Computational performance of risk-based inspection methodologies for offshore wind support structures

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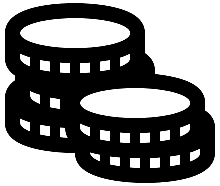
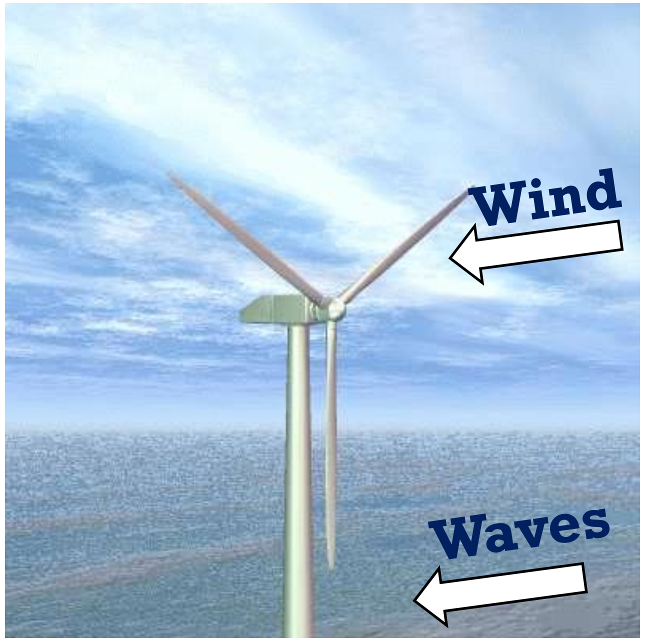
Sequential decision making under uncertainty

Deterioration
Fatigue & corrosion

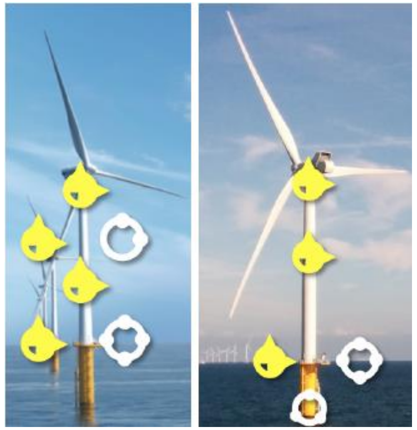
RISK



Information available
….Inspections
Monitoring…



Source:http://windpowernejikata.blogspot.com/2017/05/wind-power-gif.html

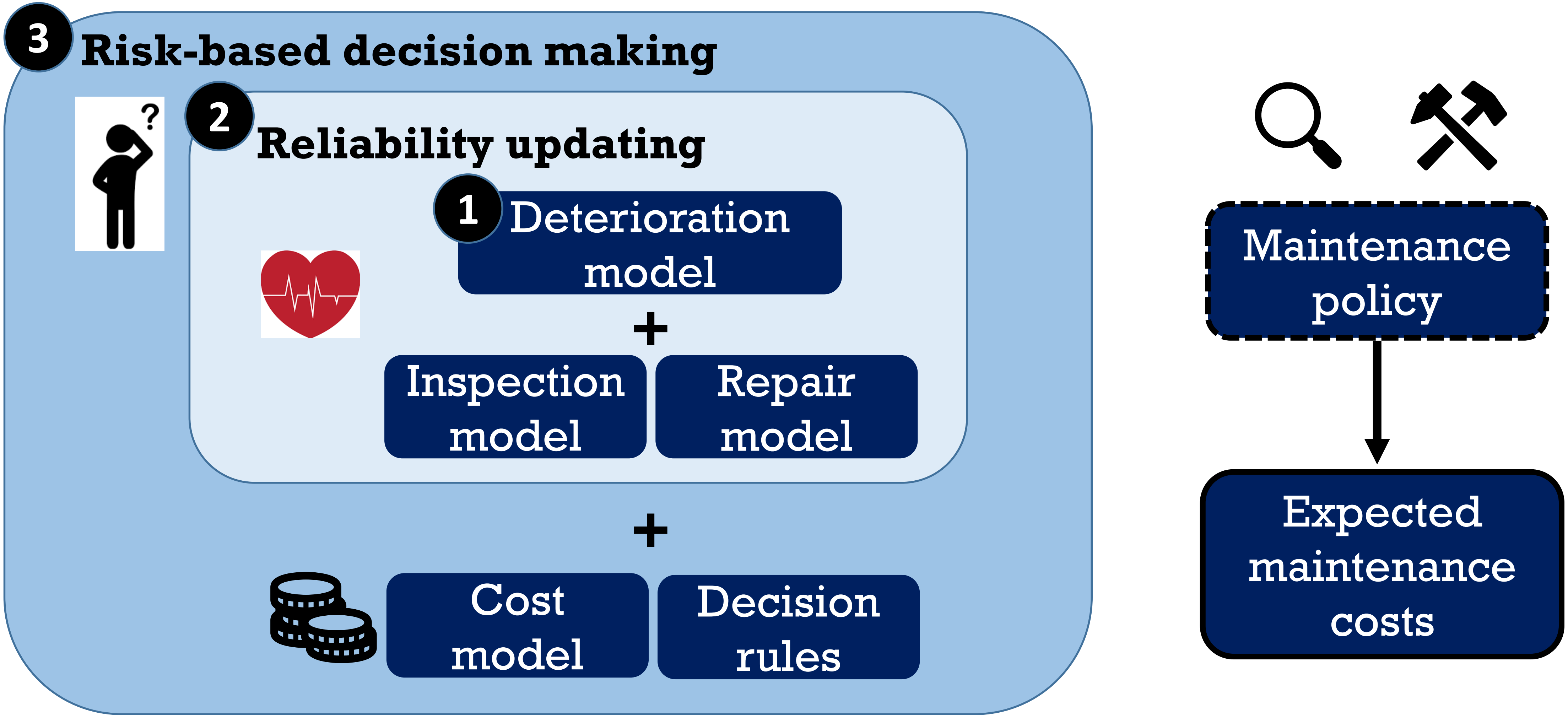


Source: https://www.researchgate.net/figure/Optical-strain-gauges-as-installed-at-a-Belwind-and-b-Northwind

Source: https://www.deltares.nl/en/projects/cutting-maintenance-costs-offshore-wind-farms-using-improved-forecasts

OWT Risk-based inspection planning

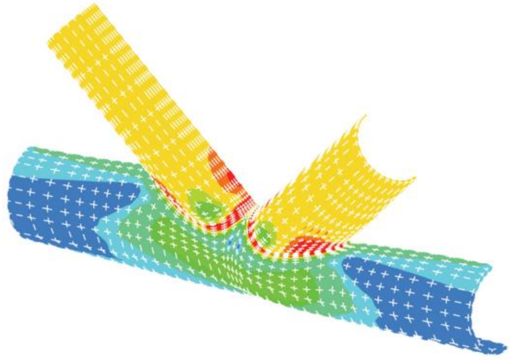
Offshore wind structures **deterioration**: fatigue & corrosion



SN Curves / Miner's Rule

Bi-linear SN Curve

$$g_{SN}(t) = \Delta - n_y t \left(\frac{q^{m_1}}{a_1} \Gamma \left\{ 1 + \frac{m_1}{h}; \left(\frac{S_1}{q} \right)^h \right\} + \frac{q^{m_2}}{a_2} \gamma \left\{ 1 + \frac{m_2}{h}; \left(\frac{S_1}{q} \right)^h \right\} \right)$$

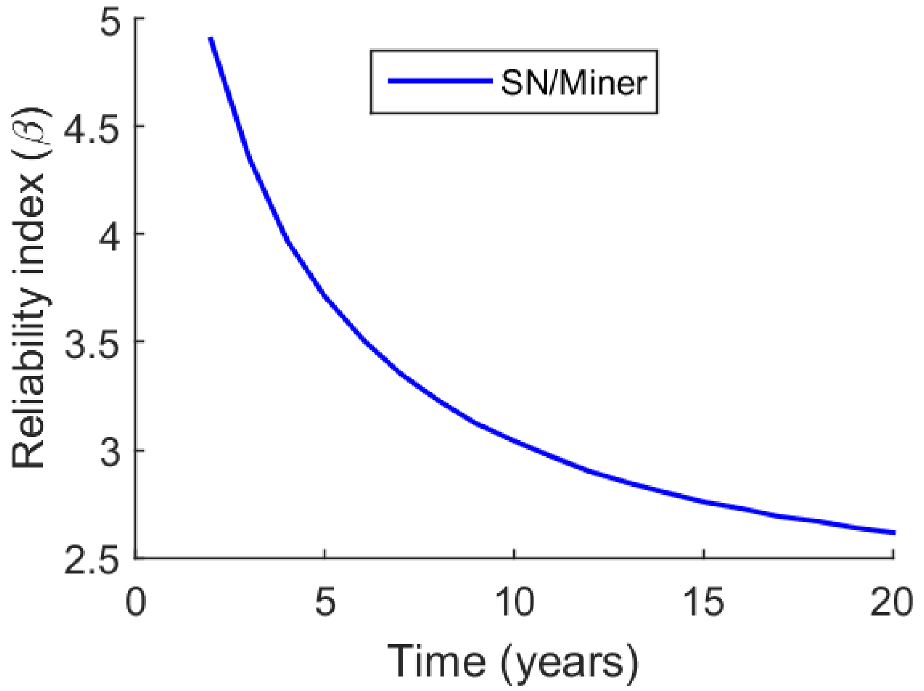


SN Curve for **tubular joints**

'DNV-GL RP C203'

FDF = 2

Design to the limit

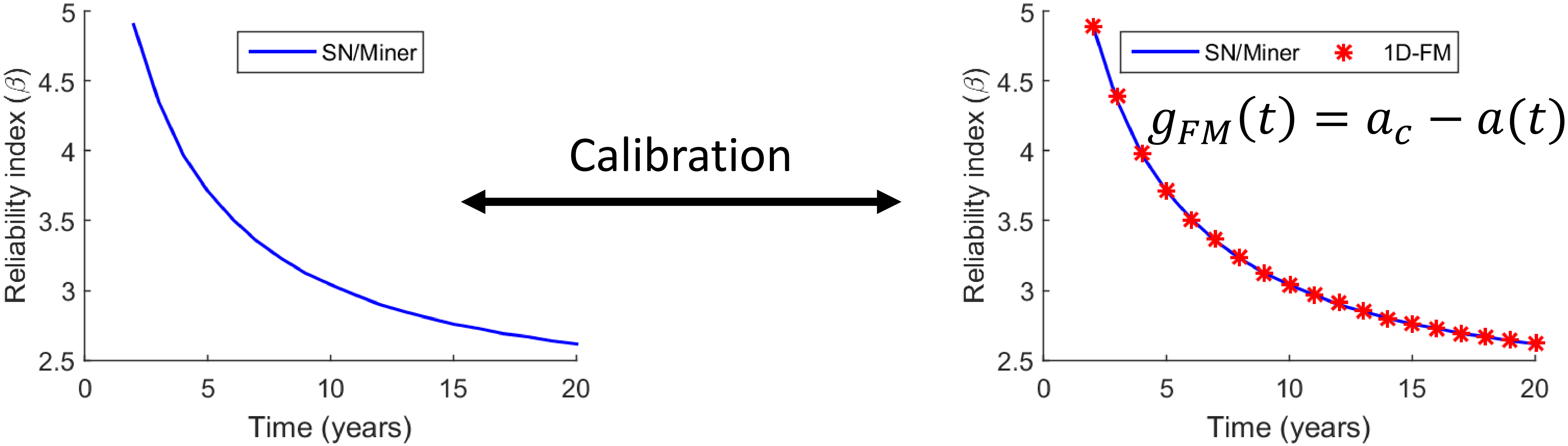


1) Deterioration – 1D FM

Calibration SN Curves – FM Model

1D Paris' Law

$$a_{t+1} = \left[a_t^{\frac{2-m}{2}} + \left(\frac{2-m}{2} \right) C \left(Y_g \pi^{0.5} S_e \right)^m n \right]^{\frac{2}{2-m}} ; given\ a_0$$



$$g_{FM}(t) = a_c - a(t)$$

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Calibration SN Curves – FM Model

2D Paris' Law – Stress intensity factor 'DNV-GL RP C210'

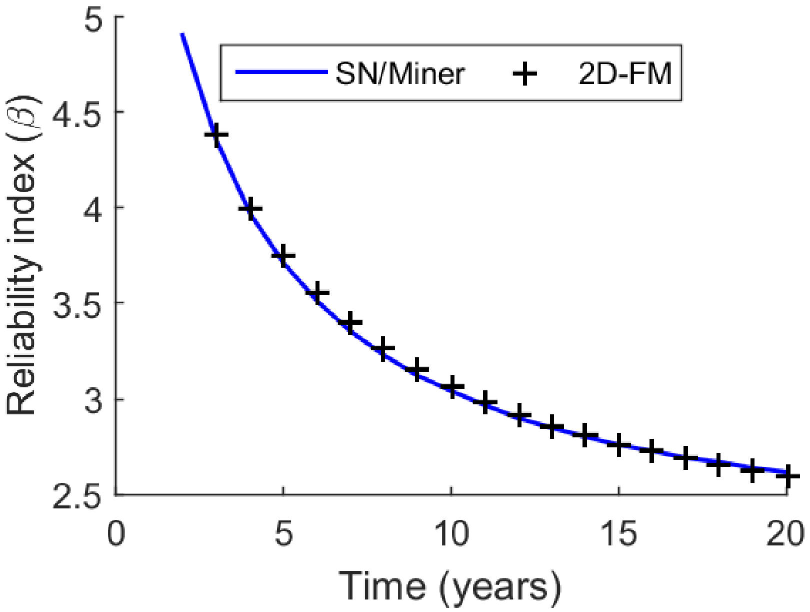
System of ordinary differential equations

$$\boxed{g_{FM}(t) = a_c - a(t)}$$

$$\begin{cases} \dfrac{da}{dn} = C(\Delta K_a)^m \\ \Delta K_a = S_e\sqrt{\pi a}\,[Y_{ma}(a,c)M_{kma}(a,c)(1-DOB) + Y_{ba}(a,c)M_{kba}(a,c)DOB] \\ \dfrac{dc}{dn} = C(\Delta K_c)^m \\ \Delta K_c = S_e\sqrt{\pi a}\,[Y_{mc}(a,c)M_{kmc}(a,c)(1-DOB) + Y_{bc}(a,c)M_{kbc}(a,c)DOB] \\ given\ a_0, a_0/c_0 \end{cases}$$

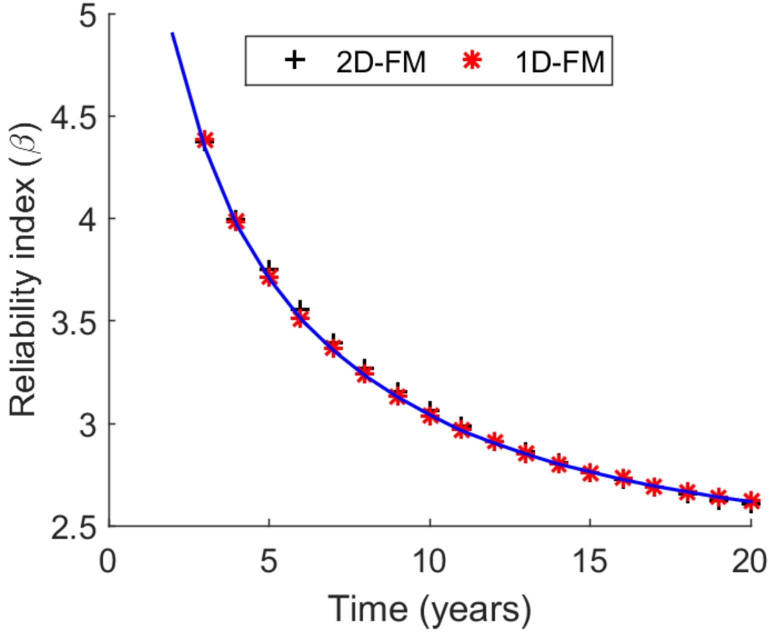
Fracture Mechanics models (Unconditional case)

2D Paris' Law
Stress intensity factor



$CPU\ time \approx 1\ day$

1D Paris' Law



$CPU\ time \approx 3\ min$

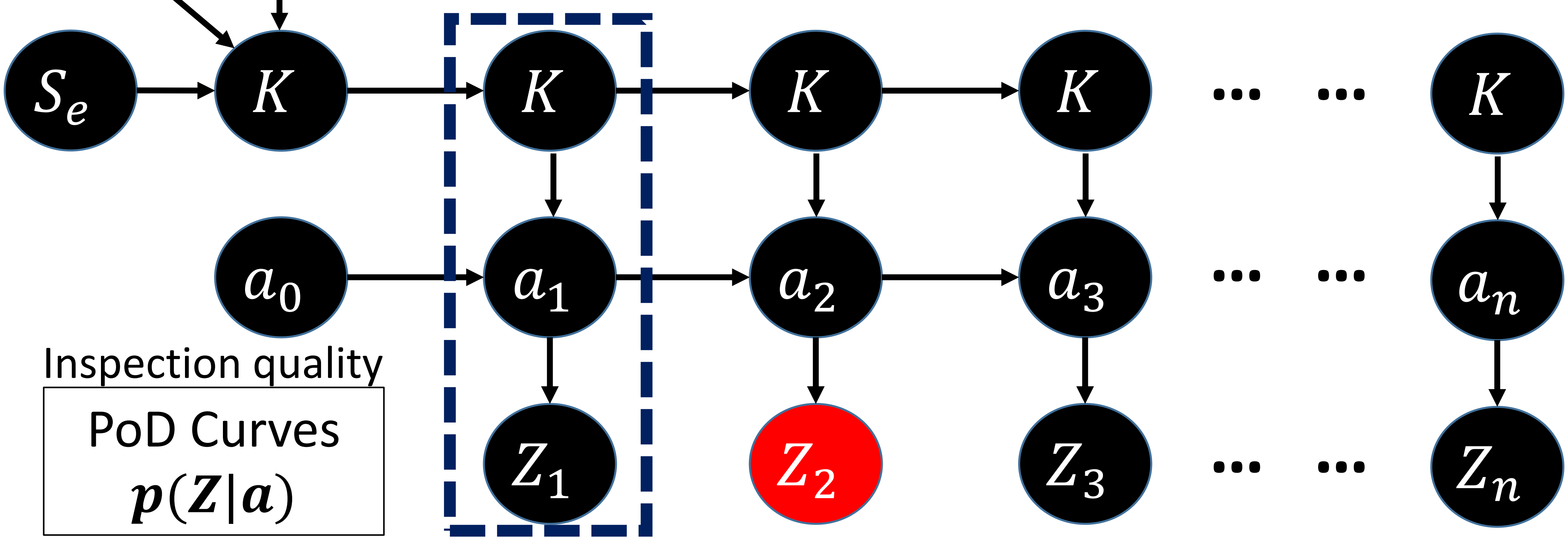
$*$ Intel Core I9 7900X @3.0 GHz and RAM 64GB / MCS 10^8 samples

2) Updating reliability (DBNs)

(1) Monte Carlo simulations

(2) **Dynamic Bayesian Networks (DBNs)**

$$a_{t+1} = \left[a_t^{\frac{2-m}{2}} + \left(\frac{2-m}{2}\right) C \left(Y_g \pi^{0.5} S_e\right)^m n \right]^{\frac{2}{2-m}} \; ; given \; a_0$$



2) Updating reliability (DBNs)

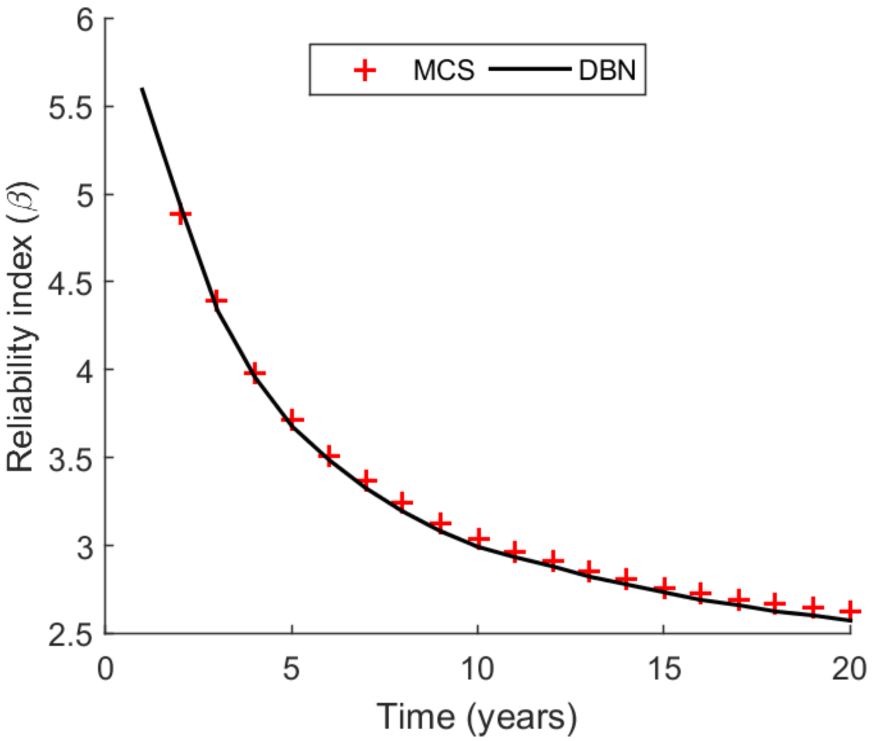
(1) Monte Carlo simulations

$CPU\ time \approx 3\ min$

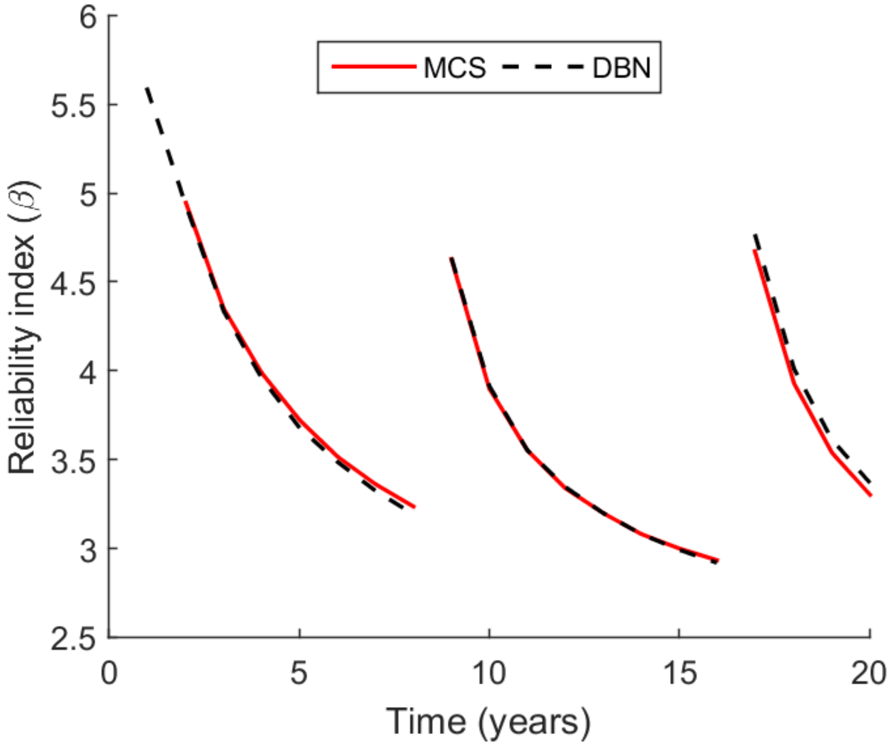
(2) Dynamic Bayesian Networks (DBNs)

$CPU\ time \approx 0.1\ \mathrm{s}$

Unconditional (No inspections)

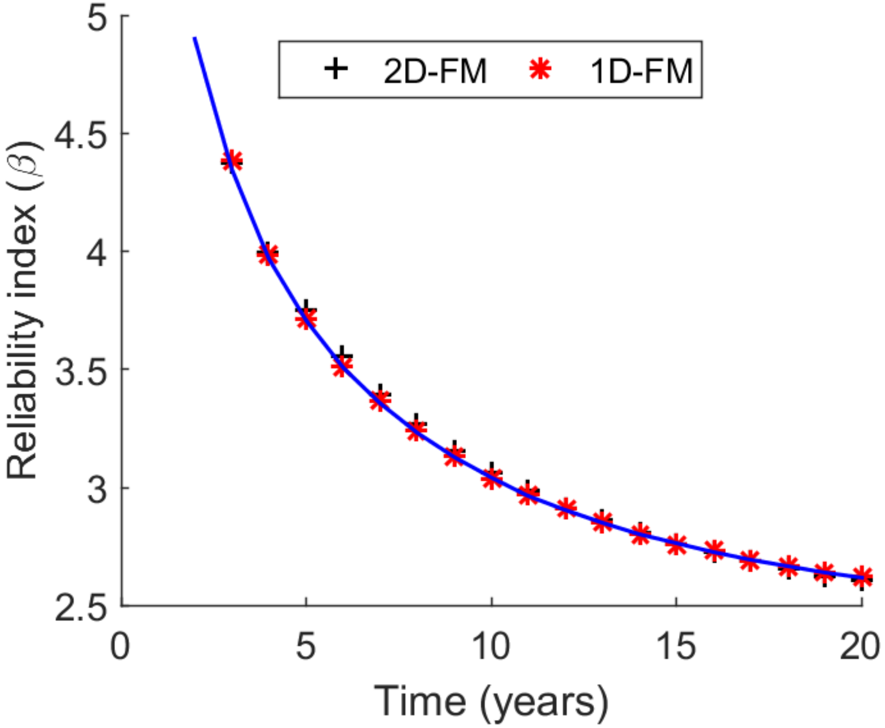


Conditional (Inspections)

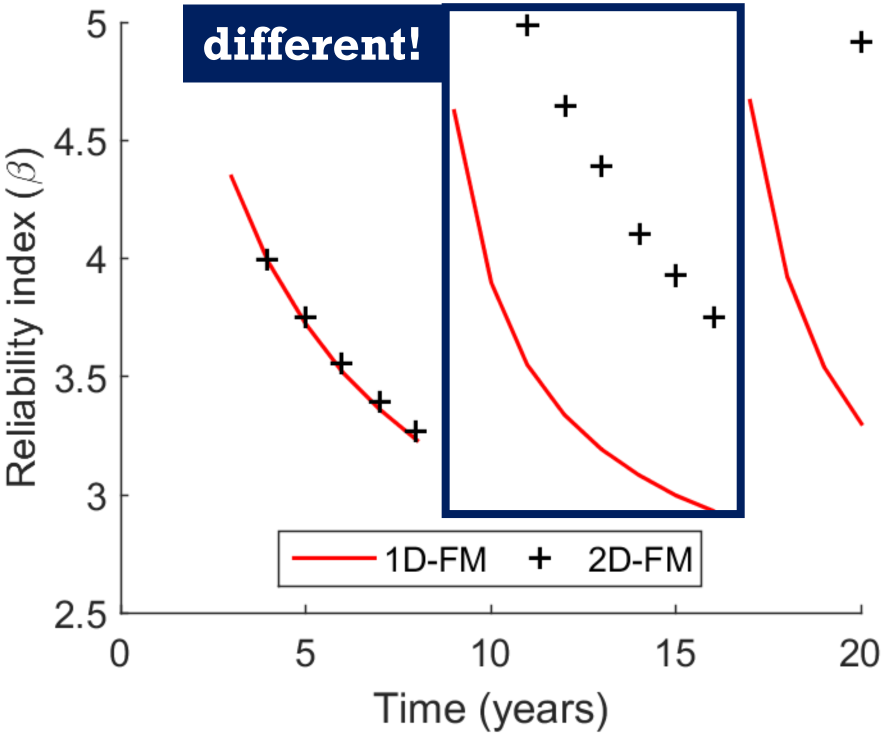


Fracture Mechanics models (including inspections)

Unconditional (No inspections)



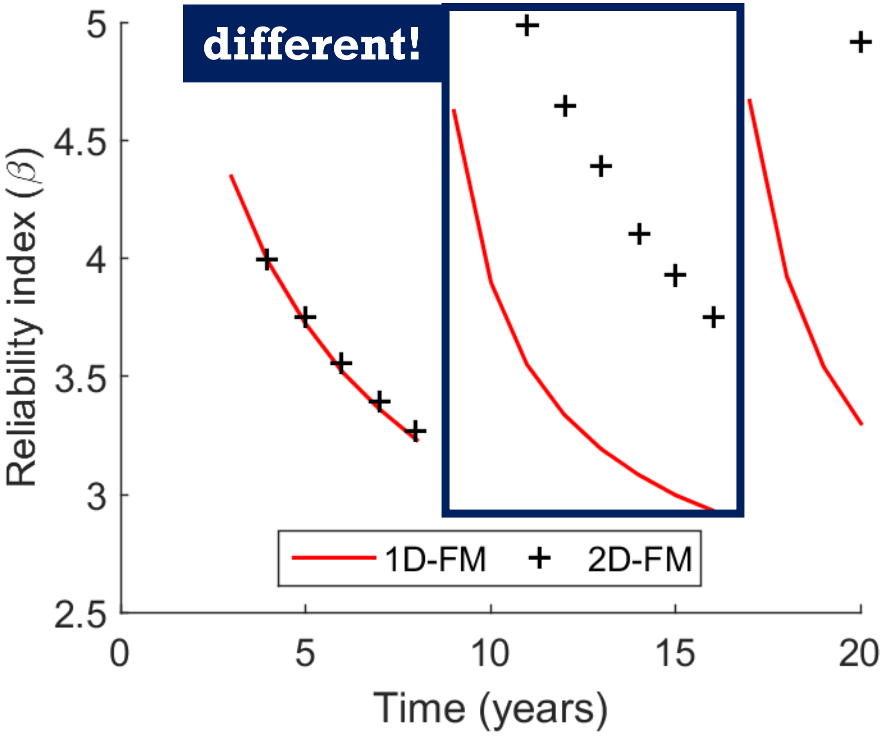
Conditional (Inspections)



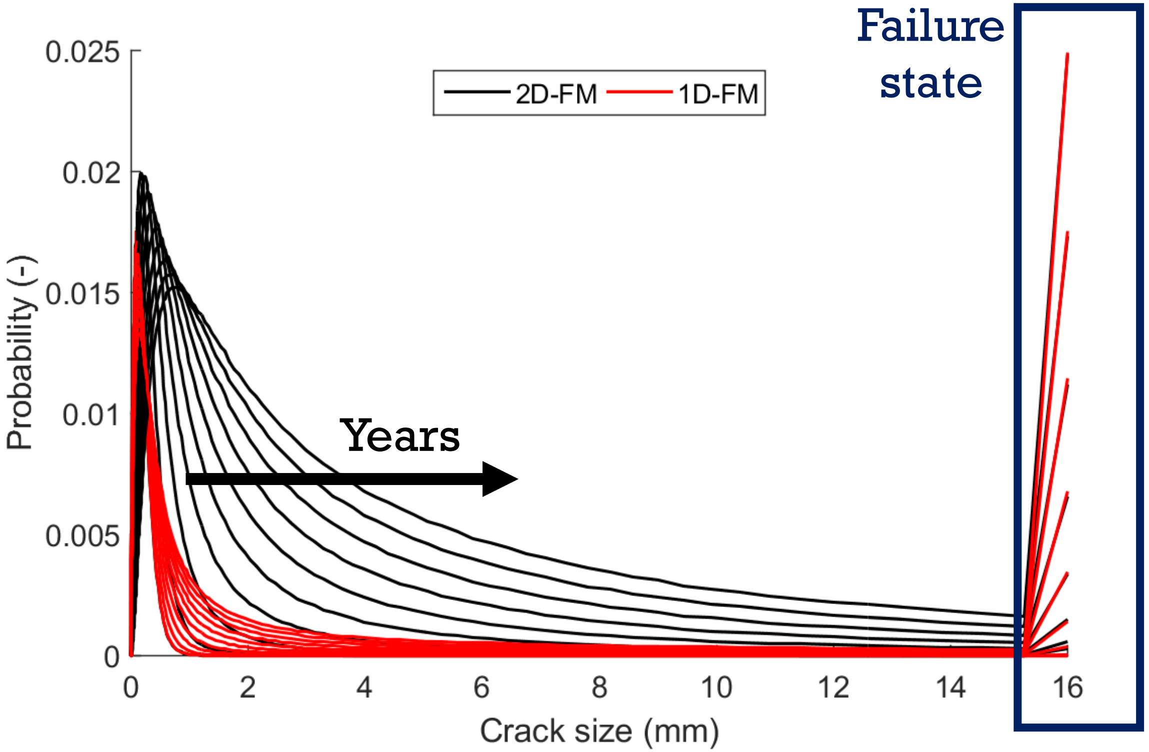
2) Updating reliability – FM 1D or 2D?

Fracture Mechanics models (including inspections)

Conditional (Inspections)



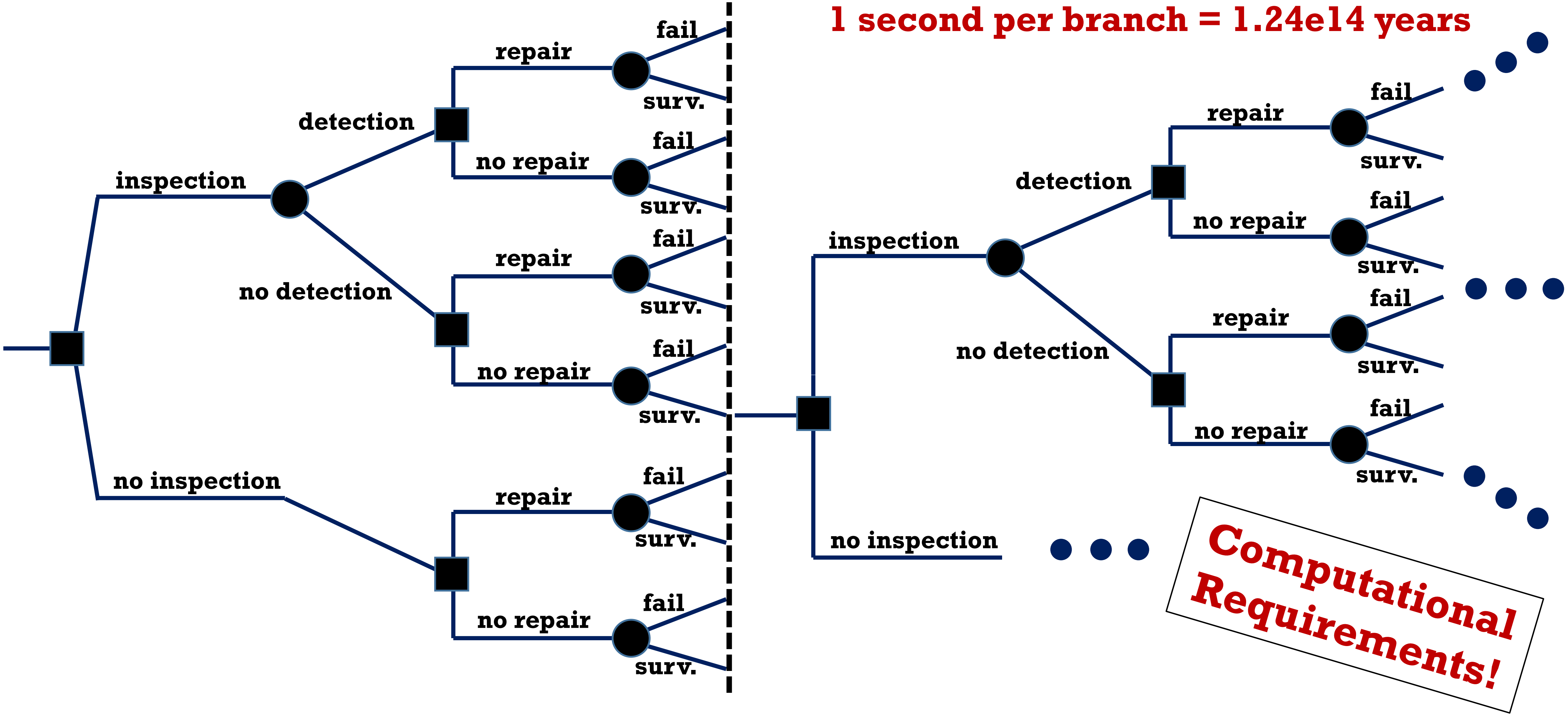
Crack distribution



3) Maintenance decision problem

‘Pre-posterior decision analysis’…

12^{20}=3.8e21 branches
1 second per branch = 1.24e14 years



3) RBI / Heuristics: Direct search policies

Deterioration model

Inspection model

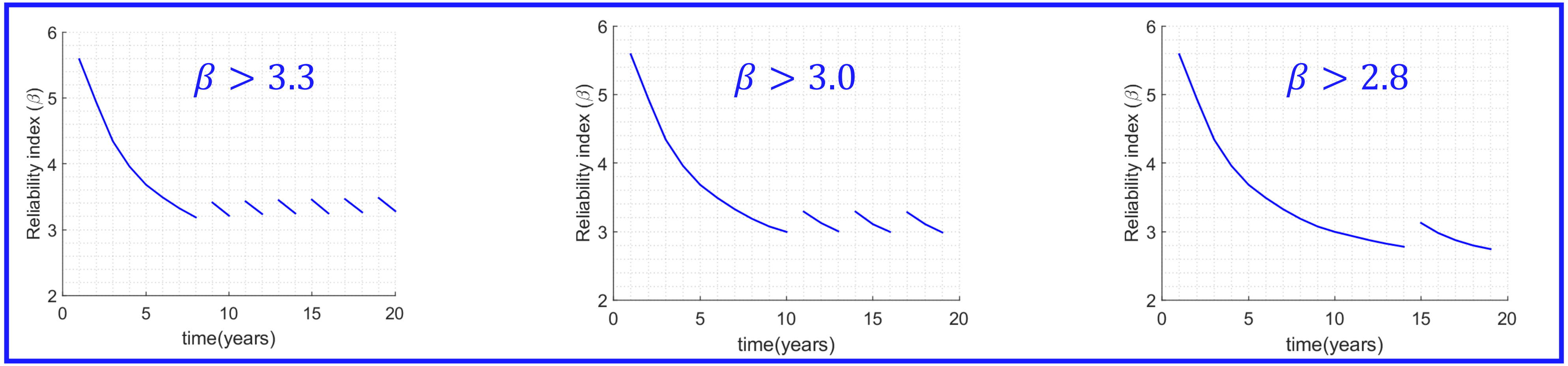
Decision rules

Repair model

Cost model

'Periodic inspections'

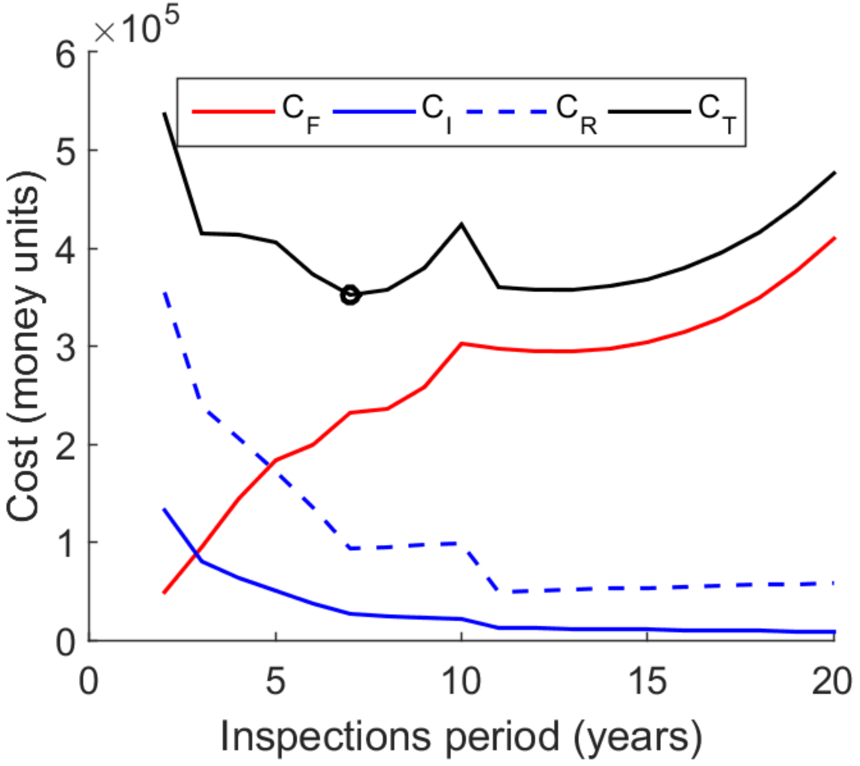
'Reliability threshold'



3) RBI / Heuristics: Direct search policies

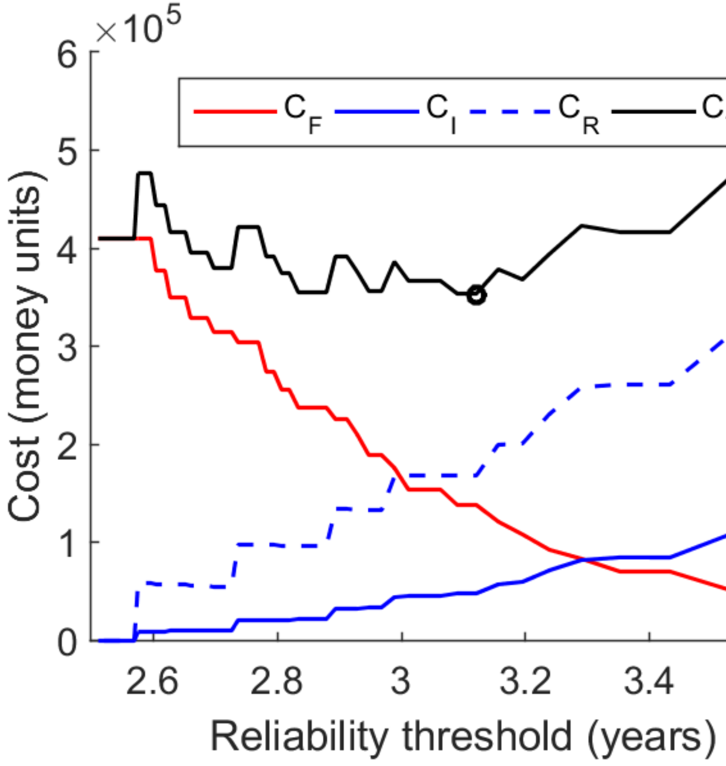
Deterioration model | Inspection model | **Decision rules** | Repair model | Cost model

'Periodic inspections'



$CPU\ time \approx 2\ s$

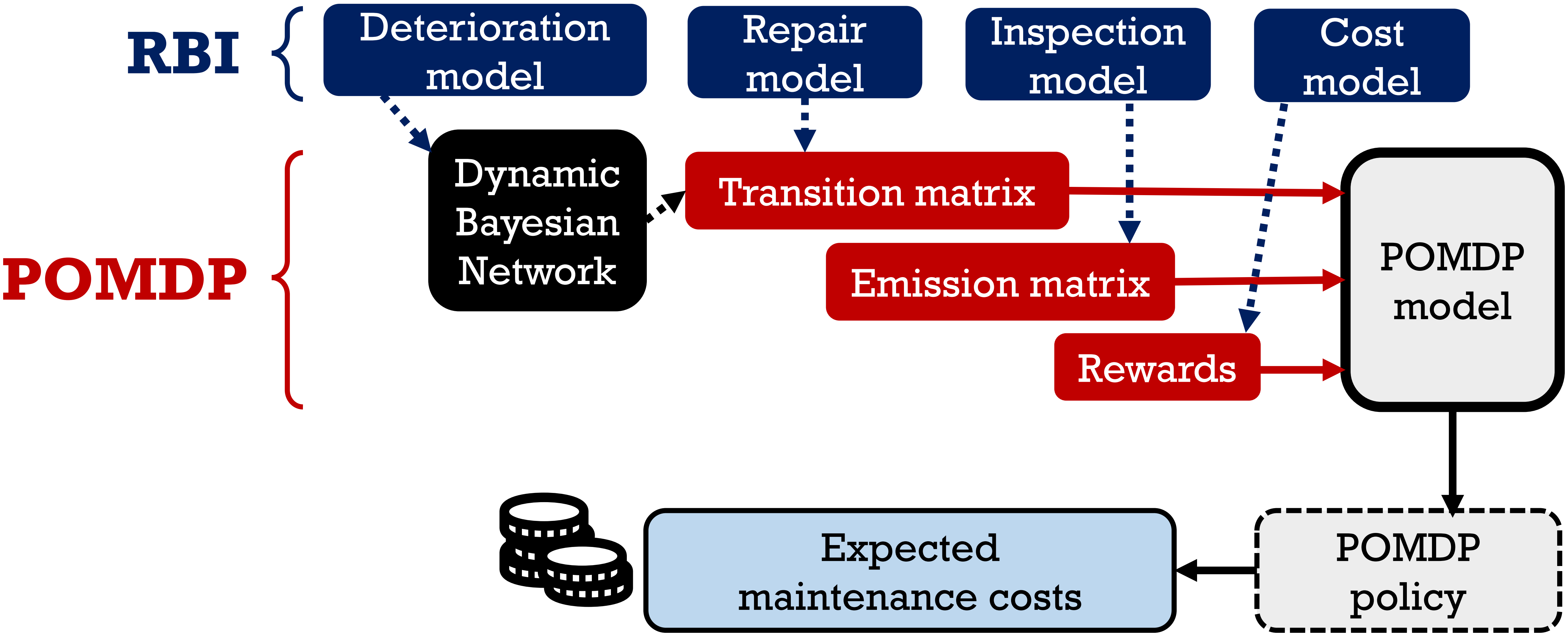
'Reliability threshold'



$CPU\ time \approx 4\ s$

3) POMDPs - Methodology

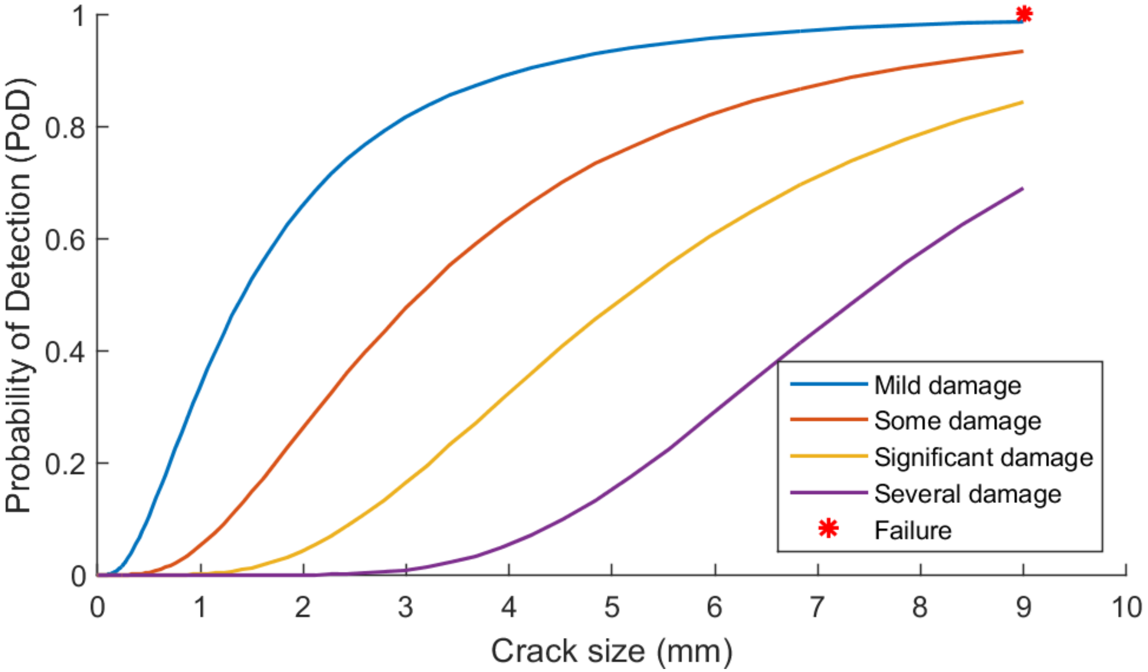
Partially Observable Markov Decision Processes



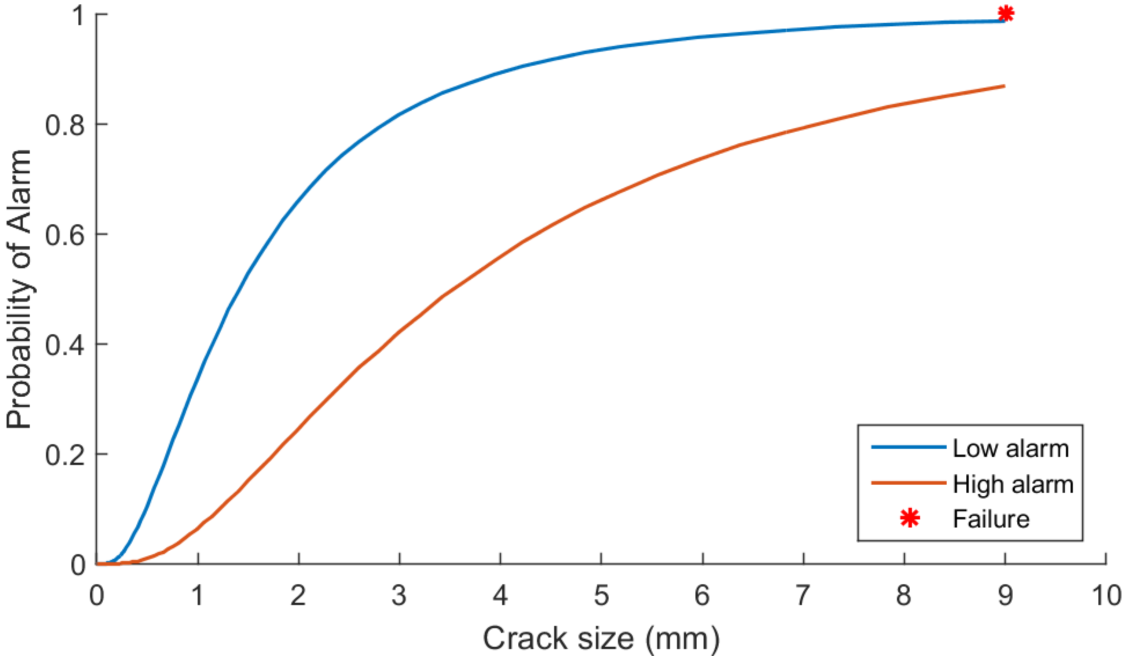
3) POMDPs – Observations (emission)

Able to solve complex decision problems

Inspections



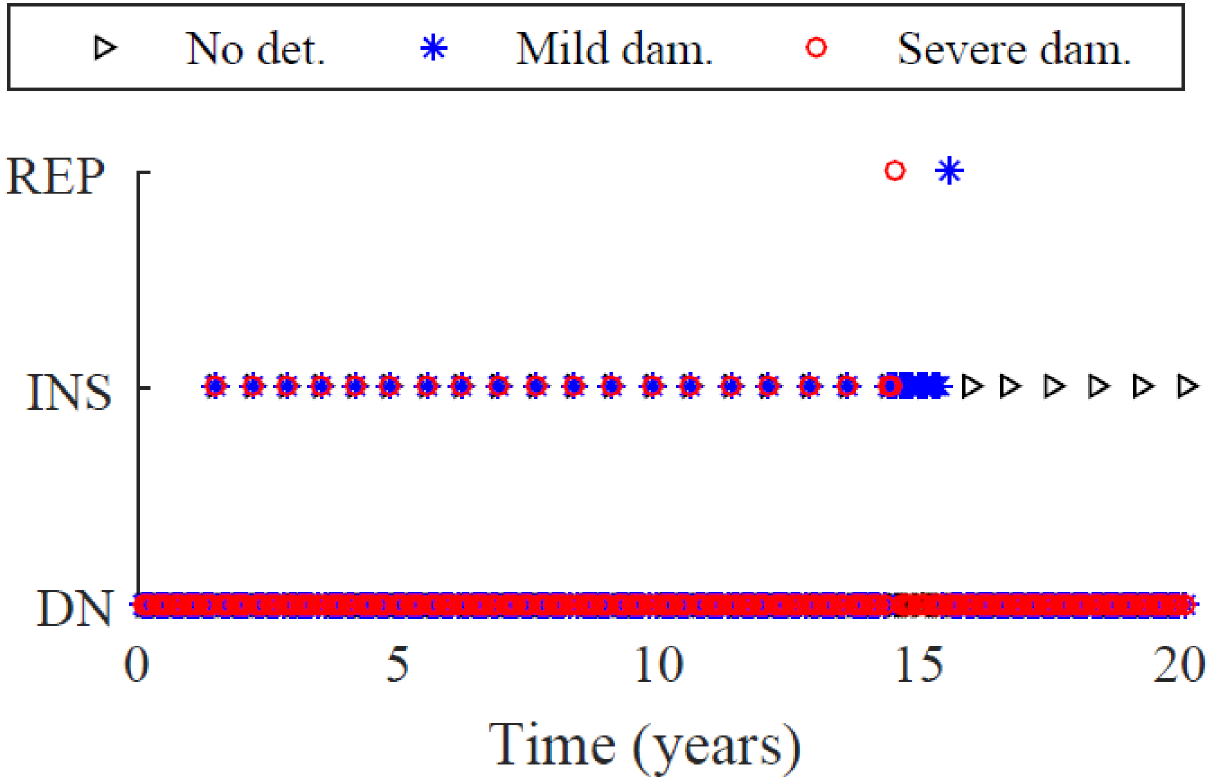
Monitoring

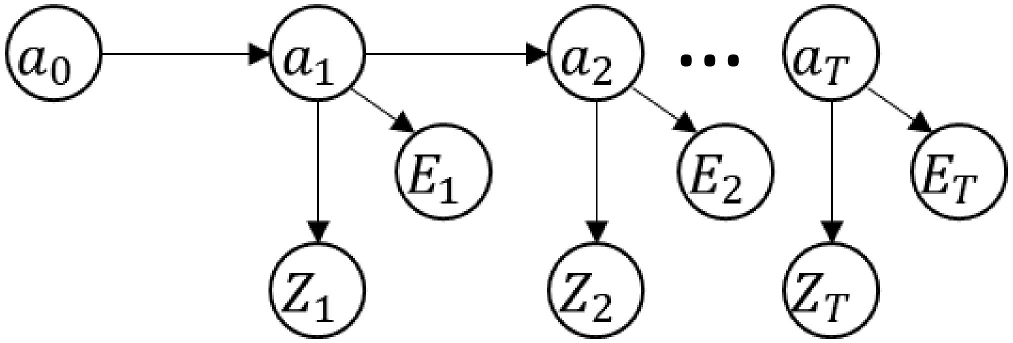


No inspection?

Application: 'SARSOP Algorithm': POMDP 200 states

$CPU\ time \approx 60\ s$





- **No detection**
- **Mild damage**
- **Severe damage**

"POMDP based Maintenance Optimization of Offshore Wind Substructures including Monitoring
Morato, P.G., Nielsen, J.S., Mai, A.Q. and Rigo, P., ICASP13 (2019)"

Discussion & Conclusions

1) Deterioration model

1D-FM is faster than 2D-FM but yields different results

2) Updating reliability

DBNs are faster than MCS (similar result)

3) Risk-based inspection planning

POMPD for complex decision problems

- Future:
  - System-level maintenance policies
  - Different deterioration models

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Questions?

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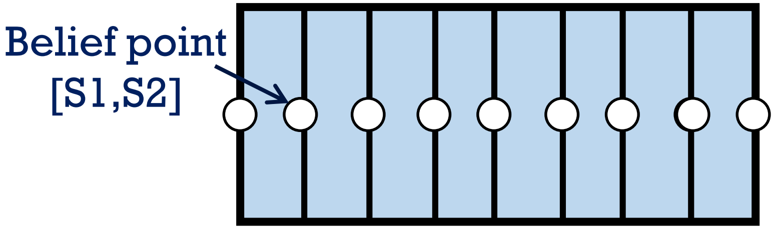
3) Solving POMDPs

Decision problem:

? Belief State ⟶ Action

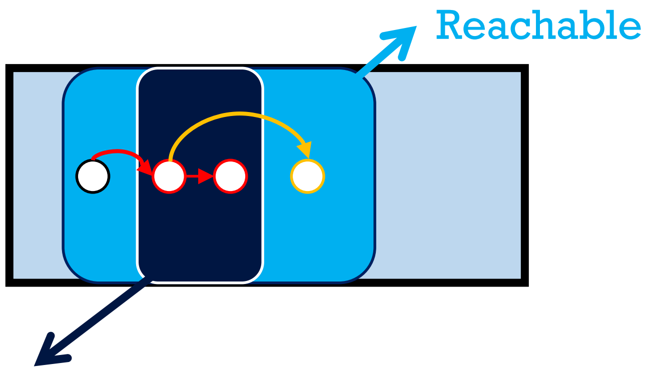
Computational Requirements!

‘Grid-based’ technique



- Finite set of belief points
- Extrapolation/interpolation

‘Point-based’ technique



- ‘Optimally’ reachable beliefs
- Large state space (Robotics)