Estimating Maintenance Cost of Offshore Substations under Uncertainty

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Rte Le réseau de transport d'électricité

CERMICS École nationale des ponts et chaussées

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Estimating Maintenance Cost of Offshore Substations under Uncertainty

Context

Key assumptions for modeling maintenance under uncertainty

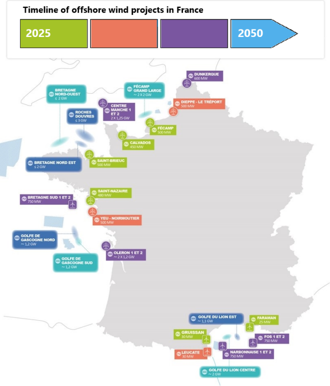
Model

Lack of reliability data leeds to model ambiguity

Takeaways

Context

Offshore wind is growing.

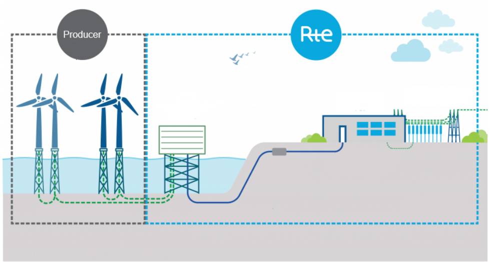


Source: RTE - 2024

France wants to promote offshore wind farms.
→ Attractive conditions for producers.

From the TSO perspective:

- Penalties proportional to curtailed energy.
- Contractual quota of free maintenance days.



Source: RTE

Context

Increasing of offshore wind farms.

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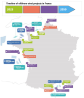
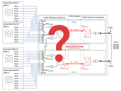


Estimating maintenance cost to make informed strategic choices.



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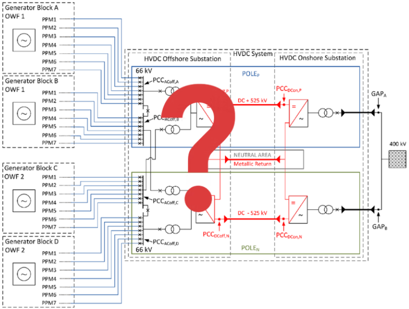


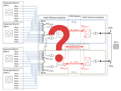
Source: TenneT

The TSO has to choose between different substation designs.
→ Maintenance cost must be taken into account.

Context

Increasing of offshore wind farms.

Estimating maintenance cost to make informed strategic choices.



Estimating cost is challenging.

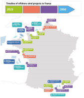
Estimating cost is challenging.

Source: RTE - PSEM Calvados

- Substations are 50/100 miles offshore.
- Workers may or may not sleep at location.
- 2 hours of effective work per day vs. 7 hours on land.

Context

Increasing of offshore wind farms.



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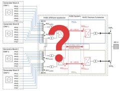

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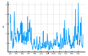

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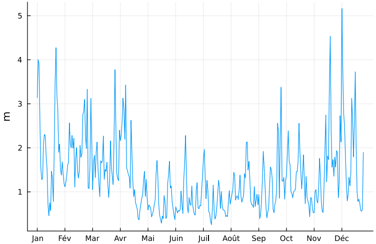


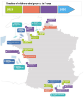
Source: Copernicus

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

If waves are too high, access to the substation is impossible.

Context

Increasing of offshore wind farms.



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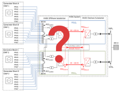

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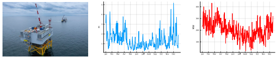

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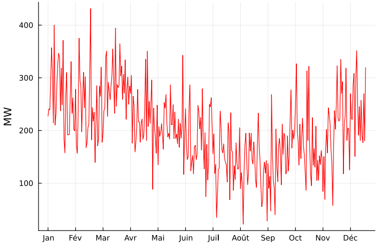


Source: RTE

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

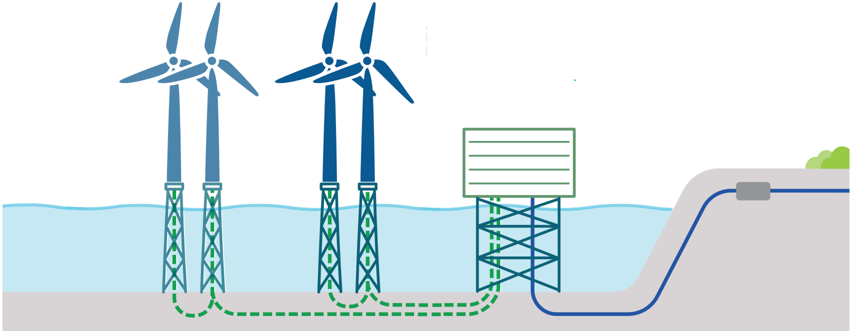
Penalties are proportional to curtailed energy.

Estimating Maintenance Cost of Offshore Substations under Uncertainty

- Context
- Key assumptions for modeling maintenance under uncertainty
- Model
- Lack of reliability data leeds to model ambiguity
- Takeaways

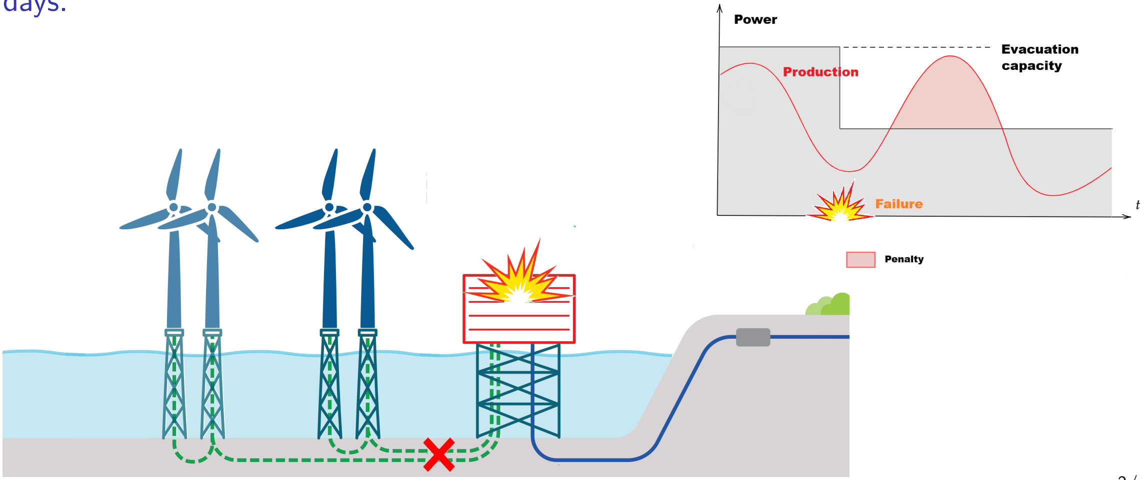
We want to estimate the penalties incurred by strategic choices under uncertainty.

Assumption 1: A single substation is considered, with no interaction with others substations.



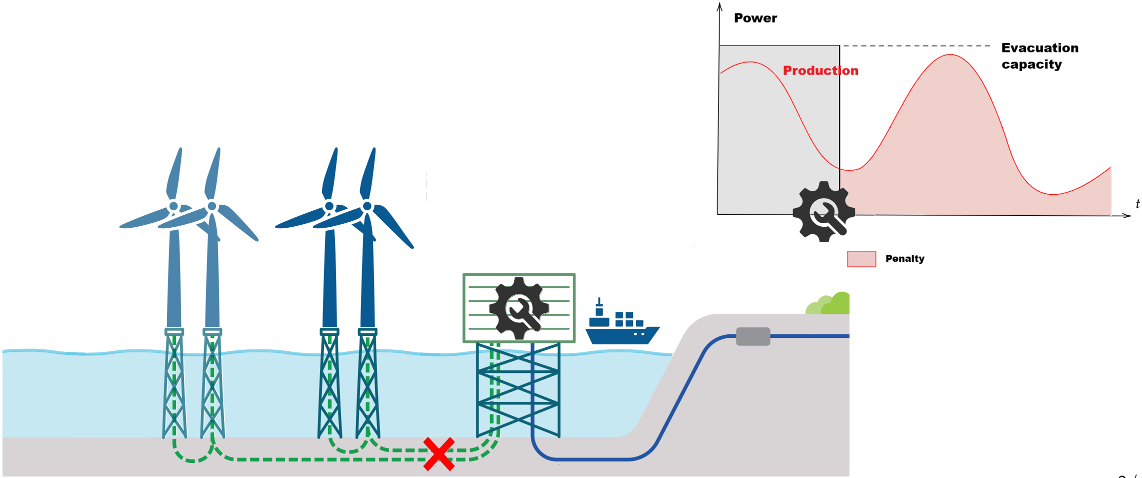
We want to estimate the penalties incurred by strategic choices under uncertainty.

Assumption 2: Penalties are proportional to curtailed energy outside free maintenance days.

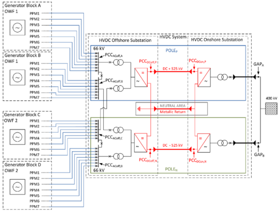


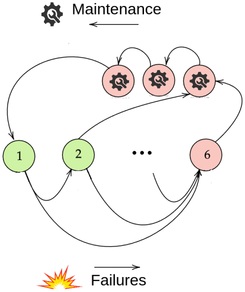
We want to estimate the penalties incurred by strategic choices under uncertainty.

Assumption 3: All maintenance operations require the substation to be shut down.



Assumption 4: Substation maintenance is a Markov Decision Process (MDP) that depends on strategic choices.





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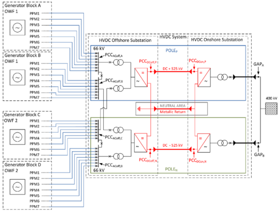
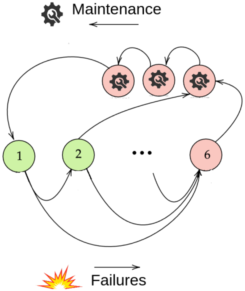


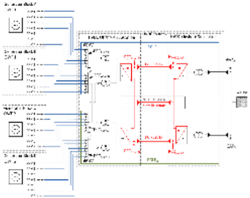


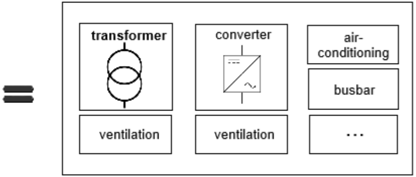
MDP with

- → state $s \in \mathcal{S}$ describing the substation;
- → control = maintenance decisions $u \in \{0;1\}^{\mathcal{C}}$ where $\mathcal{C}$ is a set of components;
- → transition matrices $P^u \in \mathbb{R}^{\mathcal{S}\times\mathcal{S}}$ where $P^u_{s,s'} = \mathbb{P}(s'|s,u)$, s' is next state;
- → transition cost = penalty.

Degradation model

A substation is a set of components.





transformer

ventilation

converter

ventilation

air-conditioning

busbar

...

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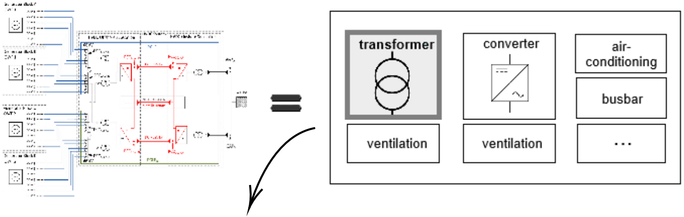
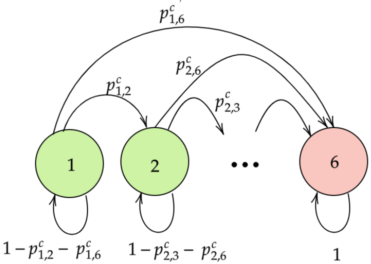


Each component is associated with a *degradation model.*

→ Discrete-time Markov chain.
→ Time step = 1 day.



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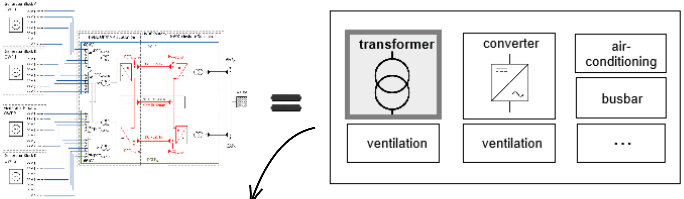

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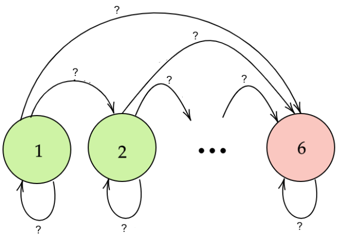

Parameters estimation using standard libraries, leveraging:

→ Manufacturer data:
Mean Time Between Failure (MTBF);

→ Expert knowledge:
Aging; standard reliability laws; number of states.

Degradation model

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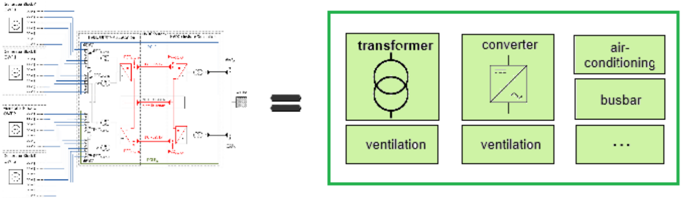

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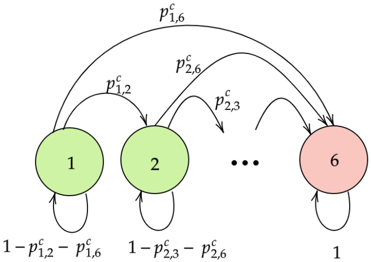

The evacuation capacity depends on component degradation.

$$C((x^c_t)_{c\in\mathcal{C}}, \qquad)$$

↙ degradation of c

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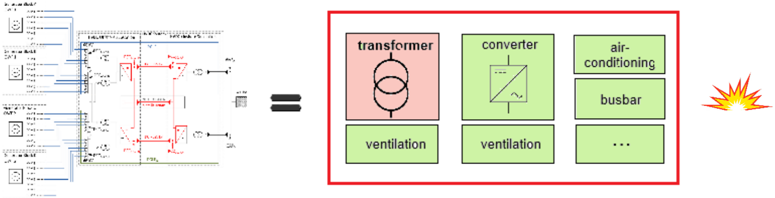

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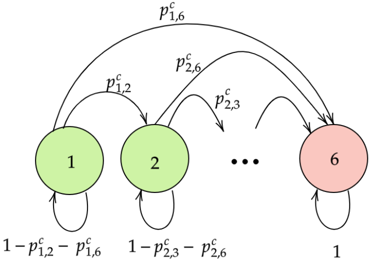

The evacuation capacity depends on component degradation.

$$C((x_t^c)_{c\in\mathcal{C}}, \qquad\qquad)$$

degradation of c

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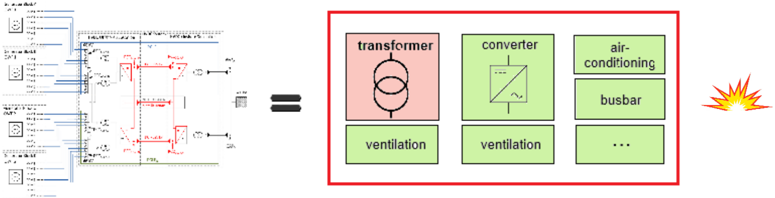

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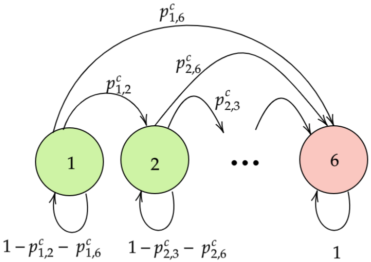

The evacuation capacity depends on component degradation and maintenance.

$$C\Big(\overbrace{(x_t^c)_{c\in\mathcal{C}}, (d_t^c)_{c\in\mathcal{C}}}^{=s_t}\Big)$$

degradation of c

ongoing maintenance days on c

Assumption 5: Weather dependent electricity production and substation accessibility.

weather scenario $w \in \mathcal{W} = (p_t^w, h_t^w)_{t \in [0:H]}$

production $\in \mathbb{R}^+$

accessibility $\in \{0; 1\}$

time step = 1 day, horizon H

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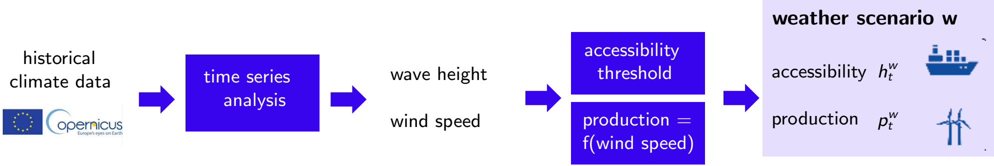

historical climate data

time series analysis

wave height

wind speed

accessibility threshold

production = f(wind speed)

weather scenario w

accessibility h_t^w

production p_t^w

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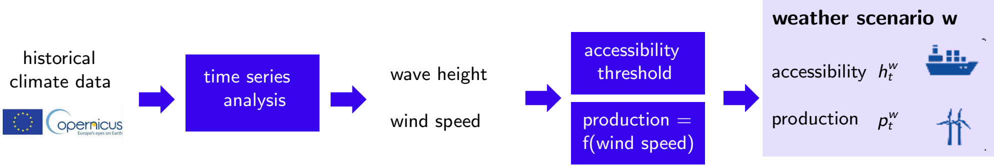

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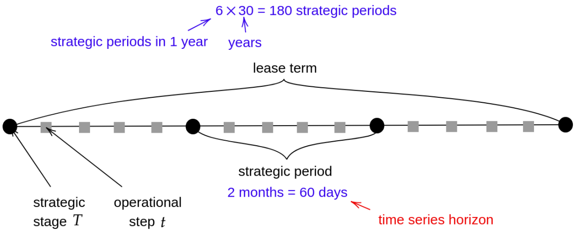
accessibility h_t^w

production p_t^w

$\rightarrow$ Penalties $= \mathbb{1}_{\{t \notin \mathcal{T}^{\text{free}}\}} (p_t^w - C(s_t^w))^+$ where $\mathcal{T}^{\text{free}}$ = free maintenance days

Assumption 6: Maintenance must be scheduled in advance, at the start of each two-month period, to use quotas and mobilize the necessary resources.

We introduce *strategic stages* and *strategic periods* of **two months** to model maintenance decisions and *operational time steps* of **one day** to model degradation and weather.



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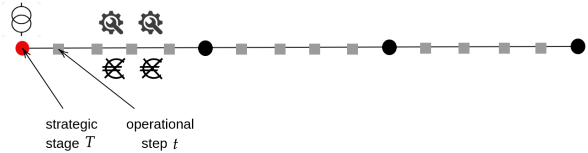

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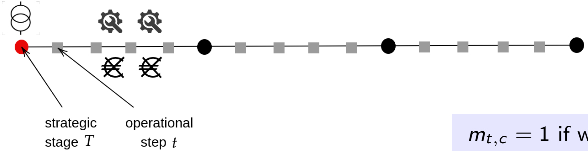

$m_{t,c} = 1$ if we want to start maintenance at t on component c.

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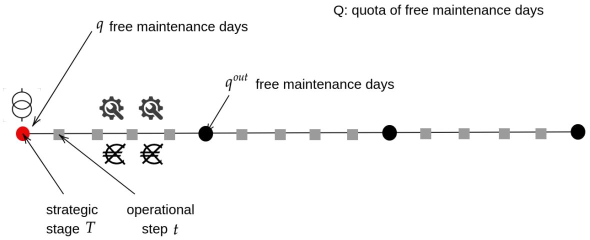
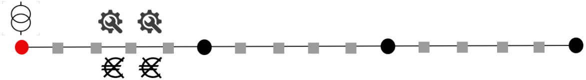


- $\boldsymbol{m} = (m_{t,c})_{t,c} \in \{0,1\}^{60 \times \mathcal{C}}$ *maintenance schedule*;
- $\mathcal{T}^{\text{free}} \subset [1:60]$ *set of free maintenance days*;
- Q number of free maintenance days available for the lease term for all components (coupling variable).

Assumption 7: Any maintenance operations scheduled at the beginning of the strategic period must be carried out.

Strategic decisions are taken without any knowledge of accessibility.



Strategic maintenance decisions

We introduce a recourse variable.

- $\boldsymbol{u}^w = (u_t^w)_t \in \{0,1\}^{\mathcal{C} \times 60}$ *operational maintenance* in weather scenario w.

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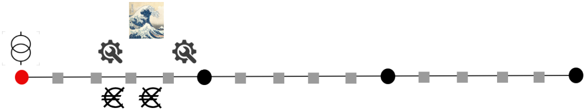

Operational maintenance

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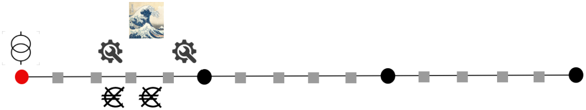

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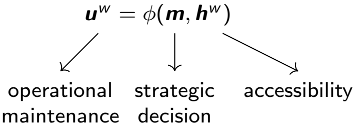
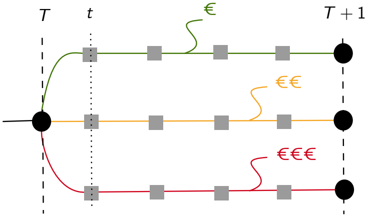
The recourse variables follow the following deterministic rule:
ϕ: "Maintain at the earliest opportunity from the desired start date."



$\boldsymbol{u}^w = \phi(\boldsymbol{m}, \boldsymbol{h}^w)$

Cost over a strategic period



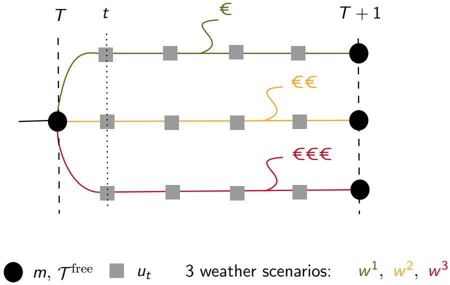
● m, $\mathcal{T}^{\text{free}}$ ■ u_t 3 weather scenarios: w^1, w^2, w^3

Operational maintenance depends on the weather, so do the penalties over the strategic period.

→ Minimize the average penalties over all weather scenarios.

$$\overbrace{\mathbb{E}_s\left[\frac{1}{|\mathcal{W}|}\sum_{w\in\mathcal{W}}\left[\sum_{t=1}^{60}\mathbb{1}_{\{t\notin\mathcal{T}^{\text{free}}\}}(p_t^w - C(s_t^w))^+\right]\right]}^{\text{Expectation under the MDP dynamics}}$$

Cost over a strategic period



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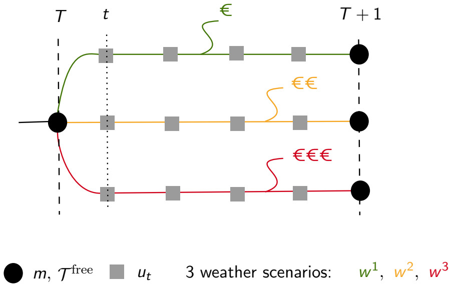
average over
weather scenarios

Cost over a strategic period

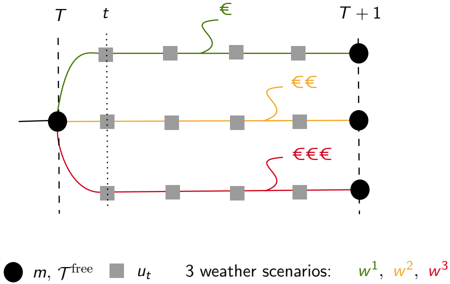


Operational maintenance depends on the weather, so do the penalties over the strategic period.

→ Minimize the average penalties over all weather scenarios.

$$\overbrace{\mathbb{E}_s\left[\frac{1}{|\mathcal{W}|}\underbrace{\sum_{w\in\mathcal{W}}}_{\text{average over weather scenarios}}\left[\underbrace{\sum_{t=1}^{60}}_{\text{sum over two months}}\mathbb{1}_{\{t\notin\mathcal{T}^{\text{free}}\}}(p_t^w - C(s_t^w))^+\right]\right]}^{\text{Expectation under the MDP dynamics}}$$

Cost over a strategic period



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average over weather scenarios

sum over two months

penalty for 1 day

Estimating Maintenance Cost of Offshore Substations under Uncertainty

Full MDP

Let us assume that we know how to model the weather as a Markov Chain.

- **Horizon:** 180×60;
- **State:**
  - $s \in \mathcal{S}$ *current substation state;*
  - $q \in [0 : Q]$ *free maintenance days still available;*
  - $p \in \mathbb{R}^+$ *production;*
  - $h \in \{0, 1\}$ *wave height;*
  - $\boldsymbol{m} \in \{0, 1\}^{\mathcal{C} \times 60}$ *last chosen maintenance schedule;*
  - $\mathcal{T}^{\text{free}} \subset [1 : 60]$ *last chosen free maintenance days*.
- **Control:** If t is not a strategic stage:
  - $\emptyset$

  If t is a strategic stage:
  - $\boldsymbol{m} \in \{0, 1\}^{\mathcal{C} \times 60}$ *maintenance schedule;*
  - $\mathcal{T}^{\text{free}} \subset [1 : 60]$ *free maintenance days.*
- **Transition cost at time** t**:** $\mathbb{1}_{\{t \in \mathcal{T}^{\text{free}}\}} \left(p_t - C(s_t)\right)^+$;
- **Transitions:** degradations, ongoing maintenance and weather.

Aggregated MDP

Decisions are taken at strategic stages. We can write an equivalent MDP at strategic time stages.

- **Horizon:** 180;
- **State:**
  - $s \in \mathcal{S}$ *substation state at the beginning of the strategic period;*
  - $q \in [0 : Q]$ *free maintenance days still available;*
  - $p \in \mathbb{R}^+$ *production at the beginning of the strategic period;*
  - $h \in \{0, 1\}$ *wave height at the beginning of the strategic period.*
- **Control:**
  - $\boldsymbol{m} \in \{0, 1\}^{\mathcal{C} \times 60}$ *maintenance schedule;*
  - $\mathcal{T}^{\text{free}} \subset [1 : 60]$ *free maintenance days.*
- **Transition cost at time** t**:** $\mathbb{E}_{s,w}\left[\sum_{t=1}^{60} \mathbb{1}_{\{t \in \mathcal{T}^{\text{free}}\}} \left(p_t - C(s_t)\right)^+\right]$;
- **Transitions:** degradations, ongoing maintenance and weather.

Approximate Aggregated MDP

Modelling the weather as a MDP is dubious.

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Computing value functions for the Approximate Aggregated MDP

$$V_T(s,q) = \min_{\boldsymbol{m},\mathcal{T}^{\text{free}}} \quad \mathbb{E}_s \left[\frac{1}{|\mathcal{W}_T|} \sum_{w \in \mathcal{W}_T} \left[\sum_{t=1}^{60} \mathbb{1}_{\{t \notin \mathcal{T}^{\text{free}}\}} \left(p_t^w - C(s_t^w)\right)^+ + V_{T+1}\left(s_{61}^w, q^{\text{out}}\right) \right] \right]$$

$$\begin{aligned} \text{s.t.} \quad & \boldsymbol{u}^w = \phi(\boldsymbol{m}, \boldsymbol{h}^w) \quad \forall w \in \mathcal{W}_T \\ & s_0^w = s \quad \forall w \in \mathcal{W}_T \\ & \mathcal{T}^{\text{free}} \subset [1:60] \\ & q^{\text{out}} = q - |\mathcal{T}^{\text{free}}| \\ & q^{\text{out}} \geq 0 \end{aligned}$$

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Operational maintenance follows the deterministic rule.

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Unique initial state at the beginning of the strategic period.

Computing value functions for the Approximate Aggregated MDP

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Free maintenance days are scheduled at the beginning of the strategic period. The number of days is limited by the quota

Computing value functions for the Approximate Aggregated MDP

$$V_T(s,q) = \min_{\boldsymbol{m},\mathcal{T}^{\text{free}}} \quad \frac{1}{|\mathcal{W}_T|} \sum_{w\in\mathcal{W}_T} \left[\left[\sum_{t=1}^{60} \sum_{s'\in\mathcal{S}} \mu_t^w(s') \mathbb{1}_{\{t\notin\mathcal{T}^{\text{free}}\}} \left(p_t^w - C(s')\right)^+ \right] + \sum_{s'\in\mathcal{S}} \mu_{61}^w(s') V_{T+1}\left(s', q^{\text{out}}\right) \right]$$

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We introduce the probabilities associated with the states $\mu_t^w = (\mathbb{P}(s_t^w = s'))_{s'\in\mathcal{S}}$ that are calculated using the Chapman-Kolmogorov equation.

Estimating Maintenance Cost of Offshore Substations under Uncertainty

Context

Key assumptions for modeling maintenance under uncertainty

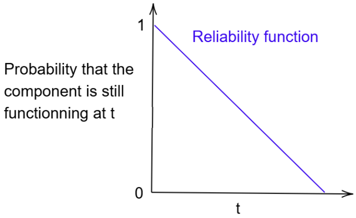
Model

Lack of reliability data leeds to model ambiguity

Takeaways

Manufacturers only provide partial information on reliability.

The only information provided by suppliers is **MTBF**. But the reliability of a component is better characterized by its **reliability function**.



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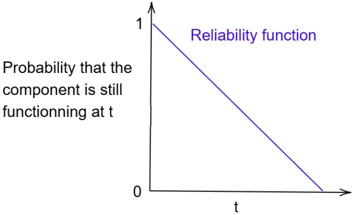
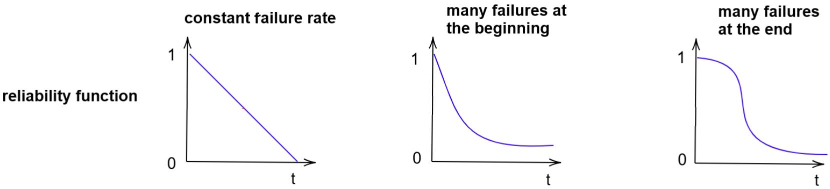
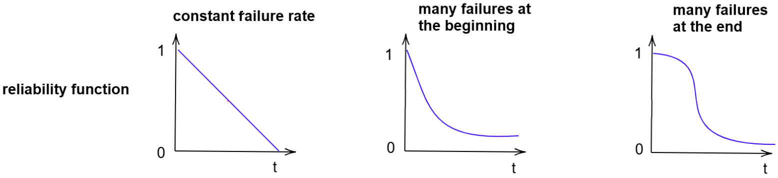


Several reliability functions correspond to the same MTBF.



Building the Ambiguity set

For each admissible reliabily function, we estimate the parameters of the Markov Chain.



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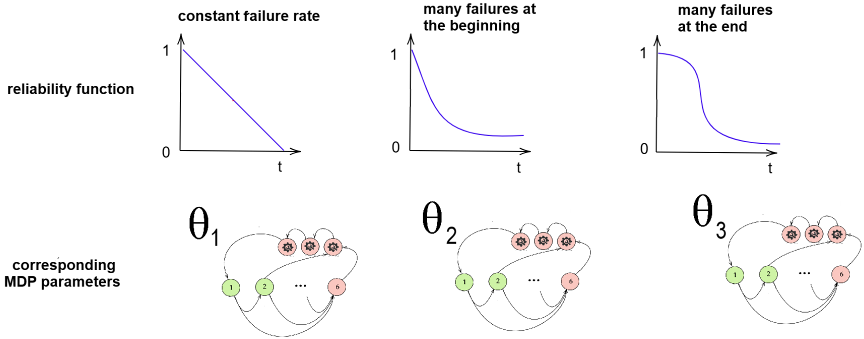

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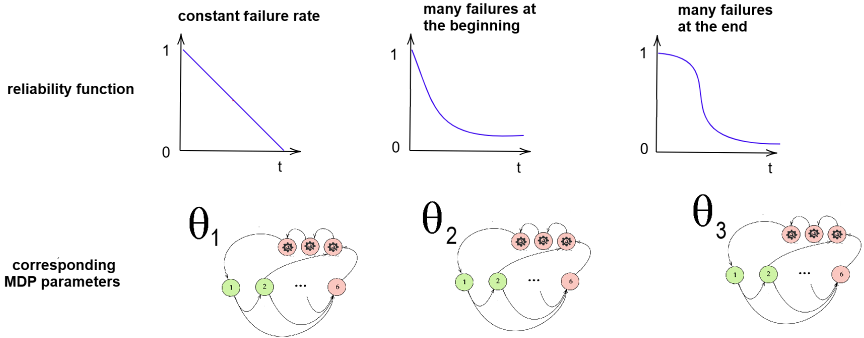
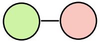
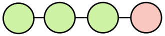


The ambiguity set $\mathcal{A}$ is the collection of MDP parameters:

$$\mathcal{A} = \{\theta_1, \theta_2, \theta_3\}$$

Same MTBF with different MDPs can lead to different controls and cost estimates

MDP	**Optimal strategy**	**Cost (normalized)**
2 states  (no aging)	Corrective maintenance	2494
4 states  (aging)	Preventive maintenance (in state 3)	1
MTBF states  (deterministic aging)	Preventive maintenance (in state MTBF-1)	0

We model the substation as as single component with a MTBF of 15 years. We evaluate the cost over a concession period of 30 years with perfect accessibility.

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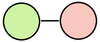
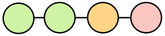
2 states  (no aging)	Corrective maintenance	2494
4 states  (aging)	Preventive maintenance (in state 3)	1
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Incorporating ambiguity in the model

Two distinct models can lead to significantly different cost estimates despite having the same MTBF. It could result in suboptimal maintenance policies and misestimated costs.
→ Ambiguity must be incorporated in the model.

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→ Ambiguity must be incorporated in the model.

We write a Distributionally Robust Optimization problem.

$$V_T(s,q) = \min_{\boldsymbol{m},\mathcal{T}^{\text{free}}} \max_{\theta\in\mathcal{A}} \quad \frac{1}{|\mathcal{W}_T|}\sum_{w\in\mathcal{W}_T}\left[\left[\sum_{t=1}^{60}\sum_{s'\in\mathcal{S}}\mu_t^w(s')\mathbb{1}_{\{t\notin\mathcal{T}^{\text{free}}\}}\left(p_t^w - C(s')\right)^+\right] + \sum_{s'\in\mathcal{S}}\mu_{61}^w(s')V_{T+1}\left(s',q^{\text{out}}\right)\right]$$

$$\text{s.t.} \quad \mu_{t+1}^w = P^{u_t^w}(\theta)\mu_t^w \quad \forall t\in[1:60]$$

$$\dots$$

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Problem is modelled

- as a Markov Decision Process;
- in a Multihorizon setting.

We need this model

- to estimate the cost of strategic choices;
- to get insights on what contracts entail for the TSO.

Optimizing maintenance for a false MDP leads to poor cost estimates.
Future works entails Distributionally Robust Optimization.