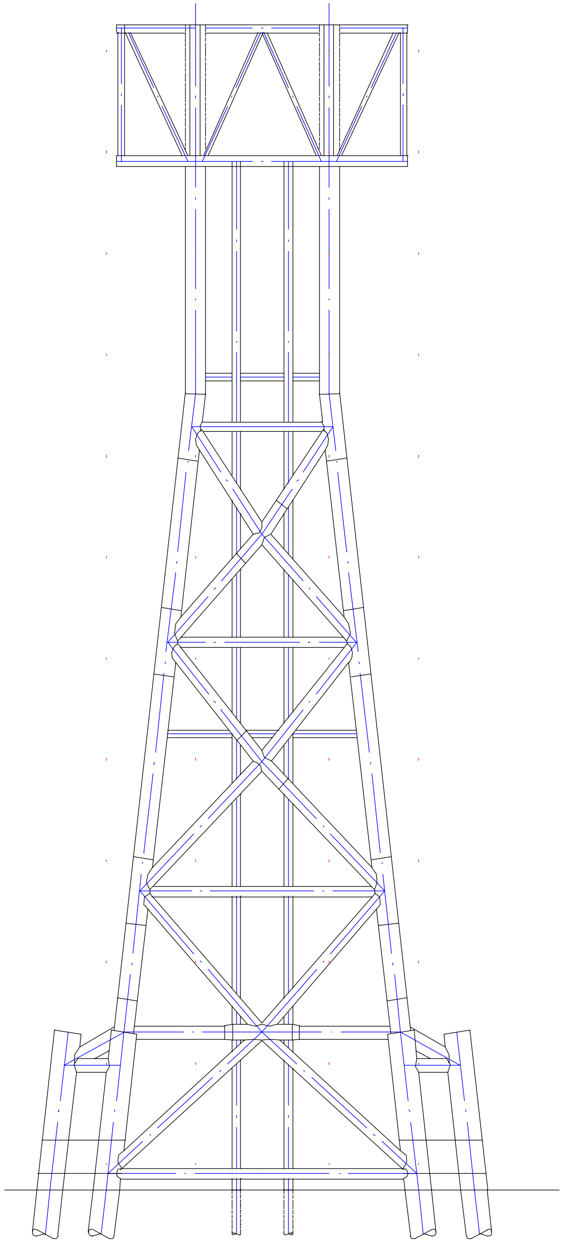
ASRANet Colloquium
Barcelona
6 July 2004



Computational Aspects of Generic Risk Based Inspection Planning

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Deterioration of Steel Structures – Need for RBI

- Structures deteriorate
- Structures are unique

→ Assessement of deterioration and the planning of inspections must be based on physical models

- Presented approaches have been succesfully applied for structures subject to fatigue, other applications (corrosion) are envisged.

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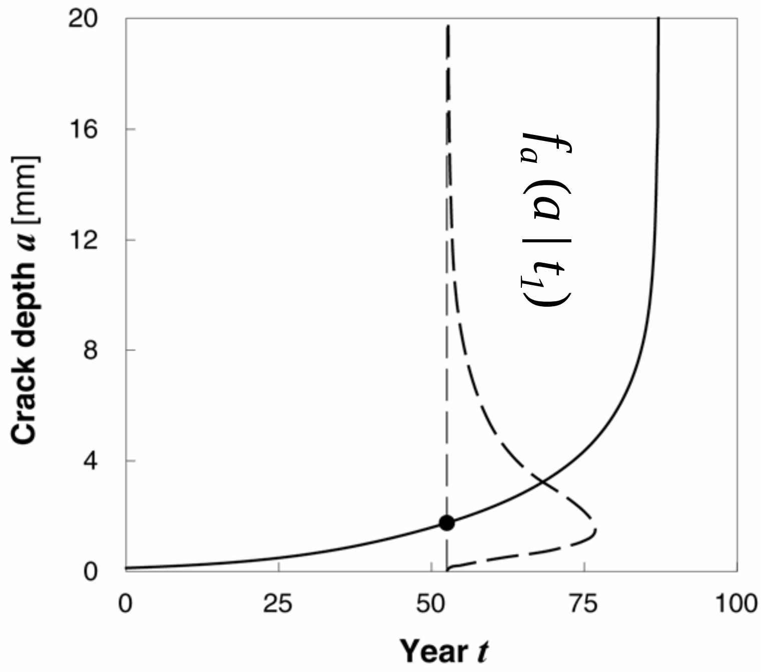
Probabilistic Deterioration Modelling

- Quantitative deterioration models:
  - Defect size as a function of time
  - E.g. for fatigue crack growth:

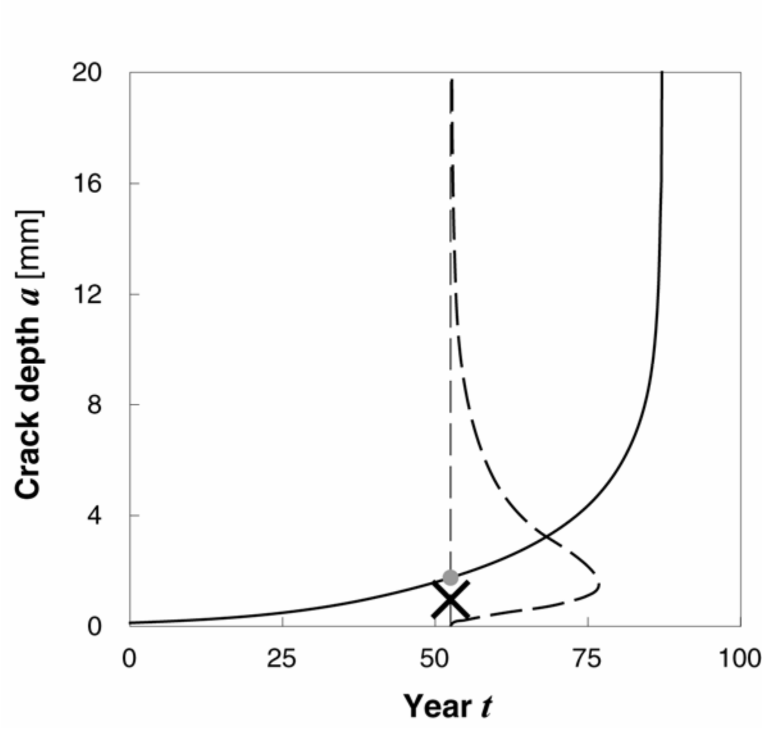
$$\frac{\mathrm{d}a}{\mathrm{d}t} = C_P \cdot \Delta K_{eff}{}^{m_{FM}} \cdot \nu$$

- Probabilistic description of deterioration mechanisms



Inspections

- Inspections reduce the uncertainty in the deterioration model:

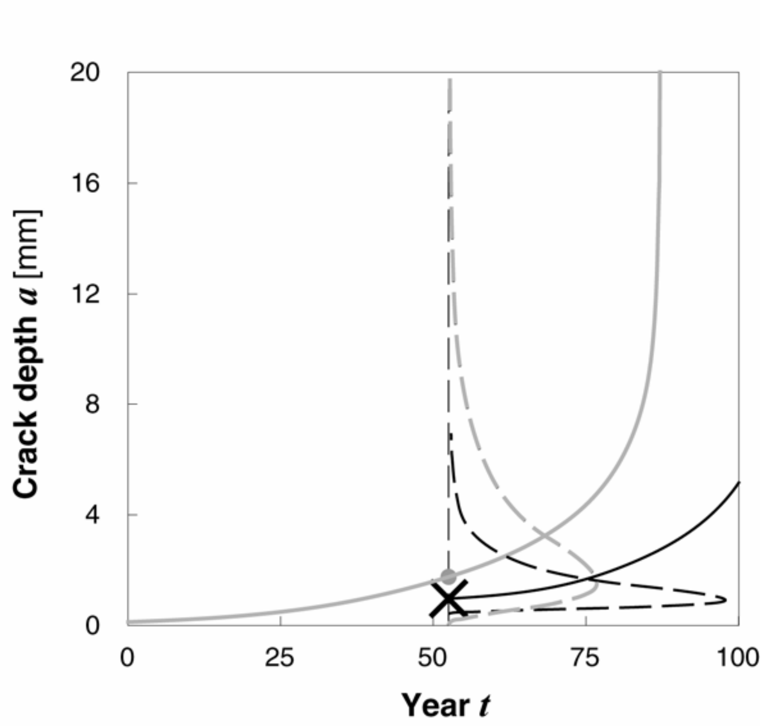


Inspections

- Inspections reduce the uncertainty in the deterioration model:

- Probability updating:
  (Bayes‘ law)

$$f''_X(x|z) = \frac{L(z|x) \cdot f'_X(x)}{\int_{\Omega_X} L(z|x) \cdot f'_X(x) \cdot dx}$$



Inspections

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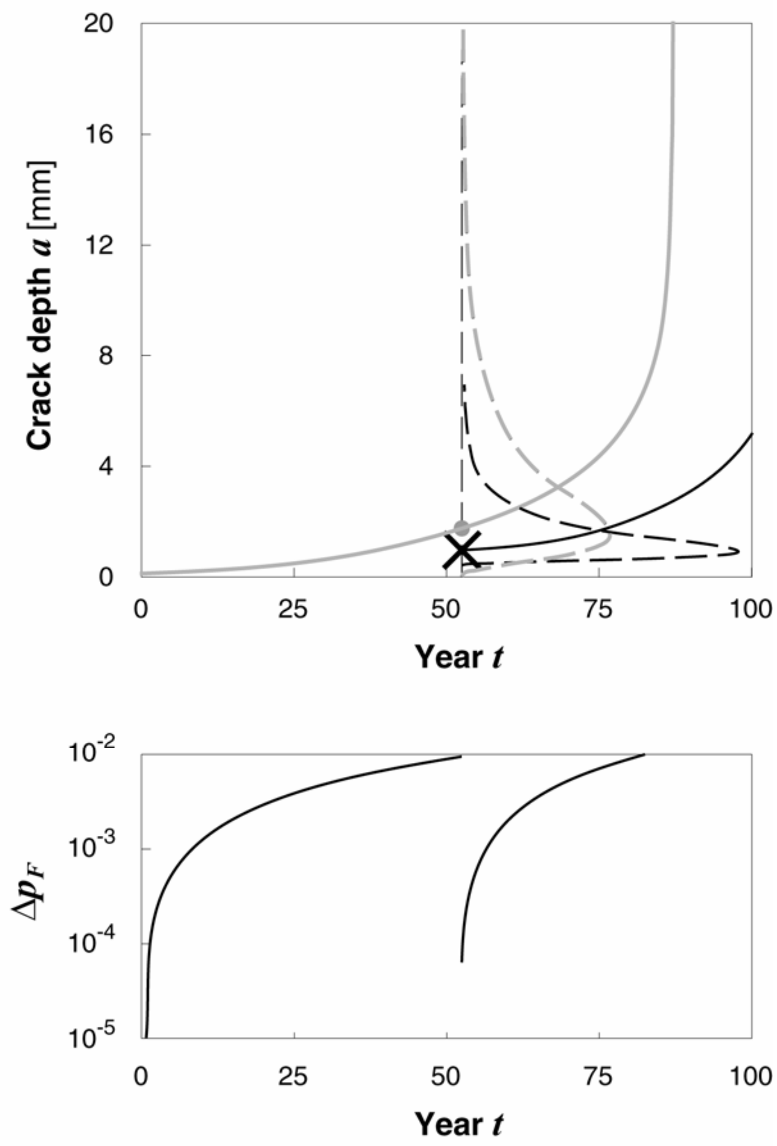
$$f''_X(x|z) = \frac{L(z|x)\cdot f'_X(x)}{\int_{\Omega_X} L(z|x)\cdot f'_X(x)\cdot dx}$$

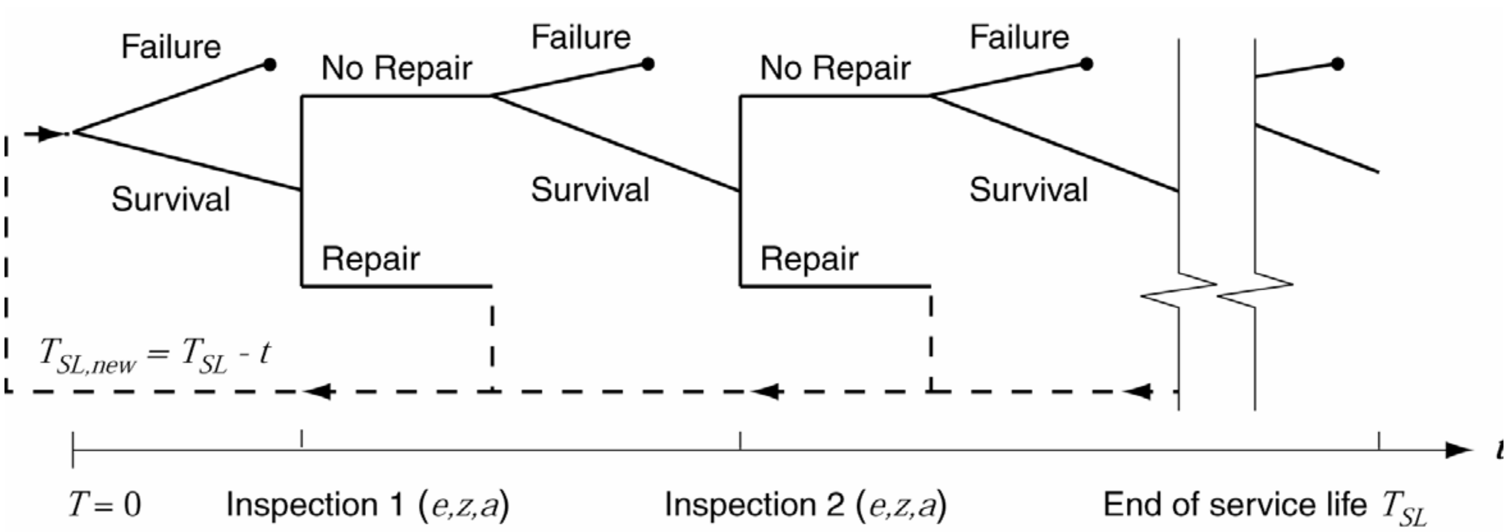
- Calculations performed with **simulation techniques** or **structural reliability analysis**

$$P(F|M) = \frac{P(F \cap M)}{P(M)}$$



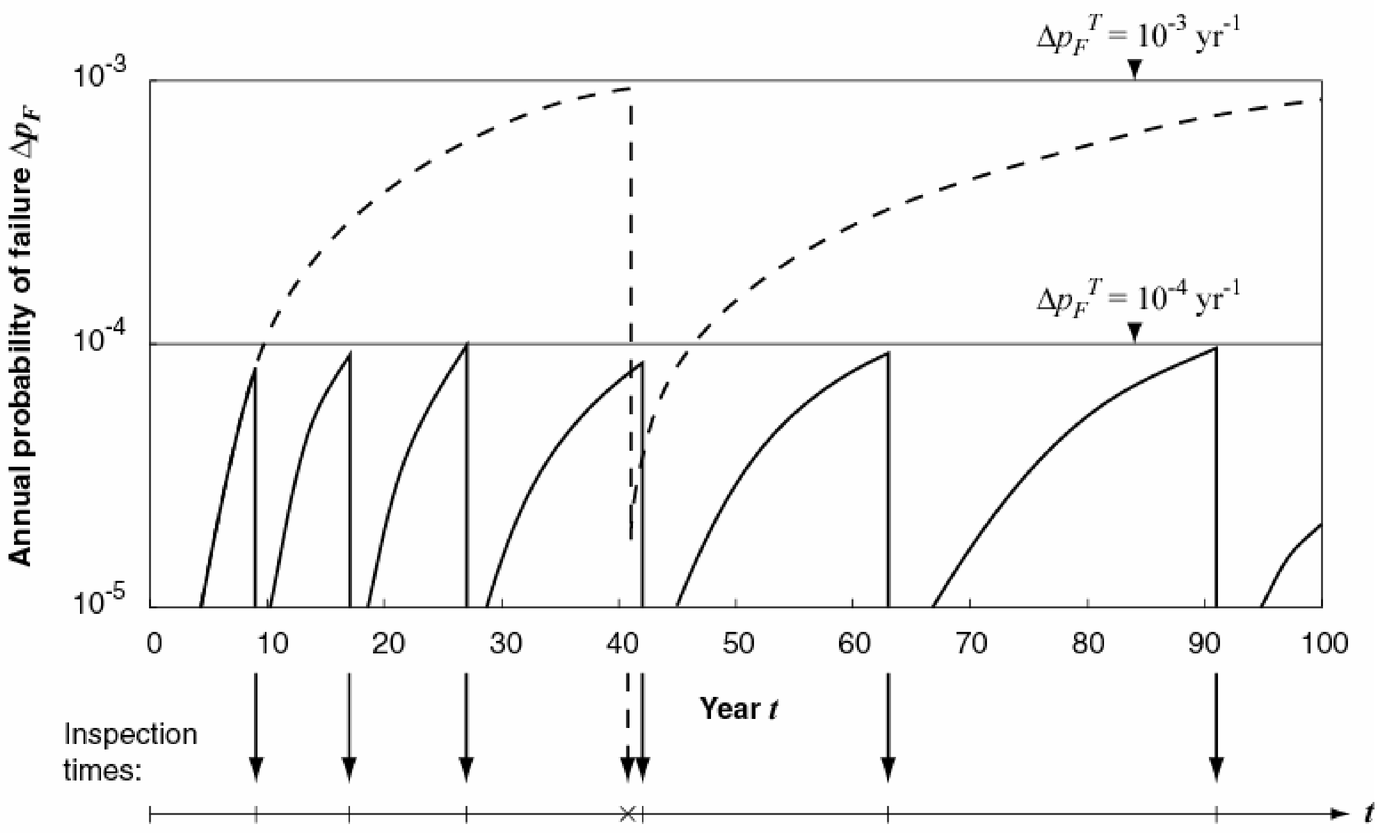
Risk Based Inspection Planning

Decision tree simplified:



Risk Based Inspection Planning - Results

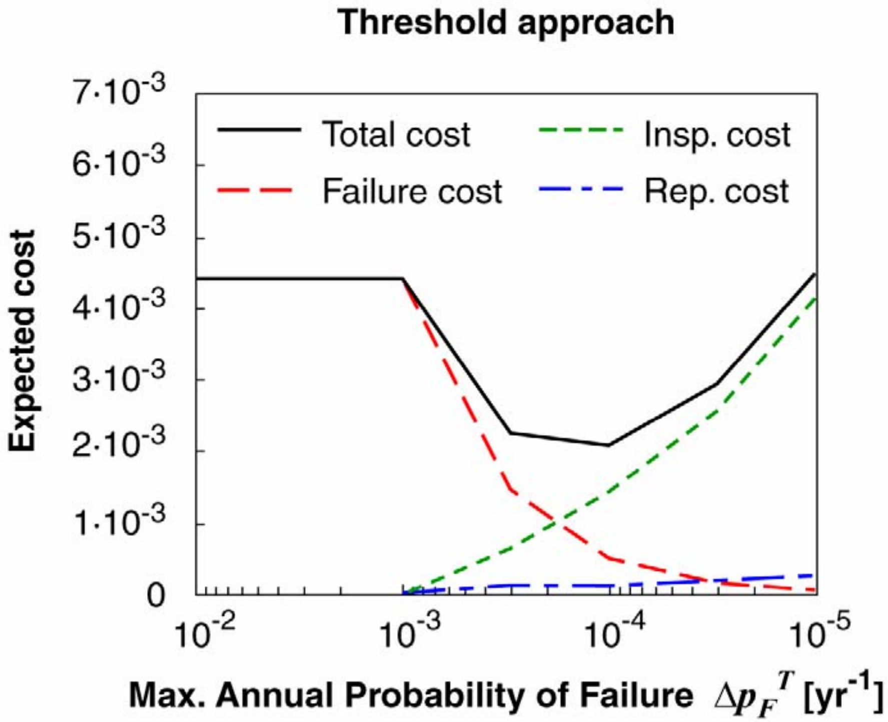
- Inspection strategies (times):



Risk Based Inspection Planning – Results

- Optimal inspection strategies

$$E\left[C_R(\underline{\mathbf{e}},d,T_{SL})\right]=\sum_{t=t_1}^{t_{n_{Insp}}}\left[\begin{array}{l}\left(1-p_F(\underline{\mathbf{e}},d,t)\right)\left(1-\sum_{i=1}^{t-1}p_R(\underline{\mathbf{e}},d,i)\right)\cdot\\ p_R(\underline{\mathbf{e}},d,t)\left(C_R+E\left[C_R(\underline{\mathbf{e}},d,T_{SL}-t)\right]\right)\dfrac{1}{(1+r)^t}\end{array}\right]$$



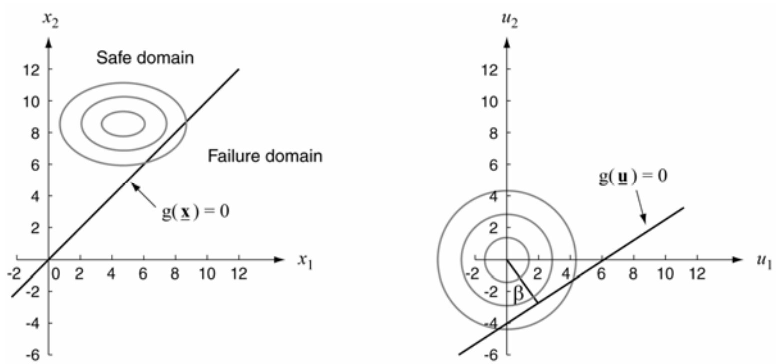
Computing the (conditional) probabilities

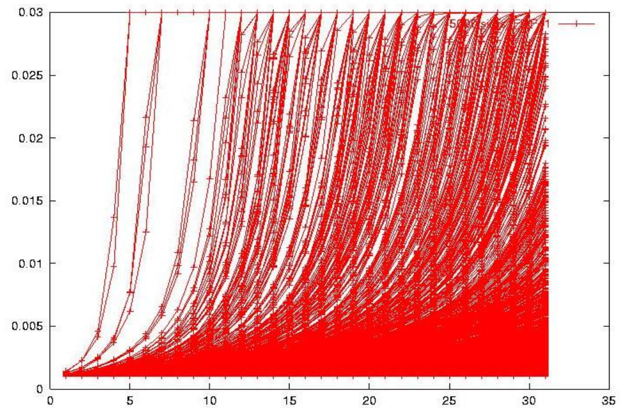
- Problem: Evaluation of the conditional probabilities of failure and repair.

- Conditional on inspection outcomes (no-detection at the different inspections)

$$P\left(F\middle|\overline{D}\right)=\frac{P\left(F\cap\overline{D}\right)}{P\left(\overline{D}\right)}$$

- Using **FORM / SORM** or Monte Carlo Simulation (**MCS**)





Computing the (conditional) probabilities FORM / SORM vs Monte Carlo Simulation

- **For a typical inspection plan (50 yrs) with different thresholds, approx. :**

	FORM / SORM	**Crude MCS**
Number of LSF calls	10^4	10^8
Equality constraints	Can be considered	Only approximate, if at all

Computing the (conditional) probabilities FORM / SORM vs Monte Carlo Simulation

- **For a typical inspection plan (50 yrs) with different thresholds, approx. :**

	FORM / SORM	**Crude MCS**
Number of LSF calls	10^4	10^8
Equality constraints	Can be considered	Only approximate, if at all
Engineer's time	5min – 2h (experienced engineer !)	5min

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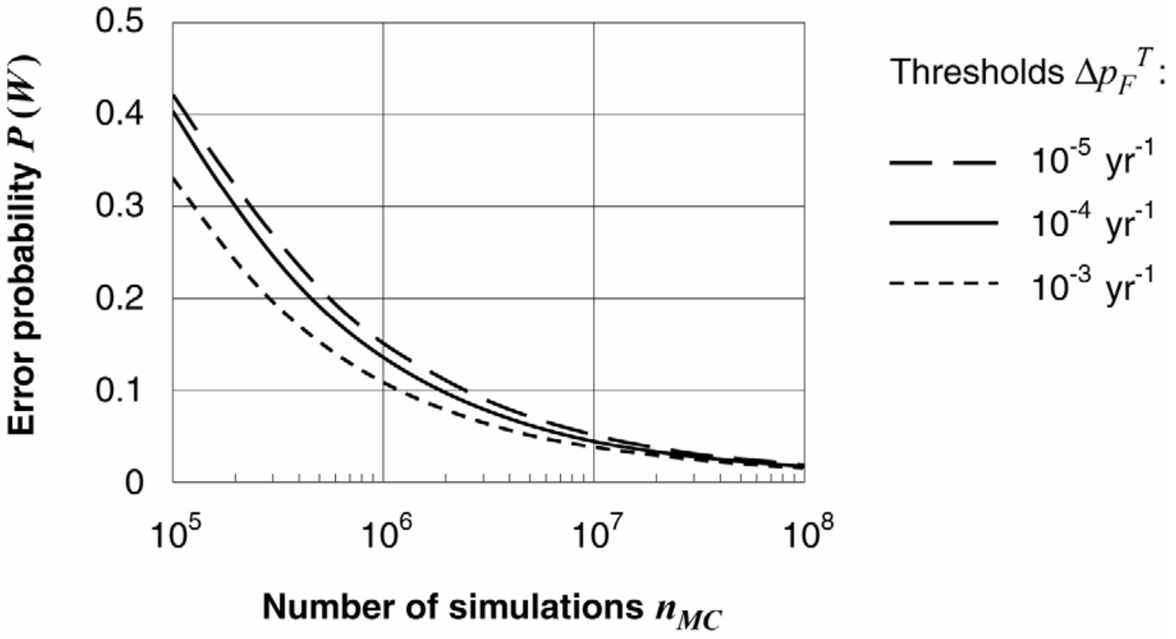
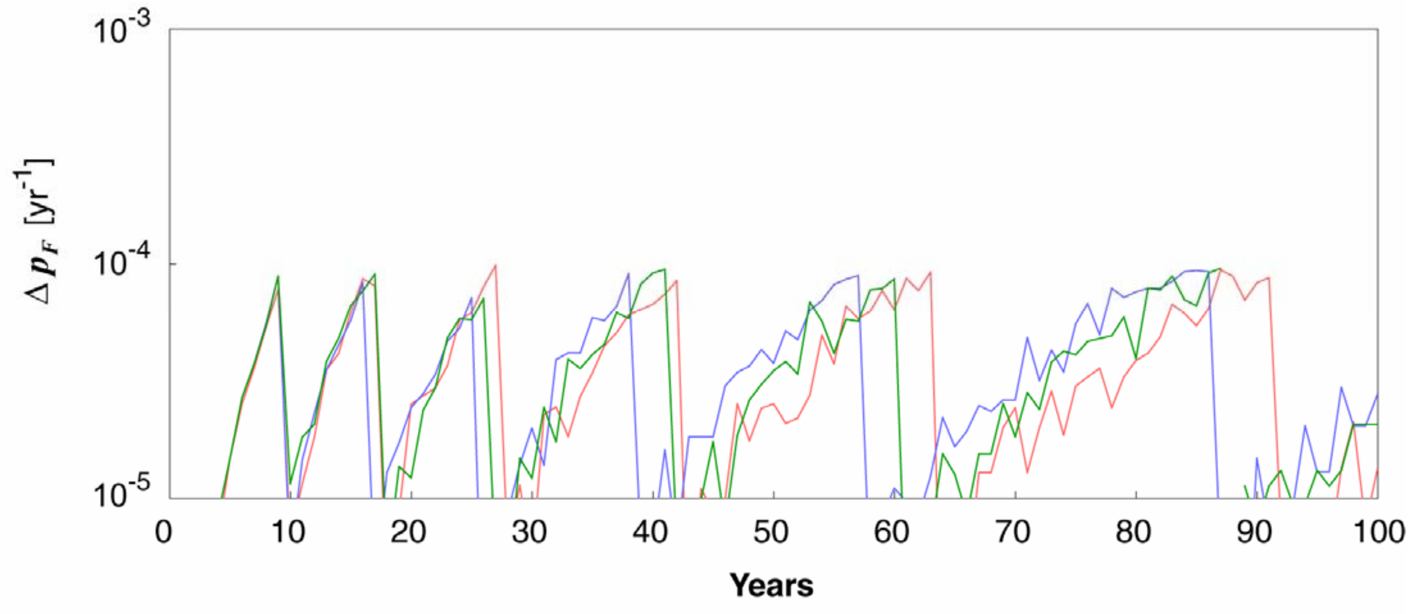
MCS for inspection planning

- In the inspection planning phase no defect measurements are considered (no equality constraints)
- Annual failure probabilities in the range of 10^{-3} to 10^{-5}
- Accuracy: The probability of predicting the first inspection in the wrong year:



MCS for inspection planning

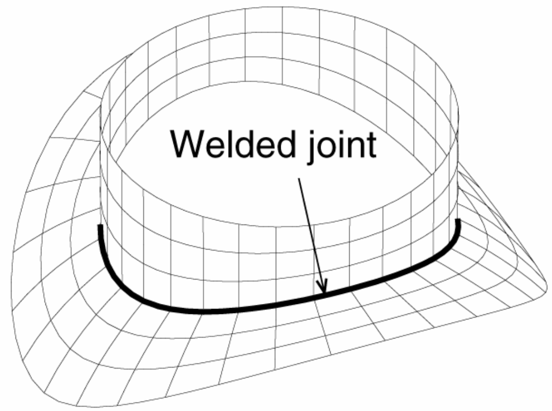
- Typically $N_{Sim} = 2\ 10^6$



- Problem of large computation times is addressed by the generic approach

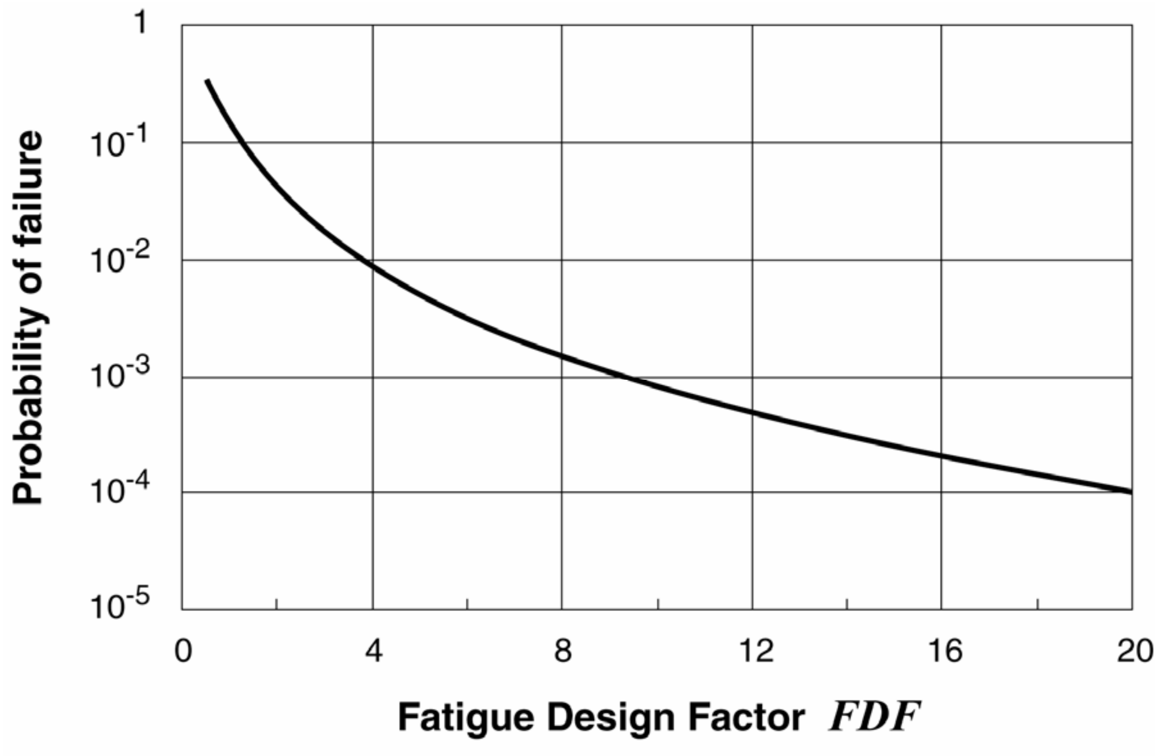
Generic Approaches – Principle

- Calculate inspection plans for generic representations of structural details
- Defined in terms of simple indicators, the generic parameters.
  Examples are:
  - Detail type
  - Environment
  - Geometrical properties (thickness)
  - Loading characteristics
  - Fatigue Design Factor *FDF* (Resulting from standard deterministic fatigue evaluations)
  - Quality of fatigue calculations
  - Initial quality control



Generic Approaches

- Fatigue Design Factor *FDF* (Resulting from standard deterministic fatigue evaluations)



Generic Approaches – Principle

Structural Details Database

Generic Parameters:

- FDF = …
- Thickness = …

…

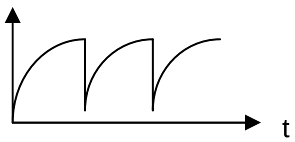
Cost Model:

- Cost of Failure =
- Cost of Inspection =

…

Generic Database

Probabilities:



as a function of the Generic Parameters:

- FDF = …
- Thickness = …

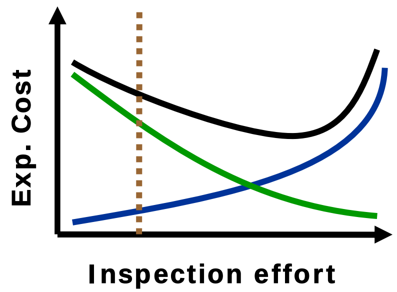
…

Decison model & interpolation

Reliability Based Inspection Planning:

	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018
9870-978		X											X			
9870-979							X									
9870-980															X	
9870-981			X													
9870-982		X														
9870-983		X												X		
9870-984		X										X				
9870-985				X												
9870-986		X					X									
9870-987				X							X					
9870-988									X							
9870-989												X				

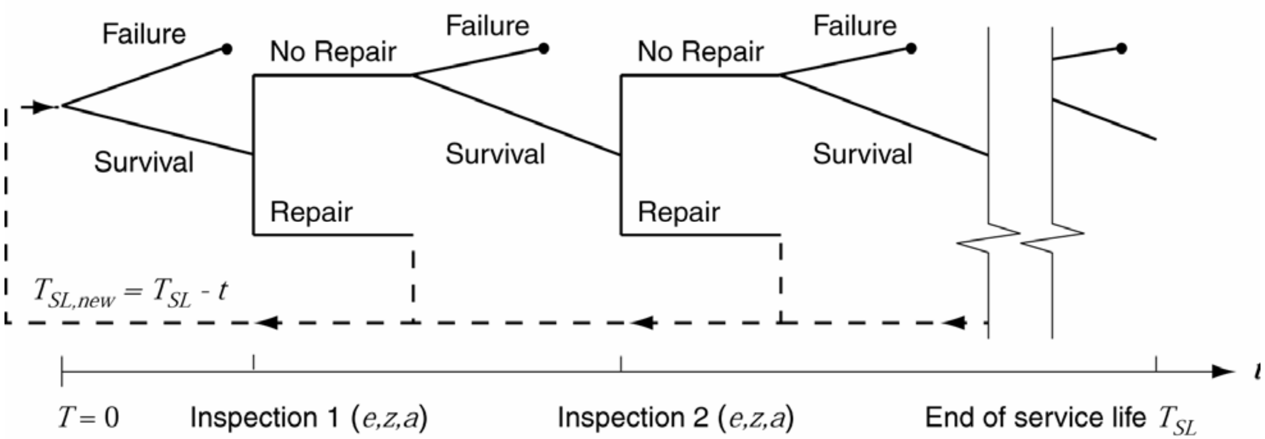
Risk Based Inspection Planning:



Interpolation in the generic approach

1. Evaluate the decision tree for the specific cost model for all generic representations

$$\mathrm{E}\left[C_R(\underline{\mathbf{e}},d,T_{SL})\right]=\sum_{t=t_1}^{t_{n_{Insp}}}\left[\begin{array}{l}(1-p_F(\underline{\mathbf{e}},d,t))\left(1-\sum_{i=1}^{t-1}p_R(\underline{\mathbf{e}},d,i)\right)\cdot \\ p_R(\underline{\mathbf{e}},d,t)\left(C_R+\mathrm{E}\left[C_R(\underline{\mathbf{e}},d,T_{SL}-t)\right]\right)\dfrac{1}{(1+r)^t}\end{array}\right]$$



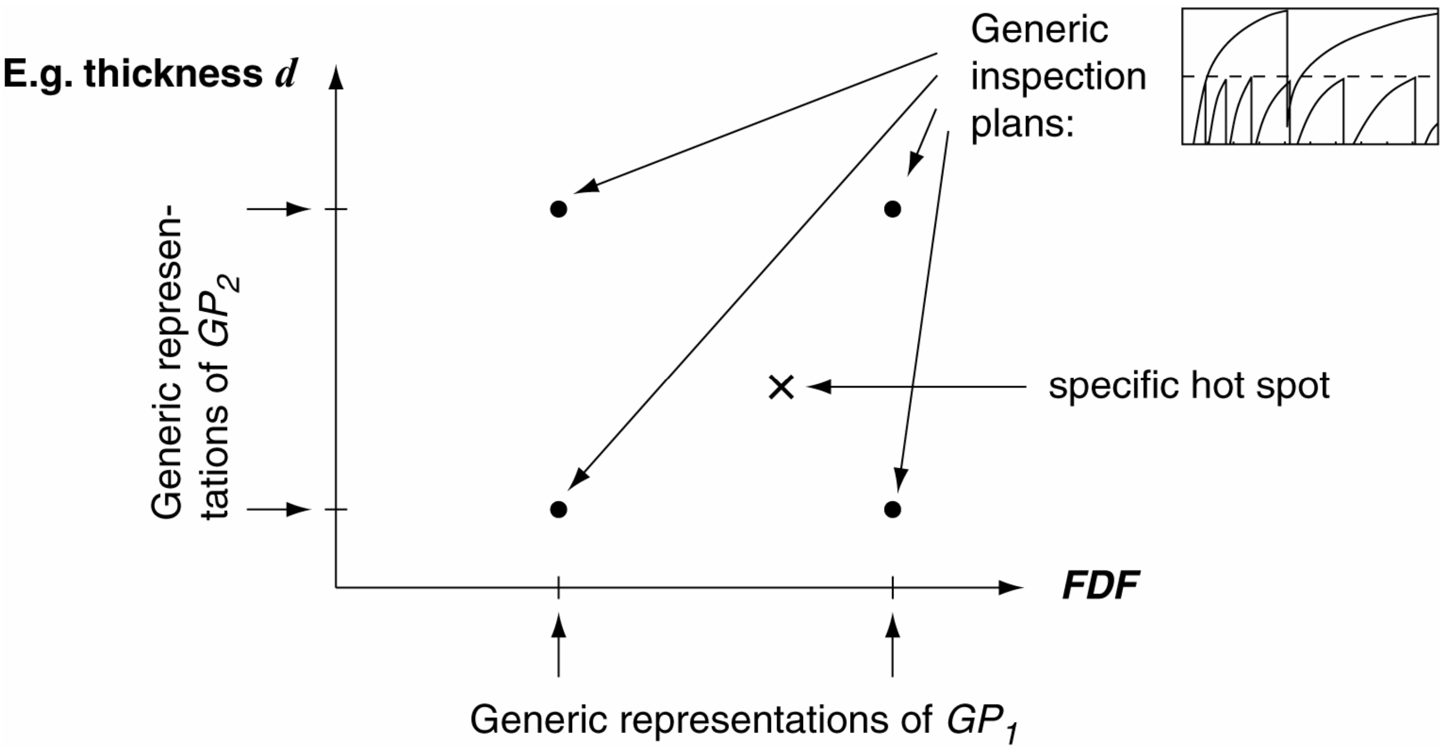
Interpolation in the generic approach

1. Evaluate the decision tree for the specific cost model for all generic representations

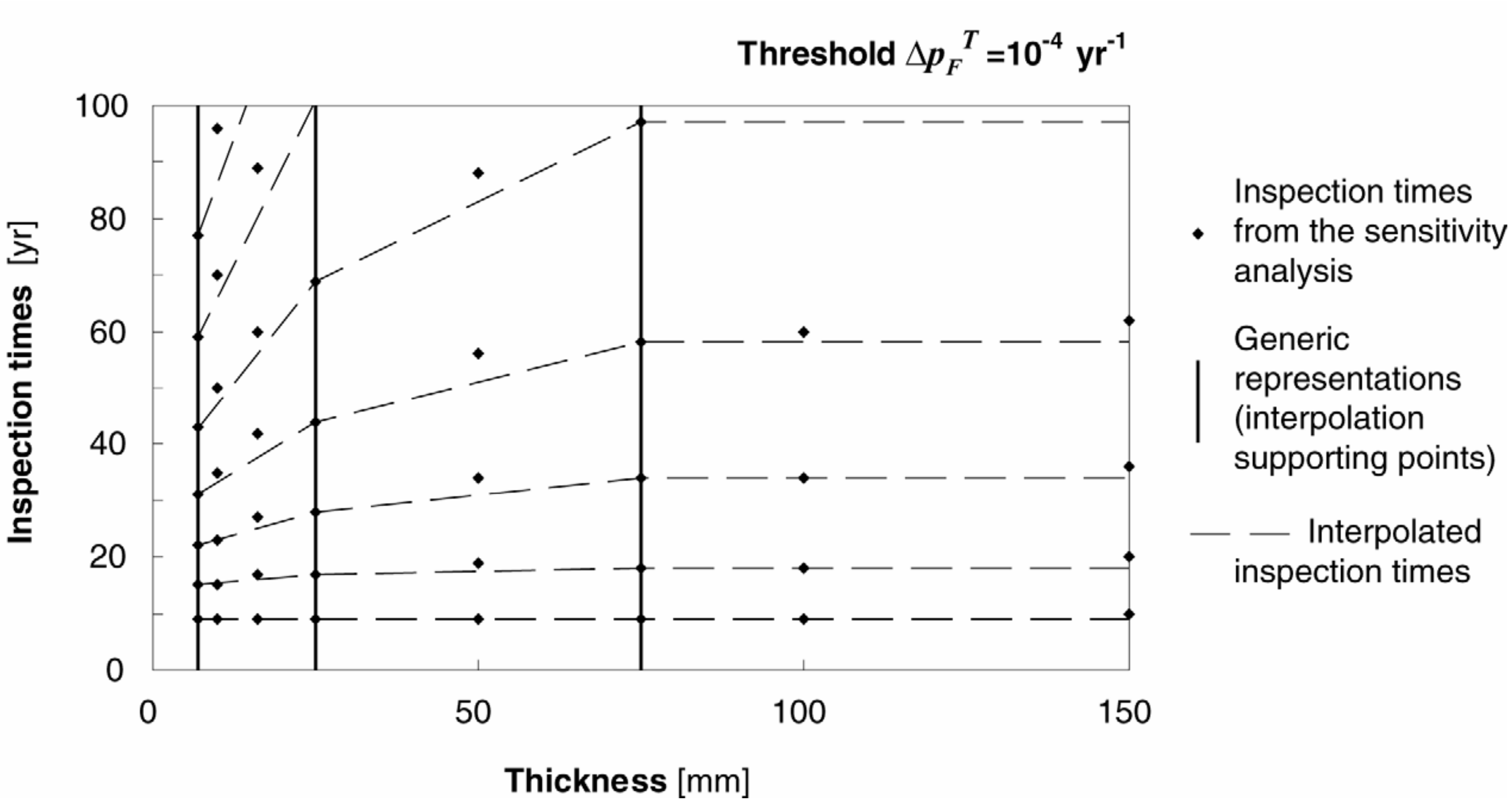
2. Interpolate the calcualated expected cost and the inspection times seperately

Interpolation in the generic approach

- Linear interpolation (multi-dimensional)



Design of the generic database



and identically for expected costs...

Verification of the generic database

- Comparison between direct calculations and the inspection plans obtained using the generic approach.

Direct:

Inspections

Index / Year	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
501-335							X									X																			X							
205-724																	X																									
205-724																							X																			
505-333				X				X							X											X											X					
467-297																											X															
502-419																																X										

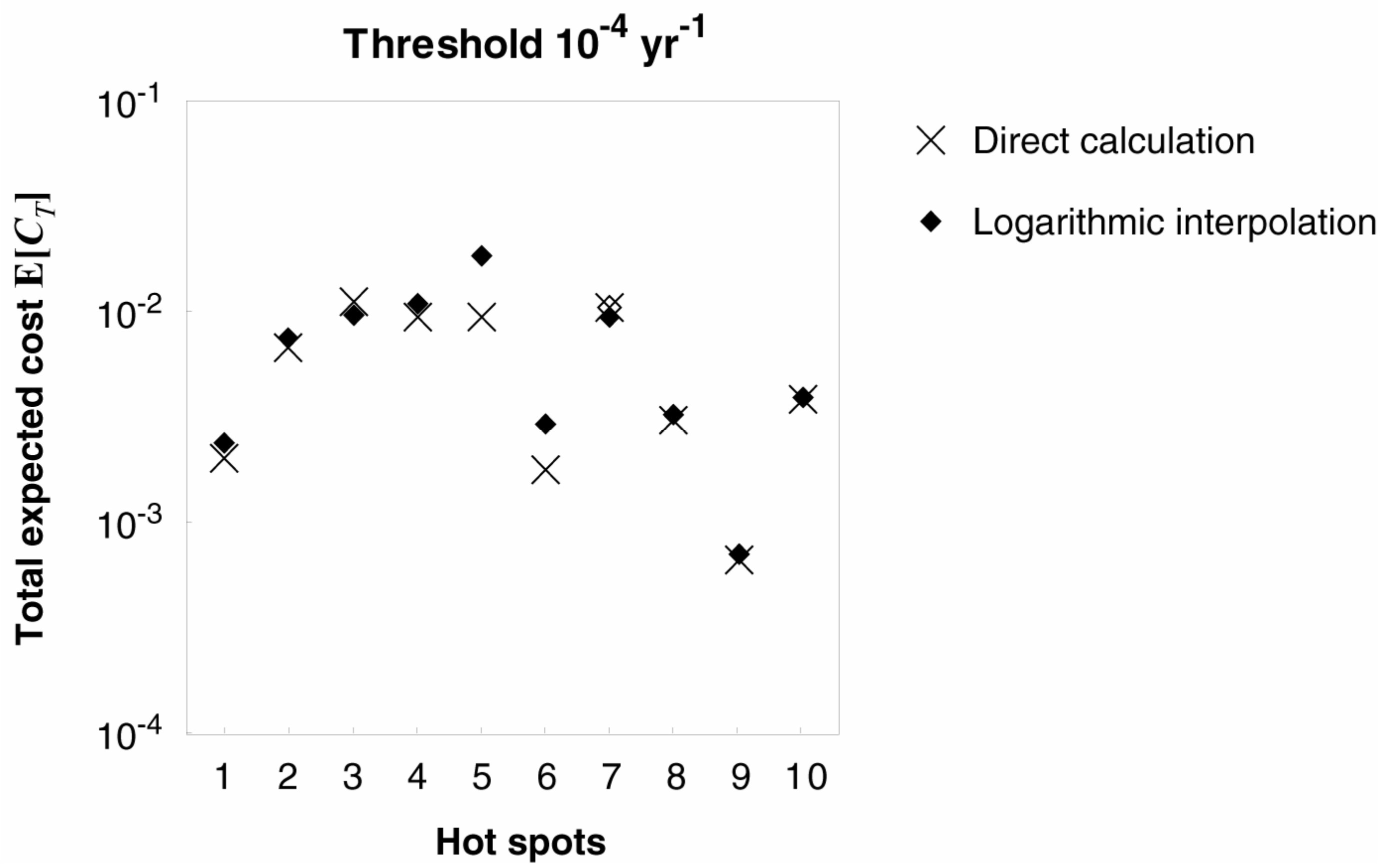
Generic approach:

Inspections

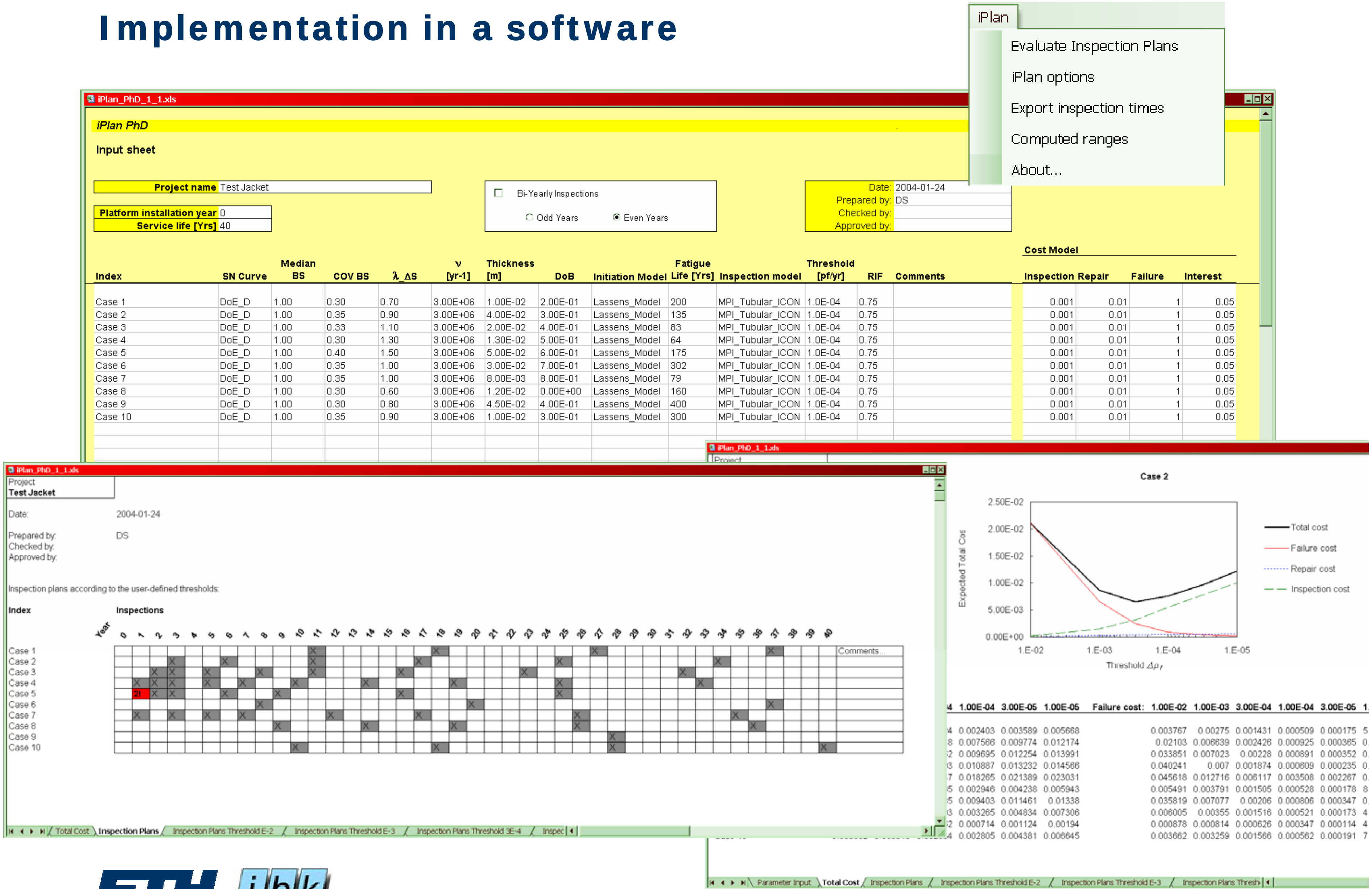
Index / Year	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
501-335							X										X																					X				
205-724																			X																							
205-724																												X														
505-333					X				X							X											X													X		
467-297																														X												
502-419																																			X							

Verification of the generic database

- Compare expected cost:



Implementation in a software



Index	SN Curve	Median BS	COV BS	λ_ΔS	ν [yr-1]	Thickness [m]	DoB	Initiation Model	Fatigue Life [Yrs]	Inspection model	Threshold [pf/yr]	RIF	Comments	Inspection	Repair	Failure	Interest
Case 1	DoE_D	1.00	0.30	0.70	3.00E+06	1.00E-02	2.00E-01	Lassens_Model	200	MPI_Tubular_ICON	1.0E-04	0.75		0.001	0.01	1	0.05
Case 2	DoE_D	1.00	0.35	0.90	3.00E+06	4.00E-02	3.00E-01	Lassens_Model	135	MPI_Tubular_ICON	1.0E-04	0.75		0.001	0.01	1	0.05
Case 3	DoE_D	1.00	0.33	1.10	3.00E+06	2.00E-02	4.00E-01	Lassens_Model	83	MPI_Tubular_ICON	1.0E-04	0.75		0.001	0.01	1	0.05
Case 4	DoE_D	1.00	0.30	1.30	3.00E+06	1.30E-02	5.00E-01	Lassens_Model	64	MPI_Tubular_ICON	1.0E-04	0.75		0.001	0.01	1	0.05
Case 5	DoE_D	1.00	0.40	1.50	3.00E+06	5.00E-02	6.00E-01	Lassens_Model	175	MPI_Tubular_ICON	1.0E-04	0.75		0.001	0.01	1	0.05
Case 6	DoE_D	1.00	0.35	1.00	3.00E+06	3.00E-02	7.00E-01	Lassens_Model	302	MPI_Tubular_ICON	1.0E-04	0.75		0.001	0.01	1	0.05
Case 7	DoE_D	1.00	0.35	1.00	3.00E+06	8.00E-03	8.00E-01	Lassens_Model	79	MPI_Tubular_ICON	1.0E-04	0.75		0.001	0.01	1	0.05
Case 8	DoE_D	1.00	0.30	0.60	3.00E+06	1.20E-02	0.00E+00	Lassens_Model	160	MPI_Tubular_ICON	1.0E-04	0.75		0.001	0.01	1	0.05
Case 9	DoE_D	1.00	0.30	0.80	3.00E+06	4.50E-02	4.00E-01	Lassens_Model	400	MPI_Tubular_ICON	1.0E-04	0.75		0.001	0.01	1	0.05
Case 10	DoE_D	1.00	0.35	0.90	3.00E+06	1.00E-02	3.00E-01	Lassens_Model	300	MPI_Tubular_ICON	1.0E-04	0.75		0.001	0.01	1	0.05

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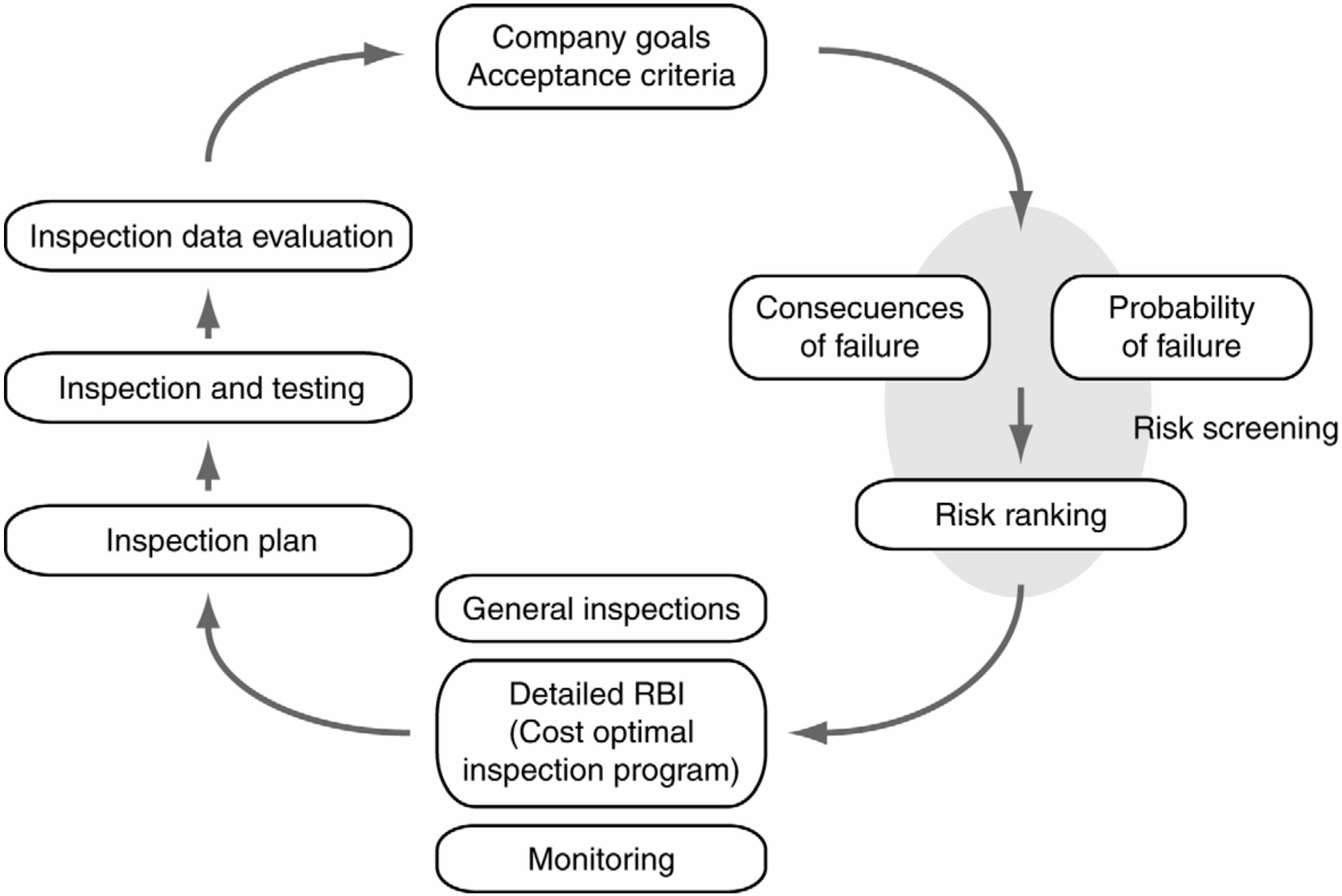
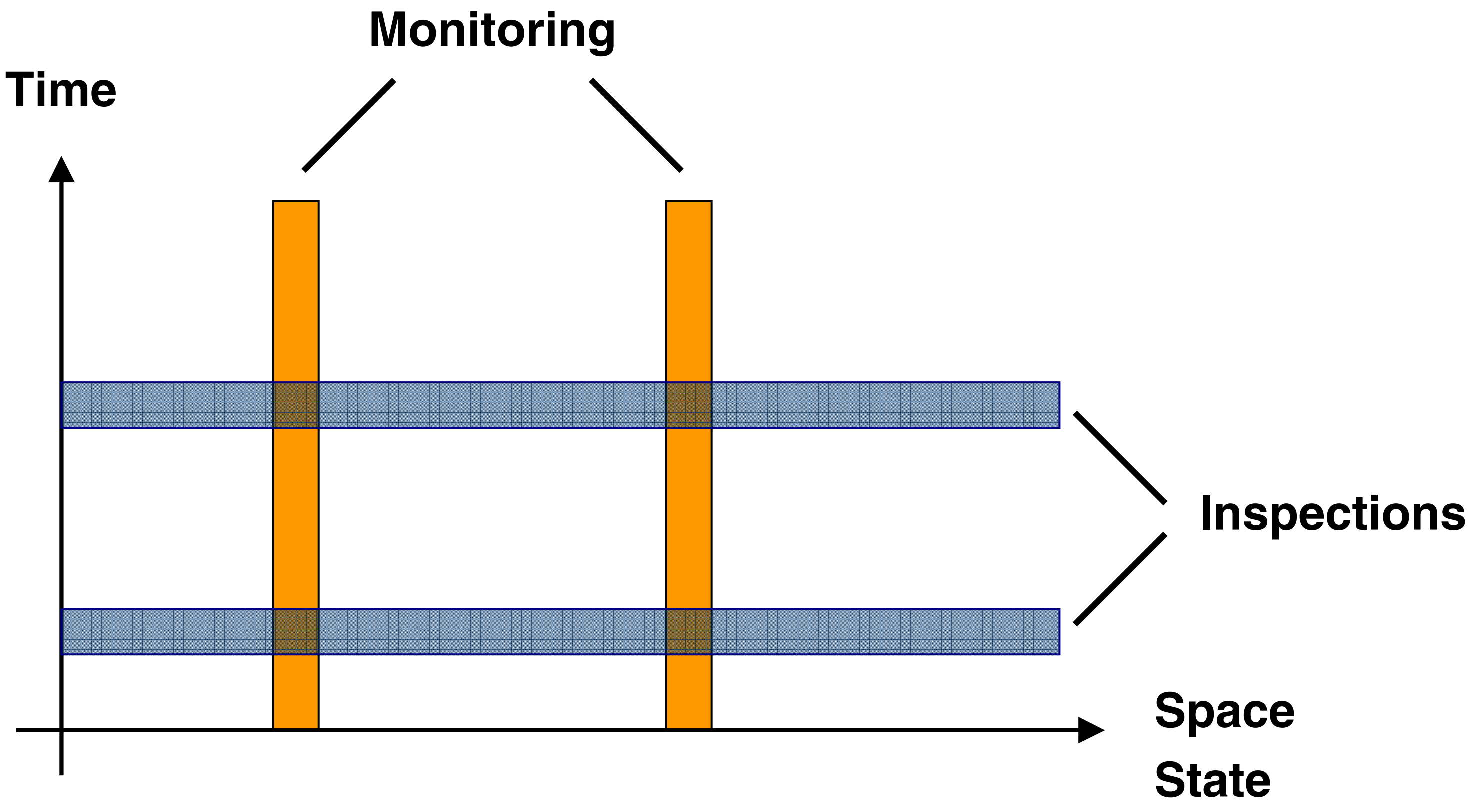
Relevance: Application of the generic approach



Relevance: Combining RBI with monitoring

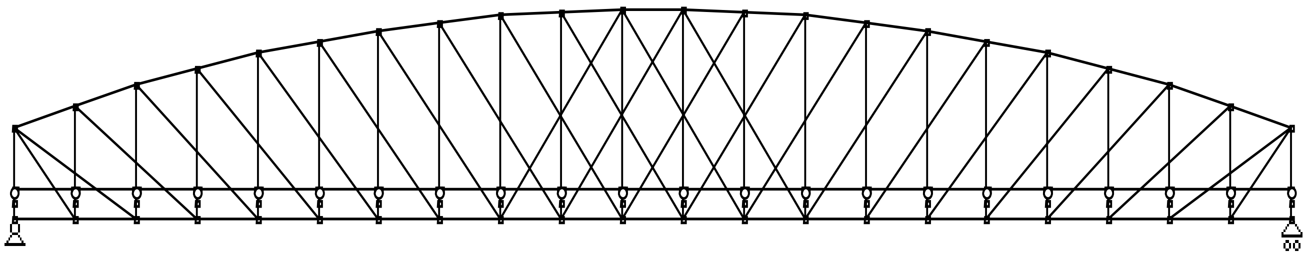
- Generic RBI allows to update the inspection planning with monitoring outcomes

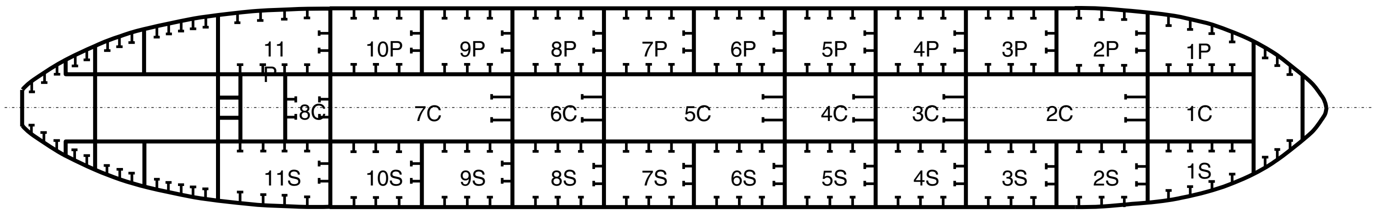


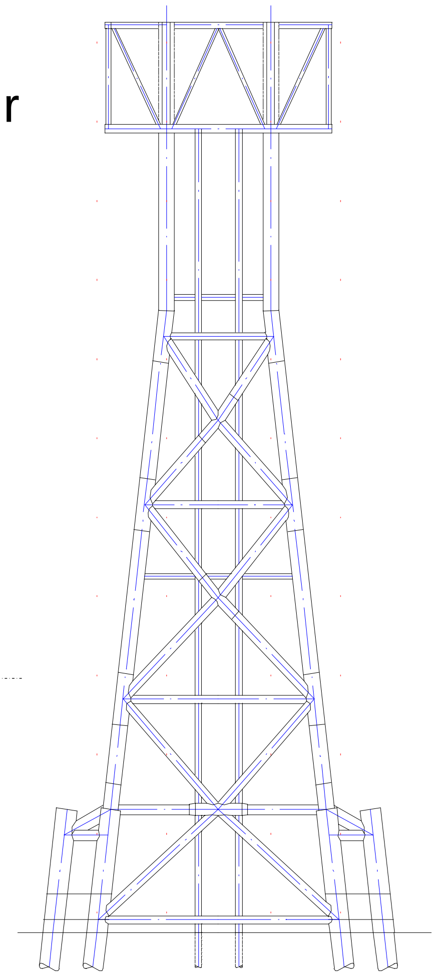
Relevance: Application of the generic approach to structural systems

- The computational efficiency of the generic approach allows to consider entire strucutural systems:

- *Systems*: The individual hot spots (details) and their functional and stochastic inter-dependancies







RBI for systems based on the generic approach

- How to quantify the value of an inspection of a dependent hot spot?

  - The change of the reliability after the inspection is described by a new FDF

RBI for systems based on the generic approach

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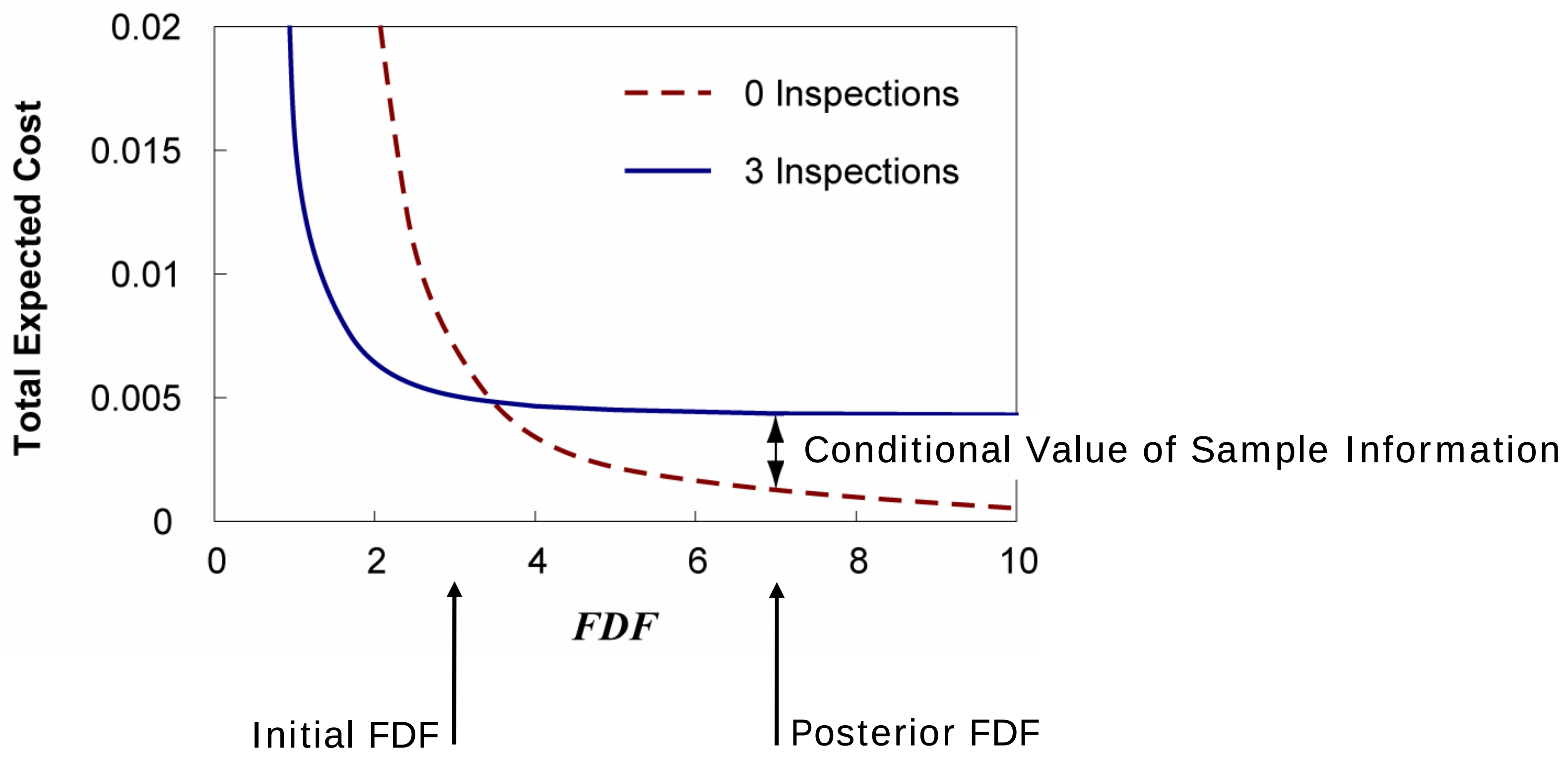


RBI for systems based on the generic approach

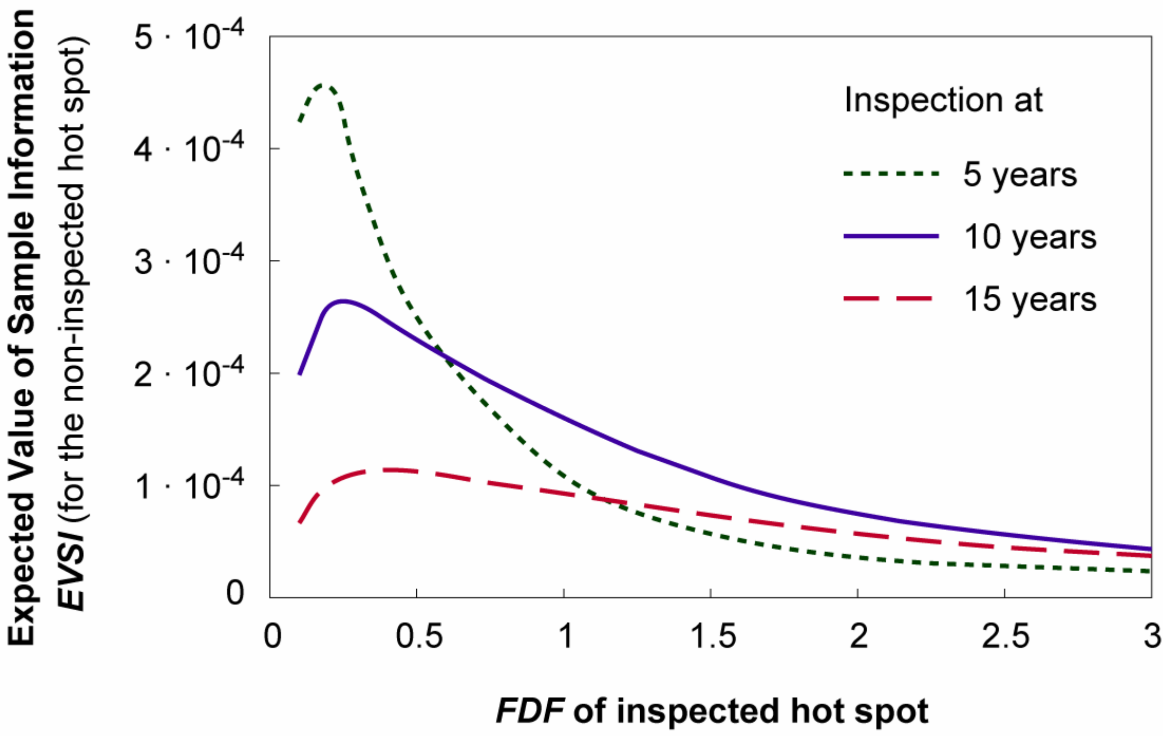
- The outcome of the inspections is unknown (the posterior FDF of the non-inspected element is unknown)

- The Expected Value of Sample Information can be calculated by integration of the Conditional Value of Sample Information:

$$EVSI = \int_{Z} f_Z(z) \cdot CVSI(z) \cdot dz$$

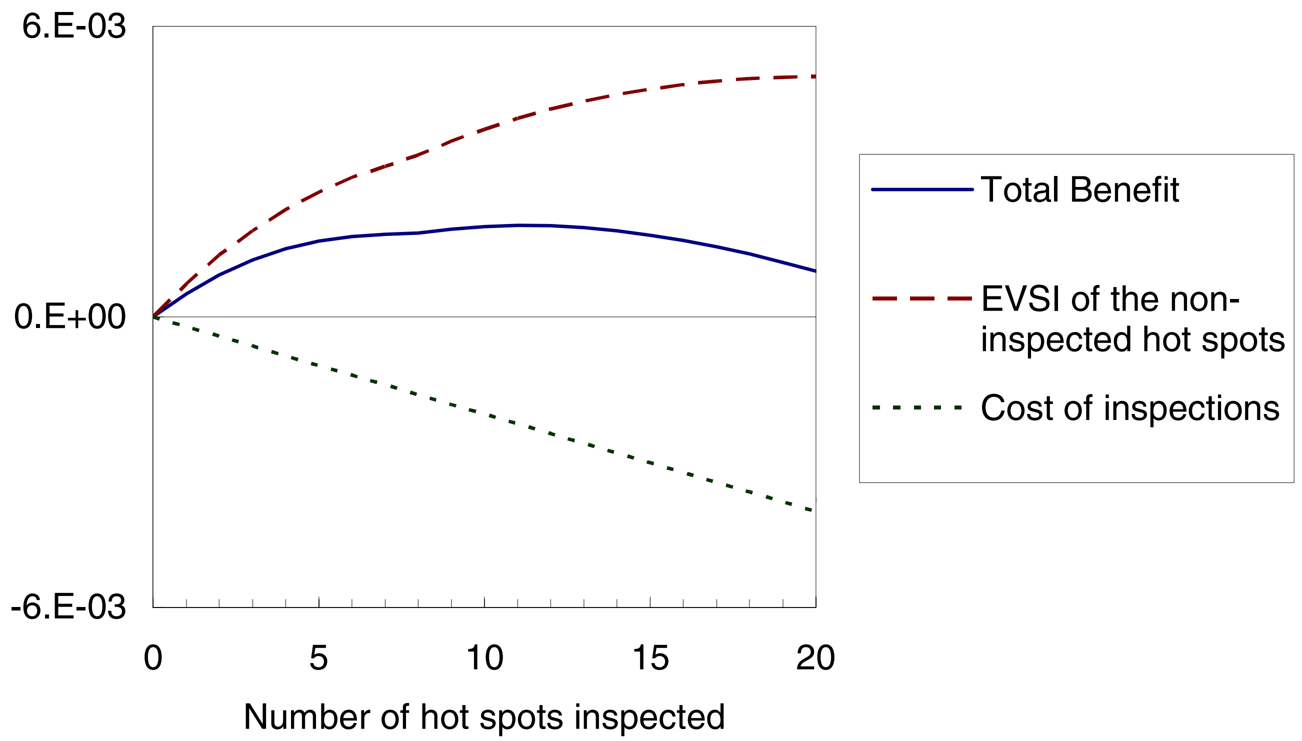
RBI for systems based on the generic approach

- Benefit of a hot spot with FDF = 2 from inspection of a dependent hot spot



RBI for systems based on the generic approach

- Inspection strategies for systems with high reliability of the individual elements



Conclusions

- Applying MCS for Risk Based Inspection planning is efficient with respect to the required man-days

- The generic approach ensures that the RBI can be efficiently included in the daily asset integrity management procedures of the owner and operators of structures

- The generic approach facilitates the consistent planning of inspections for entire structural systems