Interpretation of offshore wind management policies identified via partially observable Markov decision processes

Nandar Hlaing[1,*], Pablo G. Morato[1], Konstantinos G. Papakonstantinou[2], Charalampos P. Andriotis[3], and Philippe Rigo[1]

[1]Naval & Offshore Engineering, ArGEnCo, University of Liege, 4000 Liege, Belgium

[2]Department of Civil & Environmental Engineering, The Pennsylvania State University, University Park, PA 16802, USA

[3]Faculty of Architecture & the Built Environment, Delft University of Technology, 2628 BL Delft, The Netherlands

EAWE PhD Seminar

November 3, 2022, Bruges

PhairywinD

Belgian Offshore PhD Expertise

Introduction

- Development of offshore wind energy
- Increased risk VS complex inspection and maintenance tasks
- How to optimally allocate inspections and maintenance interventions?


Source: energy.gov


Source: www.istockphoto.com


Source: rsdiving.de


Source: rsdiving.de

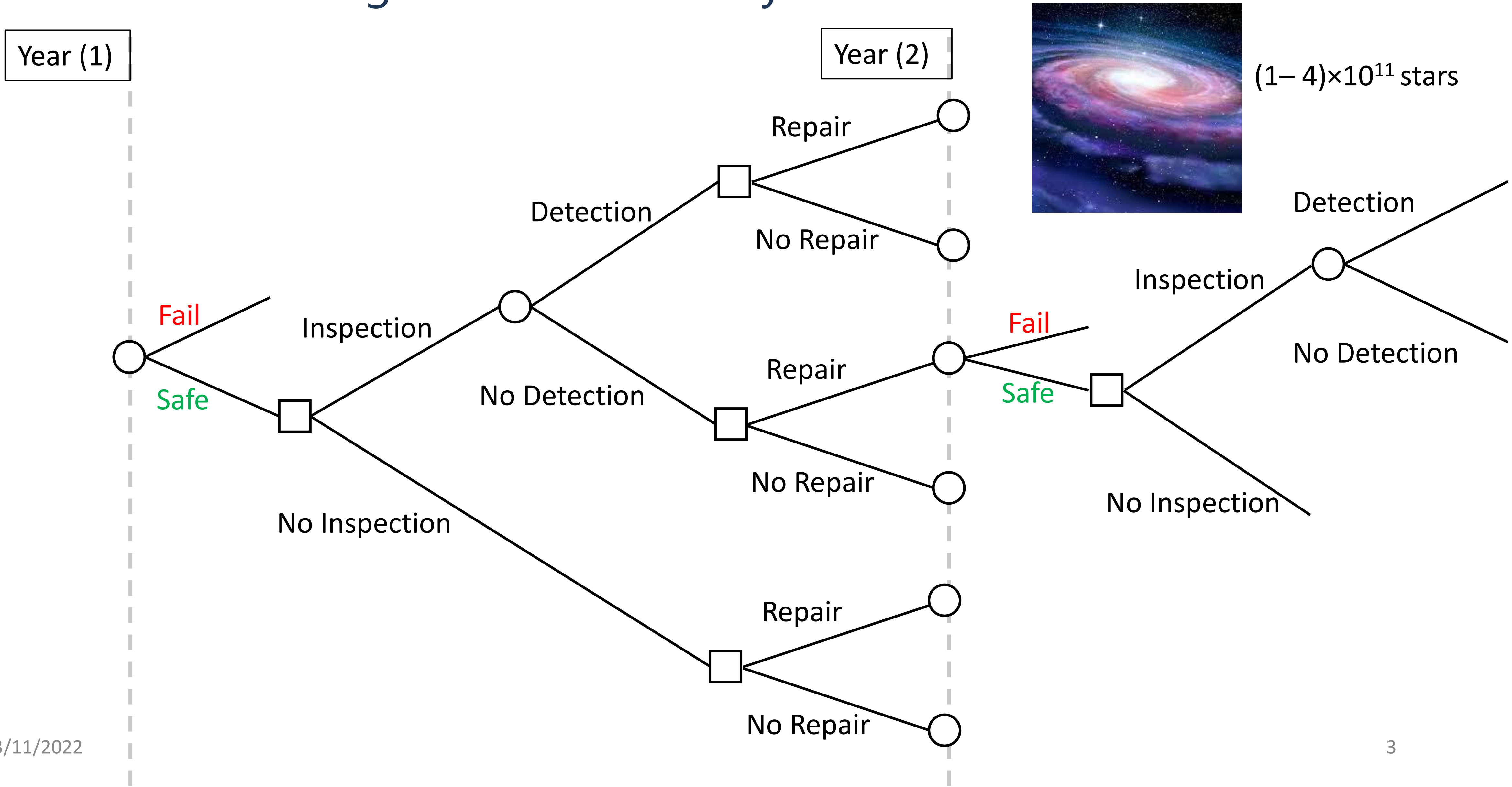
PhairywinD
Belgian Offshore PhD Expertise

Introduction

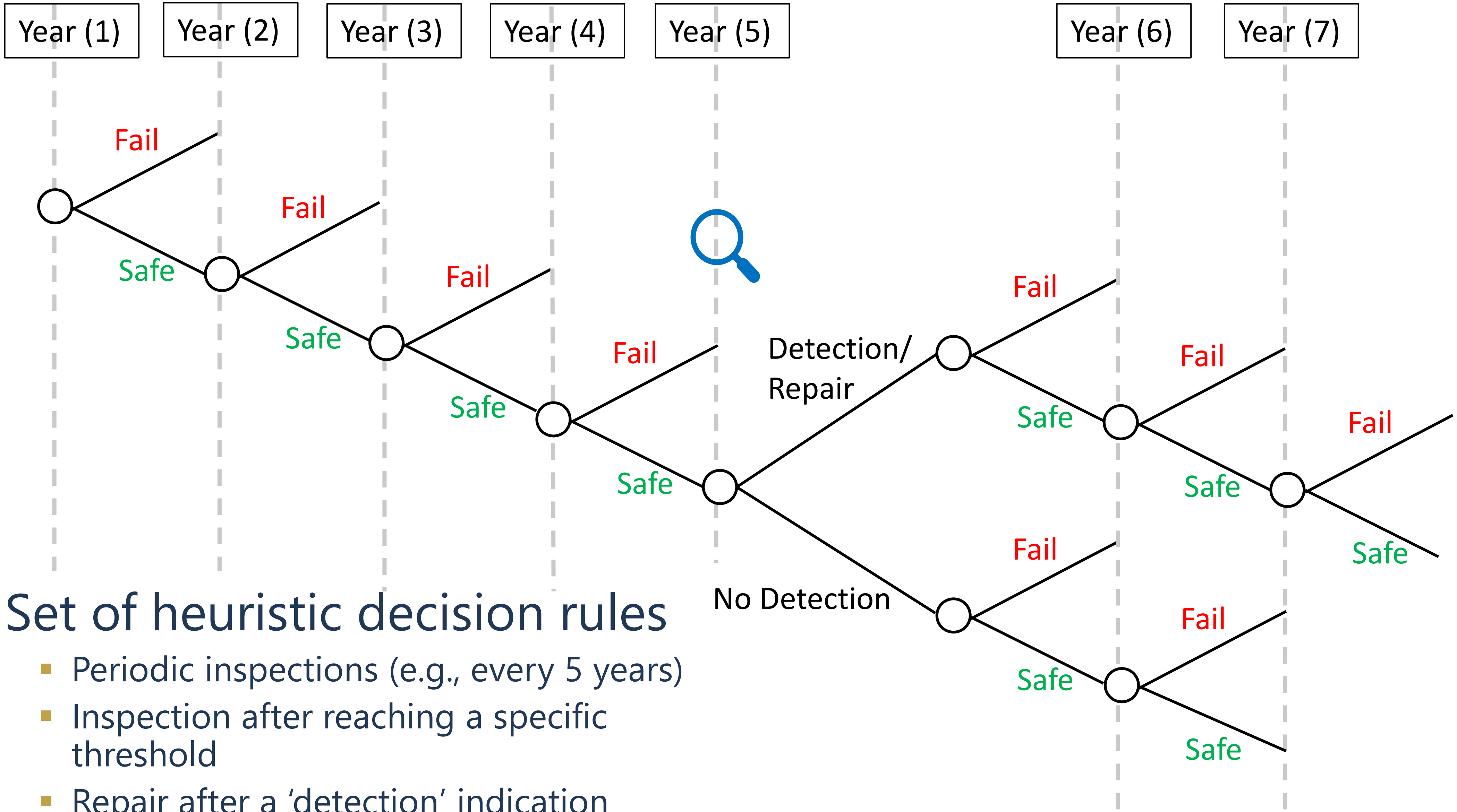
- Decision-making under uncertainty

In 20 years, > 3×10^{15} branches

$(1–4)\times10^{11}$ stars



Introduction



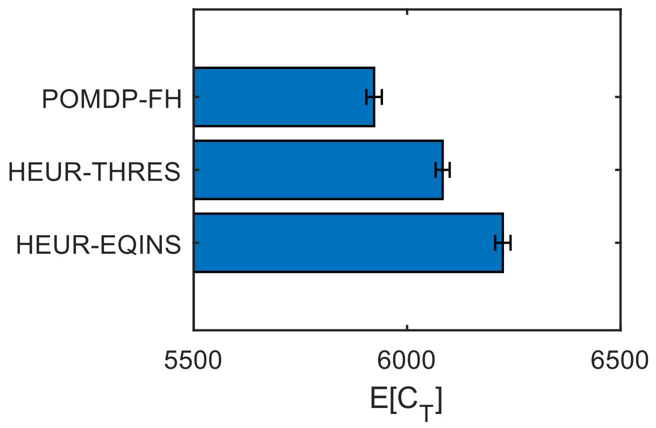
- Set of heuristic decision rules
  - Periodic inspections (e.g., every 5 years)
  - Inspection after reaching a specific threshold
  - Repair after a ‘detection’ indication

Optimality ??

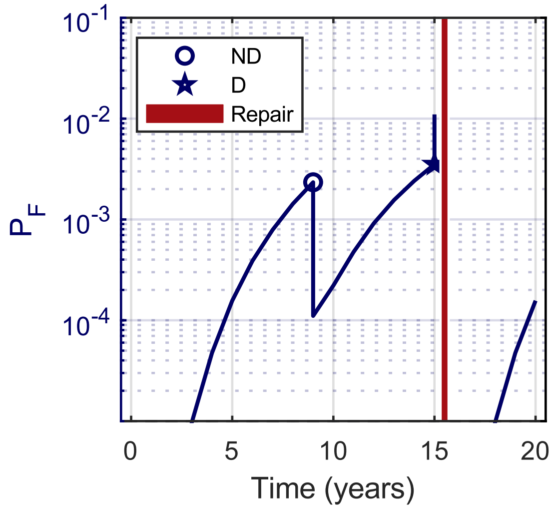
Partially observable Markov decision process

✓ Optimality

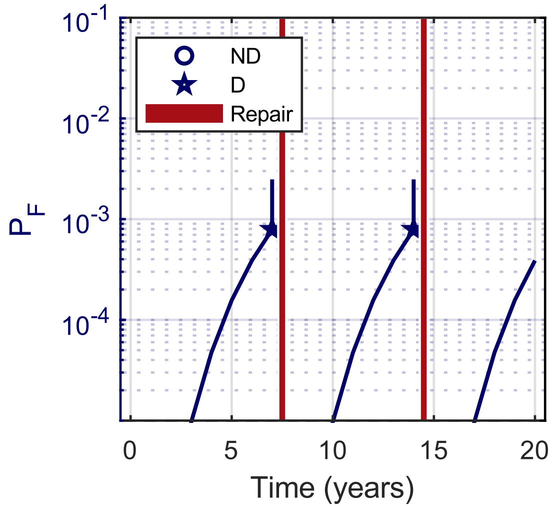
- Outperforms state-of-the-art planning methods
- Significant cost savings



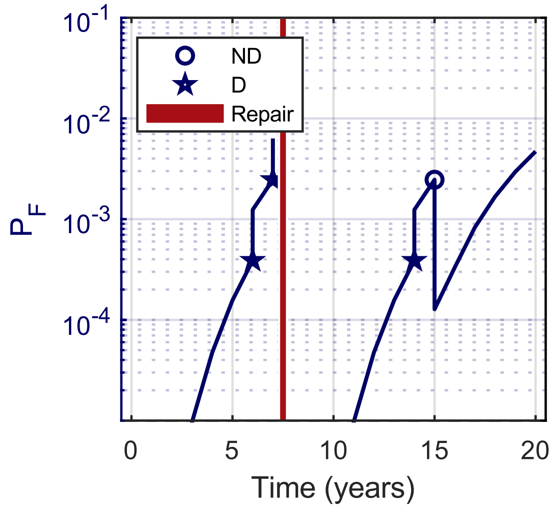
✓ Adaptability



Heuristics (THRES) policy realization



Heuristics (EQINS) policy realization



POMDP policy realization

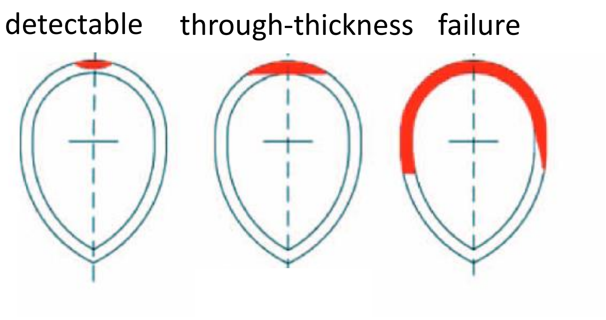
Reference: P. G. Morato, K. G. Papakonstantinou, C. P. Andriotis, J. S. Nielsen, P. Rigo, Optimal inspection and maintenance planning for deteriorating structural components through dynamic Bayesian networks and Markov decision processes, Structural Safety 94 (2022) 102140.

Partially observable Markov decision process

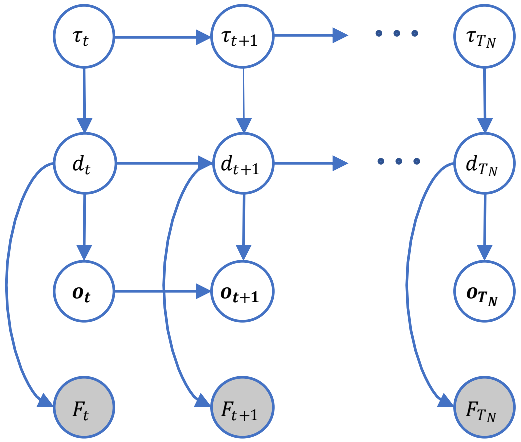
✓ Flexibility

- Deterioration models: SN curve, fracture mechanics (FM)
- Failure criteria: through-thickness, failure assessment diagram

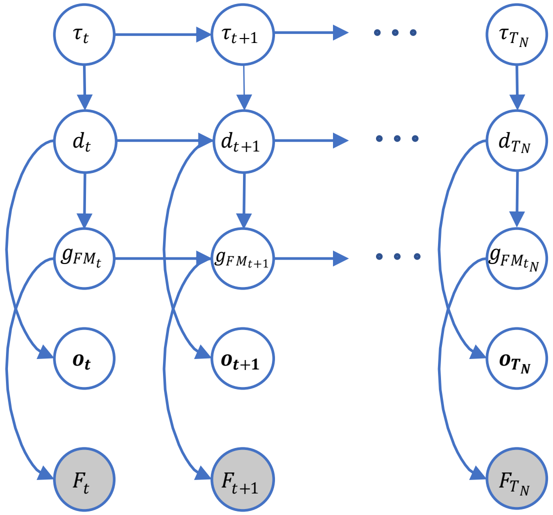
Crack growth in a tubular joint section



1D FM + Through-thickness



2D FM + Failure assessment diagram



? Interpretability

Reference: N. Hlaing, P. G. Morato, J. S. Nielsen, P. Amirafshari, A. Kolios, P. Rigo, Inspection and maintenance planning for offshore wind structural components: integrating fatigue failure criteria with Bayesian networks and Markov decision processes, Structure and Infrastructure Engineering 18 (7)(2022) 983–1001.

Partially observable Markov decision process

- POMDPs – 7-tupled control process

$$\langle S, A, O, T, Z, R, \gamma \rangle$$

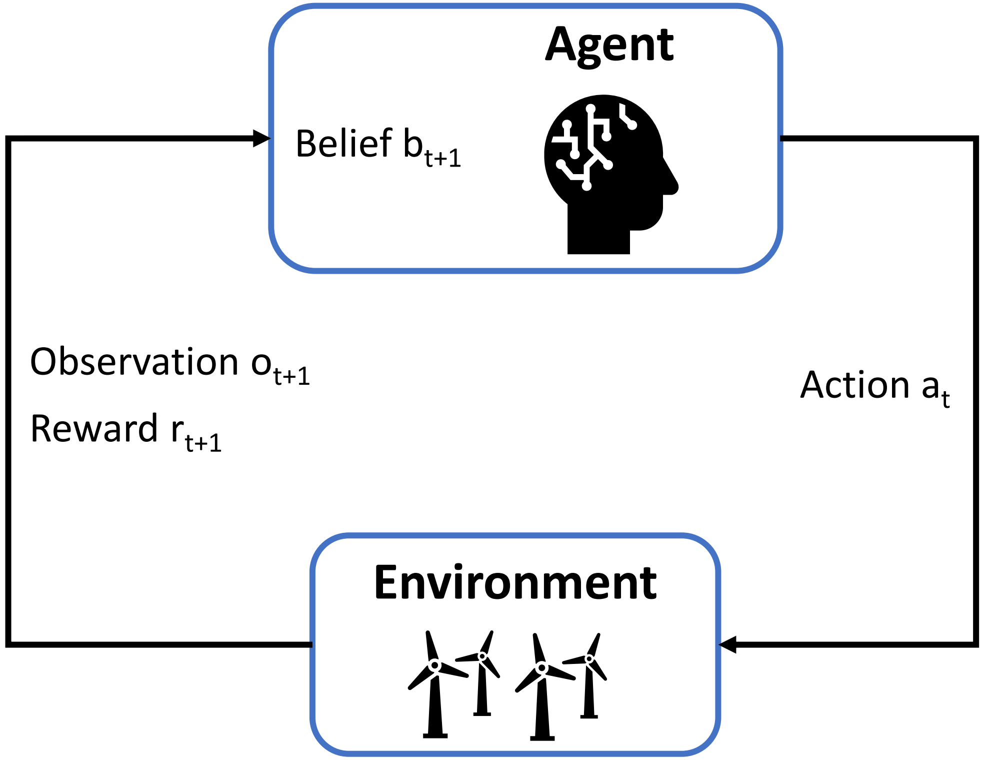
Actions
- Move left/right
- Move up/down

+1	+1	+1	+1	-100
+1	+2	+2	+2	+1
+1	+3	+5	+3	+1
+1	+2	+2	+2	+1
+1	+1	+1	+1	+1

MDP in grid world

+1	+1	+1	+1	-100
+1	+2	+2	+2	+1
+1	+3	+5	+3	+1
+1	+2	+2	+2	+1
+1	+1	+1	+1	+1

POMDP in grid world

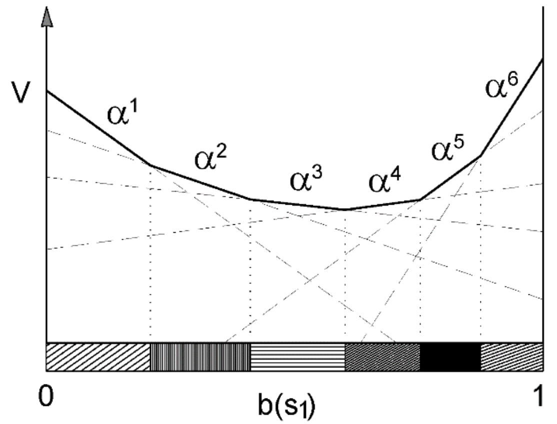


Partially observable Markov decision process

- Solving POMDPs
  - Policy is a mapping from the **belief state** to the **optimal action.**

$$\pi : \mathbb{B} \rightarrow A$$

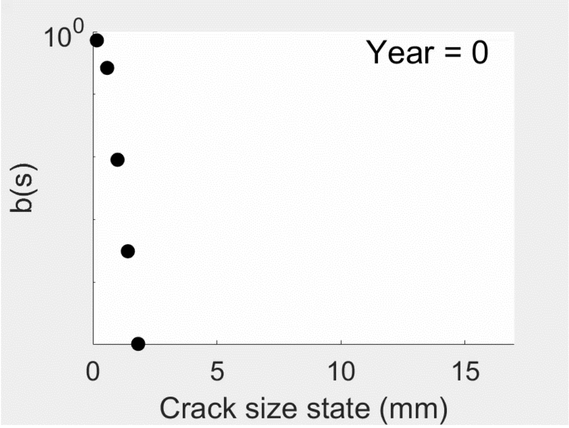
$$V(\mathbf{b}_t) = \max_{a_t \in A} \left\{ \sum_{s_t \in S} b(s_t) r(s_t, a_t) + \gamma \sum_{o_{t+1} \in \Omega} p(o_{t+1} | \mathbf{b}_t, a_t) V(\mathbf{b}_{t+1}) \right\}$$

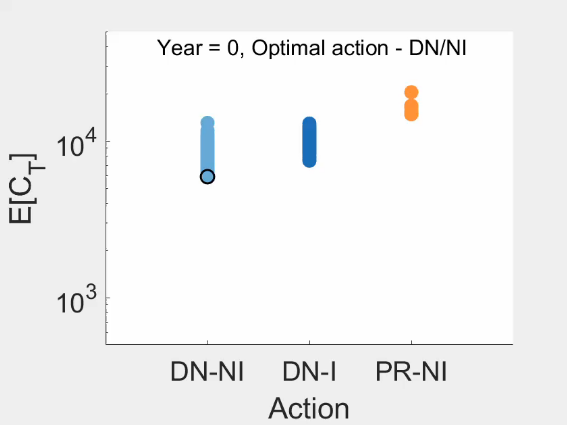


- Point-based solvers
  - Reachable beliefs
  - Optimal value function is generally piece-wise linear and convex

$$V^*(\mathbf{b}) = \max_{\alpha \in \Gamma} \sum_{s \in S} b(s) \alpha(s).$$

  - Alpha vector → Action

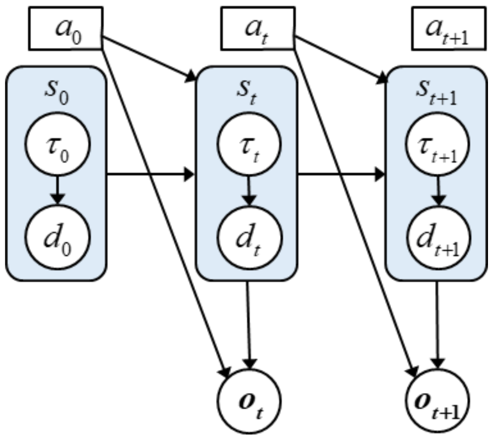




References: K. G. Papakonstantinou, M. Shinozuka, Planning structural inspection and maintenance policies via dynamic programming and Markov processes. Part I: Theory, Reliability Engineering and System Safety 130 (2014) 202–213.
K. G. Papakonstantinou, M. Shinozuka, Planning structural inspection and maintenance policies via dynamic programming and Markov processes. Part II: POMDP implementation, Reliability Engineering and System Safety 130 (2014) 214–224

Optimal I&M planning for offshore wind structures

POMDPs – $\langle S, A, O, T, Z, R, \gamma \rangle$



States:

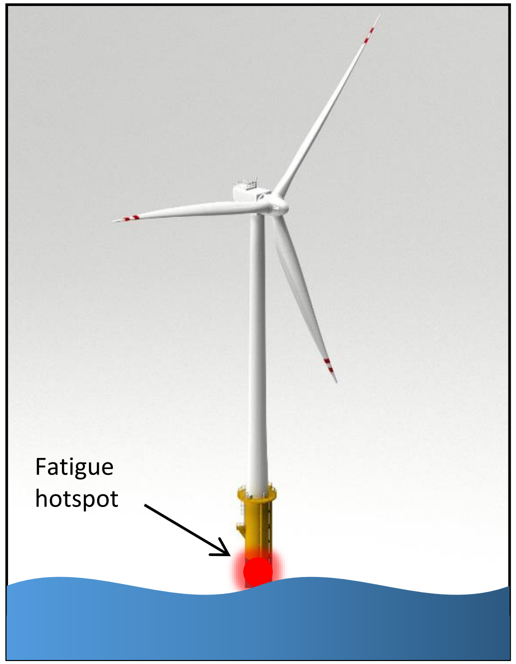
- Fatigue crack size

Actions:

- Do-nothing/No-inspection
- Do-nothing/Inspection
- Perfect-repair/No-inspection

Observations:

- Detection
- No-detection



Optimal I&M planning for offshore wind structures

POMDPs – $\langle S, A, O, T, Z, R, \gamma \rangle$

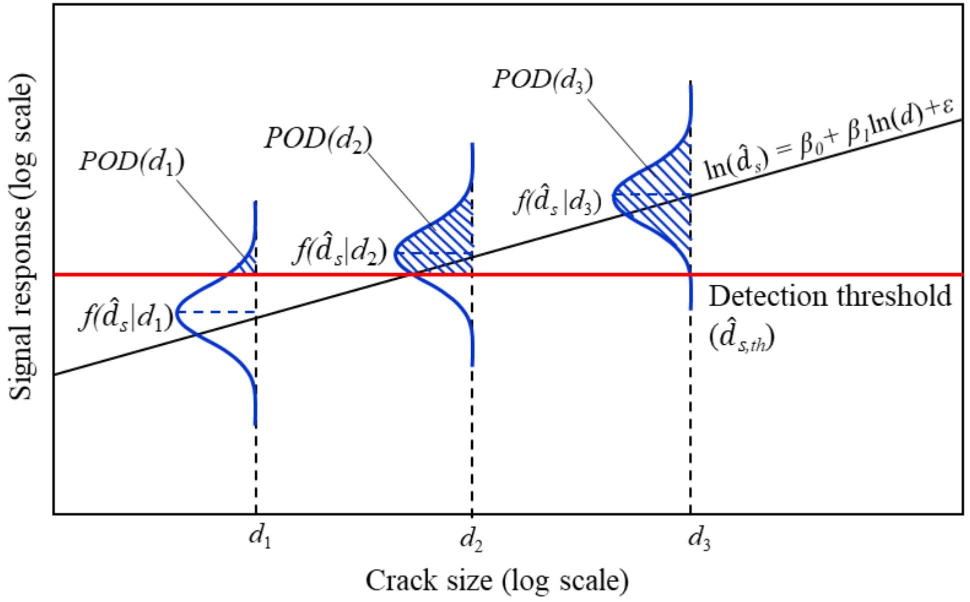
Transition model:

$$d_{t+1} = \left[d_t^{\frac{2-m}{2}} + \left(\frac{2-m}{2}\right) C_{FM} \{S_R \pi^{0.5}\}^m n \right]^{\frac{2}{2-m}}$$

- Do-nothing – Paris Law
- Perfect repair – back to initial belief

Observation model:

- Eddy current inspection method (DNV)



$$\beta_0 = 7.3074 \,,\ \beta_1 = 2.092,$$
$$\sigma_\varepsilon = 4.189 \,,\ \hat{d}_{s,th} = 5.4898$$

Cost model:

10^6 monetary units

10^4 monetary units

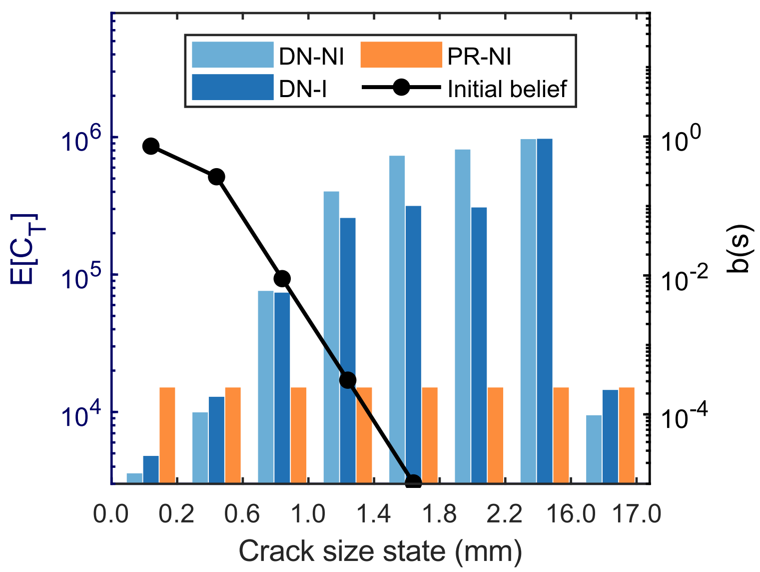
10^3 monetary units

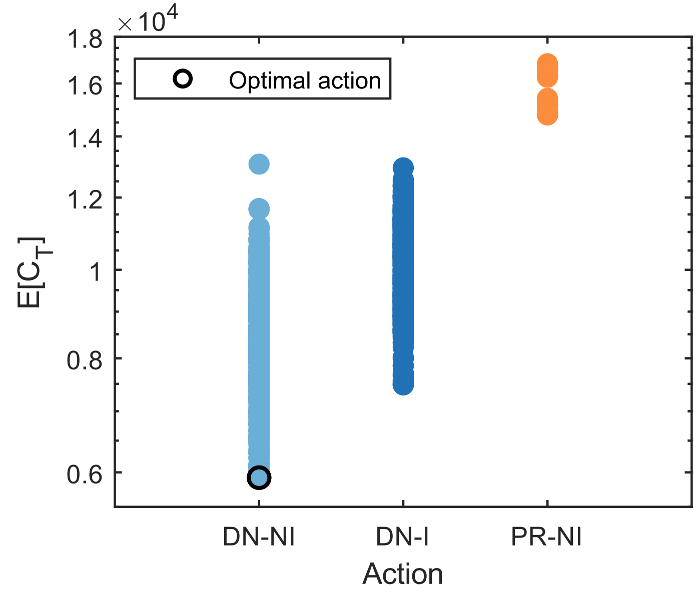
Interpretation of POMDP-based policies

- Optimal value function

$$V^*(\mathbf{b}) = \max_{\alpha\in\Gamma} \sum_{s\in S} b(s)\alpha(s).$$

- At the first decision step (initial belief), the optimal action is DN-NI.





Interpretation of POMDP-based policies

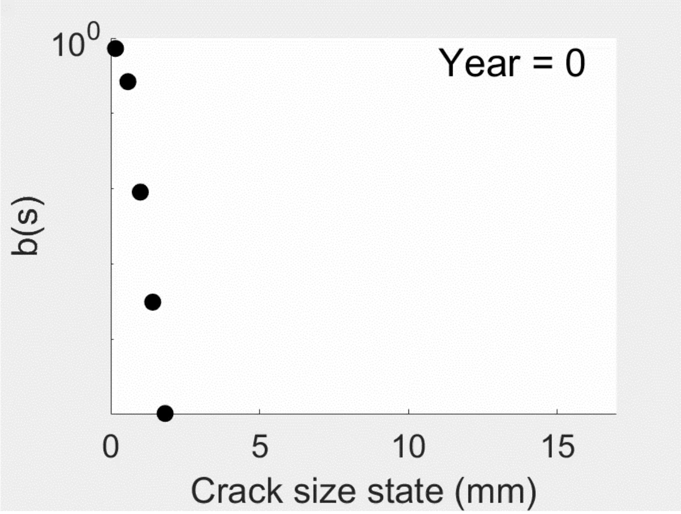
- Bayes' theorem for updating the current belief:

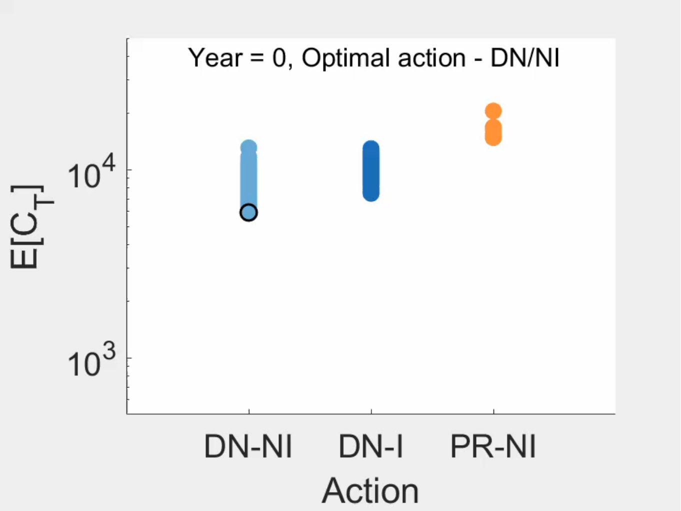
$$b(s') \propto P(o|\, s',a) \sum_{s \in S} P(s'|\, s,a) b(s).$$

Observation model

Transition model

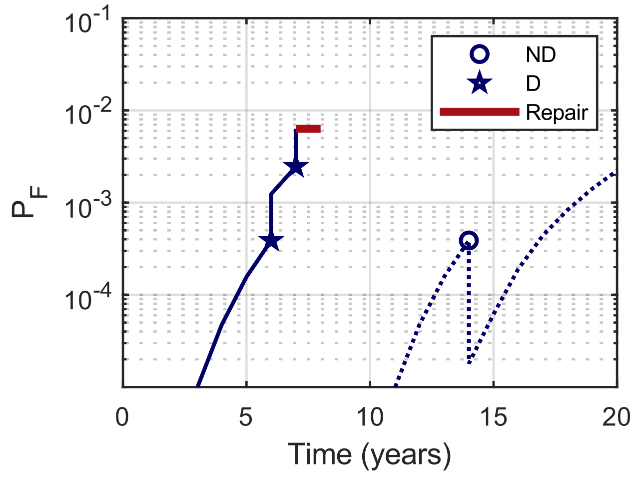
- Selecting sequential optimal actions based on updated beliefs:





What if the optimal policy is not strictly followed?

- At year 7, two subsequent detections have been observed.
- Optimal action – Perfect repair/No-inspection



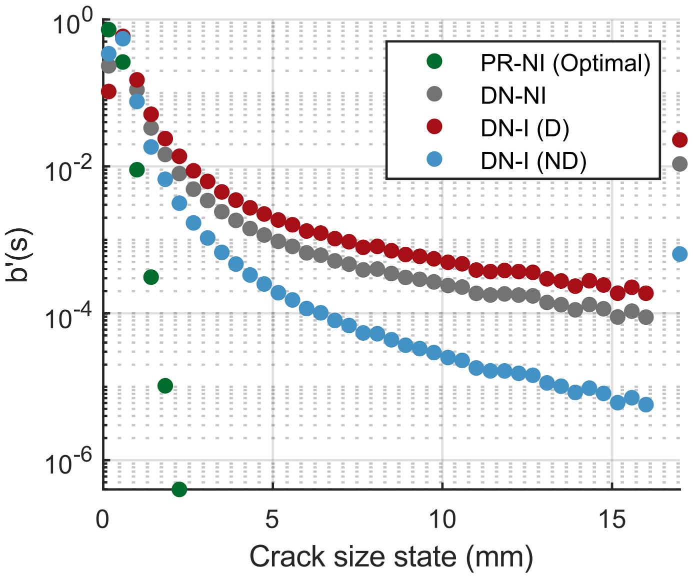
- Alternative actions
  - Do-nothing/No-inspection
  - Do-nothing/Inspection

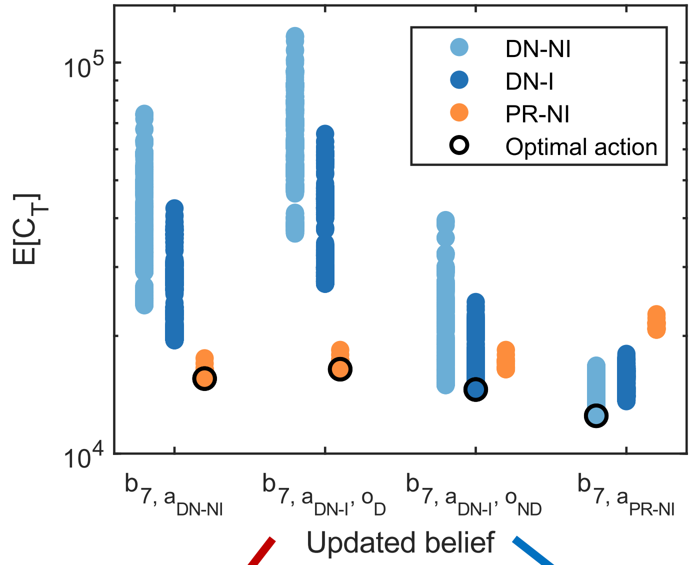
- What is the “regret” if a perfect repair is not performed.

What if the optimal policy is not strictly followed?

- Expected cost after taking alternative actions (Bellman backup):

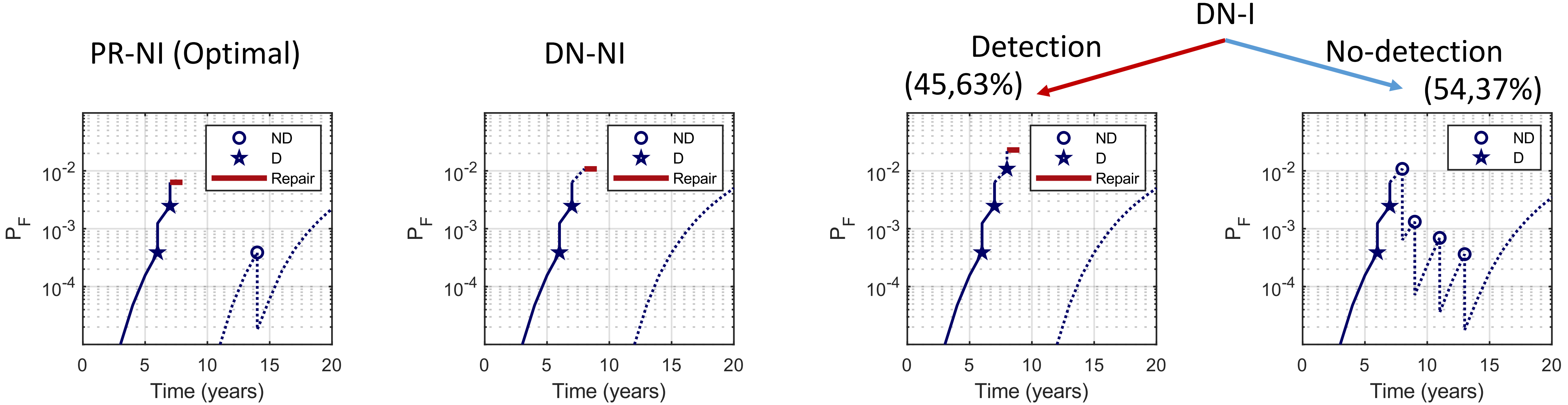
$$V(\mathbf{b}_7) = \sum_{s \in S} b_7(s) R(s,a) + \gamma V(\mathbf{b}'_7)$$

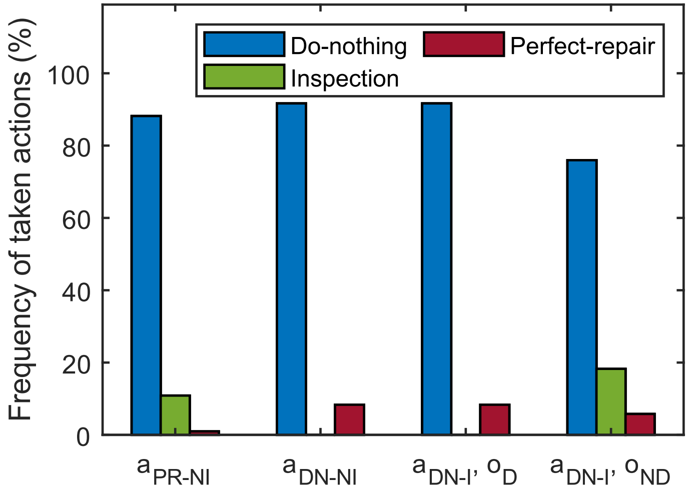




$$p(o_{ND} \mid \mathbf{b}'_{7,a_{DN-I}}) = 0.5437 \qquad p(o_D \mid \mathbf{b}'_{7,a_{DN-I}}) = 0.4563$$

What if the optimal policy is not strictly followed?





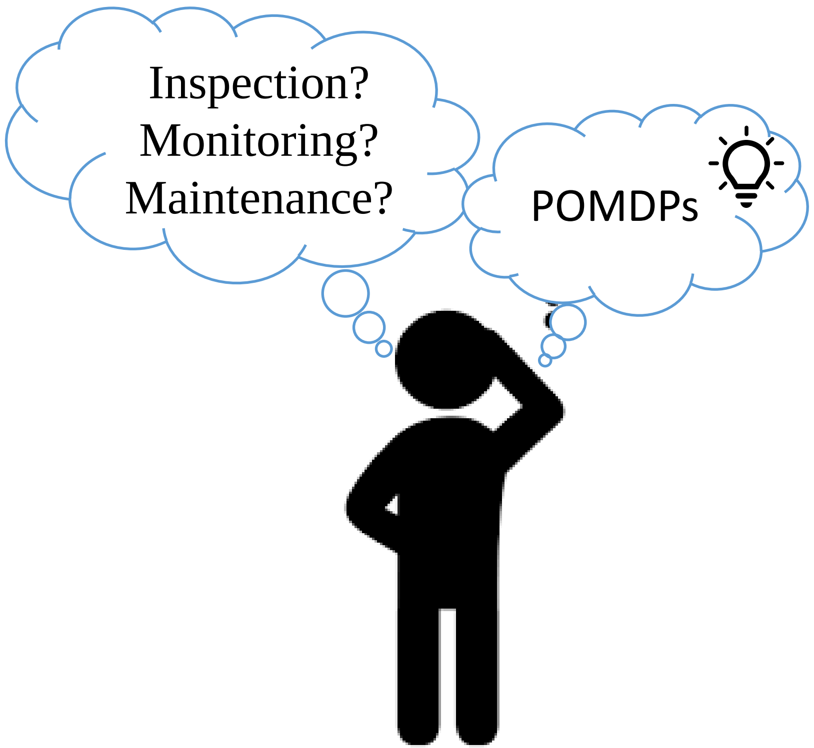
Action	$\mathbb{E}[C_T]$ (monetary units)	Regret: $\mathbb{E}[C_P]$ (%)
PR-NI (Optimal)	12493	-
DN-NI	15552	24,5 %
DN-I	15428	23,5 %

PhairywinD
Belgian Offshore PhD Expertise

Conclusion

Partially Observable Markov Decision Processes (POMDPs)

- ✓ Optimality
- ✓ Adaptability
- ✓ Flexibility
- ✓ Interpretability



Source: energy.gov

For questions and comments:

nandar.hlaing@uliege.be

Partners

With the support of Energy Transition Fund