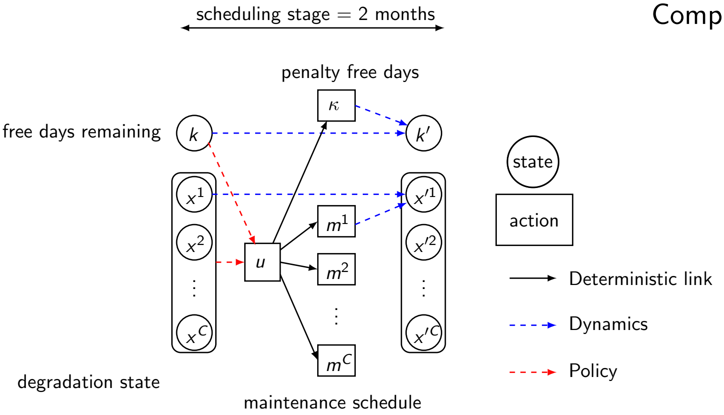
Global maintenance schedule u

➥ Combinatorial object.

⇒ binary variable m^c for $c \in [1 : C]$, equals 1 if c is maintained.

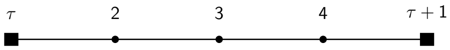
⇒ number of penalty free days used in the scheduling stage κ.

MDP: transitions



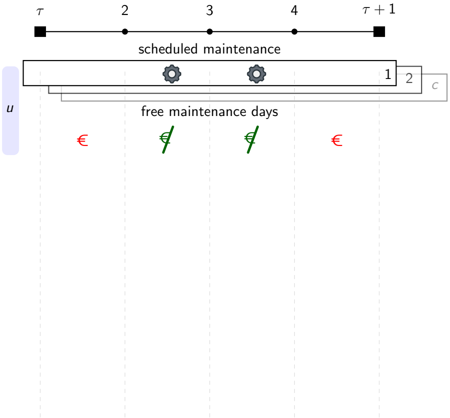
Components degrade independently.

Cost and dynamics over a scheduling stage (= 2 months)



A *scheduling stage* τ is divided into daily time steps $t \in [1 : \bar{t}]$.

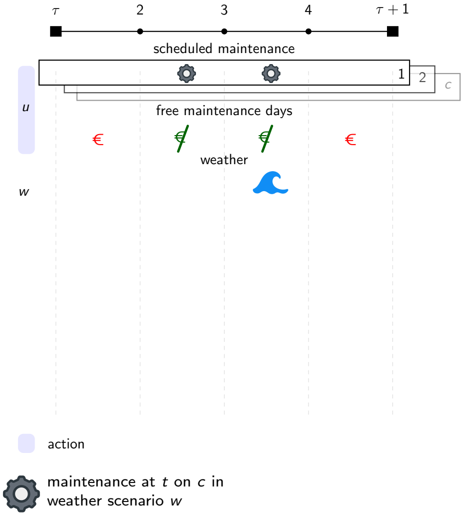
Cost and dynamics over a scheduling stage (= 2 months)



action

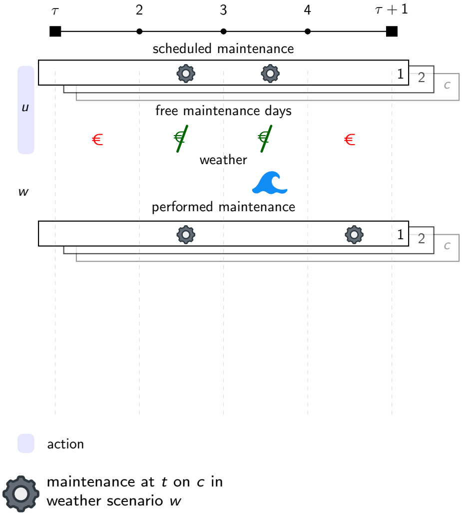
maintenance at t on c in weather scenario w

Cost and dynamics over a scheduling stage (= 2 months)

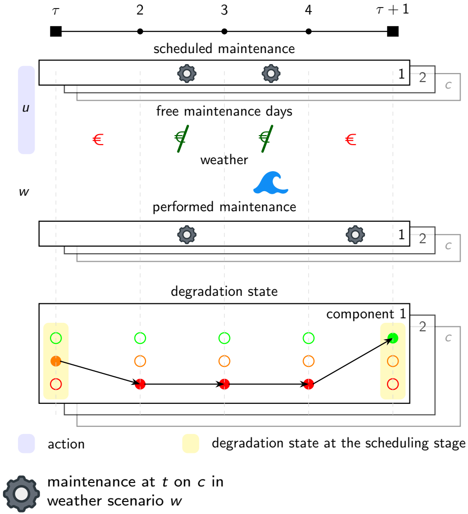


Weather scenario $w \in \mathbb{W}_\tau$.

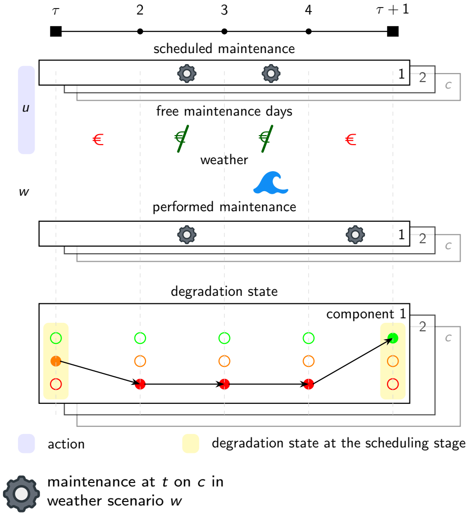
Cost and dynamics over a scheduling stage (= 2 months)



Cost and dynamics over a scheduling stage (= 2 months)



Cost and dynamics over a scheduling stage (= 2 months)



$$c_\tau(x,u) = \frac{1}{|\mathbb{W}_\tau|}\sum_{w\in\mathbb{W}_\tau} \overbrace{\text{penalty}(u,\ w,\ x)}^{\text{curtailed energy on non-penalty-free days in scenario } w} + \underbrace{\text{maintenance cost}(u)}_{\text{fixed cost per maintained component}}$$

➥ The cost does not decompose by component.

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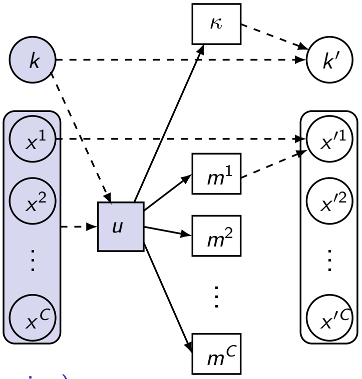
Linear Programming (LP) for MDPs

- The size of the state space prevents solving by dynamic programming.

- We can write an LP formulation in which the variables represent the probabilities of the values taken by the global (state, action) pair at each time step.



$$\text{minimize}_{\text{proba}} \sum_{\tau} \sum_{\text{state,action}} \text{cost}_\tau(\text{state}, \text{action}) \times \text{proba}_\tau(\text{state}, \text{action})$$

$$\text{s.t.} \quad \text{Flow constraints}$$

$$\text{proba}_\tau(\text{state}, \text{action}) \geq 0$$

The number of variables grows with the number of possible state/action pairs.

From exact LP to column generation

Exact LP

Variables = probabilities over global (state, action) pairs

↓ independent components

Approximate LP

Exploit the structure of the bayesian network

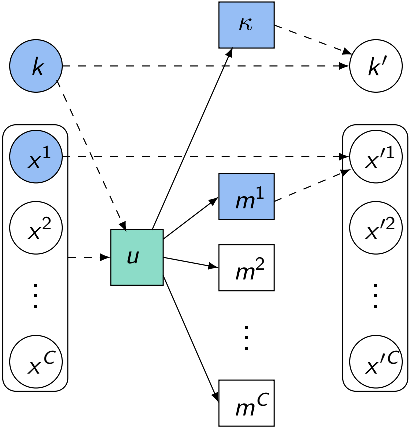
Variables = probabilities over local (state^c, action^c) pairs and schedules u

↓ too many schedules

Column generation

Solve over a small set of schedules

Add new ones via pricing

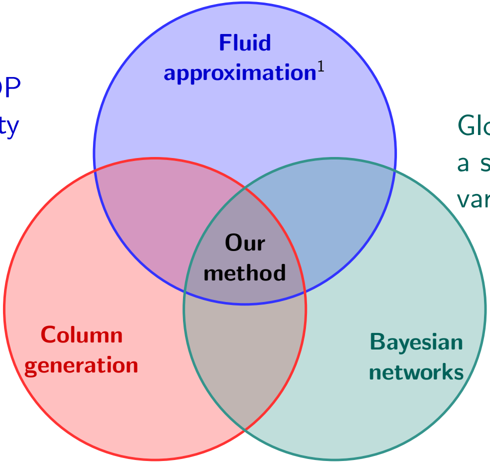


Three difficulties, three approaches

Multi-component MDP
Curse of dimentionality

Global cost approximated as a sum of terms over small variable subsets

Combinatorial actions



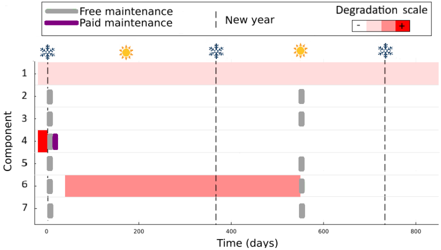
[1] Bertsimas and Mišić 2016.

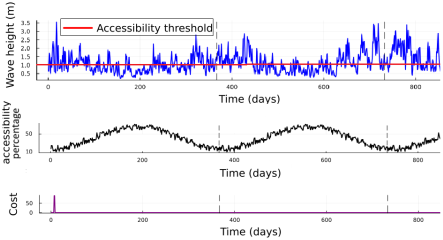
Case study

- **7** key High-Voltage Direct Current (HVDC) components.
- Weather scenarios corresponding to the upcoming **Centre Manche 1** project location, built using Copernicus data.
- Benchmark against an **operational rule**.

Table: Simulated cost over 40 years

Policy	Mean	$VaR_{0.05}$
Approximate LP	**126**	257
Operational rule	249	1671





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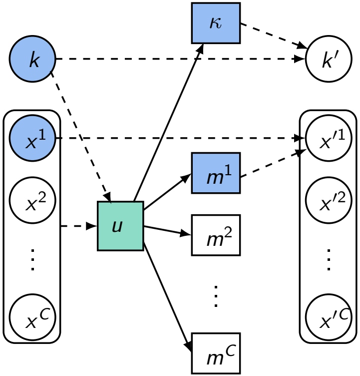
Conclusion

- Offshore substation maintenance can be modeled as a **multi-component MDP** with **combinatorial actions**.
- We propose a heuristic to solve this problem based on three ingredients: a **fluid Linear Programming formulation** of the problem, **Bayesian networks**, and **column generation**.
- We **estimate the penalties resulting from offshore substation design choices** by optimizing maintenance operations under uncertainty.

Thank you for listening!

Approximate LP

$$\begin{aligned}\underset{\text{proba},\text{proba}\geq 0}{\text{minimize}} \quad & \sum_t \sum_{\text{action}} \text{cost}_t(\text{action}) \times \text{proba}_t(\text{action}) \\ & + \sum_c \sum_{\text{state}^c,\text{action}^c} \text{cost}_t^c(\text{state}^c, \text{action}^c) \times \text{proba}_t^c(\text{state}^c, \text{action}^c) \\ \text{s.t.} \quad & \text{Local flow constraints;} \\ & \text{Consistency between } \mu \text{ and } \nu.\end{aligned}$$



- We introduce variables representing the probabilities of the value taken by the local $(\text{state}^c, \text{action}^c)$ pair for each component c[2].

[2] Bertsimas and Mišić 2016.

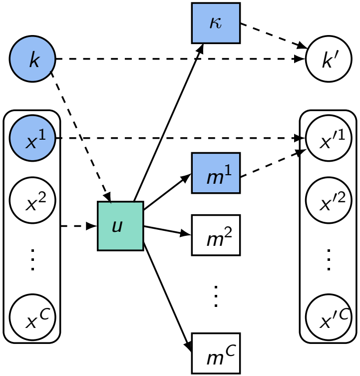
Approximate LP

$$\underset{\mu,\nu\geq 0}{\text{minimize}} \quad \sum_{t=1}^{240}\sum_{u}\tilde{c}_t(u)\nu_u(t) + \sum_{c=1}^{C}\sum_{x^c,k,m^c,\kappa}\tilde{c}_t^c(x^c,m^c)\mu^c_{x^c k m^c \kappa}(t)$$

$$\text{s.t.} \quad \sum_{m^c,\kappa}\mu^c_{x'^c k' m^c \kappa}(t) = \sum_{x^c,k,m^c,\kappa}\mathbb{1}_{\{\phi(k,\kappa)=k'\}}p^c(x'^c|x^c,m^c)\mu^c_{x^c k m^c \kappa}(t-1);$$

$$\sum_{x^c,k}\mu^c_{x^c k m^c \kappa}(t) \leq \sum_{\substack{u|M^c(u)=m^c\\K(u)=\kappa}}\nu_u(t).$$

- We introduce variables representing the probabilities of the value taken by the local (state^c, action^c) pair for each component c[2].



[2] Bertsimas and Mišić 2016.

Column generation and Rolling Horizon heuristic

Master Problem

$$\min_{\mu,\,\nu\geq 0} \quad \sum_{u\in\mathcal{U}',\,t} \tilde{c}^g_t(u)\,\nu_u(t) + \sum_{c,x^c,m^c,t} \tilde{c}^c_t(x^c,m^c)\,\mu^c_{x^c k m^c \kappa}(t)$$

s.t. flow constraint

$$\sum_{x^c,k} \mu^c_{x^c k m^c \kappa}(t) \leq \sum_{\substack{u\in\mathcal{U}':\\ M^c(u)=m^c,\,K(u)=\kappa}} \nu_u(t) \qquad [\lambda^{c,m^c,\kappa}_t].$$

Solved over restricted set $\mathcal{U}' \subseteq \mathcal{U}$

dual variables $\lambda^{c,m^c,\kappa}_t$ →

Pricing Problem

$$\min_{u\in\mathcal{U}} \; \tilde{c}^g_t(u) + \sum_c \lambda^{c,\,M^c(u),\,K(u)}_t$$

MILP over the full combinatorial set $\mathcal{U}$

← new column $u^\star$
$\overline{c}(u^\star,t) < 0$

Column generation and Rolling Horizon heuristic

Master Problem

$$\min_{\mu,\,\nu \geq 0} \sum_{u \in \mathcal{U}',\, t} \tilde{c}^g_t(u)\, \nu_u(t) + \sum_{c, x^c, m^c, t} \tilde{c}^c_t(x^c, m^c)\, \mu^c_{x^c k m^c \kappa}(t)$$

s.t. flow constraint

$$\sum_{x^c, k} \mu^c_{x^c k m^c \kappa}(t) \leq \sum_{\substack{u \in \mathcal{U}': \\ M^c(u) = m^c,\, K(u) = \kappa}} \nu_u(t) \quad [\lambda^{c, m^c, \kappa}_t].$$

Solved over restricted set $\mathcal{U}' \subseteq \mathcal{U}$

dual variables $\lambda^{c, m^c, \kappa}_t$

Pricing Problem

$$\min_{u \in \mathcal{U}} \tilde{c}^g_t(u) + \sum_c \lambda^{c,\, M^c(u),\, K(u)}_t$$

MILP over the full combinatorial set $\mathcal{U}$

new column $u^\star$

$\overline{c}(u^\star, t) < 0$

Rolling Horizon heuristic

1. Fix the first-stage distribution to the current state.
2. Solve the LP over a cropped horizon.
3. Apply the highest-probability action: $a^\star = \arg\max_{\text{action}^g} \text{proba}_1(\text{action}^g)$.