WIND ENERGY DIGITALIZATION

IEA WIND TASK 43

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O&M Working Group

Risk Based Maintenance

NREL 2023 Drivetrain Reliability Collaborative Workshop

Outline

- Committee objectives
- Risk based maintenance framework
- Defect Categorization
- Damage growth model
- Decision model
- Recommendations

Overview

IEA Wind Task 43 Mission Statement

Our mission is to help bring about a revolution in the way the wind energy industry uses technology. We aim to provide a platform for dissemination of great ideas, best practices and collaboration. Specifically, we are working to understand the optimal pathways for the adoption of digital technologies such as:

- *Data Standards and Data Sharing*
- *Machine Learning and AI*
- *Data Analytics and Visualization*
- *Open Source Tools*
- *IoT instrumentation*

IEA Wind Task 43 is broken down into 5 Work Packages / Technical Areas:

- WP1: Digitalization Roadmap
- TA2: Data Standards & Sharing
- TA3: Data Science
- WP4: Digital Resource Assessment
- WP5: Digital Operations & Maintenance

WP5 participants

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https://www.ieawindtask43.org/

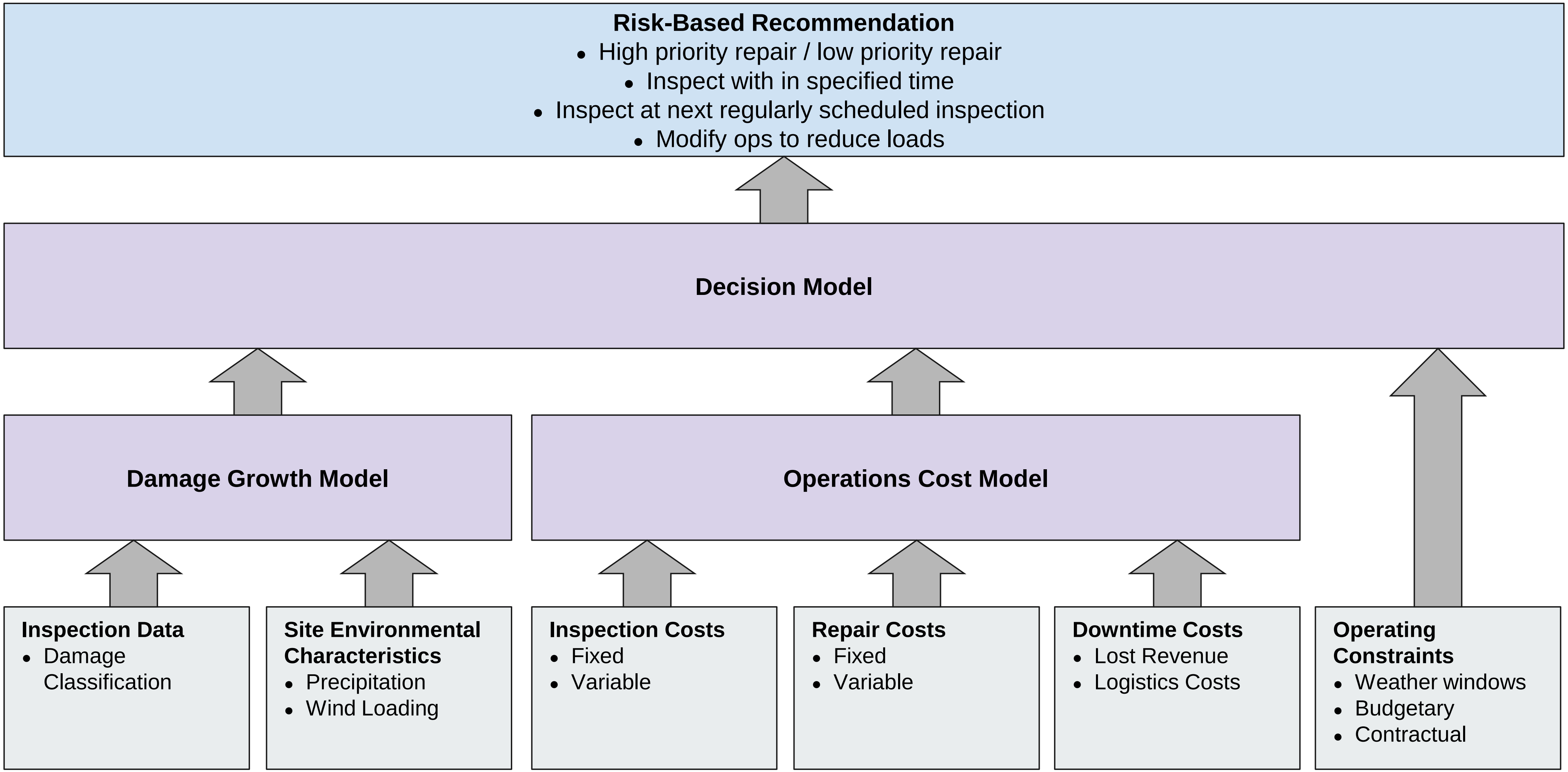
WP5 Objectives

- Demonstrate the value or return on investment in data collection, management, and analytics for applications in risk based maintenance (RBM)
- Provide readers with an approach for assessing the value of digitalization applications within their company
- Demonstrate the specific value of a specific technology (RBM for blades) in a specific situation
    - Provide users with specific models that can be applied to their own RBM for blades
    - Identify requirements and approach for a minimum viable solution to RBM for blades
- Identify gaps for achieving the highest value implementation of RBM broadly across industry (such as standards needed)

WP5 Use Case

- **Intent is to pick a use case and “digitalize it”**
- **Failure mode:** leading edge erosion
- **Decision options:** high priority repair, low priority repair, or monitor at next inspection interval
- Decision model optimizes the inspection interval, based on the damage category, as well as when we should repair
  - E.g., repair immediately versus wait 1 year

Data/Model Stack



Data requirements (LEE)

1. Inspection data:
    a. Damage classification for each instance
2. Environmental data:
    a. Wind loading (how is this defined?)
    b. Rain (how is this defined?)
3. Inspection costs
    a. Per inspection cost for whole wind farm
    b. Per inspection cost for one turbine
    c. Premiums for inspections during off-season
4. Repair costs
    a. Per damage classification
    b. Cost savings for bundling repairs
    c. Premiums for repairs during off-season
    d. Damage level at which it is no longer safe to operate and cost
5. Downtime costs

6. Logistical constraints

    a. Budget
    b. Penalty for going over budget
    c. Inspector and repair lead times
    d. Defined on and off season for inspections and repairs

7. Blade history (optional?)

    a. Repair history + quality of repairs (could make this a function of season repaired)
    b. Age

*Everything should be defined with uncertainty distributions

Inputs

Springer Model

Quasi-empirical model based on classical fatigue analysis fit to experimental results

Incubation period (number of impacts) for coated laminates

$$n_i^* = 7.1 \times 10^{-6} \left[\frac{S}{\bar{\sigma}_o} \frac{1}{1 + 2\bar{k} \|\psi_{sc}\|} \right]^{5.7} \rightarrow n_i = \frac{4}{\pi d^2} n_i^*$$

Incubation period for uncoated laminates

$$n_i^* = 7.1 \times 10^{-6} \left(\frac{S}{P} \right)^{5.7} \rightarrow n_i = \frac{4}{\pi d^2} n_i^*$$

Damage Rate - Palmgren-Miner Rule

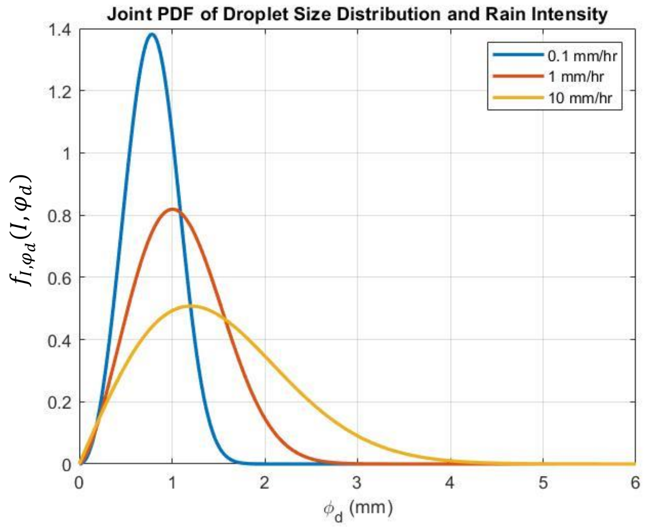
$$D^{ST} = \sum_i^k \frac{n}{n_i} = \frac{q V_{imp} \beta_d}{n_i}$$

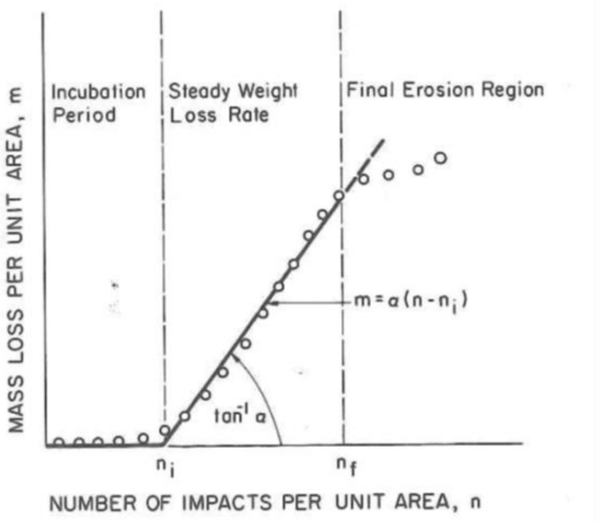
Mass loss rate

$$\alpha^* = 0.023 \left(\frac{1}{n_i^*} \right)^{0.7} \rightarrow \alpha = \frac{\alpha^* \pi \rho d^3}{4} \rightarrow \alpha^t = \alpha(q V_{imp} \beta_d)$$

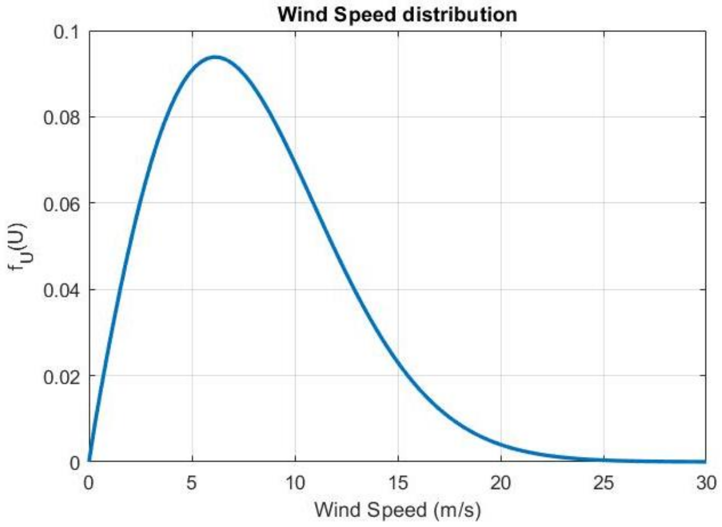
$$m = \alpha(n - n_i) \rightarrow m = \alpha^t (t - t_i)$$

Rain Statistics

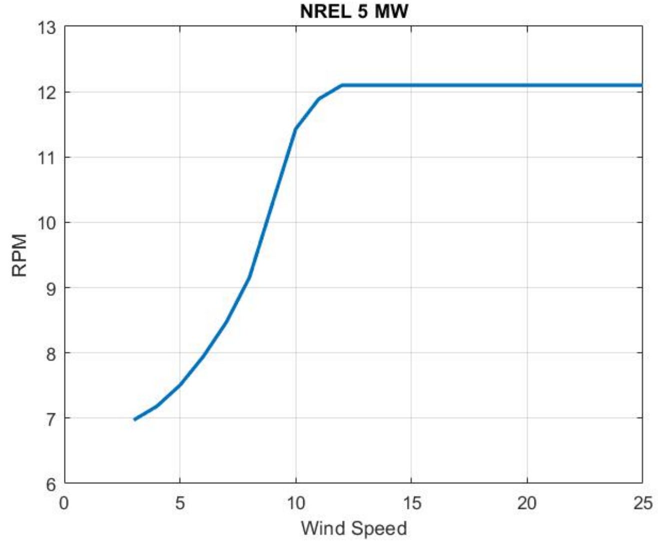




Wind Statistics

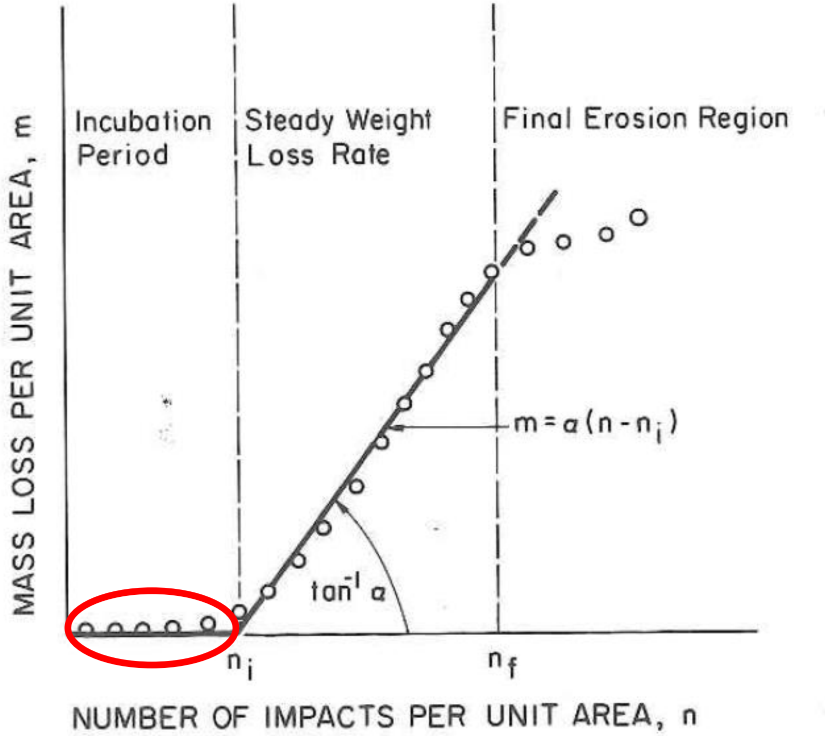


Turbine Power Curve



Relationship Between Mass Loss and Erosion Category

Category	Example 1	Example 2	Example 3	Example 4	Example 5
1	 Pinholes in coating at leading edge	 Broken vortex generators.	 Scratch in coating.	 Erosion or chipped coating	 Grease leakage on blade collar

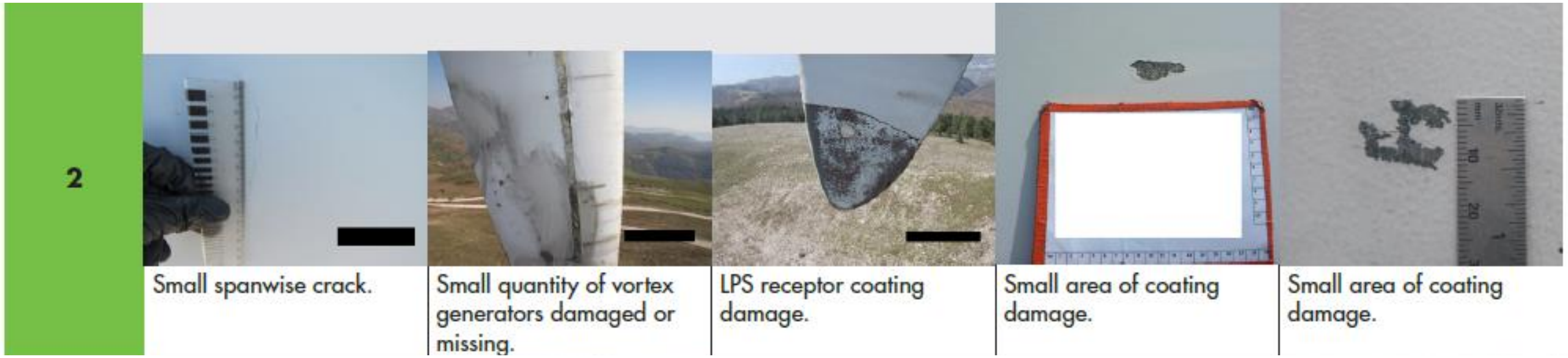


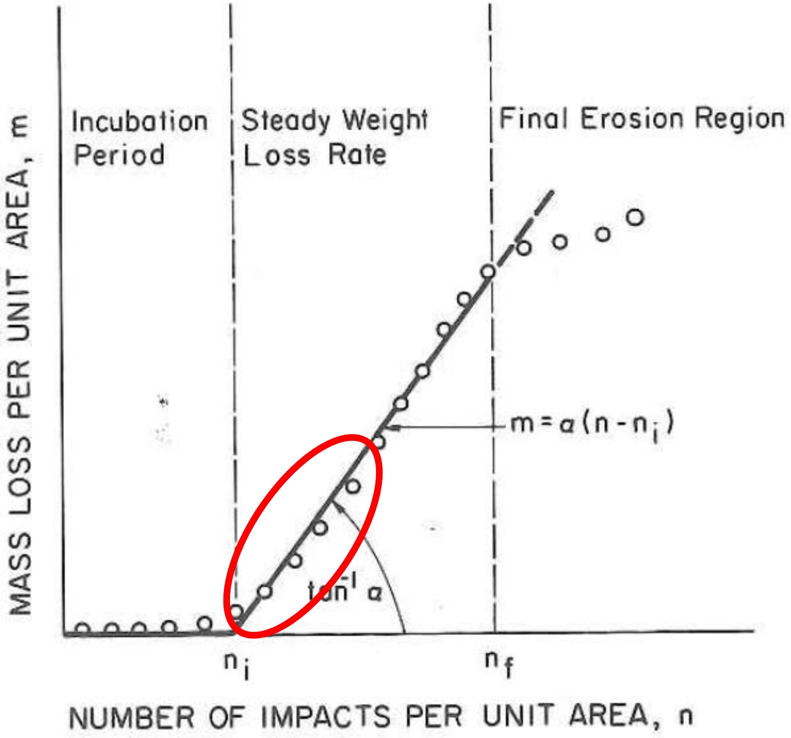
coating mass loss < 10%
laminate mass loss = 0%

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

"Model for the Rain Erosion of Fiber Reinforced Composites" George S. Springer and Cheng I. Yangt, VOL. 13, No, 7, July 1975 AIAAJournal 877

Relationship Between Mass Loss and Erosion Category

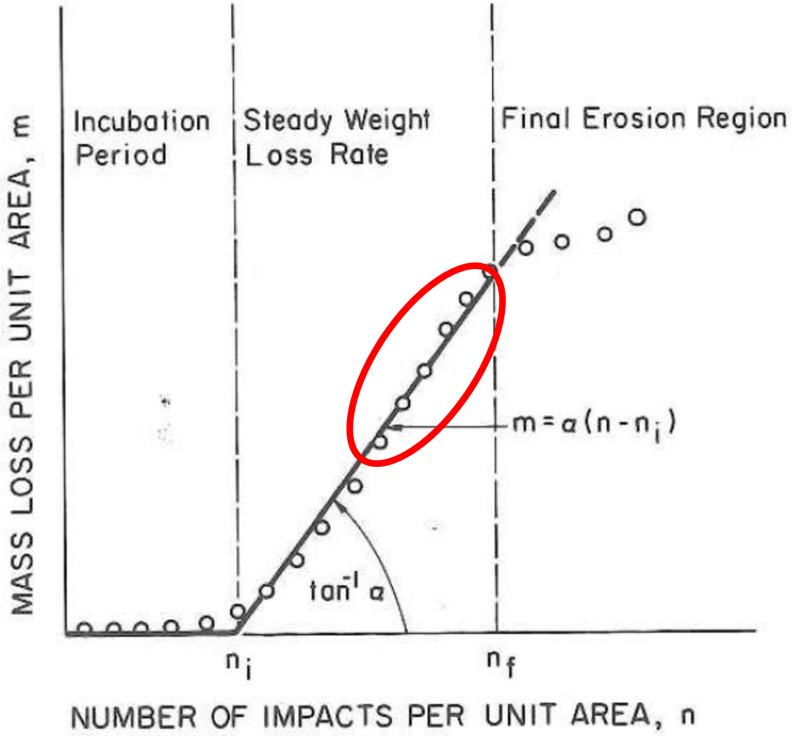




10% < coating mass loss < 50%

laminate mass loss = 0%

Relationship Between Mass Loss and Erosion Category

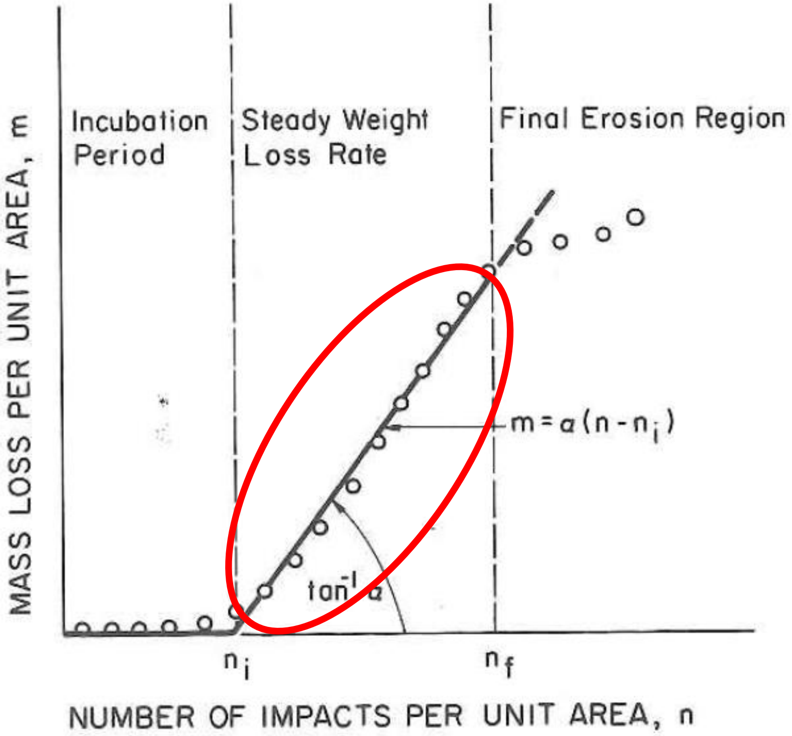


50% < coating mass loss < 100%

laminate mass loss < 10%

Relationship Between Mass Loss and Erosion Category

4	Leading edge erosion with large exposed surfaces of fiberglass. Signs of damage to the underlying fiberglass.	Coating damage with damage to and exposure of the underlying fiberglass.	Trailing edge open over a small length.		Chordwise crack.



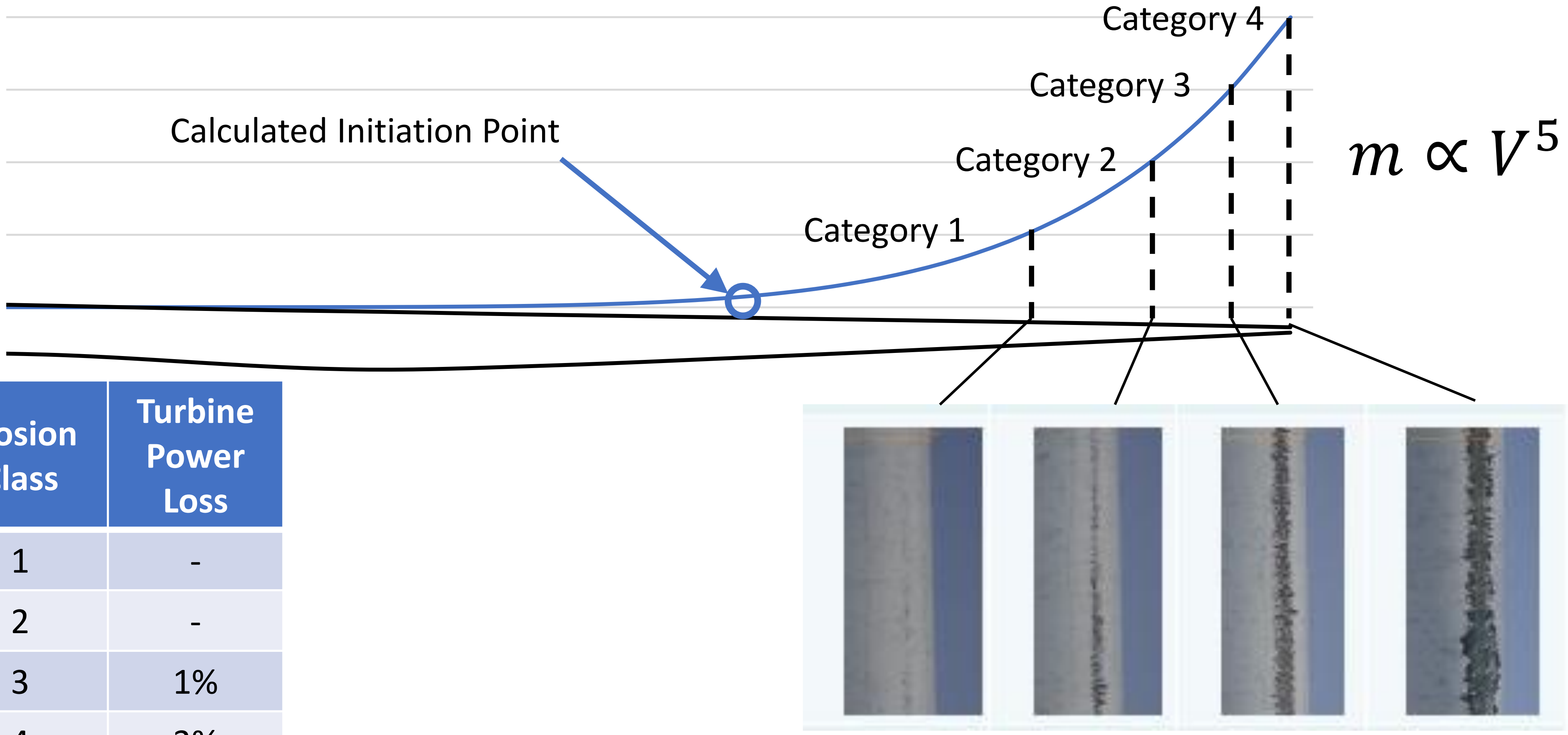
coating mass loss = 100%

10% < laminate mass loss < 100%

Relationship Between Mass Loss and Erosion Class

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

Idealized Spanwise Erosion Distribution



$$m \propto V^5$$

Erosion Class	Turbine Power Loss
1	-
2	-
3	1%
4	3%
5	5%

“Leading Edge Protection Lifetime Prediction Model Creation and Validation.” Drew Eisenberg, Steffen Laustsen, Jason Stege. Wind Europe 2016

Blade O&M decisions

- Inspections – when, where, how?
  - Telephoto, drone, rope
- Repairs – when, where, how?
  - Can the repair be delayed? Should it?

Damage and defect categorization survey (2020)

- Questions
  - Respondent's role in damage and defect categorization
  - Specific examples of damage and defects, including photographs, with request to categorize on a 1 through 5 scale
  - Assign a category, select action to take (monitor/repair/shut down)
  - Estimate extent of damage growth to recategorize of change action
  - Freeform question about description of blade maintenance program
  - Questions regarding frequency and methods of inspections
  - Limited information!

This damage is at 80% span on the suction side shell.

The damage measures approximately 10 cm x 3 cm.

This turbine has been running for approximately 30% of its design lifetime.

Blade damage and defect categorization system

Category	Characteristics	
1	**Description**	Minor variances from supply specifications but within acceptable (or industry typical) tolerances; may affect the appearance of the blade or blade feature. Though minor, can be useful to identify as position references, or for blade identification.
	Potential for growth	None expected.
	Impact to aerodynamics	None expected.
	Impact to life	None expected.
2	**Description**	Minor damage or defects that exceed supply specification acceptance criteria. Multiple cosmetic findings and/or a single major cosmetic finding that are damage, defects, or former repairs. Findings exceed tolerances of supply conditions or industry typical manufacturing variability. Repairs of more severe damage or defects can be recategorized to category 2 upon review of repair.
	Potential for growth	Not likely but may accelerate leading edge erosion when located on the leading edge, additionally may leave laminate or bond lines exposed to environmental degradation. Generally 100% growth in size or severity pushes finding into next category.
	Impact to aerodynamics	May have minor impact to aerodynamics depending on details, though beyond what could reasonably be measured.
	Impact to life	None expected.
3	**Description**	Moderate to minor structural damage or minor manufacturing defects in non-critical areas. Features are moderately out of compliance with supply conditions and/or below minimum typical industry practice. May present as surface indications when in fact there is damage to the underlying structural laminate. Internal inspection may be needed to determine the extent of the finding. May be particularly challenging to assess criticality due to lack of design data such as load margins. Findings may be category 3 when category 4 actions seem too drastic and category 2 is not appropriate, because there is a slight risk of loss of structural capability.
	Potential for growth	Likely to increase in size or extent over time and become more severe. Growth in size or severity by 50% or more is likely to push finding into next category.
	Impact to aerodynamics	May have an impact to aerodynamics depending on details.
	Impact to life	Life is expected to be reduced without some other measures such as monitoring or repair or engineering evaluation (in the case where there is sufficient margin).
4	**Description**	Significant damage or defects that have notable impact to structural capability and/or aerodynamic performance.
	Potential for growth	Likely to increase in size or extent over time and become more severe. Growth in size or severity of 10-50% is likely to push finding into next category.
	Impact to aerodynamics	Likely to have an impact to aerodynamics depending on details.
	Impact to life	High confidence the blade will not achieve intended life.
5	**Description**	Severe degree of damage or defect such that there is a high risk of imminent failure.
	Potential for growth	Likely to rapidly increase in size or extent.
	Impact to aerodynamics	Likely to have an impact to aerodynamics depending on details.
	Impact to life	The blade is expected to fail within a short period of time if operated.

Blade damage and defect categorization system

Category	Actions	
1	**Repair**	None needed, though some can be remedied with minimal effort in conjunction with other blade maintenance activities.
	Continued operation of turbine	Yes.
	Additional monitoring	None needed.
2	**Repair**	Evaluate cost/benefit of repairs.
	Continued operation of turbine	Yes.
	Additional monitoring	Monitor during routinely scheduled maintenance for damage initiation or progression. Depending on the damage, internal inspection may be warranted to differentiate surface cracks from more severe laminate damage.
3	**Repair**	Determine depending on circumstances, criticality, and O&M approach. If found during manufacturing, should be repaired prior to installation. Investigation and repair or replacement of missing aerodynamic devices should be performed to regain energy capture benefits. Timing of repairs can be linked to other blade-related needs. Leading edge erosion or small external cracks should be repaired to prevent damage progression.
	Continued operation of turbine	Yes.
	Additional monitoring	Inspection frequency driven by assessment of risk; may be more frequent than routinely scheduled inspections recommended by the OEM. If no growth in damage over time, an engineering assessment may downgrade finding to category 2.
4	**Repair**	Repair within a limited number of months of initial observation. Repairs may be performed uptower or blade removal and ground repair maybe necessary, depending on the finding. If found during manufacturing, should be repaired prior to installation and a manufacturing quality assessment should be undertaken to find and correct root causes.
	Continued operation of turbine	Engineering evaluation required to deem blade can operate until repair is scheduled. Operation shall stop if repair cannot be implemented within the allowable time period.
	Additional monitoring	More frequent or more comprehensive monitoring than routine inspections are required until repairs are complete.
5	**Repair**	Replace, or repair depending on repair feasibility and cost/benefit relative to replacement.
	Continued operation of turbine	The blade is not safe to operate until the damage or defect is repaired or the blade is replaced.
	Additional monitoring	If repair is implemented, repair should be deemed a Category 3 defect until sufficient operating experience is gained to provide confidence that the repair is sufficient to achieve expected remaining operating life.
	Further steps	A formal root cause analysis should be performed to ensure complete understanding of events or defects and prevent repeated occurrences.

Damage and defect categorization survey takeaways

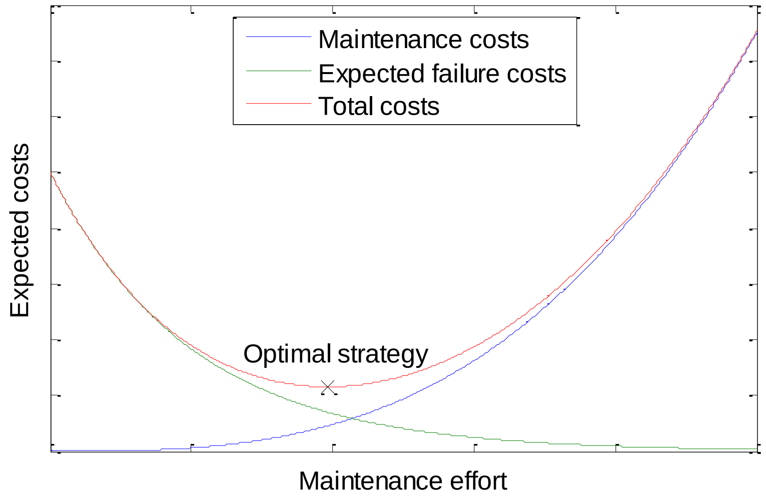
- Category 1-3 typically operated with inspections every 6 to 12 mo.
- Category 3 or 4 typically repaired or shut down within 6 to 12 mo with inspection every 6 mo.
- Category 4 or 5 typically repaired or shut down immediately or within 12 months with monthly monitoring

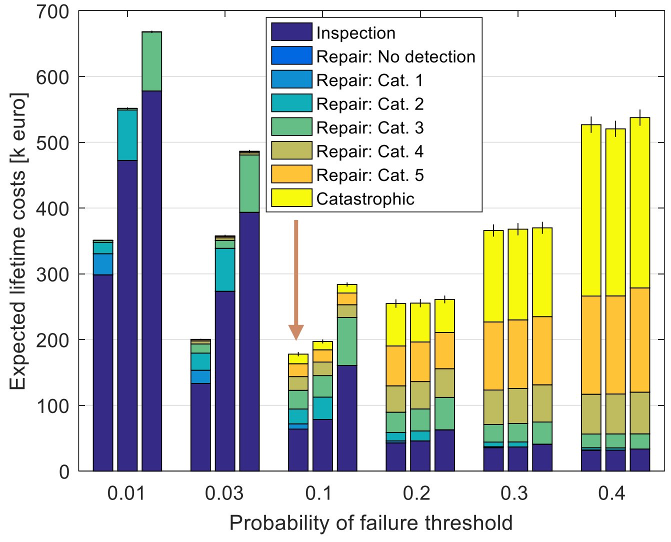
Only the most severe damage and defects were considered serious enough to stop the turbine until repair.

Moderate and less serious damage were monitored once or twice a year with operation.

Optimal blade O&M

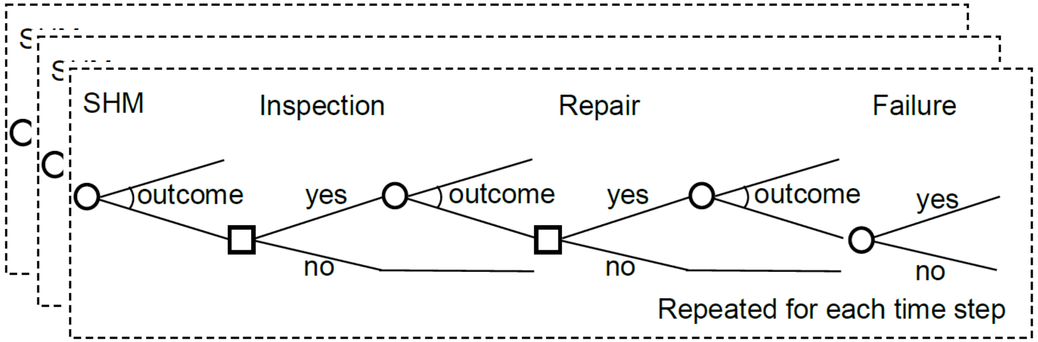
- Balance between doing too much and too little
- Minimize expected costs
  - Considering present value of direct and indirect costs
- How do we find the optimal strategy?





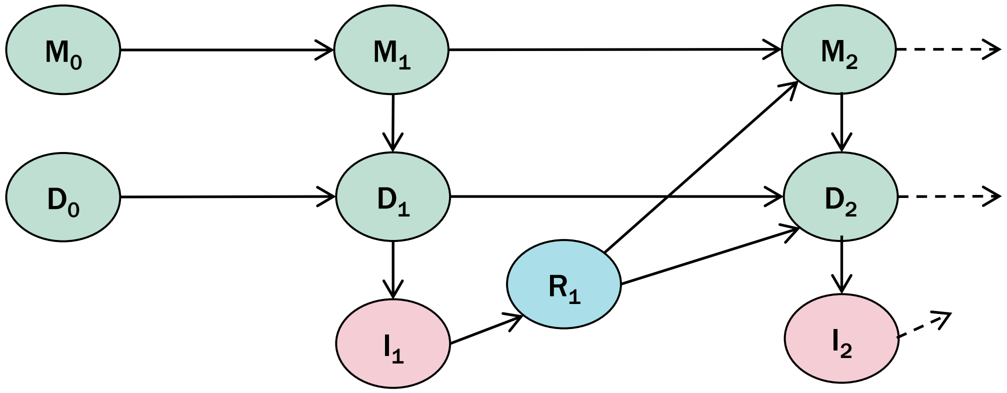
A sequential decision problem

- Approaches for decision optimization
  - Bayesian decision theory
    - Exact solution intractable for O&M problems
    - Heuristic decision rules: Inspect with fixed interval / inspect when probability of failure drops below threshold
  - Computer science – dynamic programming
    - Approximate methods for O&M problems
    - Markov decision processes, POMDP
- Optimality vs. simplicity



Decision model

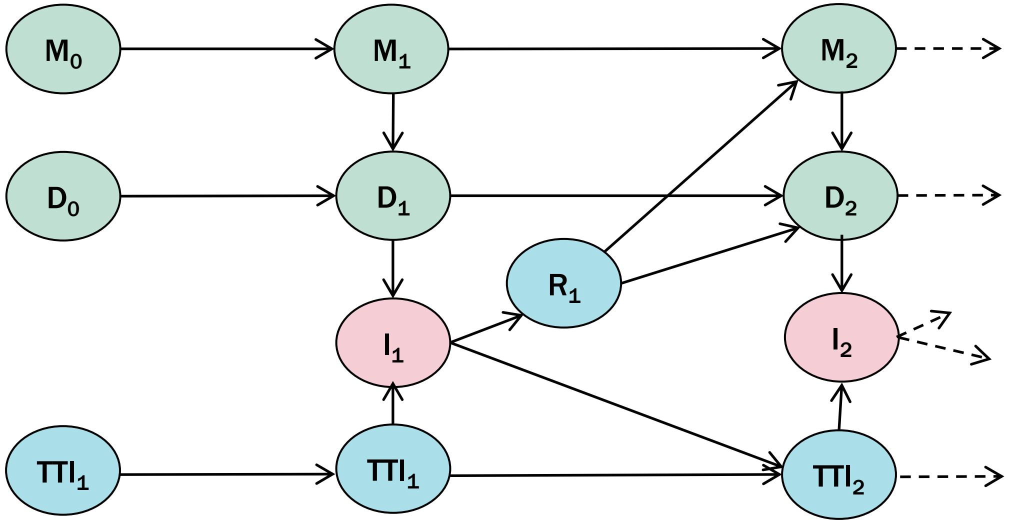
- Input
  - Deterioration and repair model
  - Inspection model
  - Cost model
- Output
  - Optimal decision – strategy for inspections and repairs
  - Expected lifetime costs



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

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

Decision model

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

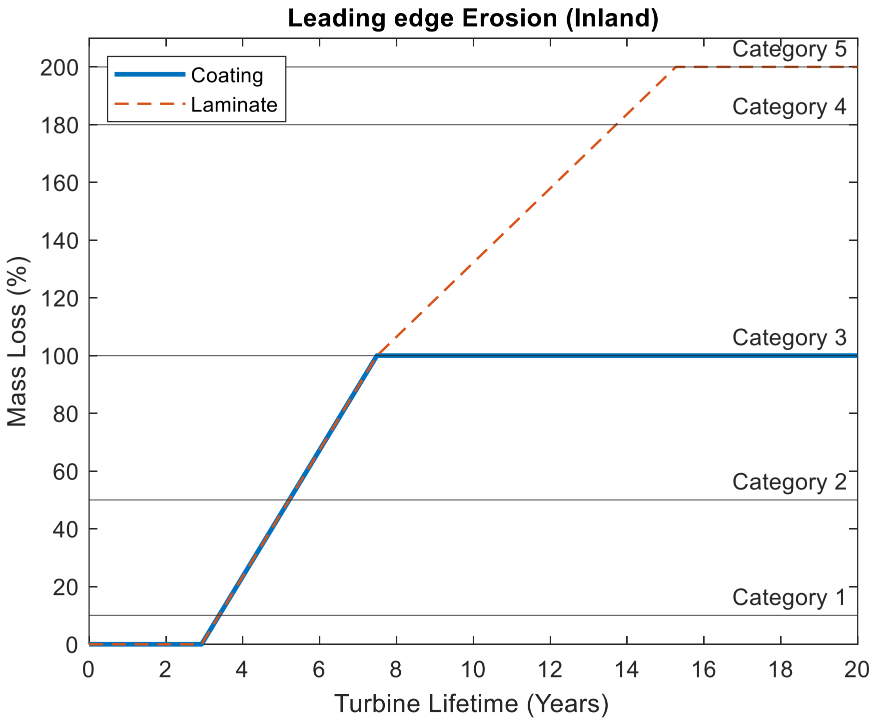
State of node I	Inspection outcome	Repair	Next inspection
1	No inspection	No	TTI-1
2	Category 1	No	12
3	Category 2	No	12
4	Category 3	No	6
5	Category 4	No	6
6	Category 5	Yes	12
7	Category 6 / failure	Yes	12

Leading edge erosion

- Analytical LEE deterioration model

- Input
  - Rain intensity, droplet size distributions
  - Velocity (Wind distribution, Wind Turbine type)
  - Material properties

- Large uncertainties
  - Update model based on inspection data



Conclusion

- This use case demonstrates how digitalization can enable more effective risk based maintenance decision-making
- This methodology can also help to identify industry-wide gaps in need of further standardization
- The decision model can potentially be applied to other turbine components in determining optimal inspection intervals

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