Utilizing digitalization through heuristic risk-based blade maintenance for leading edge erosion

Jannie Sønderkær Nielsen, AAU
Nikolay Dimitrov, DTU
Ryan Clarke, Joshua Paquette, Sandia
Alex Byrne, DNV GL

WESC 2023 Glasgow 25/5-2023
5.2a Mini Symposia: Structural integrity assessment and life cycle management of wind farms

CORTIR II

WIND ENERGY DIGITALIZATION
IEA WIND TASK 43

EUDP

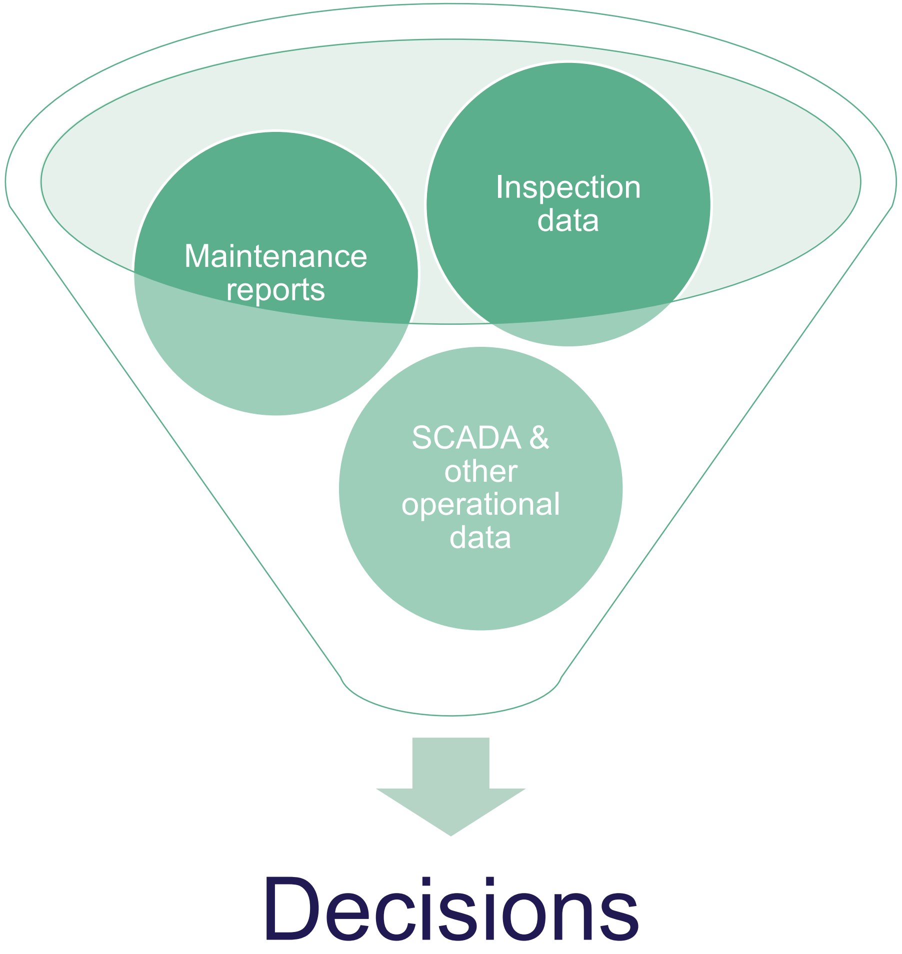
AALBORG UNIVERSITY

IEA Wind T43
WP5 – O&M

- Provide guidance on digitalization practices and implementations with the potential to deliver wind O&M advancements and new opportunities
- Team:
  - Alex Byrne – DNV GL
  - Joshua Paquette – Sandia National Laboratories
  - Ryan Clarke – Sandia National Laboratories
  - Jannie Sønderkær Nielsen – Aalborg University
  - Nikolay Krasimirov Dimitrov – DTU
  - Pablo G. Morato – DTU
  - Des Farren – Servusnet
  - Nathan Hoerning – Wisconsin Public Utility
  - Liliana Haus – EPRI
  - Noah Myrent – EPRI
  - Evan Sproul - Sandia National Laboratories
  - Murray Fisher – Gulf Wind Technology

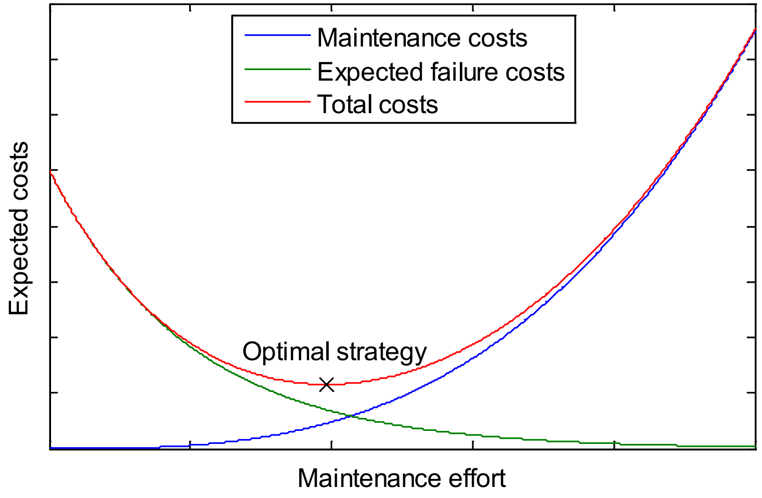
Risk-based blade maintenance

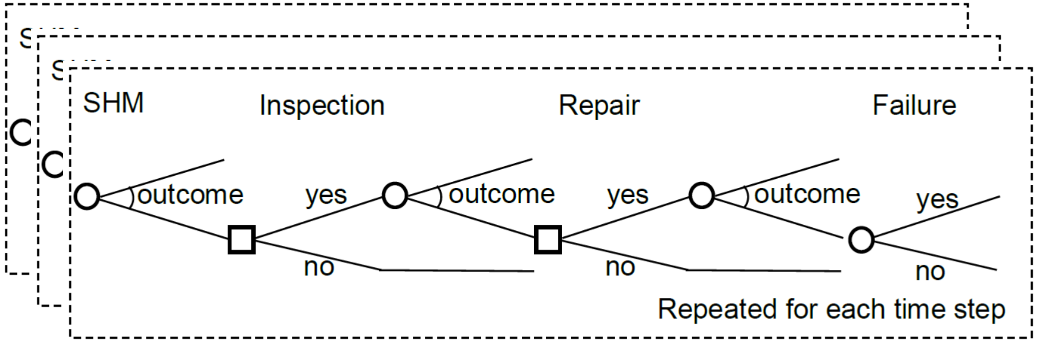
- How can digitalization can be utilized to optimize inspection and maintenance decisions for leading edge erosion (LEE) of wind turbine blades?



Risk-based blade maintenance

- Balance between doing too much and too little
- Minimize expected costs
  - Considering present value of direct and indirect costs
- How to find the optimal strategy?
- Bayesian decision theory
  - Heuristic decision rules
  - POMDP, ML approaches
  - Optimality vs. simplicity

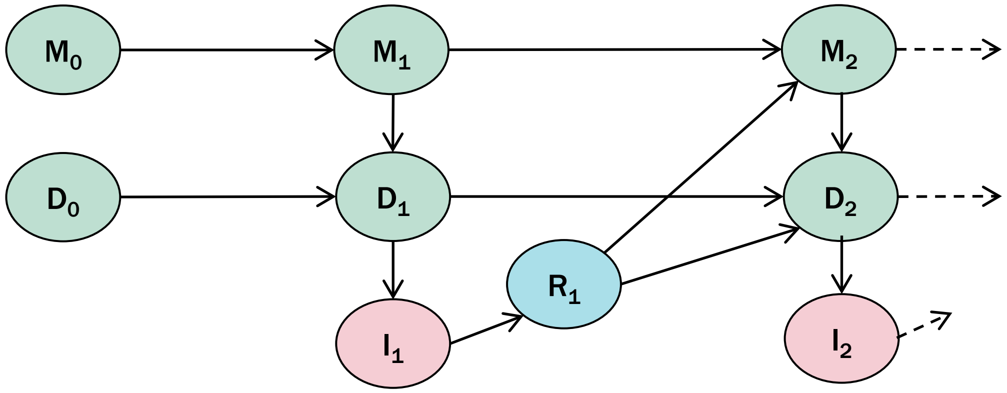




AALBORG UNIVERSITY

Risk-based decision model

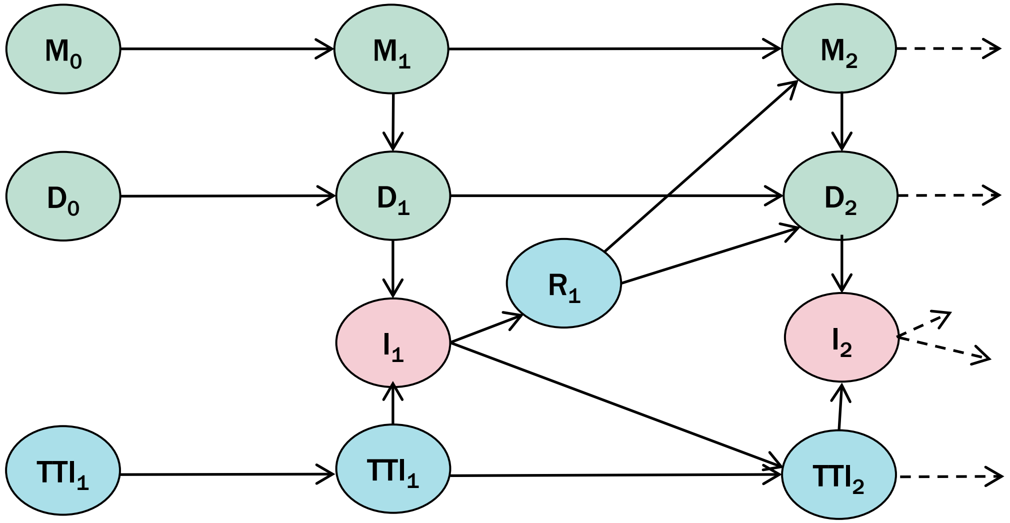
- Input
  - Deterioration and repair model
  - Inspection model
  - Cost model
- Output
  - Optimal decision – strategy for inspections and repairs
  - Expected lifetime costs



Nodes / variables
Damage size: D_i
Model parameter: M_i
Inspection outcome: I_i
Preventive repair decision: R_i

Risk-based decision model

- Inspection: time steps to next inspection – depends on inspection outcome
- TTI is a “count down node” between inspections: 6 – 5 – 4 – 3 – 2 – 1



Nodes / variables
Damage size: D_i
Model parameter: M_i
Inspection outcome: I_i
Preventive repair decision: R_i
Time to inspection: TTI_i

Risk-based decision model

- Which inspection outcome should result in repair now?
- For less severe inspection outcomes, when should the next inspection be scheduled?
- Example:

State of node I	Inspection outcome	Repair	Next inspection
1	No inspection	No	
2	No detection	No	2
3	Category 1	No	2
4	Category 2	No	1
5	Category 3	No	1
6	Category 4	Yes	2
7	Category 5	Yes	2

Case study –
Leading edge erosion

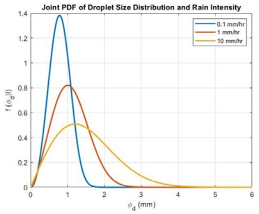
- The repeated impact of raindrops and other particles on the leading edge of wind turbine blades leads to initiation of erosion and progressive damage development.
- LEE negatively impacts aerodynamic performance, thereby decreasing the power production.
- When to do drone inspections and when to repair?

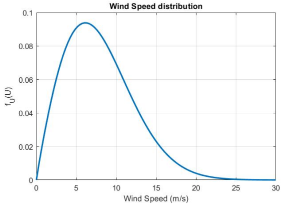
Leading edge erosion classification

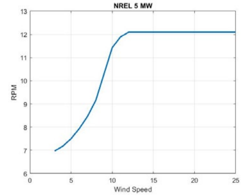
Erosion CAT	Description	Coating Mass Loss	Laminate Mass Loss	Turbine Power Loss
1	Light pitting of coating	<10%	0%	-
2	Small patches of missing coating	10% - 50%	0%	1%
3	Large patches of missing coating	50% - 100%	<10%	2%
4	Erosion of laminate	100%	10% - 100%	3%
5	Complete loss of laminate	100%	100%	5%

Assessment based on: “A White Paper on Blade Defect and Damage Categorization: Current State of the Industry.” EPRI, Palo Alto, CA: 2020. 3002019669.

Erosion damage growth model





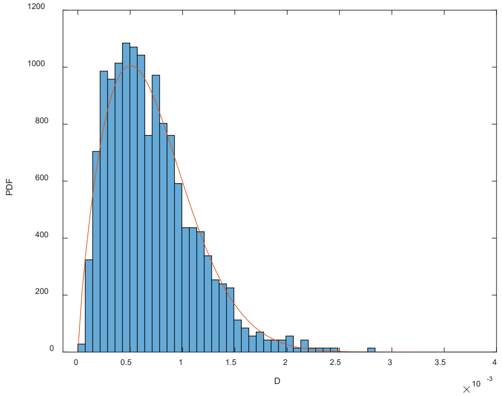


Short-Term Damage Rate/Mass Loss Rate
(Springer Model [1])

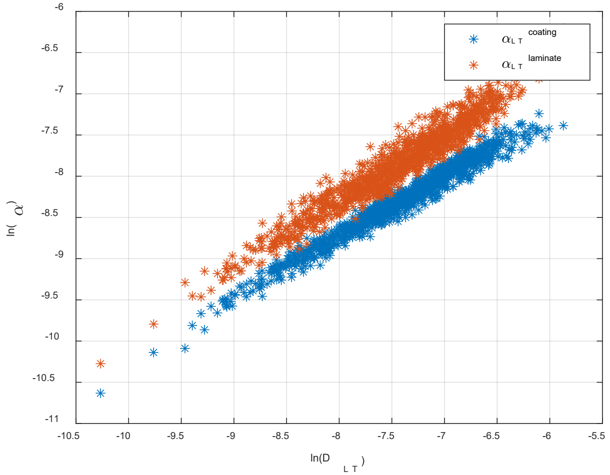
Rain Statistics
(Rain Intensity, Droplet Size Distribution)

Wind Statistics
(Wind Speed)

Turbine Model
(Power Curve)



Long-Term Damage Rate [2]
(Weighted sum of short term erosion damage rate together with probability of occurrence of all possible rain and wind conditions)



Incubation Period Prediction

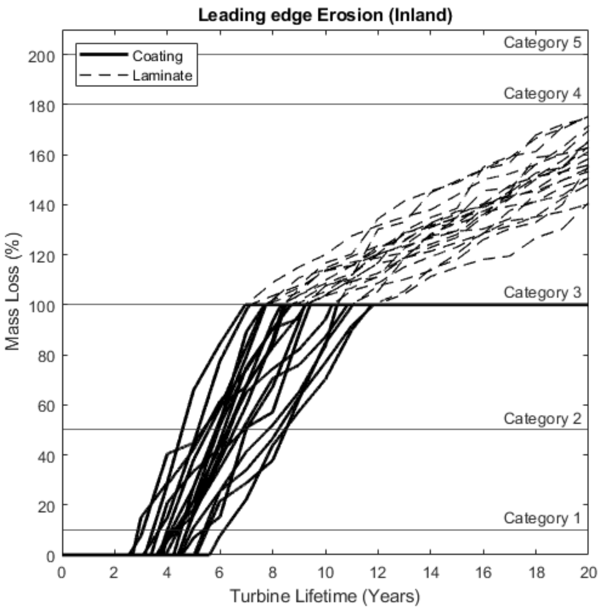
Rate of Mass Loss

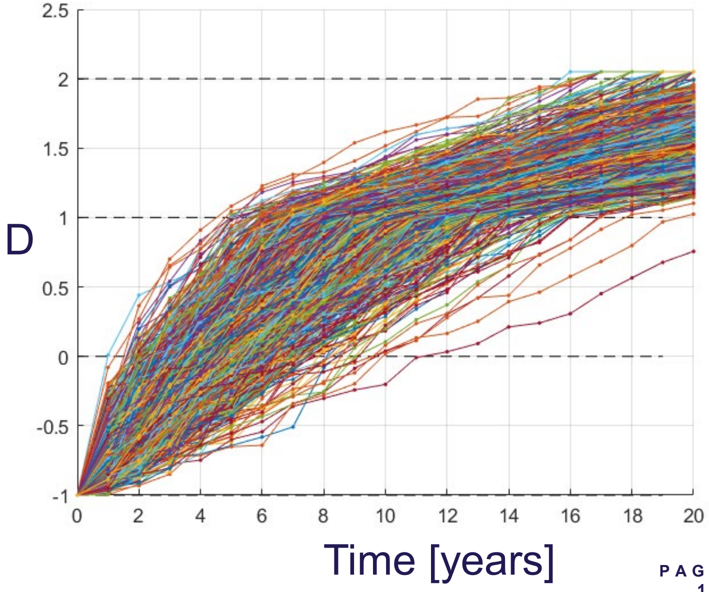
Erosion Damage
(Severity of erosion at all points in a wind blades lifetime)

[1] GS Springer, CL Yang; PS Larsen, "Analysis of Rain Erosion of Coated Materials," *Journal of Composite Materials,* vol. 8, pp. 229-252, 1974.
[2] A. Shankar Verma *et al.*, "A probabilistic long-term framework for site-specific erosion analysis of wind turbine blades: A case study of 31 Dutch sites," *Wind Energy,* vol. 24, no. 11, pp. 1315-1336, 2021, doi: 10.1002/we.2634.

Probabilistic damage growth model

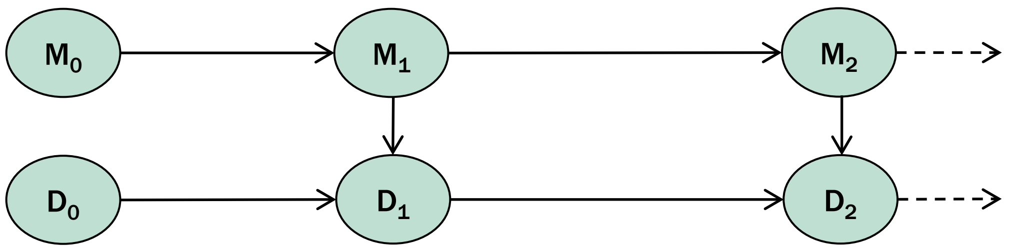
- Physics based modelling of LEE
  - Initiation phase (damage rate)
  - Coating mass loss phase (mass loss rate)
  - Laminate mass loss phase (mass loss rate)
- Year to year variations in distribution parameters for rain intensity, wind distribution, droplet size
- Additional uncertainty added on damage rate D_{LT} (which also affects mass loss rates)
  - $\Delta D = D_{LT} \cdot X_{short} \cdot X_{long}$
  - X_{short}: additional short term variation (lognormal)
  - X_{long}: time-invariant uncertainty (lognormal)

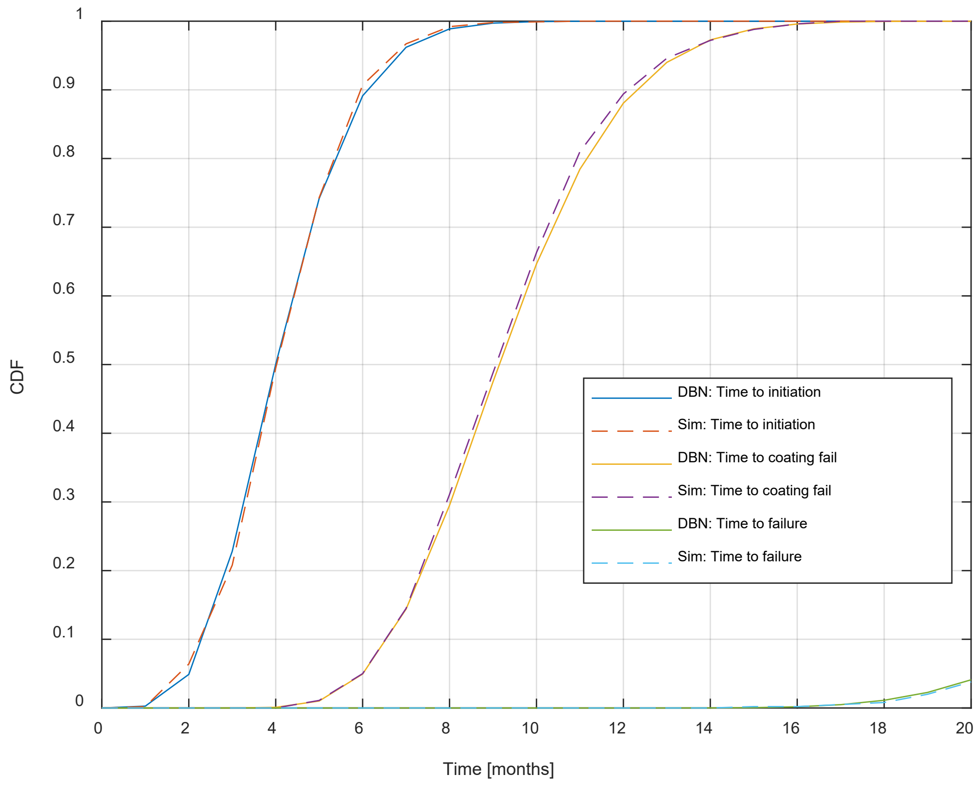




Bayesian network model

- D: damage size, 151 states
- M: model parameter X_{long}, 10 states
- Distribution $P(D_i|D_{i-1}, M_i)$ found using 50 subintervals for D_{i-1} and M_i, and 100 simulated values of X_{short}, D_{LT}, etc.





Inspection model

	Likelihood of reported erosion CAT					
Actual Erosion CAT	No detection	CAT 1	CAT 2	CAT 3	CAT 4	CAT 5
CAT 1	75%	10%	9%	5%	1%	0%
CAT 2	30%	11%	28%	21%	7%	4%
CAT 3	20%	4%	16%	36%	20%	4%
CAT 4	5%	0%	14%	24%	43%	14%
CAT 5	0%	0%	5%	10%	40%	45%

Cost model

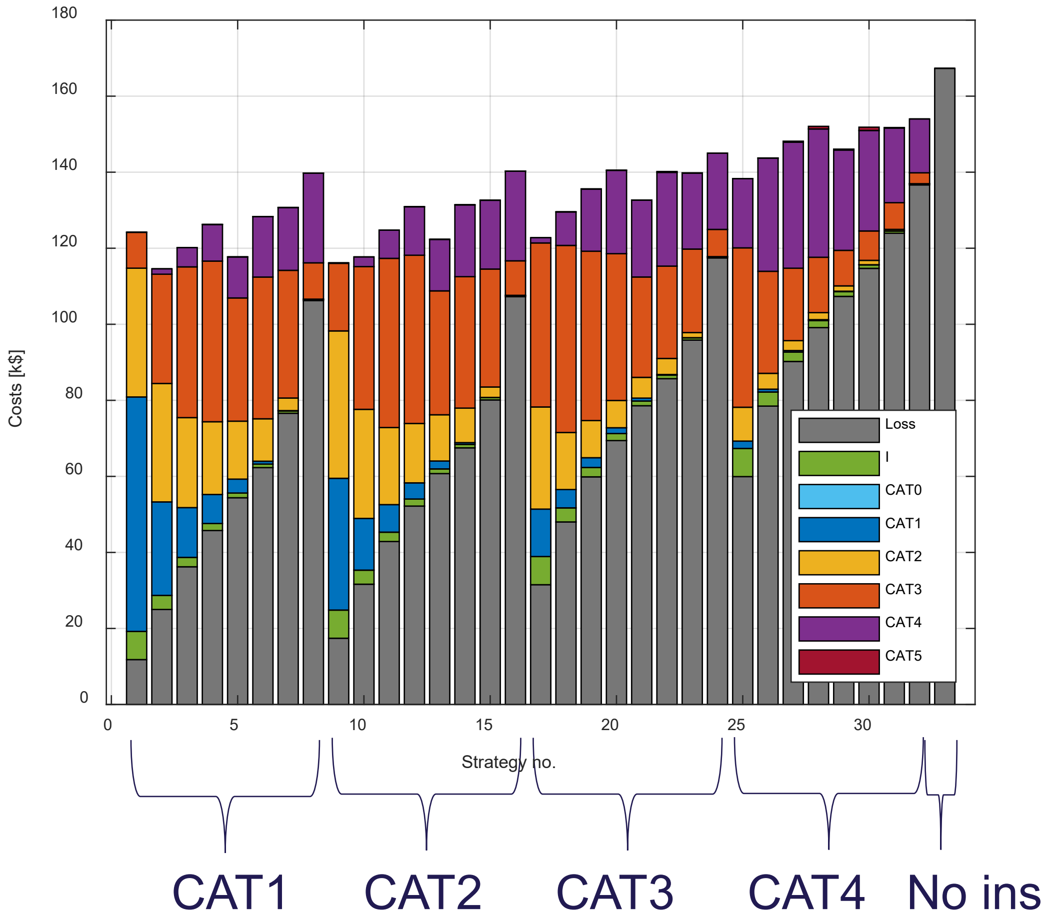
- Onshore US site
- Inspection cost: $300
- Mobilization costs: $1000
- Repair costs per day: $5000

- Electricity price: 25 $/MWh
- Power rating: 3.66 MW
- Capacity factor: 0.4 (0.19 for inspections/repairs)

	Duration	Direct costs $	Revenue loss $	Power loss	Annual AEP loss $
Inspection	0.5 hour	300	8	-	-
CAT 1	2 days	11000	824	0%	-
CAT 2	3 days	16000	1236	1%	1603
CAT 3	6 days	31000	51668	2%	6412
CAT 4	7 days	36000	77502	3%	9618
CAT 5	14 days	71000	129171	5%	16031

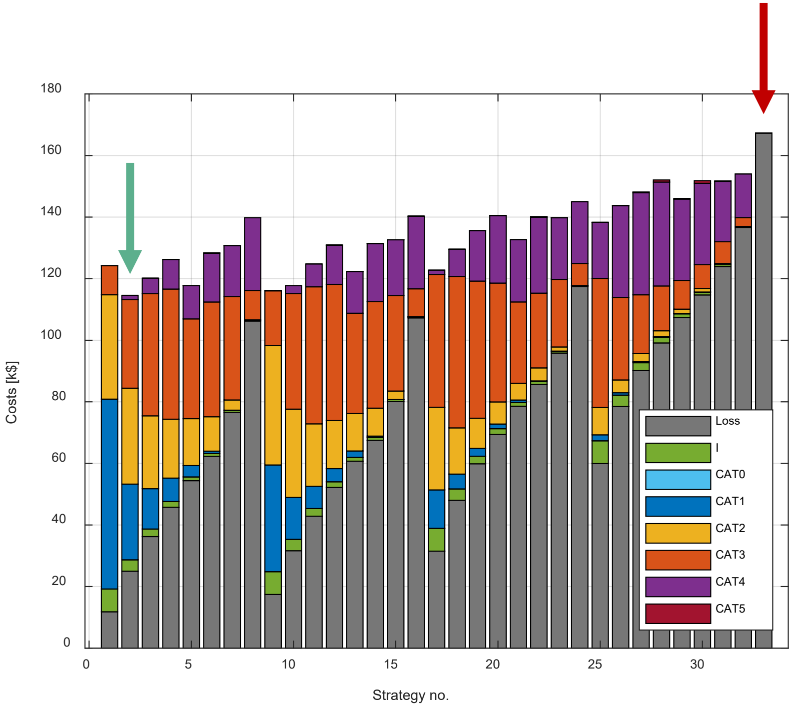
Strategies

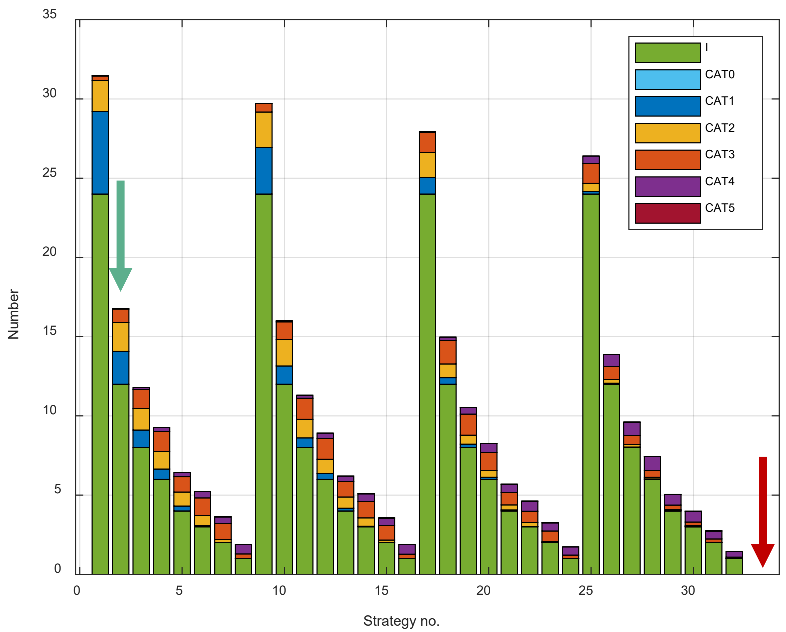
- Strategies:
  - Repair threshold CAT1 to CAT4
  - Inspection interval 1, 2, 3, 4, 5, 7, 9, 13 year

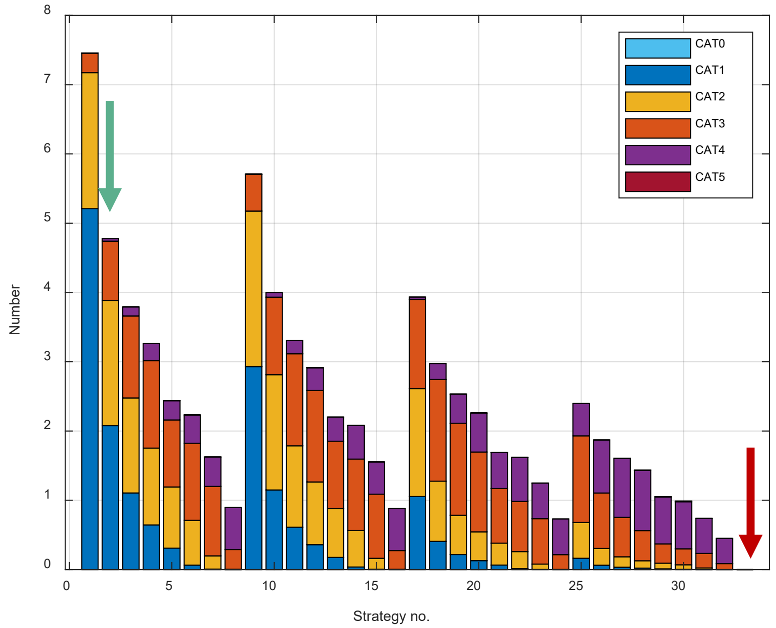


AALBORG UNIVERSITY

Costs and number of inspections/repairs



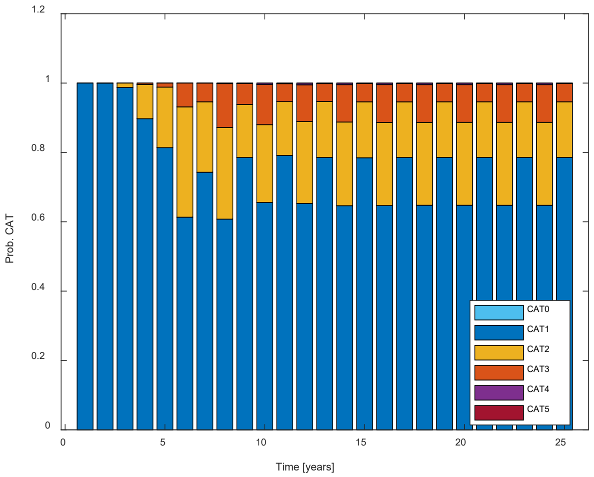


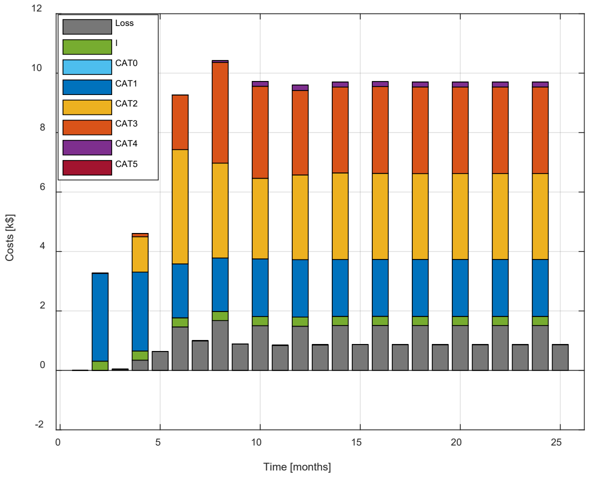


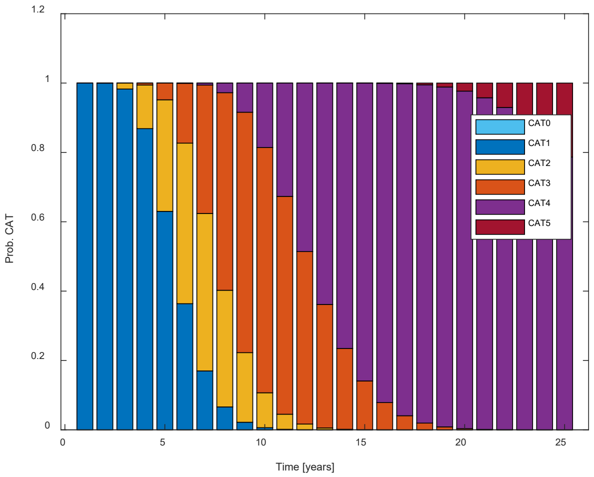
Comparison of strategies

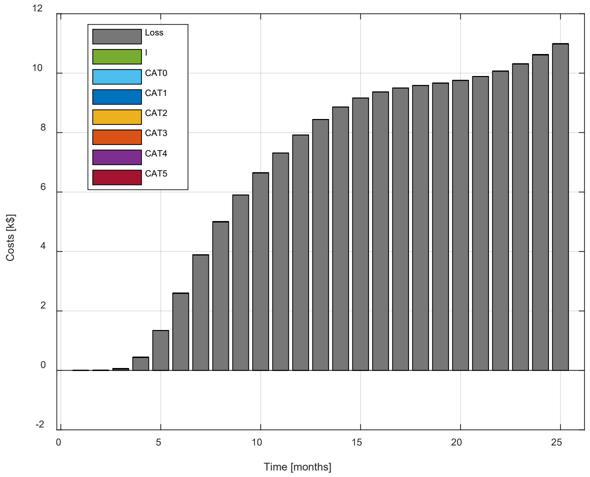
- Optimal strategy
  - Inspection every second year
  - Repair CAT 1

- Worst strategy
  - No inspections
  - No repairs



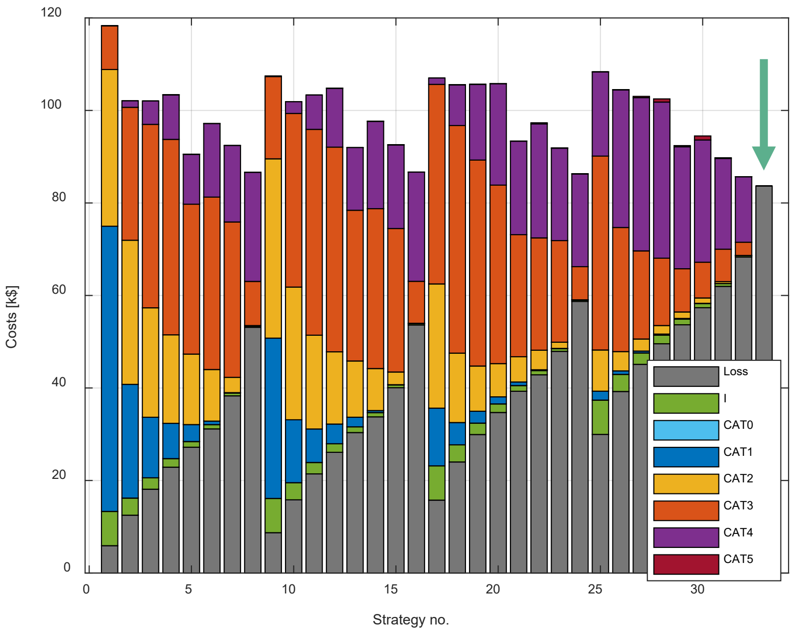




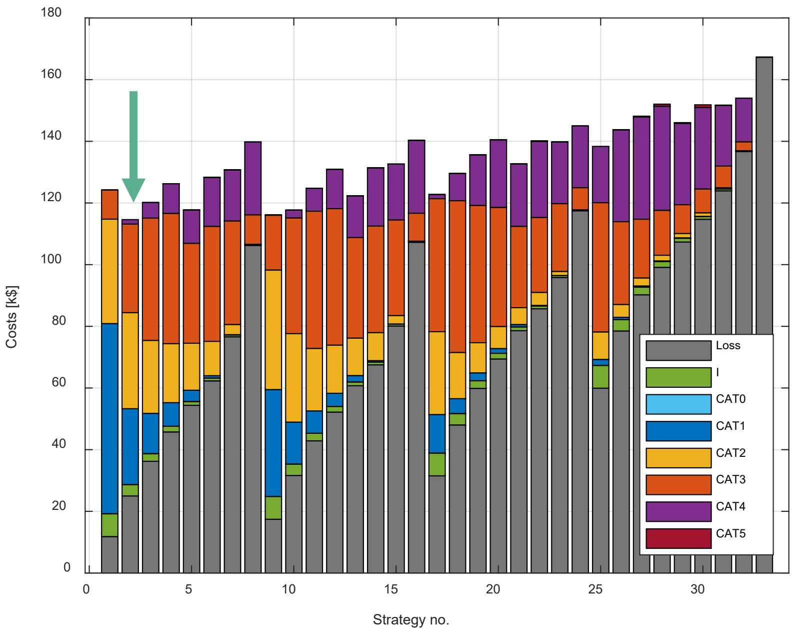


Influence of production loss

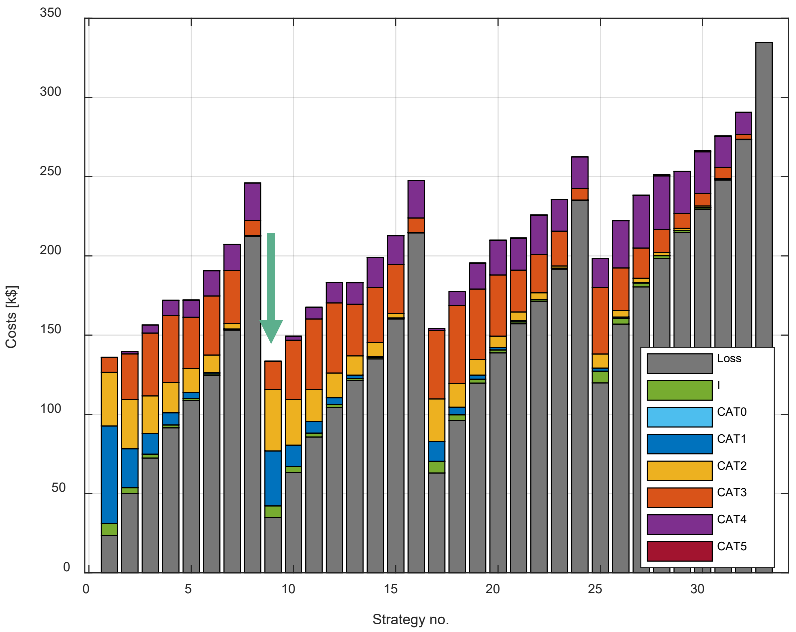
- Max 2.5%
  - No inspections



- Max 5% (base case)
  - 2 year, CAT1

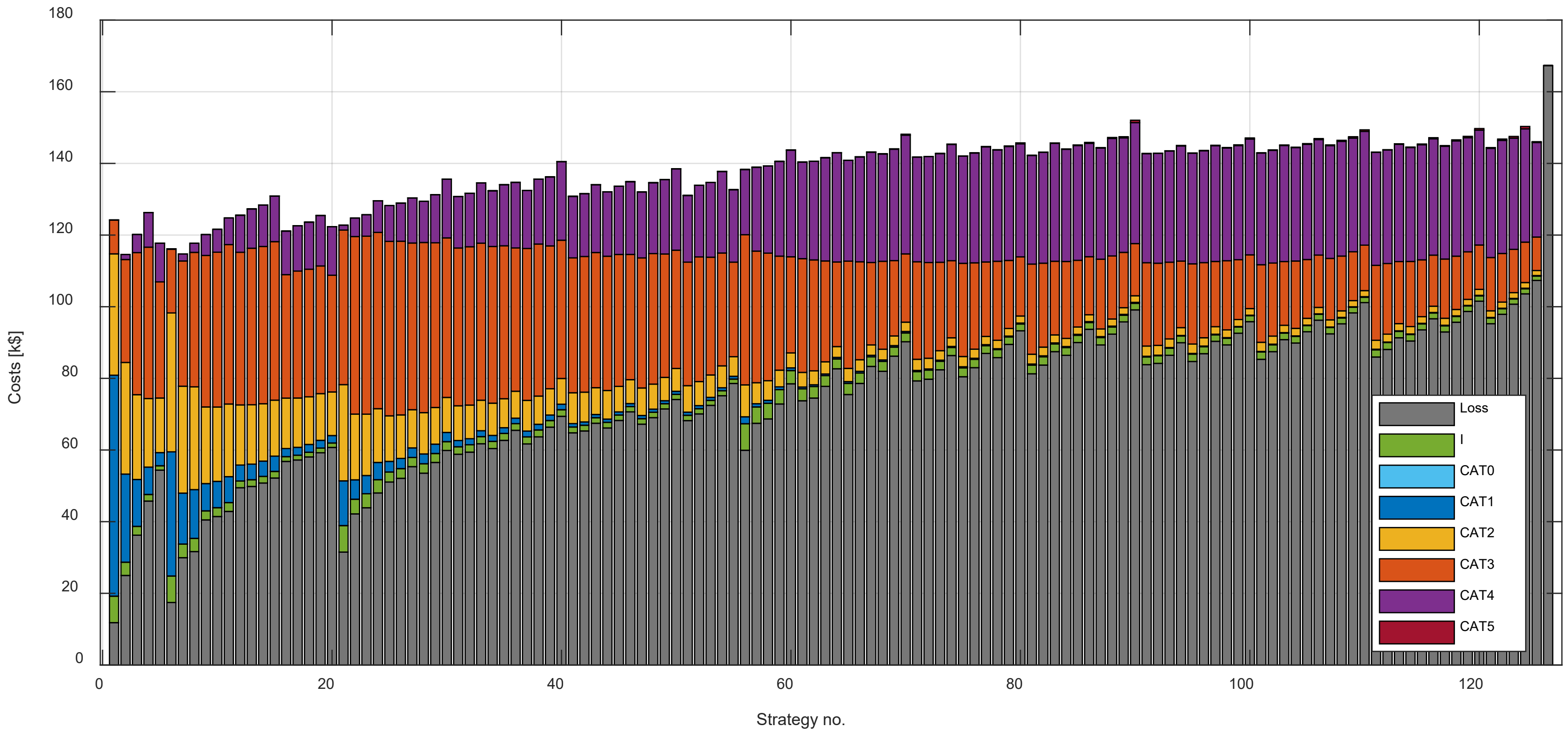


- Max 10%
  - 1 year, CAT2



AALBORG UNIVERSITY

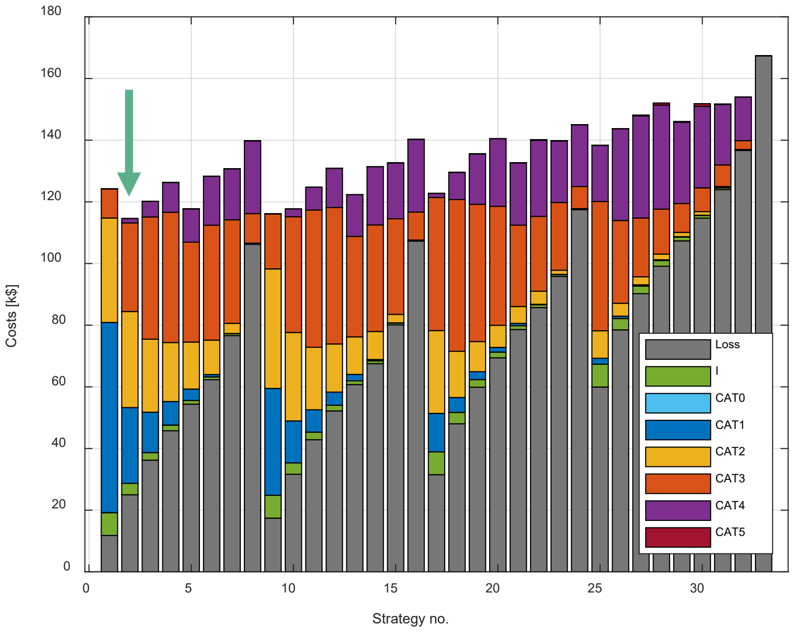
Variable inspection interval 1-5 yr

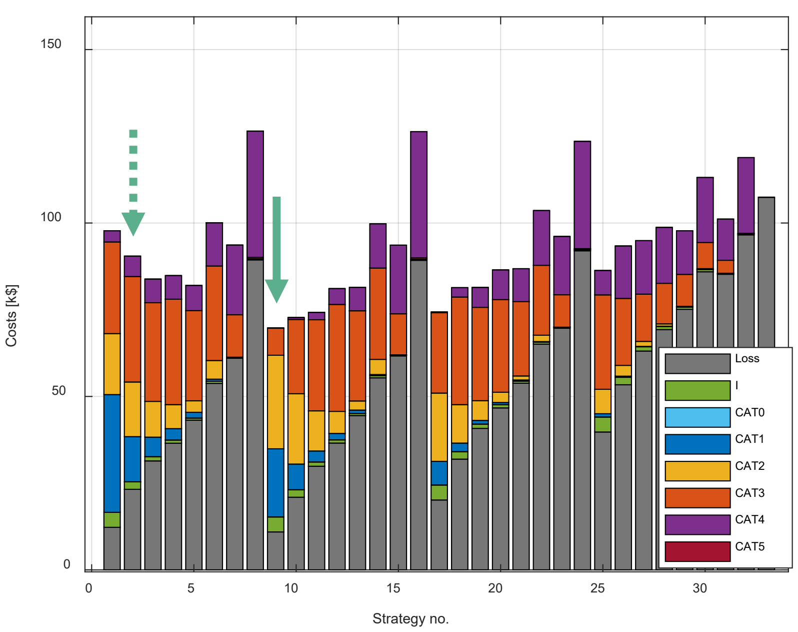


AALBORG UNIVERSITY

Adaptive strategy - example

- Following the initially optimal strategy the first 10 years (2 year, CAT1)
  - Nothing detected in any years -> change to 1 year inspections, CAT 2 repairs





AALBORG UNIVERSITY

Conclusions

- Demonstrates a framework for optimal O&M strategies for leading edge erosion
- Heuristic adaptive strategies as an alternative to ML approaches
- To be further developed to include additional data
- Important for the results that models are realistic (repair, loss, …)

Thank you for your attention

Jannie Sønderkær Nielsen jsn@build.aau.dk