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Reducing Uncertainty in Structural Safety
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Training in Reducing Uncertainty in Structural Safety

Probabilistic decision basis and objectives for inspection planning and optimization

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Lloyd's Register

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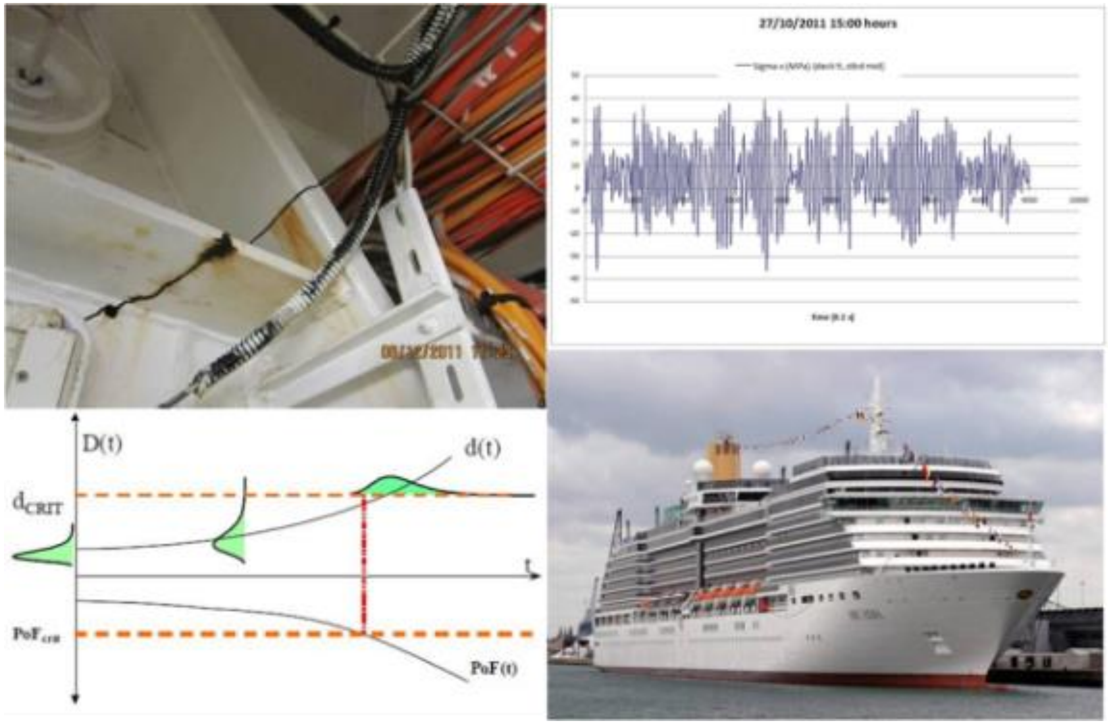
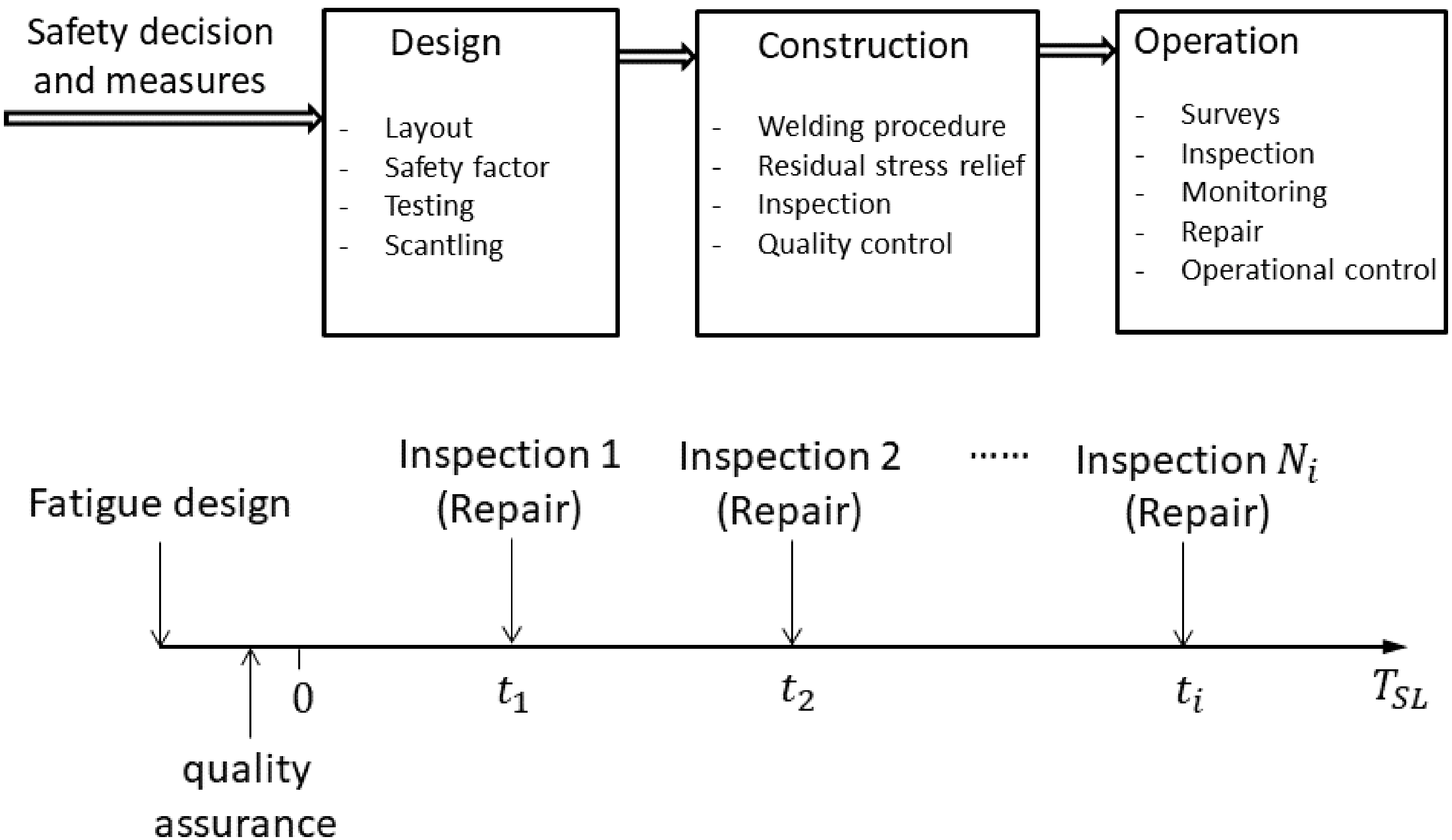
Fatigue cracks & failures

- Hot-spot areas
- Consequences
- Operational safety
- Uncertainties
- Life cycle costs



Engineering decisions against fatigue



Aim of this research

- The role of inspection in reliability and cost management

Maintenance Strategies	
Case 1	Do Nothing
Case 2	Repair (or replacement)
Case 3	Inspection before repair

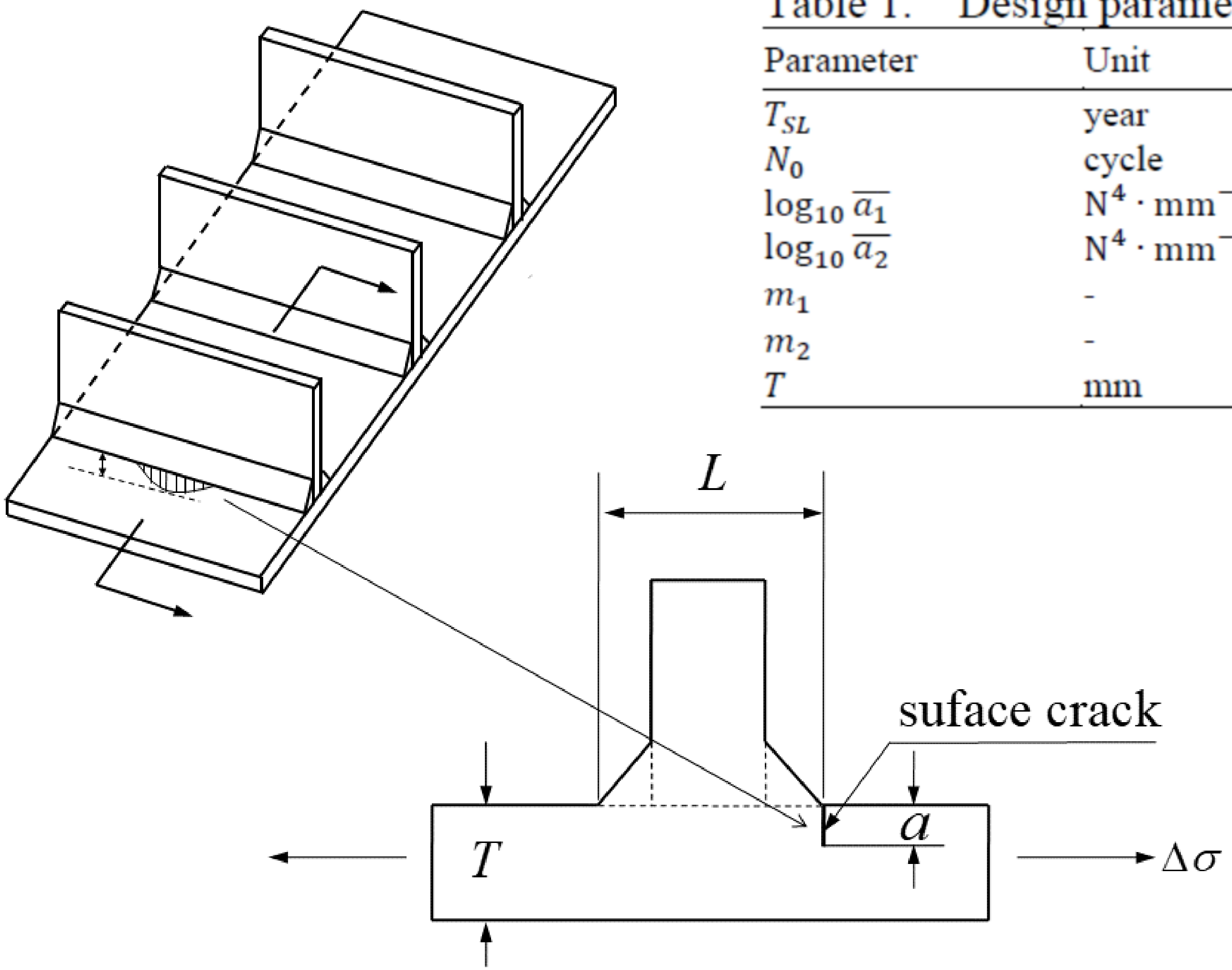
- Influences of different decision basis & objectives on integrity management
  1. Fatigue & fracture reliability
  2. Life cycle costs
  3. Value of information (VoI)

Case study

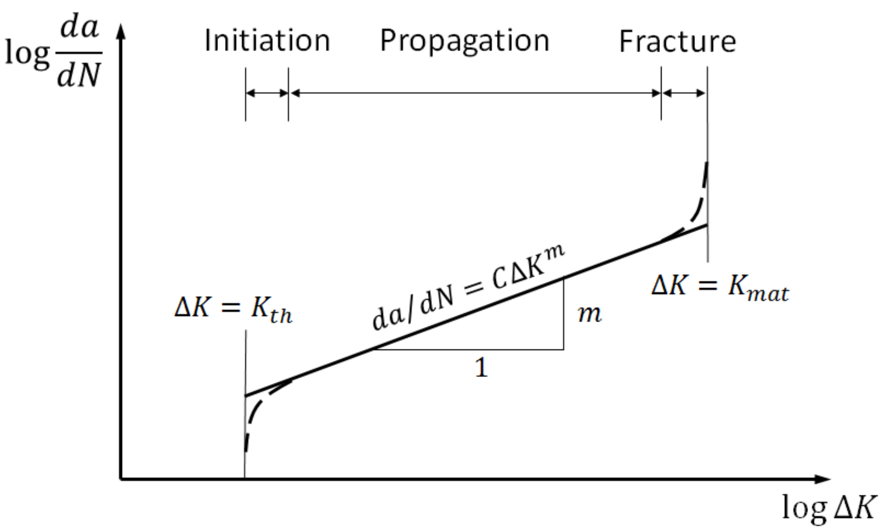
For simplicity, schedule one maintenance intervention

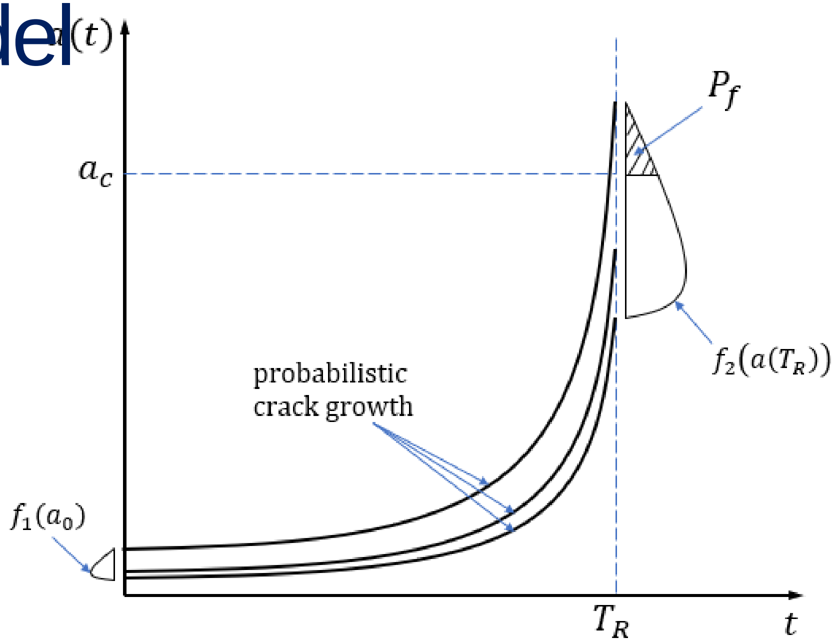
Table 1. Design parameters of the fatigue detail

Parameter	Unit	Value
T_{SL}	year	20
N_0	cycle	5×10^6
$\log_{10} \overline{a_1}$	$N^4 \cdot mm^{-6}$	11.855
$\log_{10} \overline{a_2}$	$N^4 \cdot mm^{-6}$	15.091
m_1	-	3
m_2	-	5
T	mm	25



Probabilistic physical model





$$\frac{da}{dN} = C\Delta K^m, \Delta K_{th} \leq \Delta K \leq K_{mat}$$

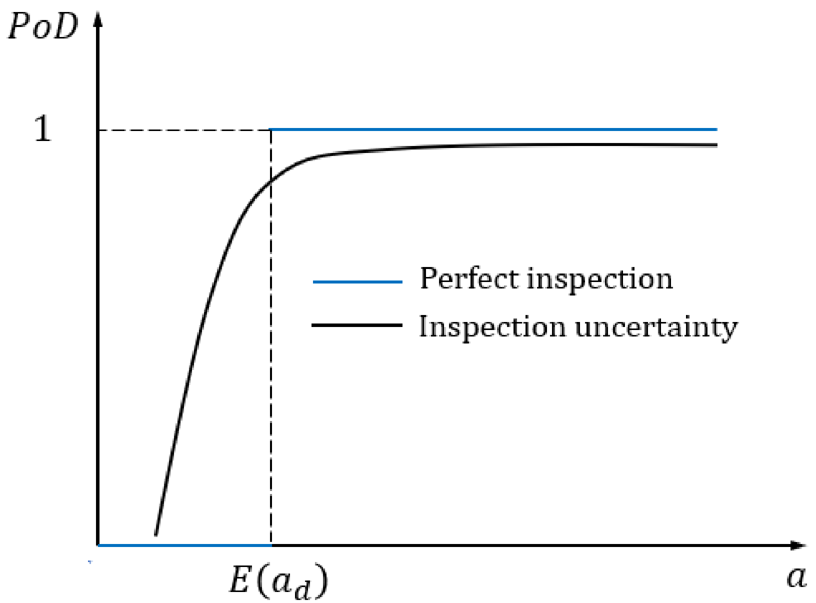
$$\Delta K = \Delta\sigma Y(a)\sqrt{\pi a}$$

$$N_P = \frac{1}{\pi^{m/2} C \Delta\sigma^m} \int_{a_0}^{a_c} \frac{da}{a^{m/2} Y(a)^m}$$

$$\Delta a(t) = \pi^{m/2} C \Delta\sigma^m \int_0^{N(t)} a^{m/2} Y(a)^m dN$$

Variable	Distribution	Unit	Mean	Standard Deviation
a_0	Exponential	mm	0.04	0.04
$\log_{10} C$	Normal	[N, mm]	-12.74	0.11
B	Normal	-	1.00	0.15

Probabilistic inspection modelling

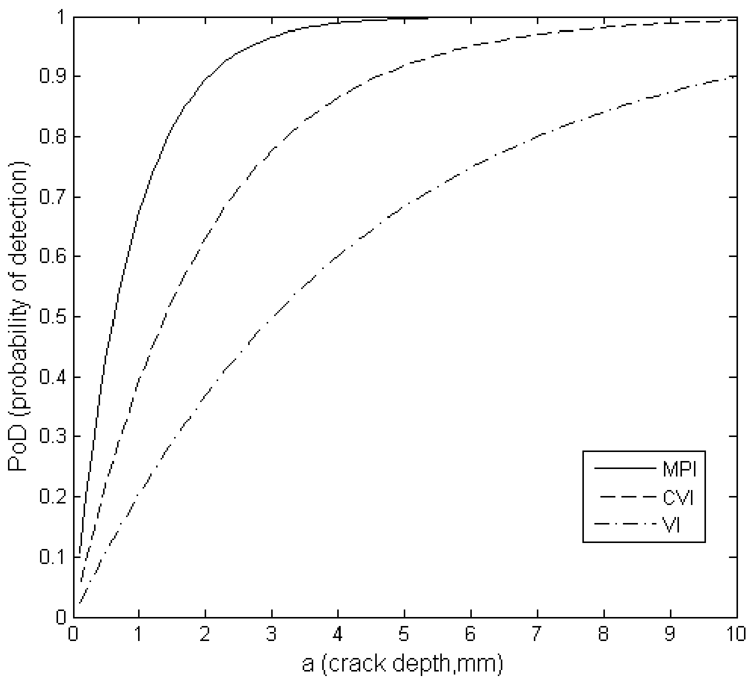


$$PoD(a) = F(a) = 1 - \exp(-a/E(a_d))$$

$$PoD(a) = \begin{cases} 0 & a < E(a_d) \\ 1 & a \geq E(a_d) \end{cases}$$

For Magnetic Particle Inspection, $a_d = 0.89$ mm

- Crack characteristics
- Instrumentation reliability
- The environment
- Inspection procedure
- Human factors



Maintenance strategy and repair effect

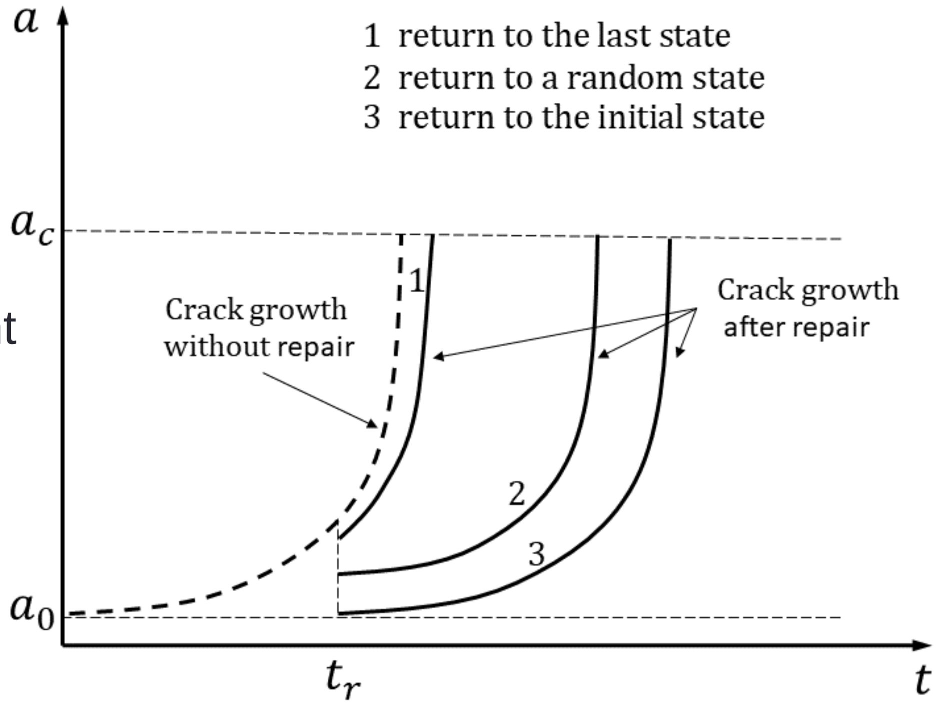
The time, criterion or condition to carry out repair?

(time-based & condition-based maintenance)

In case of repair, what's the repair effect on a structural details?

(crack dimension returns to initial state)

- Drilling a stop hole
- Welding
- Welding plus post-weld treatment
- Replacement
- Grinding



Fracture reliability

$$M(t) = a_c - a(t)$$

$$P_f(t) = P(M(t) < 0)$$

$$\beta(t) = -\Phi^{-1}\left(P_f(t)\right)$$

Maintenance Strategies	
Case 1	Do Nothing
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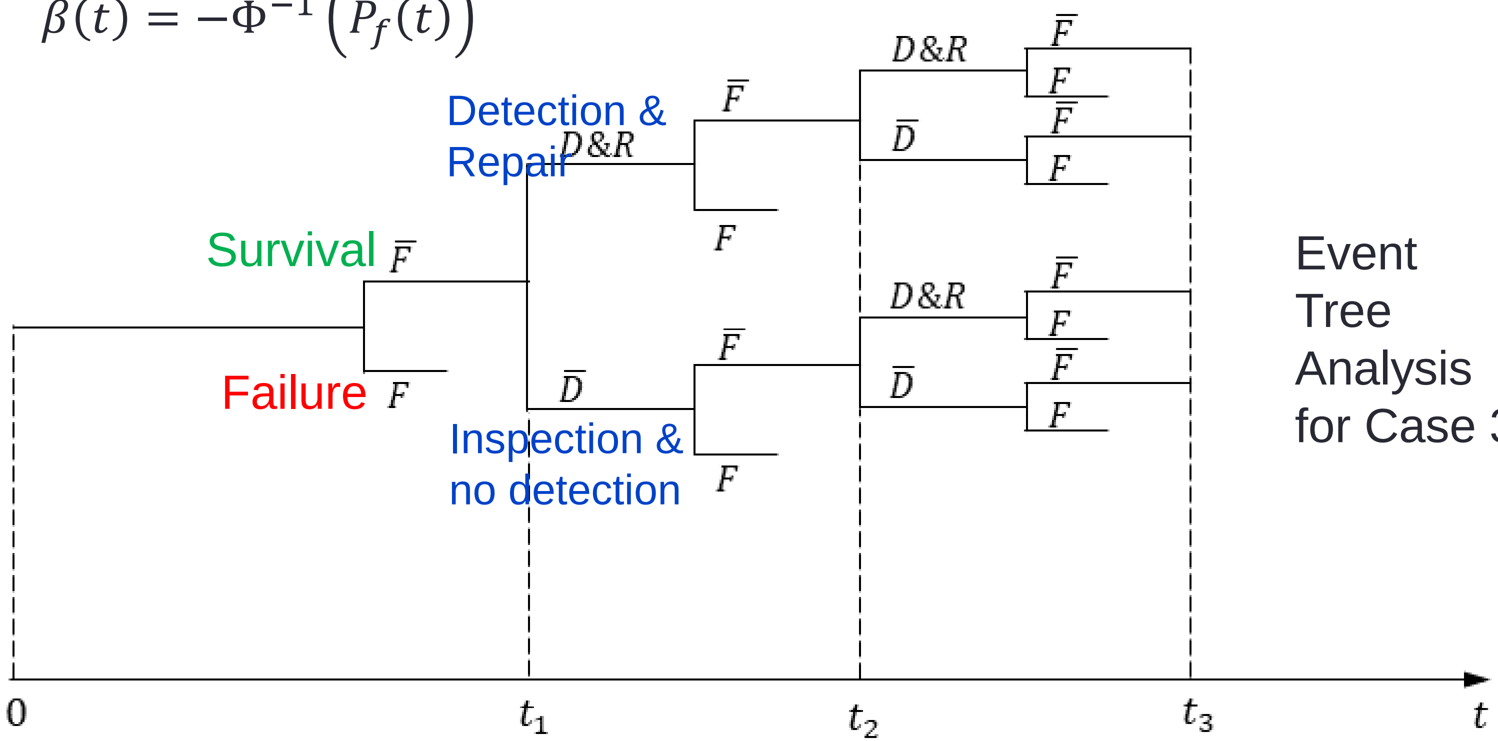

Event Tree Analysis for Case 3

Probabilistic maintenance optimization

Inputs
- Select structural detail and S-N curve
- Required service life
- Fatigue crack growth model and associated parameters
- Critical crack size
- Inspection method and the associated PoD function
- Repair method and model for repair effect
- The number of interventions
- Probabilistic models for variables
- Number of samples for variables

↓

Probabilistic crack growth modelling
- Simulate random variables for crack growth model
- Compute crack sizes

↓

Reliability-based maintenance optimization

Objective
- Maximize lifetime fatigue reliability

Constraints
- $\Delta t_i \geq 0.5$ year

With respect to
- Repair criterion
- Inspection times

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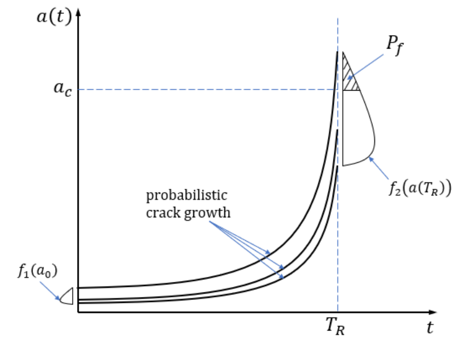
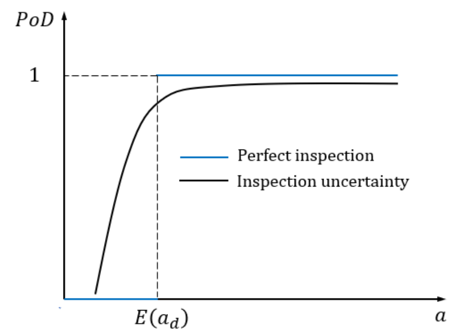
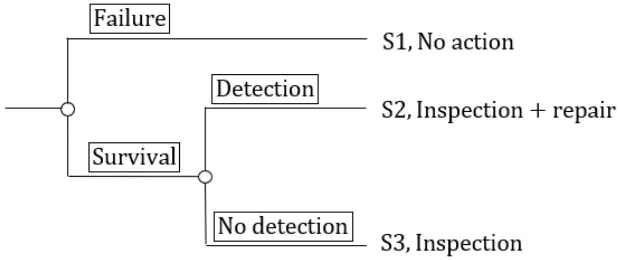
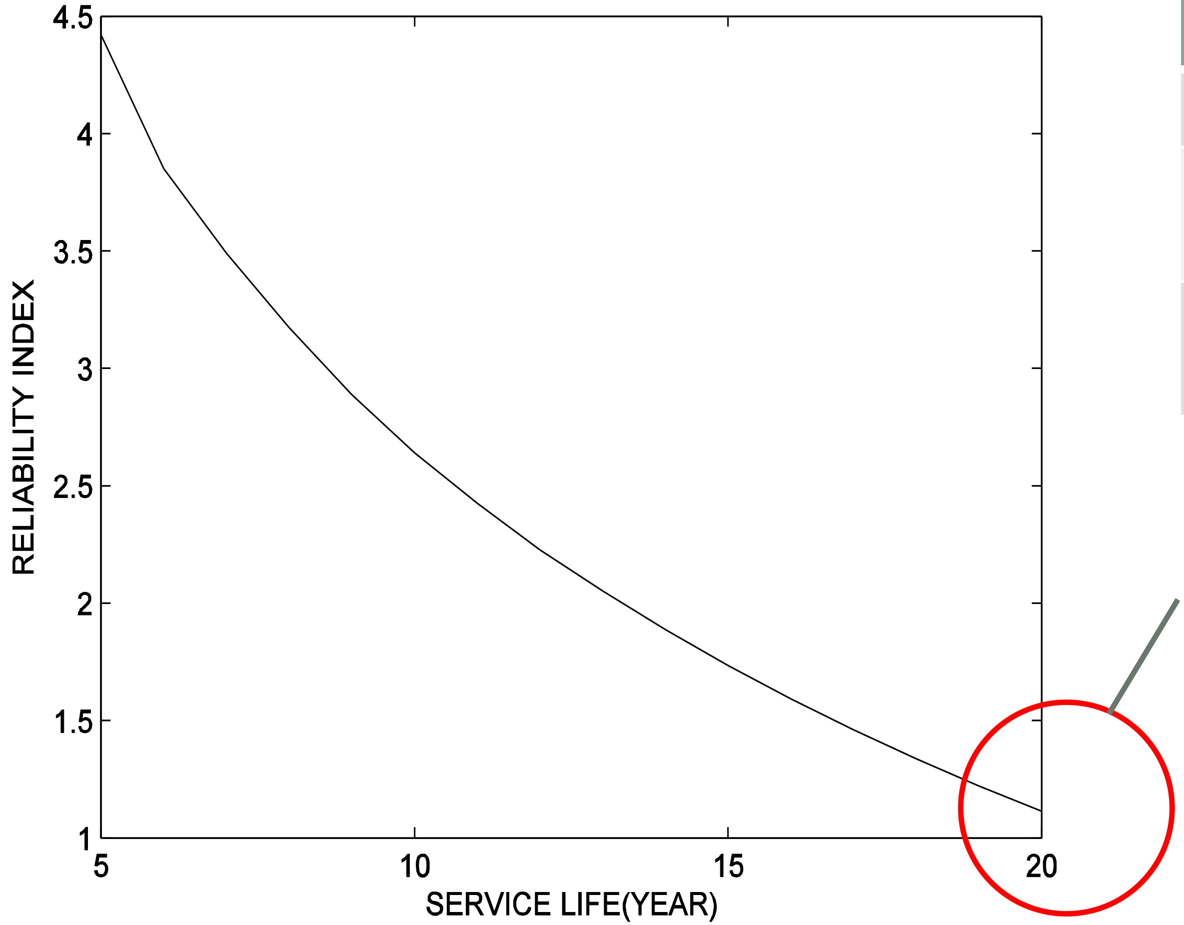
Reliability-based optimum maintenance plans







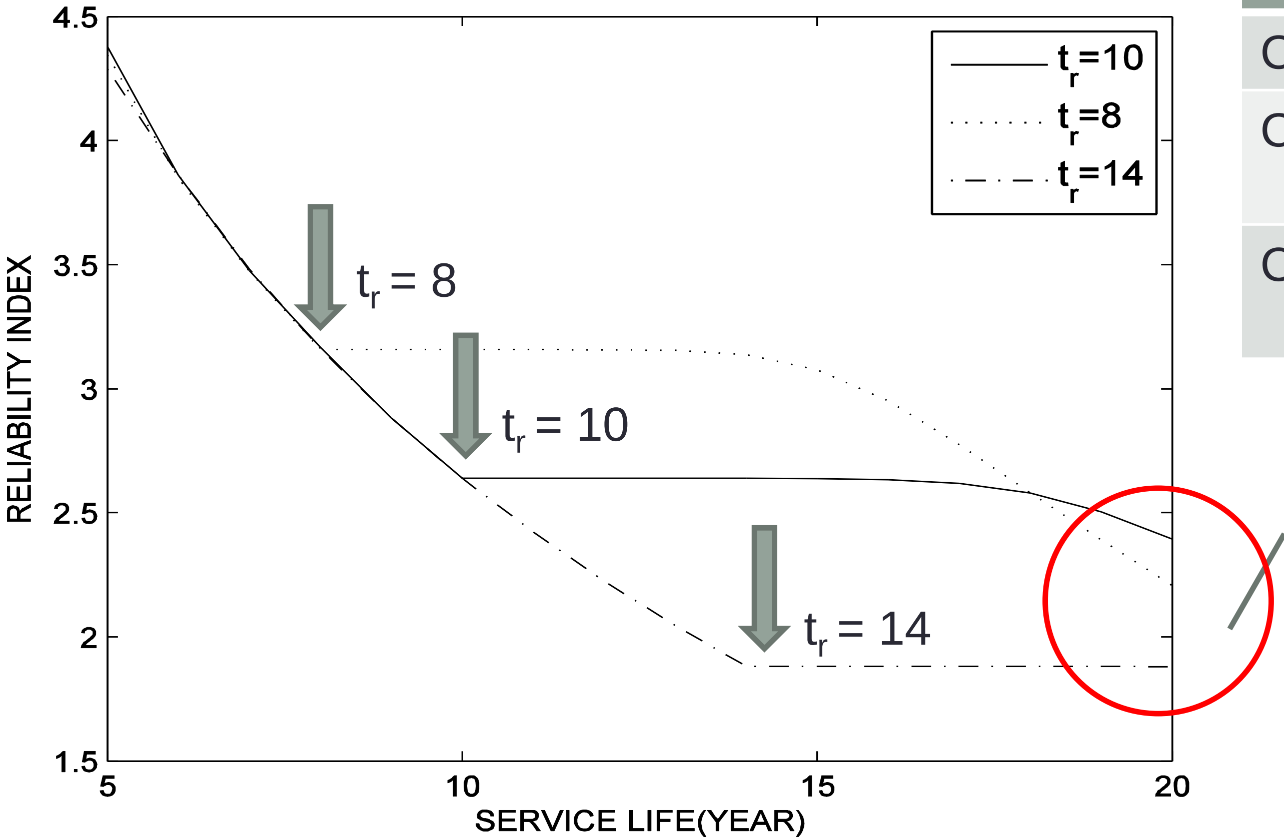
Decrease of reliability with service year (case 1)



Maintenance Strategies	
Case 1	Do Nothing
Case 2	Repair (or replacement)
Case 3	Inspection before repair

Reliability index at end of service life of 1.1

Decrease of reliability with service year (case 2)



Maintenance Strategies	
Case 1	Do Nothing
Case 2	Repair (or replacement)
Case 3	Inspection before repair

Reliability index at end of service life varies depending on the time of the intervention

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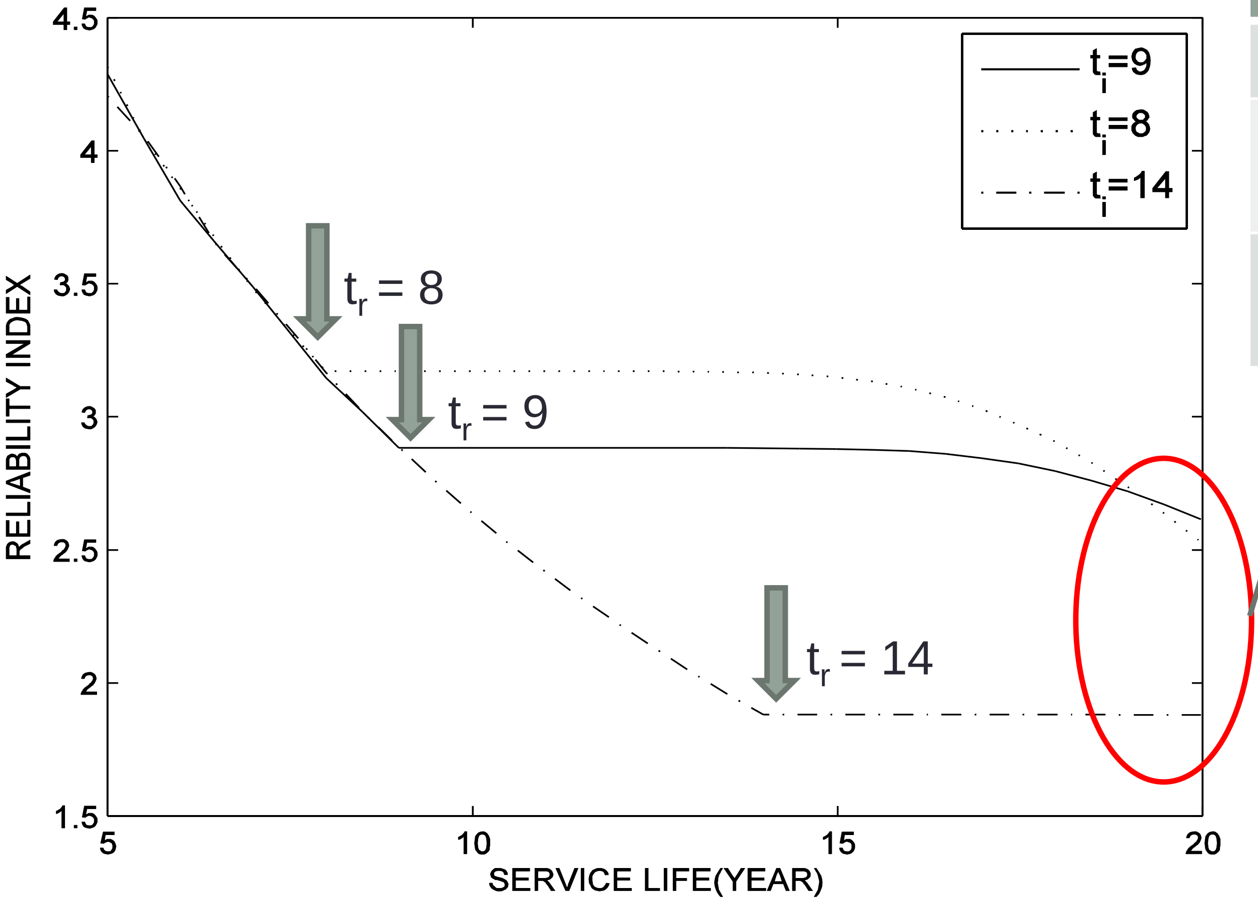
Decrease of reliability with service year (case 3)



Maintenance Strategies	
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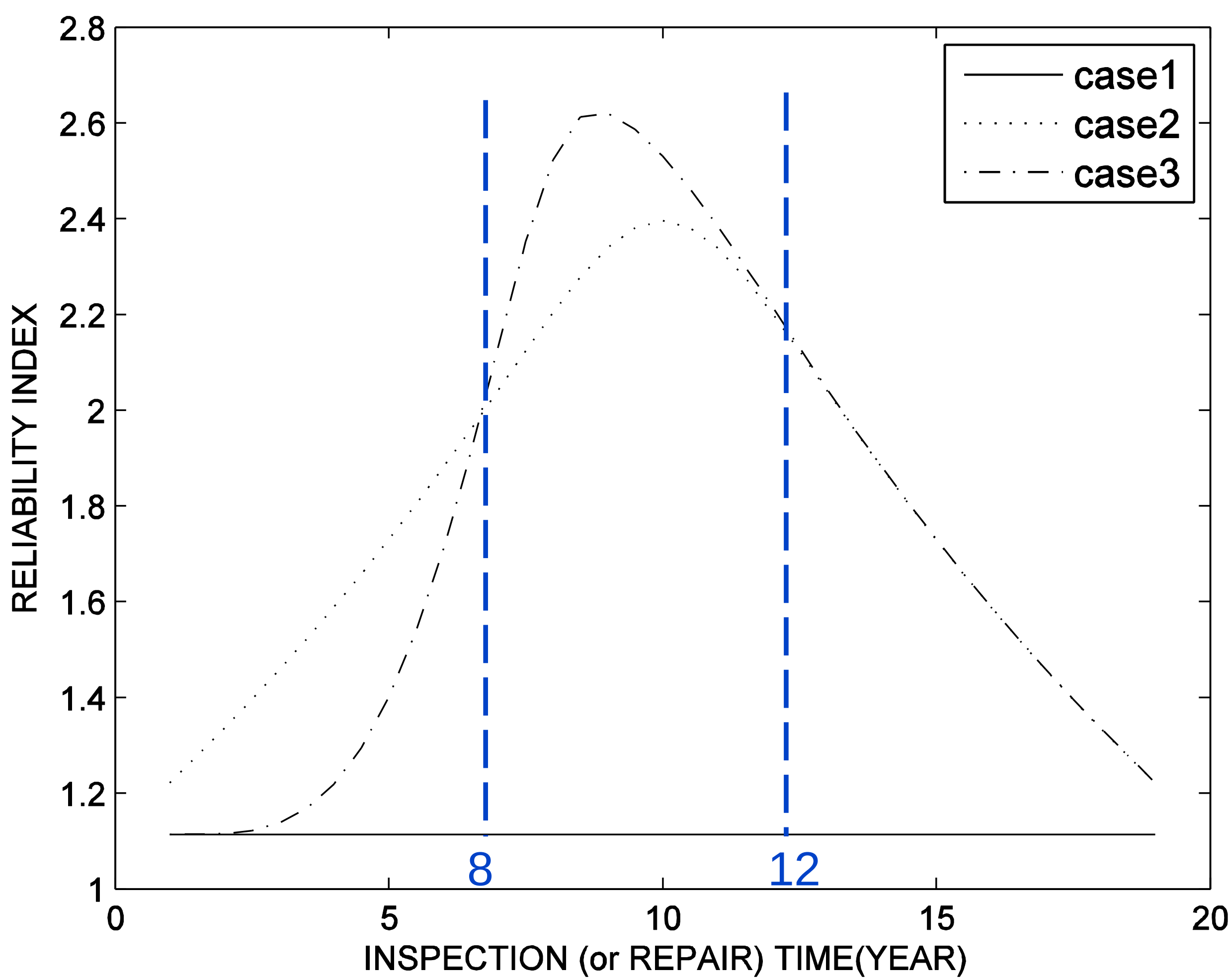
Reliability index at end of service life varies depending on the time of the intervention

Reliability index at end of service life



Maintenance Strategies	
Case 1	Do Nothing
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There is an optimal intervention time achieving maximum reliability. For case 3, it is 9 years, and for case 2, it is 10 years.

There are ranges when one strategy outperforms the other

Life cycle costs

The costs for operational integrity management

- Costs of inspections, repairs and failure

$$LCC = C_I + C_R + C_F$$

The time of analysis and decision is the beginning of service

The costs are variables, and subjected to uncertainties

- expected values of costs

Average annual discounting rate r

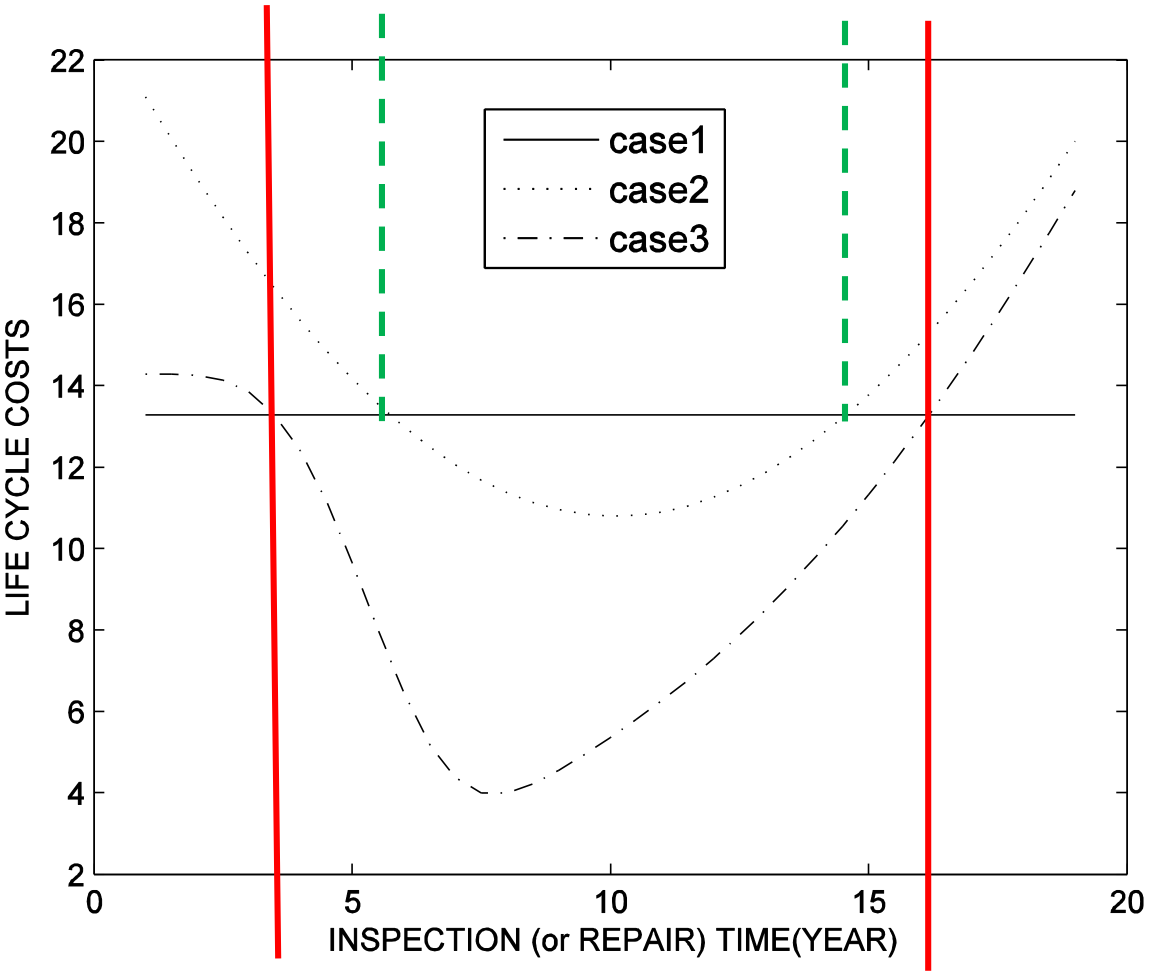
$$C_I = \sum_{k=1}^{N_I} P_{insp}^k \cdot C_{insp}^k \cdot \frac{1}{(1+r)^{t_i^k}}$$

$$C_R = \sum_{k=1}^{N_R} P_{rep}^k \cdot C_{rep}^k \cdot \frac{1}{(1+r)^{t_r^k}}$$

$$C_F = P_f^N \cdot C_{fail} \cdot \frac{1}{(1+r)^T}$$

Life cycle costs

$$LCC = C_I + C_R + C_F$$



Maintenance Strategies	
Case 1	Do Nothing
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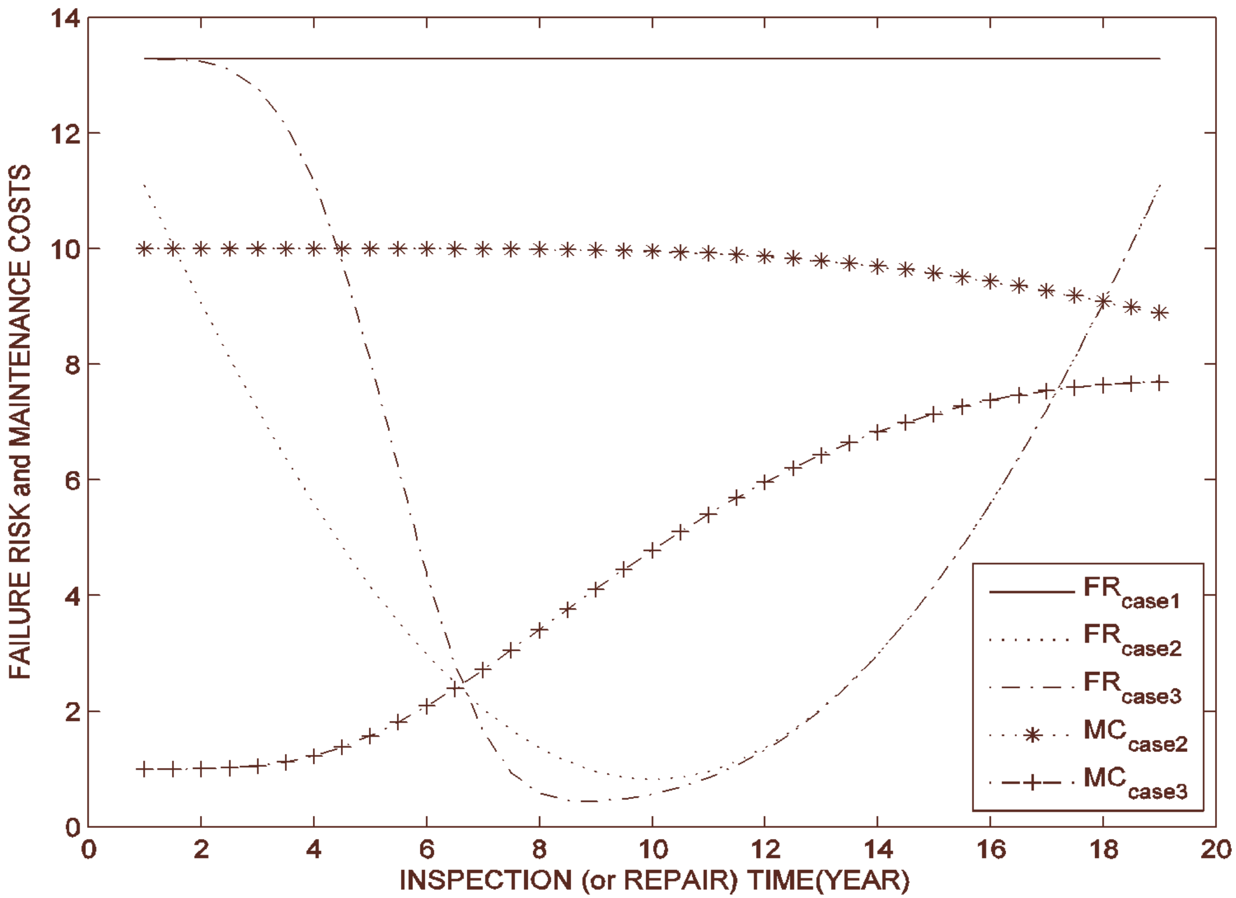
Case 3	Inspection before repair

Planned inspection or repair maintenance interventions can reduce LCC if planned at appropriate times

Optimal inspection/repair times for maximum reliability and minimum LCC may differ

Failure Risk and Maintenance Costs



Maintenance Strategies	
Case 1	Do Nothing
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Failure risk for case 3 is lower than for case 2 for an intervention time between 8 and 12 years

Maintenance costs decrease slightly for case 2, but increase dramatically for case 3 with intervention time

Value Of Inspection Information

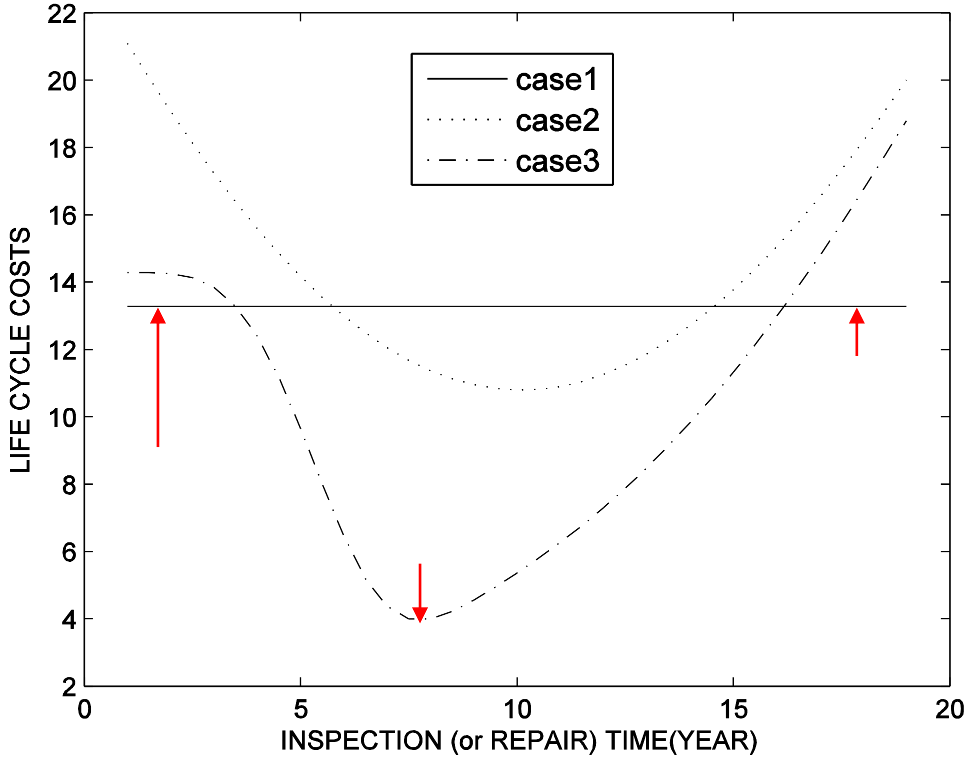
Information contributes to uncertainty reduction and improvement of decision, but comes at a cost. VoI quantification facilitates rational Inspection optimization and decision-making.

VoI calculation:

$$V = U_i - U_0$$

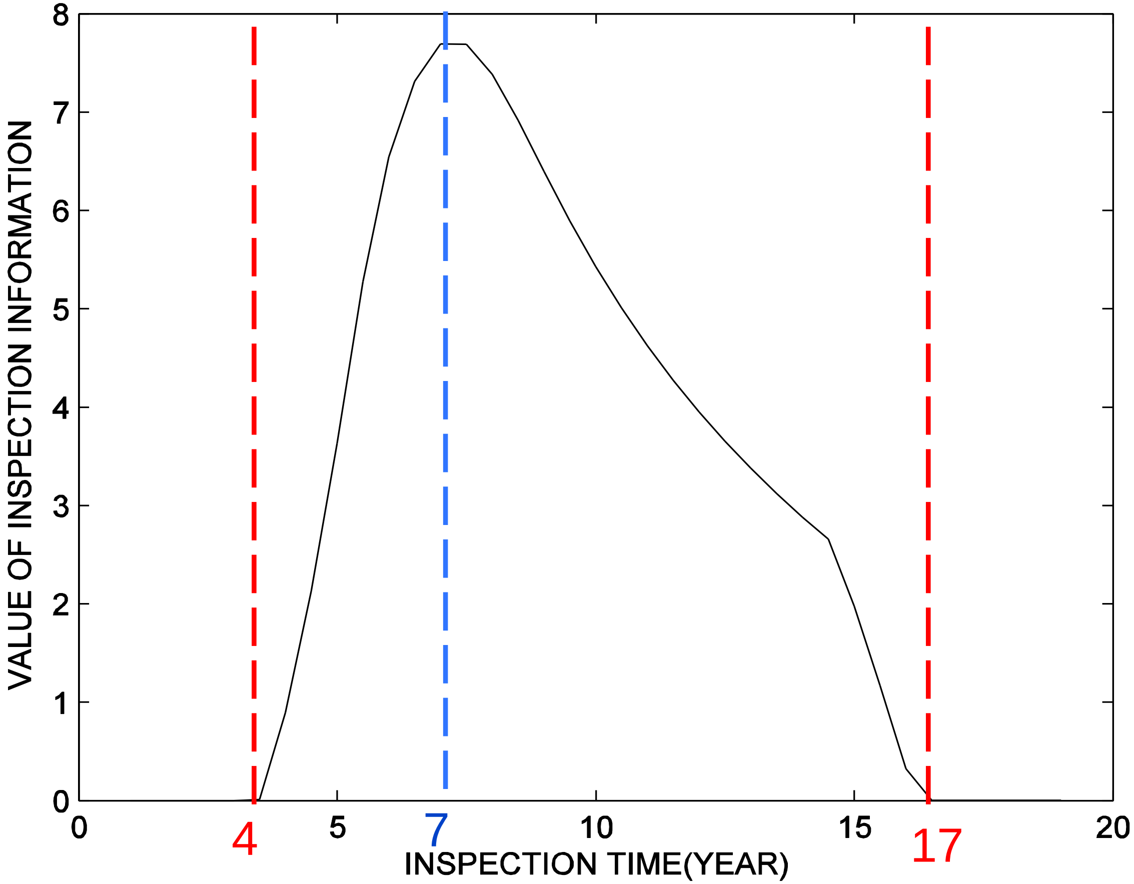
Optimal decision while adopting inspection

Optimal decision without inspection



$$V = \min(LCC_{case1}, LCC_{case2}) - \min(LCC_{case1}, LCC_{case2}, LCC_{case3})$$

Value of information (VoI)



Maintenance Strategies	
Case 1	Do Nothing
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The VoI can be zero for inspections scheduled in the beginning and at the end of service life

VoI decreases after year 7

$$V = \min(LCC_{case1}, LCC_{case2}) - \min(LCC_{case1}, LCC_{case2}, LCC_{case3})$$

Conclusions

- **Reliability Optimization**: Condition-based maintenance can sometimes achieve higher reliability with fewer repairs than repair without inspection in time-based maintenance.

- **Life Cycle Cost Optimization**: The optimal inspection time by cost-based optimization takes place earlier than by reliability-based optimization. As the inspection and repair costs become smaller compared to failure consequence, then both optimal times get closer.

- **Value of Information Optimization**: The VoI can be zero when inspection system and activity is not properly devised and scheduled. Although the VoI can be calculated based on life cycle costs, the inspection times by VoI-based and cost-based optimization can be different.

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Thanks for your attention

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