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Fatigue crack detection for lifetime extension of monopile-based offshore wind turbines

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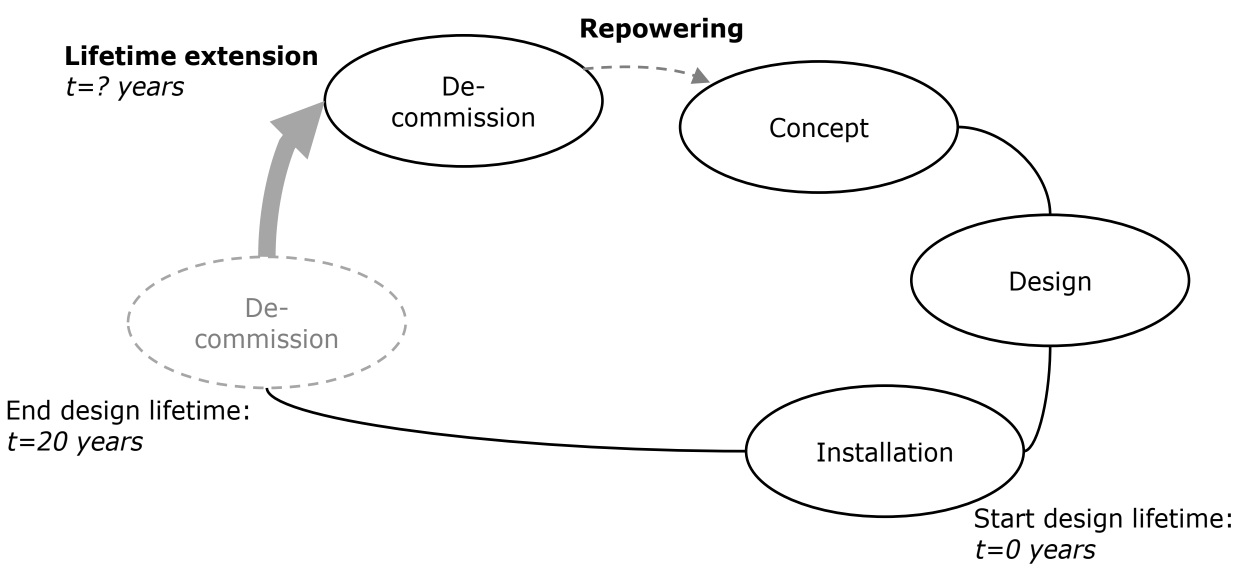
Why lifetime extension?

- Design lifetime at least 20 years
- Lifetime extension possible if structural reserves are left
- Increases profit and reduces environmental impact



What do we need for lifetime extension?

We need to…

- keep the target safety level
- know structural reserves and remaining useful lifetime

This can be done by…

- analytical assessments
- practical assessments

Problems of inspections are…

- access
- safety risks
- costs
- detection uncertainty

→ *Is it worth to do inspections?*

Agenda

1. Inspection of fatigue cracks

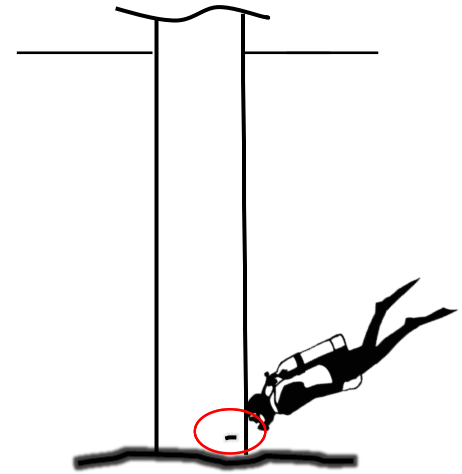
2. Simulation of fatigue cracks

3. How to link inspections and simulations: Bayes Theorem

4. Results: Reduction of uncertainty

AWESOME

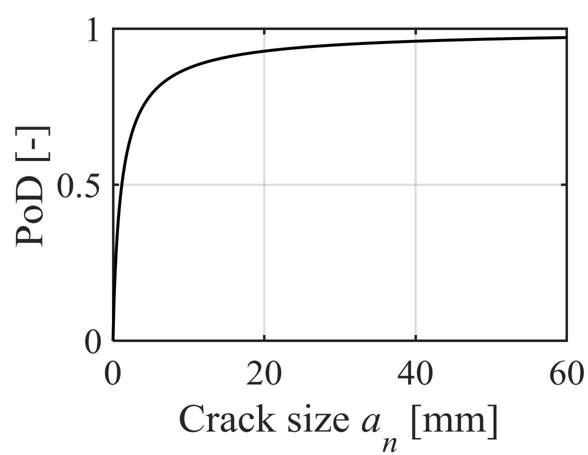
Inspection for fatigue cracks

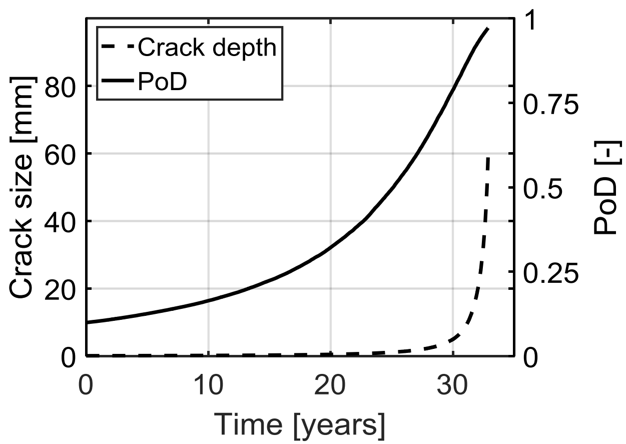


- Probability of detection
  - Inspection method (eddy current, visual inspection,...)
  - Ease of access
  - Crack size

$$PoD(a_n) = 1 - \frac{1}{1 + \left(\frac{a_n}{X_0}\right)^b}$$

PoD parameters given in DNVGL RP-C210





Simulation of fatigue cracks

- DeepWind 2016:
  Load sequence is negligible using Paris law
- Integration of Paris law now possible ☺

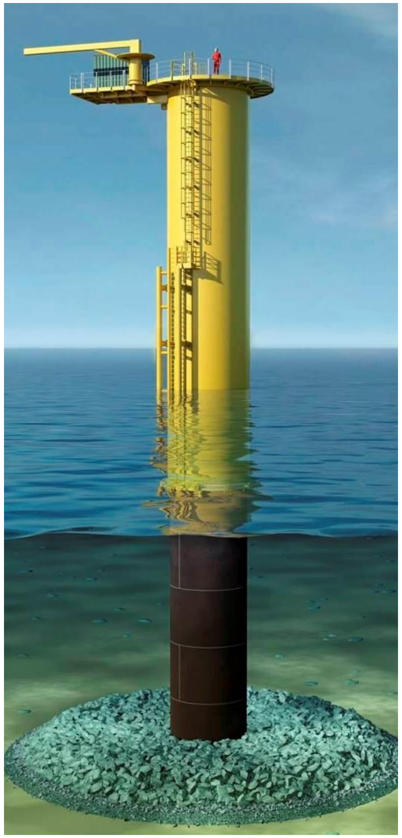
$$\frac{da}{dN} = C(\Delta K_I)^m \quad \text{with} \quad \Delta K_I = \Delta S Y \sqrt{\pi a}$$

$$C S^m \Delta N = \int_{a_0}^{a_n} \frac{da}{Y^m (a\pi)^m}$$

a : crack depth [mm]
N : number of cycles [-]
ΔK_I : stress intensity factor
ΔS : stress range [MPa]
Y : geometry factor [-]
C, m : material constants

- Variable amplitude loading

  ⇒ bins of 1MPa

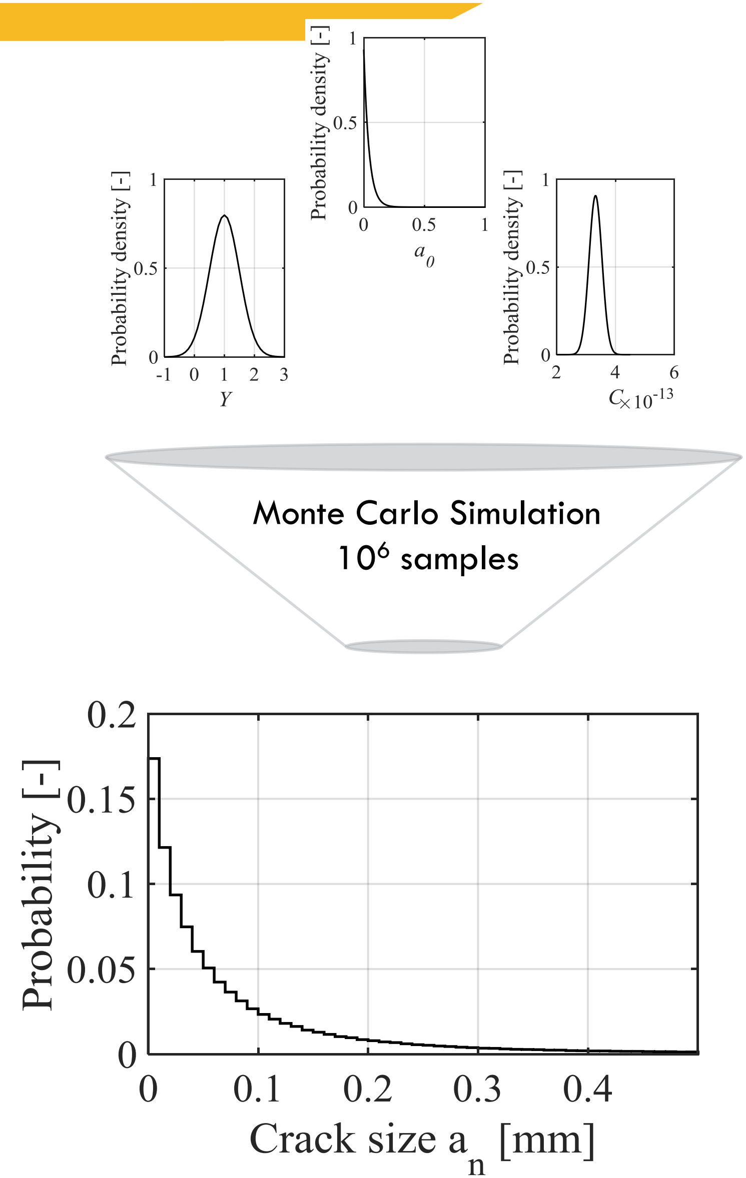


Simulation of fatigue cracks

- Why integration of Paris Law?
  - Because it is fast
- Why do we need it fast?
  - Monte Carlo Simulation

Monte Carlo Simulations

- Uncertainties: C, Y, a_0
- Deterministic loads from case study
- Distribution of crack size in year 20



Simulation of fatigue cracks

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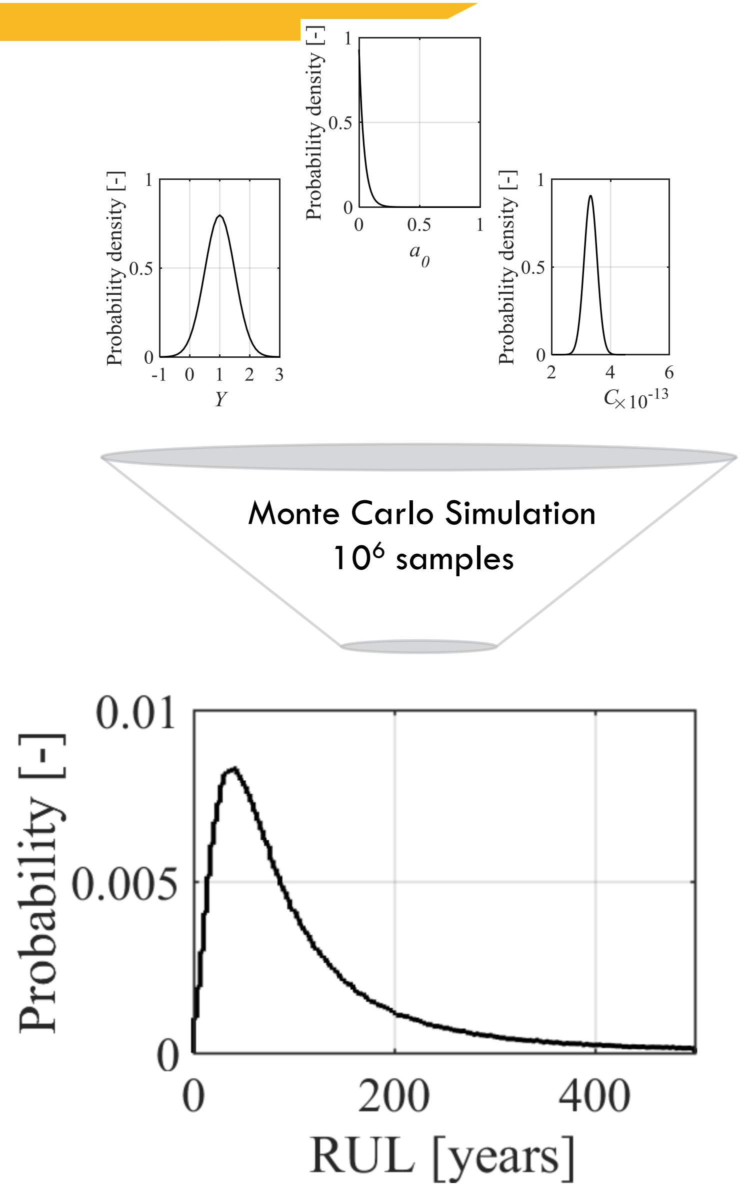
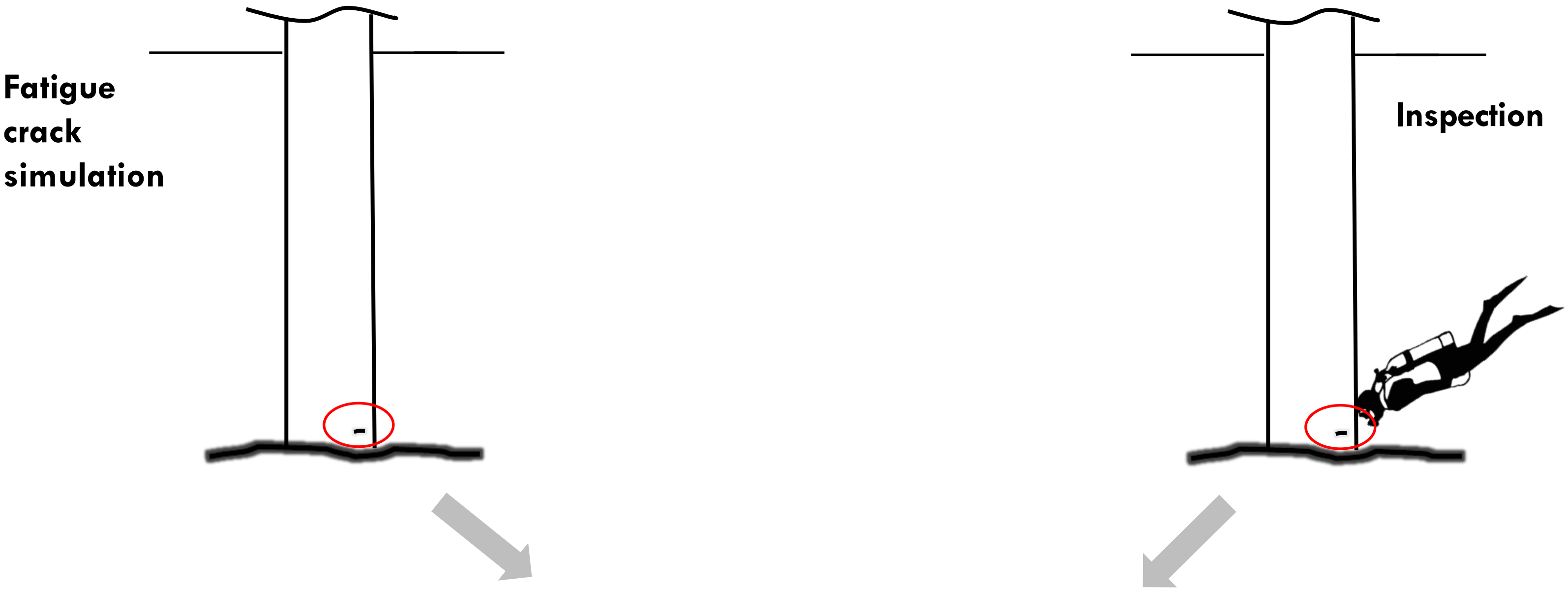
Remaining useful lifetime

- Time until a_n reaches a_{fail}

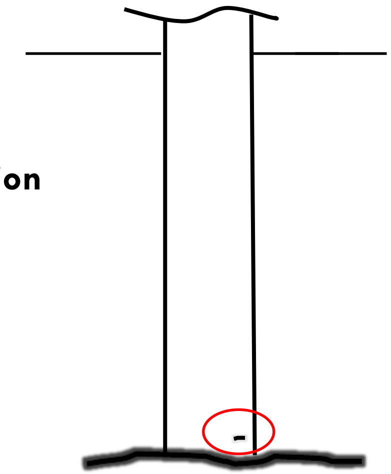


How to link inspections and simulations: Bayes Theorem

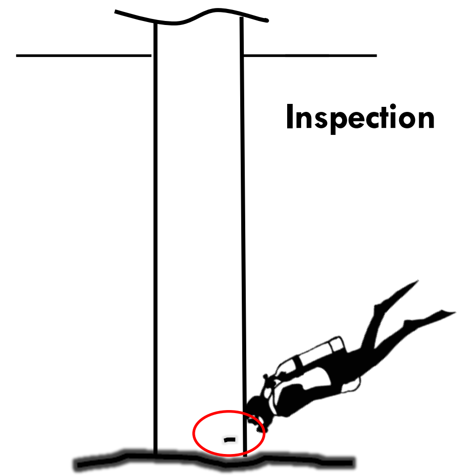


How to link inspections and simulations: Bayes Theorem

Fatigue crack simulation



Inspection



$$P(a_n \mid z) = \frac{P(a_n)P(z \mid a_n)}{P(z)}$$

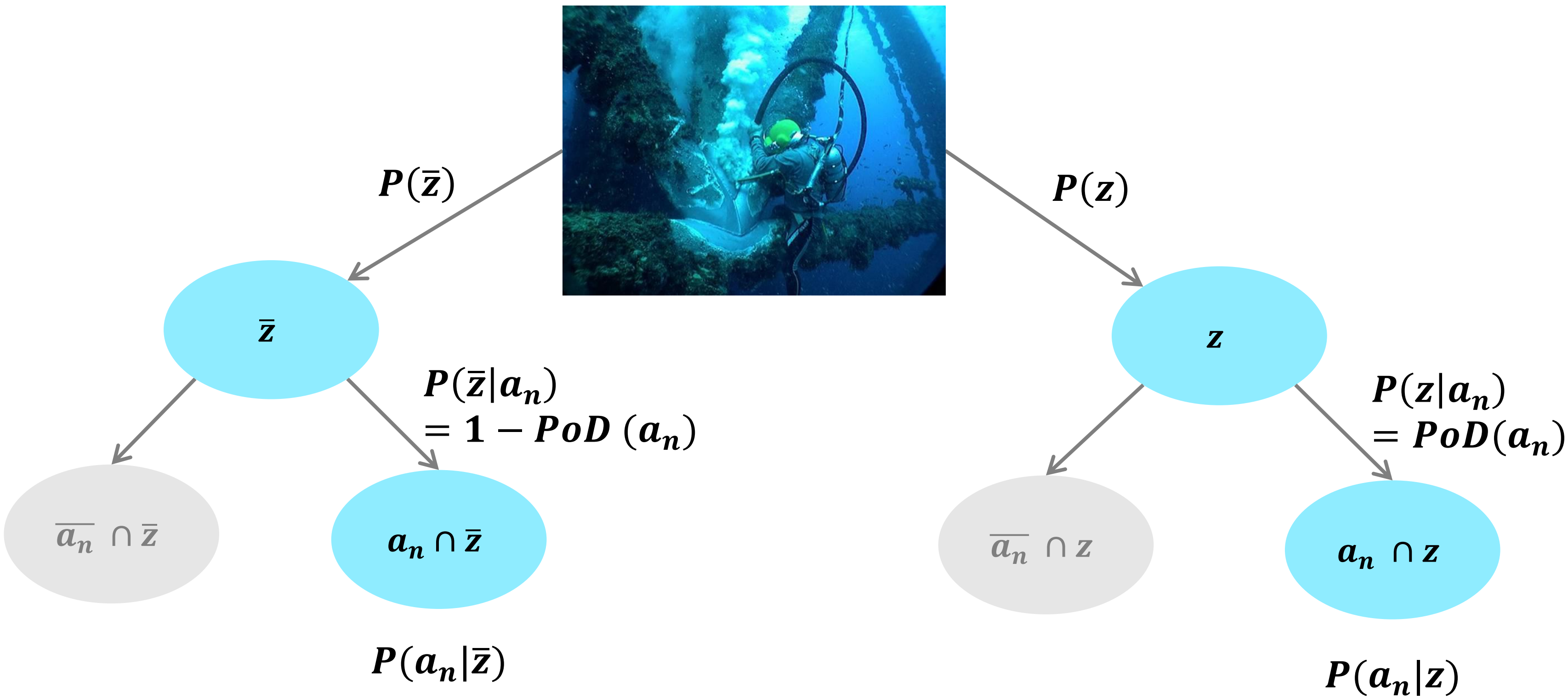
$P(a_n)$: Probability of crack size a_n

$P(z \mid a_n)$: Probability of detection (POD)

$P(z)$: Probability of inspection outcome

$$P(z) = \sum_{a_{\min}}^{a_{\max}} POD(a_n)P(a_n)$$

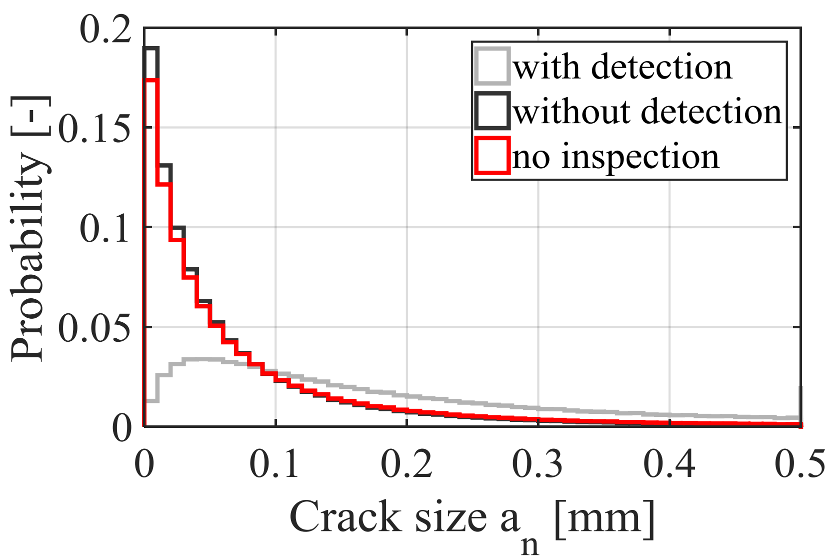
Inspection outcomes and Bayesian updating

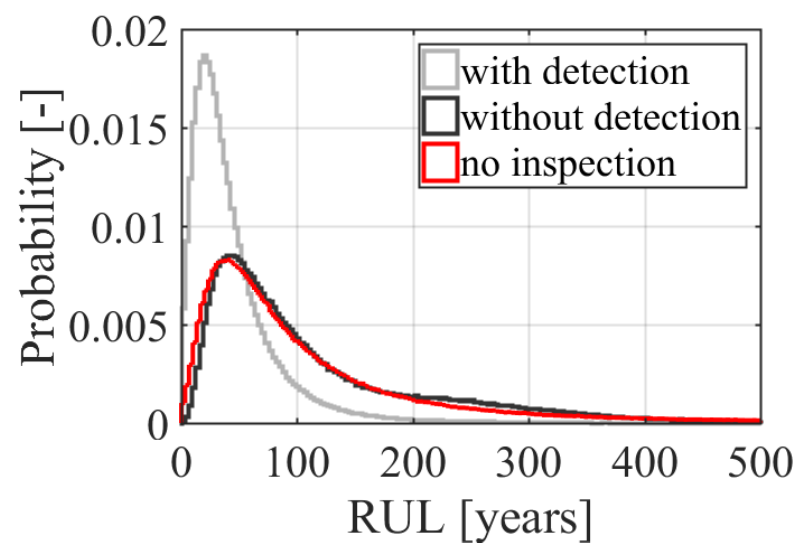


$P(a_n)$: Probability of crack size a_n
$P(z)$: Probability of detection
$\bar{x}$: complement of x

$P(z|a_n)$: Probability of detection (POD)
$P(a_n|z)$: Updated probability of crack size

Results: Reduction of uncertainty



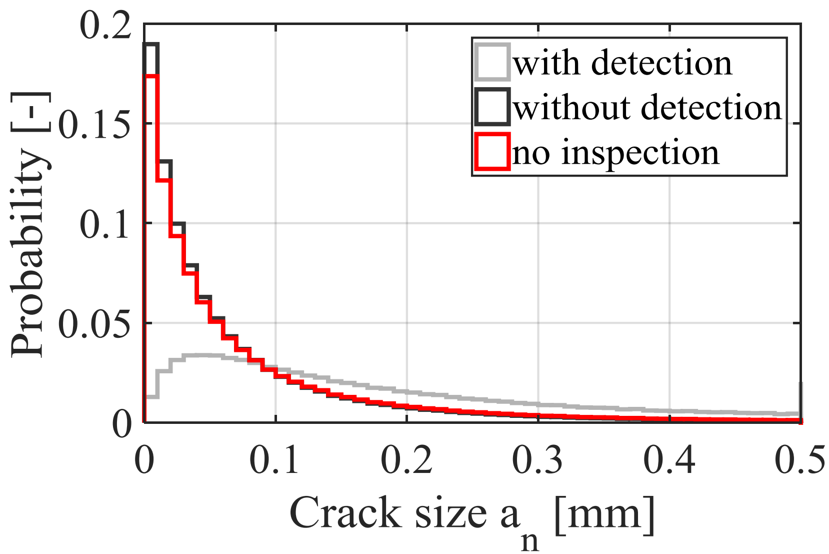


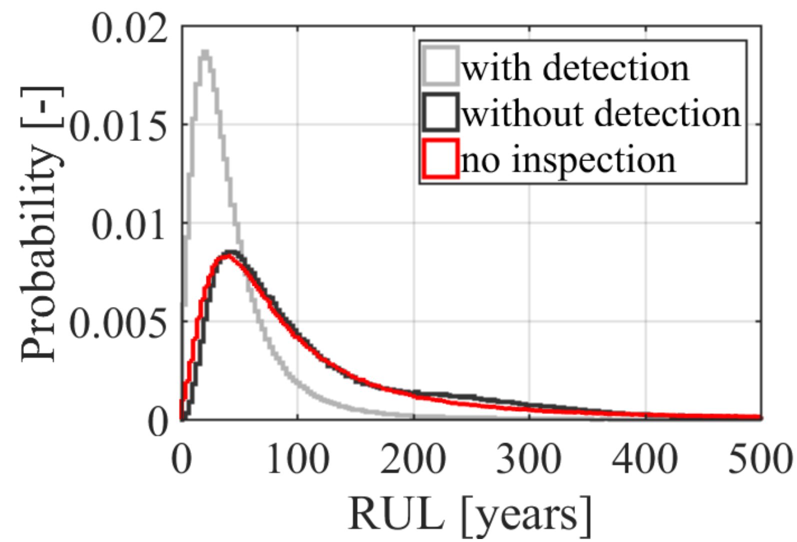
	Median crack size an [mm]	Median RUL [years]	Standard deviation RUL [years]
No inspection	0.04	78	446
With detection	0.20	33	47
Without detection	0.04	83	103

-90%

-77%

Results: Reduction of uncertainty





- Results influenced by tails of distribution
- Case with detection: 10% of RUL is below 10 years
- Case without detection: 10% of RUL is below 30 years
- Larger reduction of uncertainty in case of detection
- Individual results for every structural detail – Where is the hot spot?

Conclusion

Inspections are costly and risky.

Is it worth to do it?

We showed the value of inspections is:

- Reduction of uncertainty
- Eliminate risks of large cracks

Conclusion:

- A trade-off between costs and benefits necessary!
- Is the safety level without inspections acceptable?
  ⇨ Design fatigue factor of 3 = inspection free
- Alternative: Structural health monitoring

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Thanks for your attention

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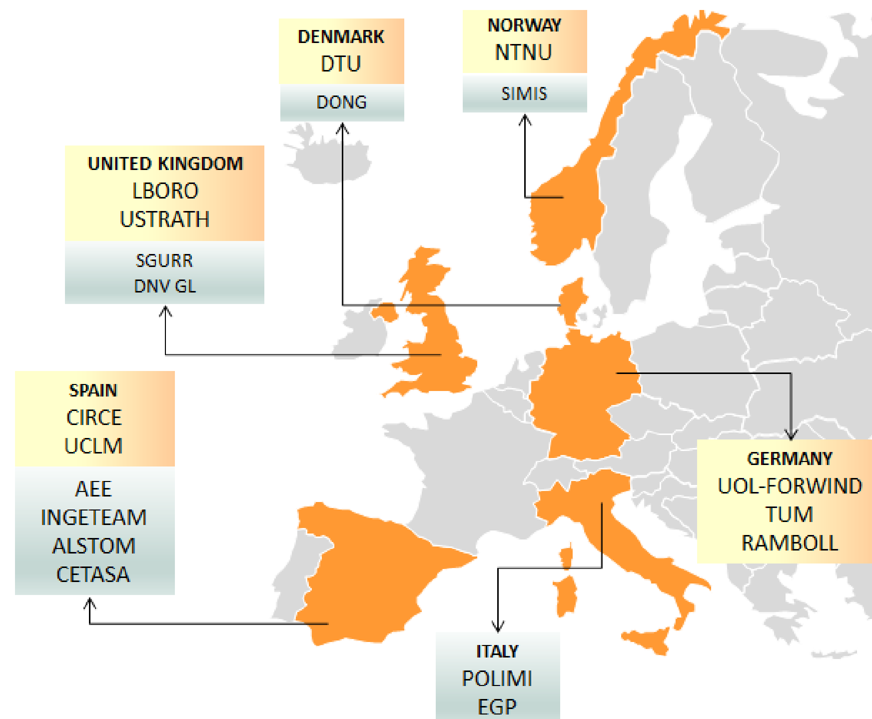
AWESOME

- AWESOME = Advanced wind energy systems operation and maintenance expertise
- Marie Skłodowska-Curie Innovative Training Networks
- 11 PhD's
- O&M
  - Failure diagnostic and prognostic
  - Maintenance scheduling
  - Strategy optimization



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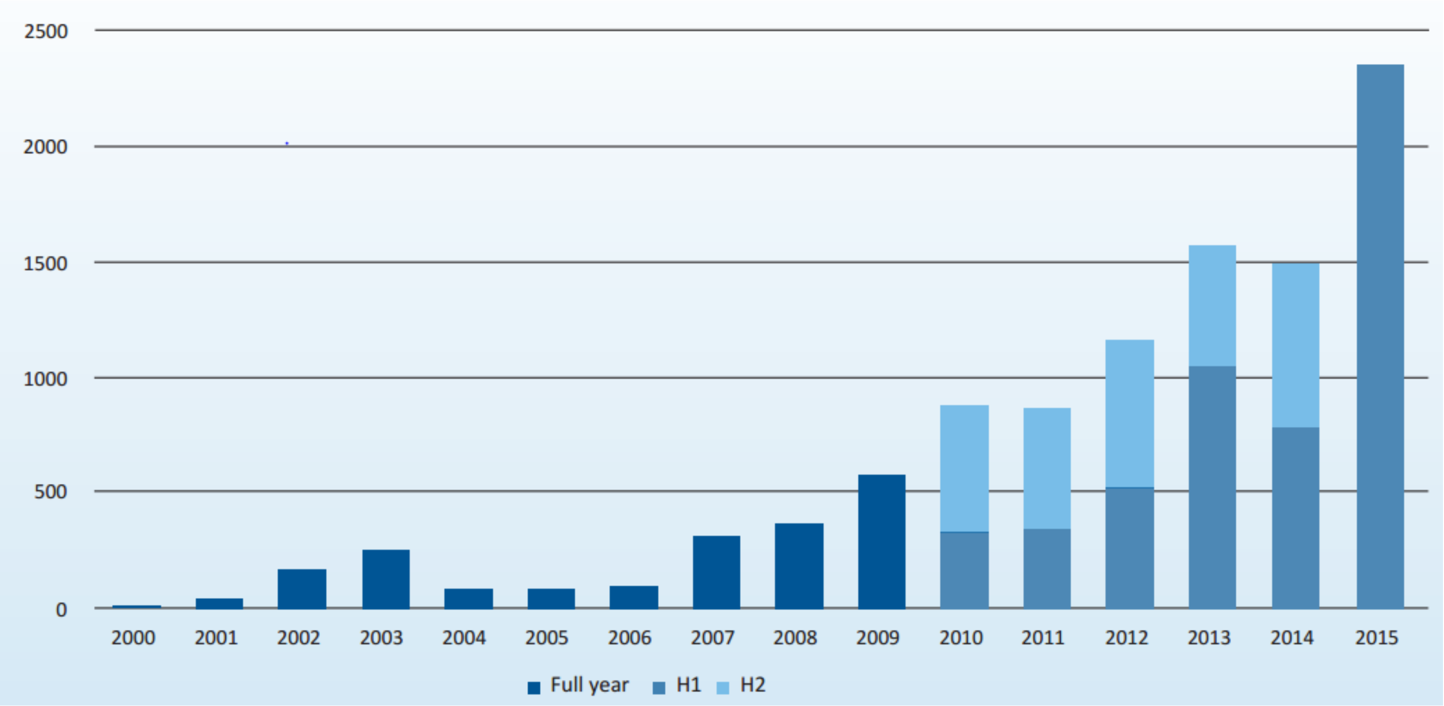
Lifetime extension – a future problem?



Annual installed offshore wind capacity in Europe (MW). Source: EWEA 2015.

Lifetime extension assessment

Analytical assessment

- Renewed simulations with focus on fatigue
- Calculate remaining useful lifetime

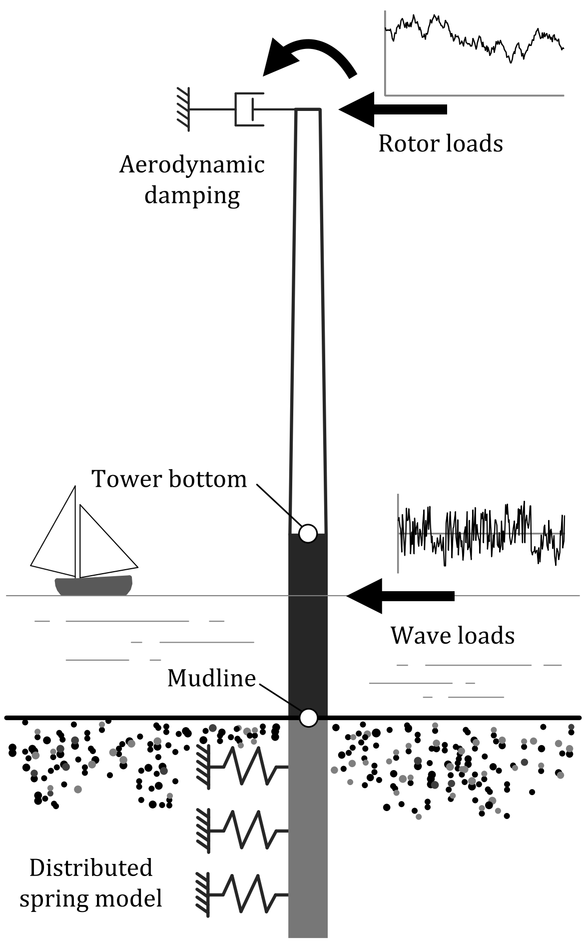
Practical assessment

- Inspections, maintenance history
- Foundations are one component
- Cracks as fatigue damage
- Other failure modes: corrosion, scour,…

Case study

- NREL 5MW and monopile from OC3 project (Nichols et al. 2009)
- Met-ocean data from Upwind project (Fischer et al. 2010)
- Fatigue load cases: power production, idling
- Structural response to aerodynamic and hydrodynamic loading (impulse-based substructuring)

⟹ Simulation of fatigue crack growth with Paris law



Model of offshore wind monopile.