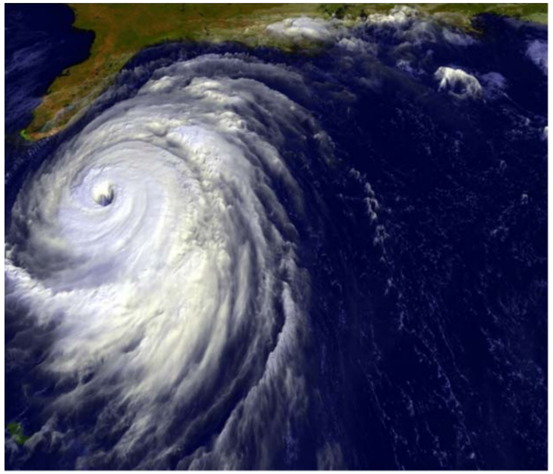
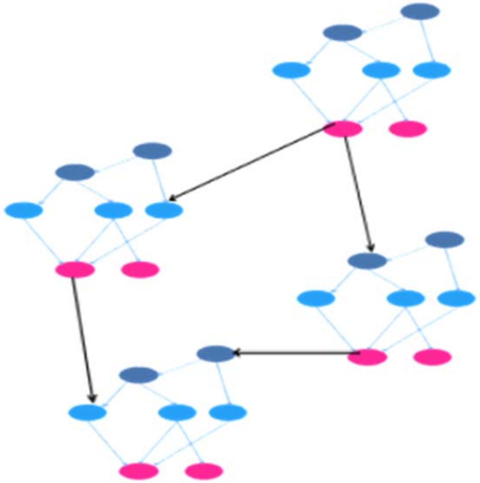
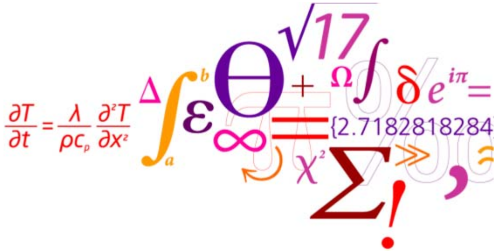


BAM, November 29, 2012

Kolloquium der Abteilung 7 “Bauwerkssicherheit”



On the Value of Structural Health Monitoring



M. H. Faber

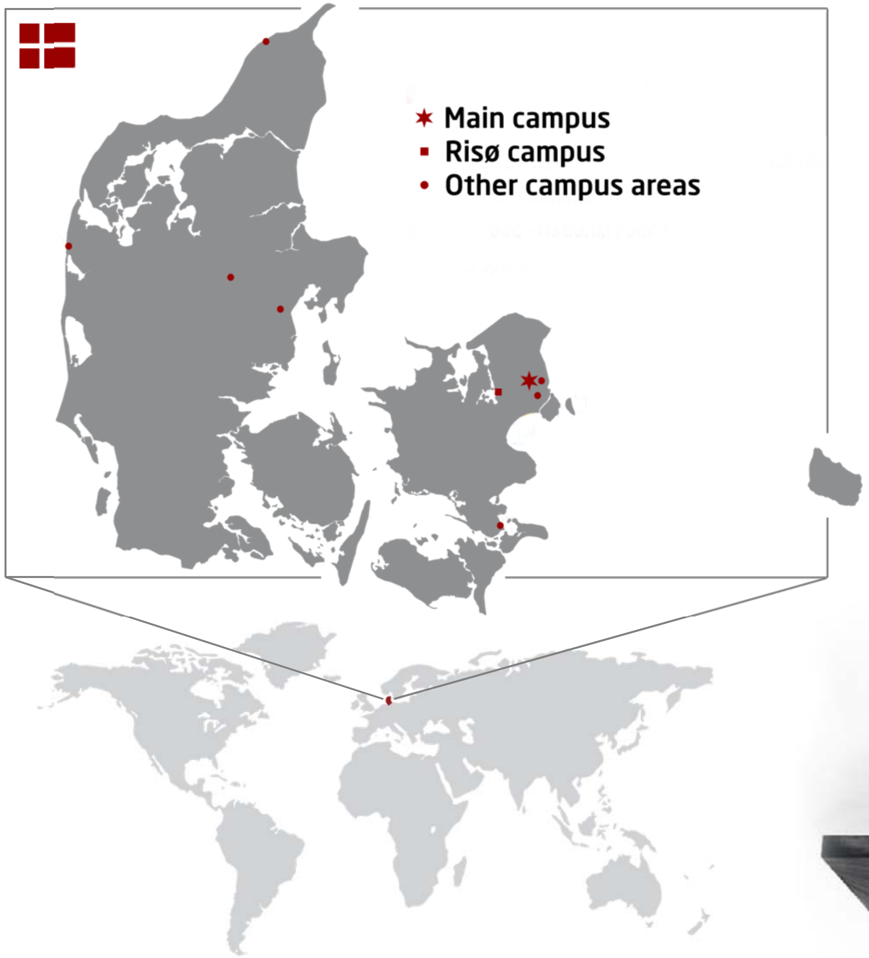
Professor, Chair of Risk and Safety
Head of DTU Civil Engineering
Technical University of Denmark

Contents of Presentation

- A little about DTU
- Short outline of research interests
- The context of engineering decision making
- Structural Health Monitoring
- Example – SHM for Steel Offshore Structures
- Conclusions and Outlook

Technical University of Denmark

(founded 1829; first rector H.C. Ørsted)



Key figures

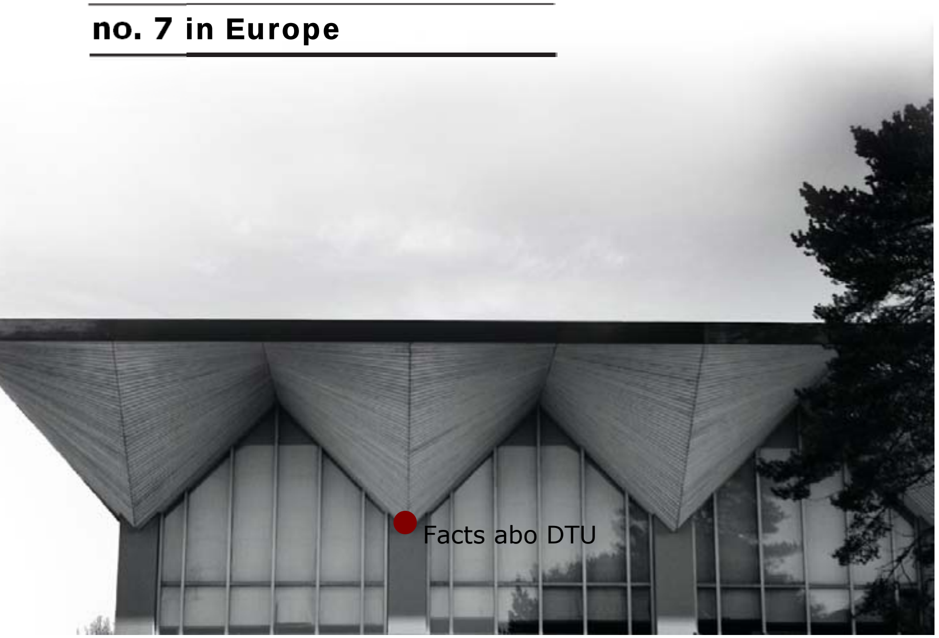
Total students	~8,500
including PhDs	1,100
and international MSc	650
Research publications	3,200

Ranking

Leiden *Crown Indicator* 2010:

no. 1 in Scandinavia

no. 7 in Europe



About DTU Civil Engineering

DTU Civil Engineering conducts research and education within the following areas:

- Building design
- Structural engineering
- Construction materials
- Building physics and services
- Geotechnics
- Indoor environment
- Arctic technology and engineering geology

Staff and finances

DTU Civil Engineering staff

- 86 scientific staff
- 49 technical/administrative staff
- 60 PhD students

Total: 195 employees

DTU Civil Engineering finances

- DKK 130 million

Where do I Come From

Bridges (design basis and reassessment)

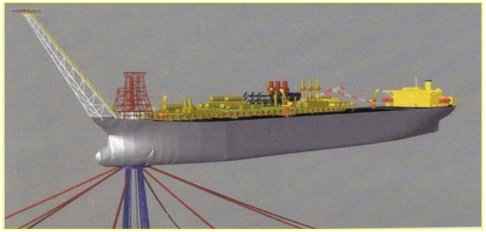
Zarate-Brazo Largo,
Argentina

Lillebaeltsbroen, DK

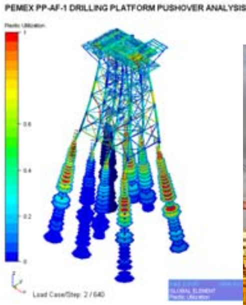
Great belt, DK

Where do I Come From

Offshore (design basis, reassessment, insp. & maint)



FPSO‘s

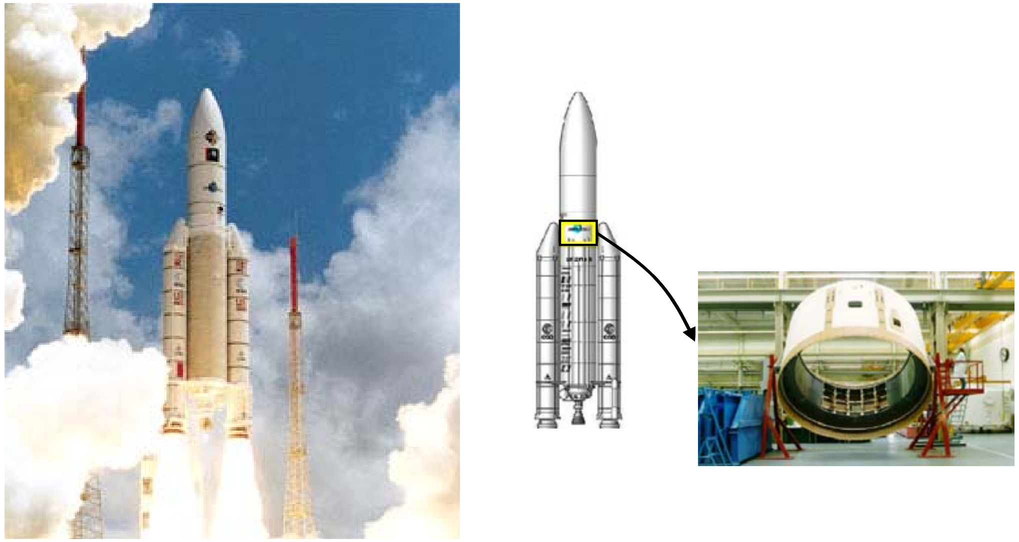


Steel jacket‘s

Process facilities

Where do I Come From

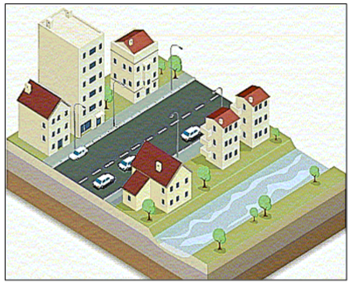
Aeronautics (design)



Front skirt, Ariane 5

Where do I Come From

Earthquake - Large scale risk management

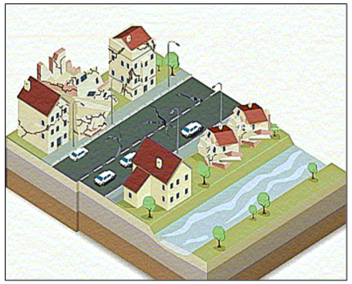


Before

Optimal allocation of available resources for risk reduction

- retrofitting
- rebuilding

in regard to possible earthquakes



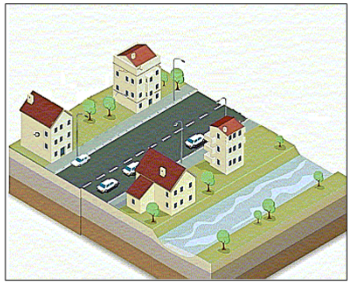
During

Damage monitoring/control

Emergency help and rescue

Aftershock hazard assessment

Identification of the seismic event



After

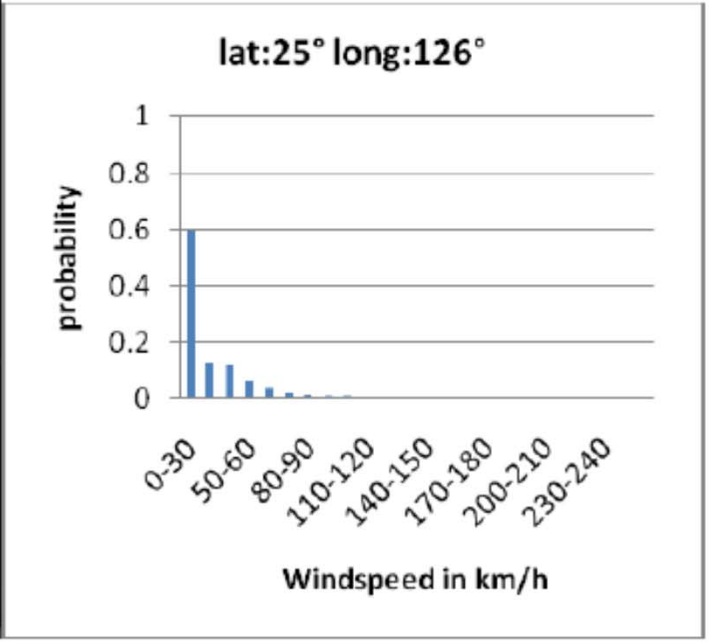
Rehabilitation of infrastructure functionality

Condition assessment and updating

Optimal allocation of resources for retrofitting and rebuilding

Where do I Come From

Typhoon - Large scale risk management



Where do I Come From

Present research

- Design basis
- Maintenance planning
- Risk management
- Robustness of structures
- Natural hazards
- Portfolio loss estimation
- Catastrophic Risks
- Sustainability and life safety investment

The Context of Engineering Decision Making

- **What do engineers do ?**

Hoover Dam - USA

The Context of Engineering Decision Making

- **What do engineers do ?**

Big Dig Boston/USA

The Context of Engineering Decision Making

- **What do engineers do ?**

Hong Kong Island - China

The Context of Engineering Decision Making

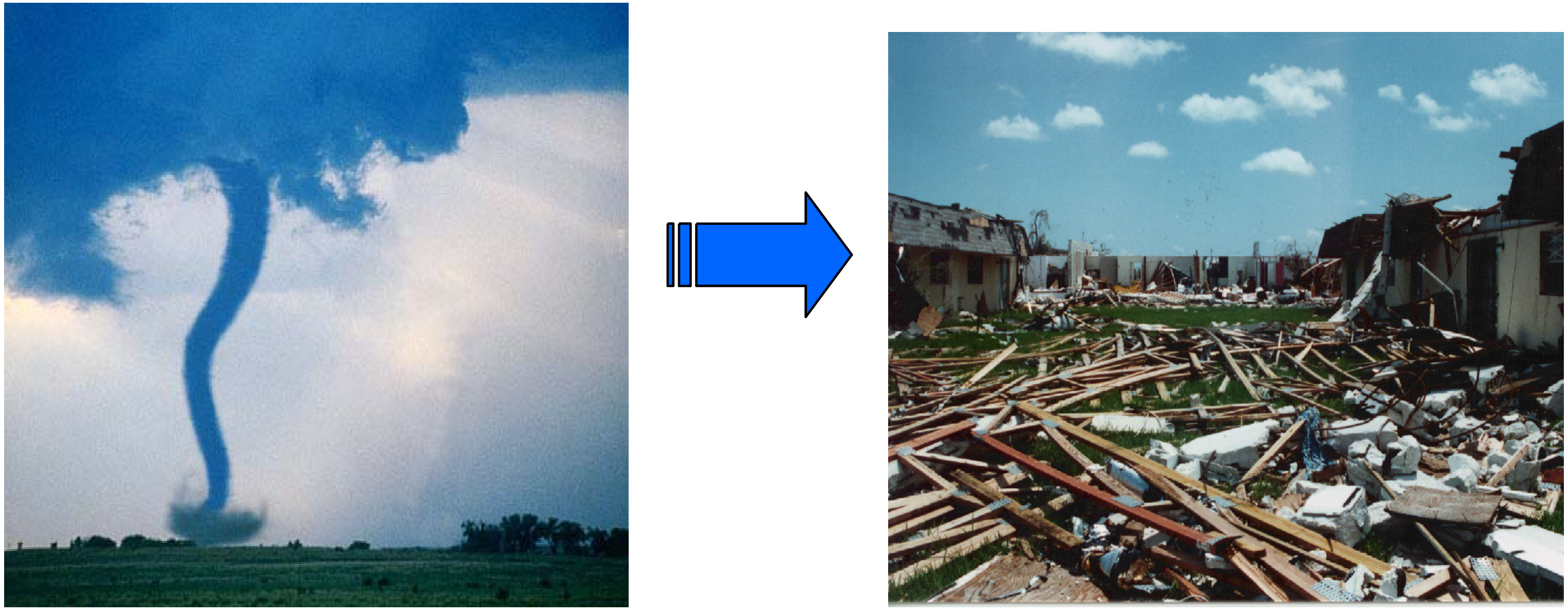
- **What are we up against?**

Corrosion

Fatigue

The Context of Engineering Decision Making

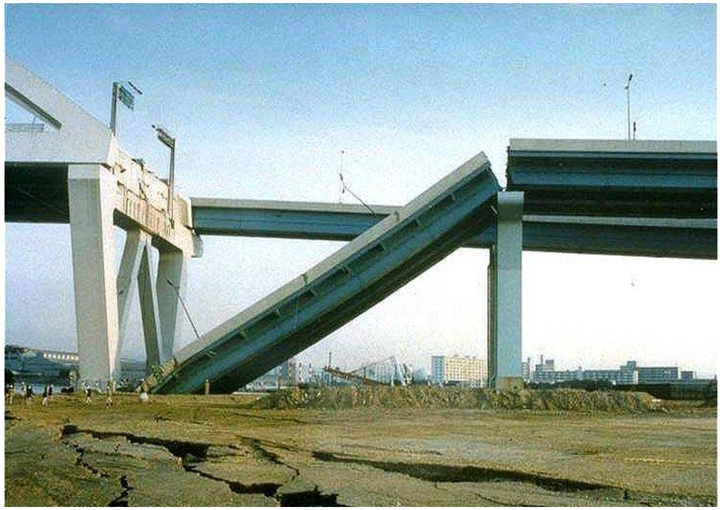
- **What are we up against?**



Tornados and strong winds

The Context of Engineering Decision Making

- **What are we up against?**



Earthquakes

The Context of Engineering Decision Making

- **What are we up against?**

Earth slide

Rock fall

The Context of Engineering Decision Making

- **What are we up against?**

Fires

Explosions

The Context of Engineering Decision Making

- **What are we up against?**

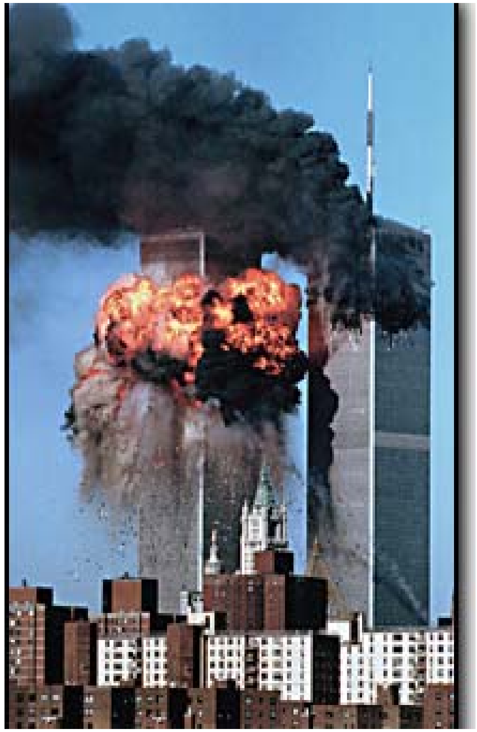
Over load

Design error

The Context of Engineering Decision Making

- **What are we up against?**

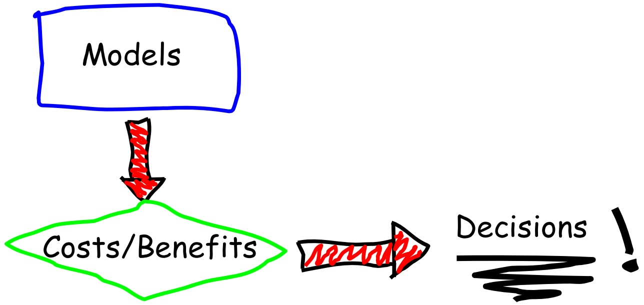
Bombs



Airplane impacts

Structural Health Monitoring

In a perfectly known world



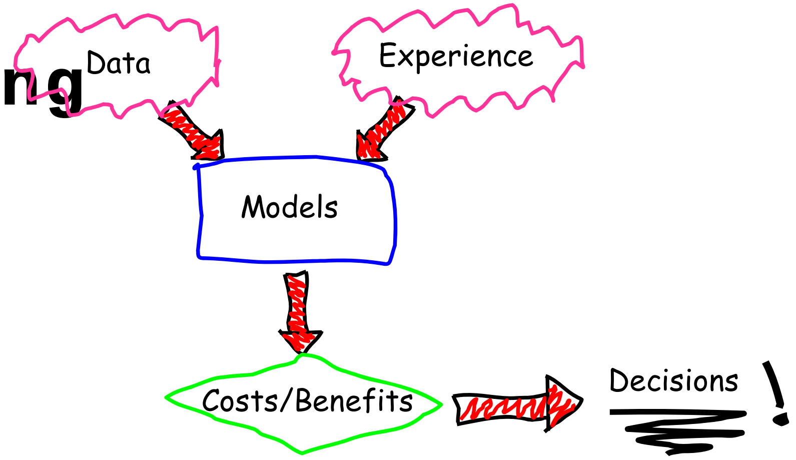
If we

- know exactly what we want
- fully understand our decision options
- have all the skills to carry them out
- have complete information about their effects

Decision making is a matter of weighing

benefits and costs

Structural Health Monitoring



But …. we don't

- know exactly what we want

- fully understand our decision options

- have all the skills to carry them out

- have complete information about their effects

Therefore - decision making is a matter of weighing

knowledge and uncertainty

Structural Health Monitoring

Different types of uncertainties influence decision making

- Inherent natural variability – aleatory uncertainty
  - result of throwing dices
  - variations in material properties
  - variations of wind loads
  - variations in rain fall

- Model uncertainty – epistemic uncertainty
  - lack of knowledge (future developments)
  - inadequate/imprecise models (simplistic physical modelling)

- Statistical uncertainties – epistemic uncertainty
  - sparse information/small number of data

Structural Health Monitoring

Risk is a characteristic of an activity relating to all possible events n_E which may follow as a result of the activity

The risk contribution R_{E_i} from the event E_i is defined through the product between

the Event probability P_{E_i}

and the Consequences of the event C_{E_i}

The risk associated with a given activity A, i.e. R_A is

$$R_A = \sum_{i=1}^{n_E} R_{E_i} = \sum_{i=1}^{n_E} P_{E_i} \cdot C_{E_i}$$

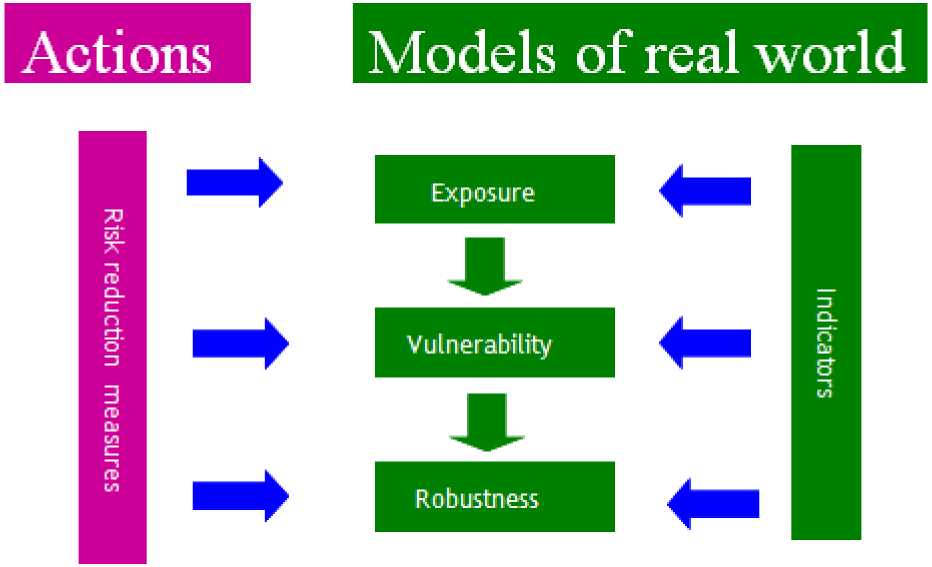
Structural Health Monitoring

Structural health monitoring has the potential to provide value as a means of reducing costs or/and saving human lives:

- Prototype development
- Code making and code calibration for the design and assessment of structures
- In devising warning measures to allow for loss reduction in situations where structures, or systems involving structures, due to accumulated damage or extreme load events perform unreliably
- For the optimization of maintenance strategies

Structural Health Monitoring

Structural health monitoring has the potential to provide value as a means of reducing costs or / and saving human lives:



Actions

Models of real world

Real World

Risk reduction measures

Exposure

Vulnerability

Robustness

Indicators

Structural Health Monitoring

Prototype development

Health monitoring of new structural concepts intended for larger productions, facilitates concept optimization with respect to life-cycle benefit, before the initiation of a series production.

By instrumentation and subsequent monitoring and analysis of monitoring results it is possible to gather knowledge on important (model) uncertainties associated with the response and performance of the prototype.

Such information may be utilized for the purpose of optimizing design decisions which in turn can be related to the service life benefit.

Structural Health Monitoring

Code making and code calibration for the design and assessment of structures

Systematic and strategically undertaken monitoring of structures may facilitate that design basis for the considered category/type of structure is modified or adapted in accordance with the information collected.

The monitoring could e.g. focus on information concerning the model uncertainties associated with codified design equations, reflecting uncertainty in the relevant load-response transfer functions.

The value of monitoring in this application would be realized through the improved design rationale facilitating that material and costs are minimized and risk, safety and reliability are controlled at adequate acceptable and affordable levels.

Structural Health Monitoring

In devising warning measures to allow for loss reduction in situations where structures, or systems involving structures, due to accumulated damage or extreme load events perform unreliably

Monitoring may adequately facilitate that indications of possible adverse performances or damages of structures in operation can be observed, and utilized as trigger for remediate actions.

The information collected from monitoring could relate to changes in stiffness properties monitored e.g. in terms of dynamic and static responses.

The value of monitoring would relate to the possibility of loss reduction by shutting down the function or reducing the loading of the structure, before human lives, environment and structure are lost and/or damaged further.

Structural Health Monitoring

For the optimization of maintenance strategies

Collection of information concerning the performance of a structure may facilitate improved decision basis for optimizing inspection and maintenance activities.

The monitoring may provide information of relevance for improving the understanding of the performance and response of the structure and this improved understanding may in turn be utilized during the life of the structure to adapt inspection and maintenance activities accordingly.

Structural Health Monitoring

The fundamental logic of SHM is:

- Monitoring may provide information concerning variables which have a significant influence on the service life performance of a structure
- The information can be collected at a cost and with a given precision which depends on the technique and thereby also depends on the costs
- The information collected through monitoring facilitates that adaptive actions are taken to reduce service life costs or increase service life benefits

Structural Health Monitoring

The fundamental logic of SHM is:

- If the collected information is not correct or biased the actions will not be optimal and may even cause basis for adaptive actions which increase the service life costs
- When assessing the benefit or value of different monitoring schemes and corresponding optimal strategies for adaptive actions the only basis for the modeling of the not yet collected information is the a priori available data and models concerning the variables of interest.

The benefit of health monitoring cannot be assessed through one or a few anticipated monitoring results

Structural Health Monitoring

Structural Health Monitoring (SHM) is applied at very large scale

There is no doubt that SHM provides valuable information and supports decisions

But so far very little effort has been devoted on the formal and quantitative assessment of the value of SHM

There is good reason to doubt whether present best practices on SHM are economically efficient or even in some cases relevant

Structural Health Monitoring

Theoretical Framework for Health Monitoring

- The decision theory (Raiffa and Schlaifer) forms the fundamental mathematical framework for assessing the value of information – and thus also the value of Structural Health Monitoring

- A fundamental result of utility theory is (van Neumann and Morgenstern) that:

  Decisions shall be ranked in accordance with the expected value of their associated utility

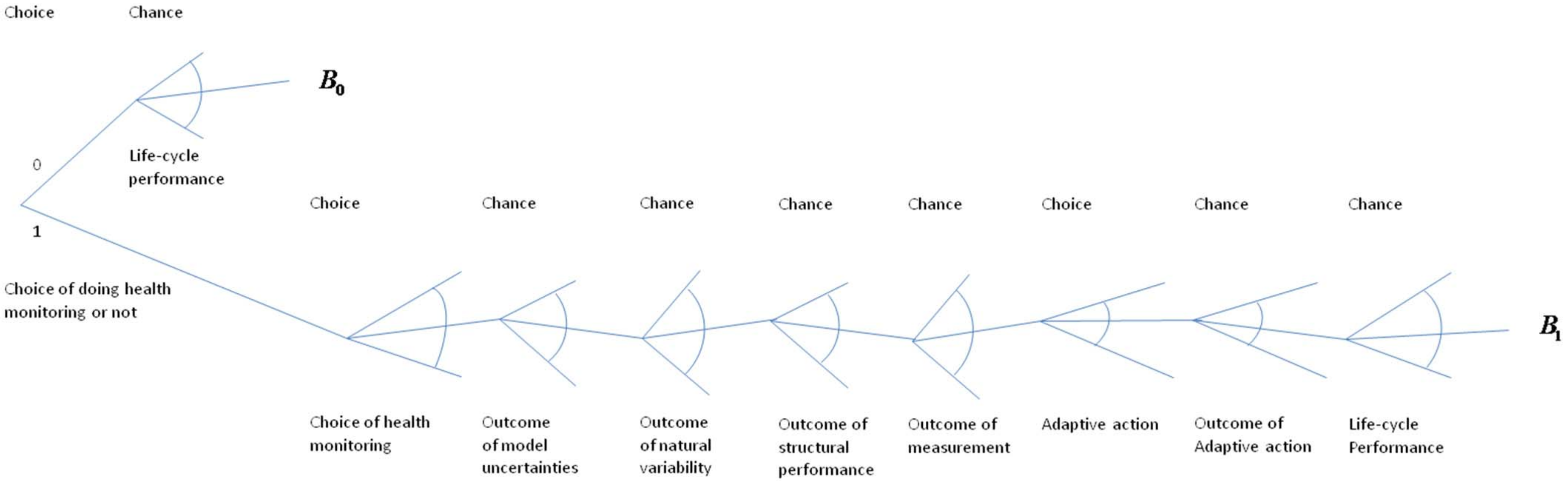
  For our purposes we may associate "the expected value of utility" with *risk*

Structural Health Monitoring

Theoretical Framework for Health Monitoring

The value of health monitoring may be quantified in accordance with the pre-posterior decision theory:

$$V = B_1 - B_0$$



Structural Health Monitoring

Theoretical Framework for Health Monitoring

The value of health monitoring may be quantified in accordance with the pre-posterior decision theory:

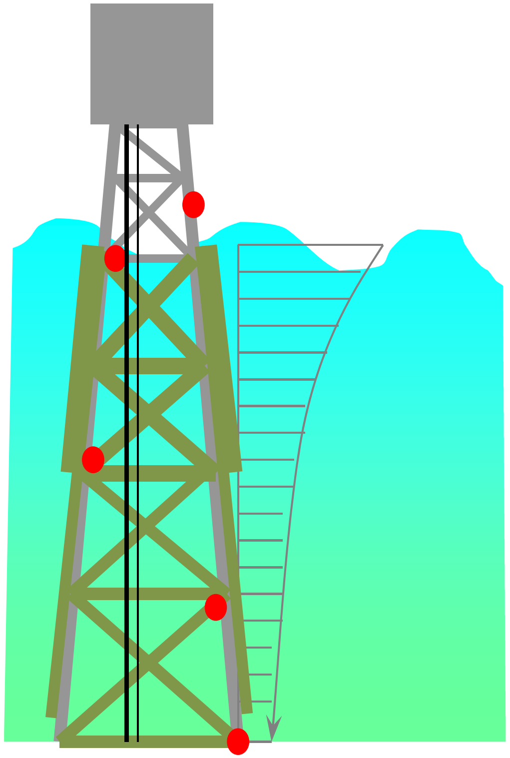
$$V = B_1 - B_0$$

$$V = \max_{s} E_{\mathbf{Z}_E}\left[E_{\mathbf{Z}_A}\left[\max_{\mathbf{a}} E_{\mathbf{X}|\mathbf{Z}_E,\mathbf{Z}_A}\left[B(\mathbf{X}, \mathbf{z}_E, \mathbf{z}_A, s, d(\mathbf{a}, \mathbf{X})) \right] \right] \right] - E_{\mathbf{Z}_E}\left[E_{\mathbf{Z}_A}\left[B(\mathbf{Z}_E, \mathbf{Z}_A) \right] \right]$$

s: Monitoring strategy
$\mathbf{X}$: Random variable representing uncertain monitoring results
$\mathbf{Z}_A$: Random variables representing aleatory uncertainties
$\mathbf{Z}_E$: Random variables representing epistemic uncertainties
$d(\,)$: Decision rule defining the adaptive action

SHM for Steel Offshore Structures

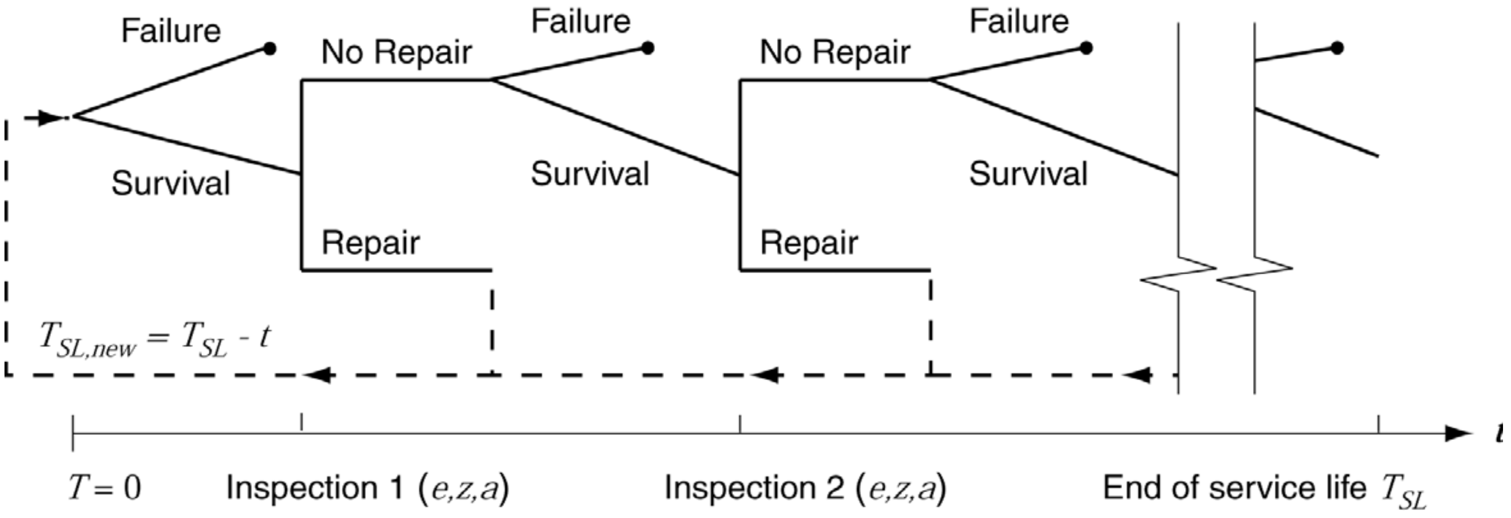
Steel jacket structure subject to fatigue deterioration



SHM for Steel Offshore Structures

Steel jacket structure subject to fatigue deterioration

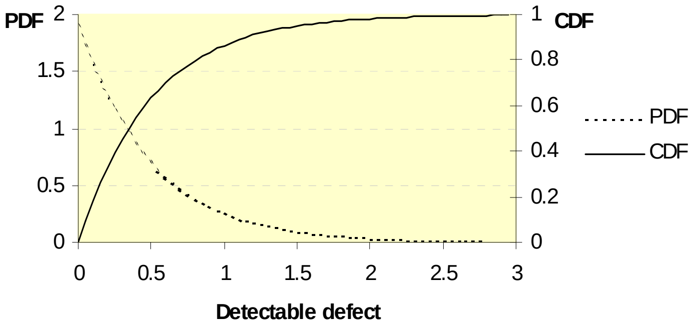
It is assumed that a risk based approach to inspection and maintenance planning is utilized such that the annual probability of fatigue failure does not exceed a given threshold

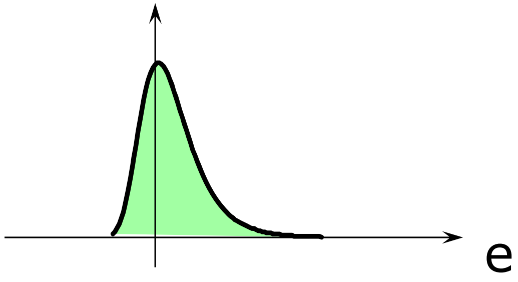


SHM for Steel Offshore Structures

Steel jacket structure subject to fatigue deterioration

Inspections may result in
- detection of defects - which are present
- false detection of defects - even though no defects are present
- no detection - even though defects are present





SHM for Steel Offshore Structures

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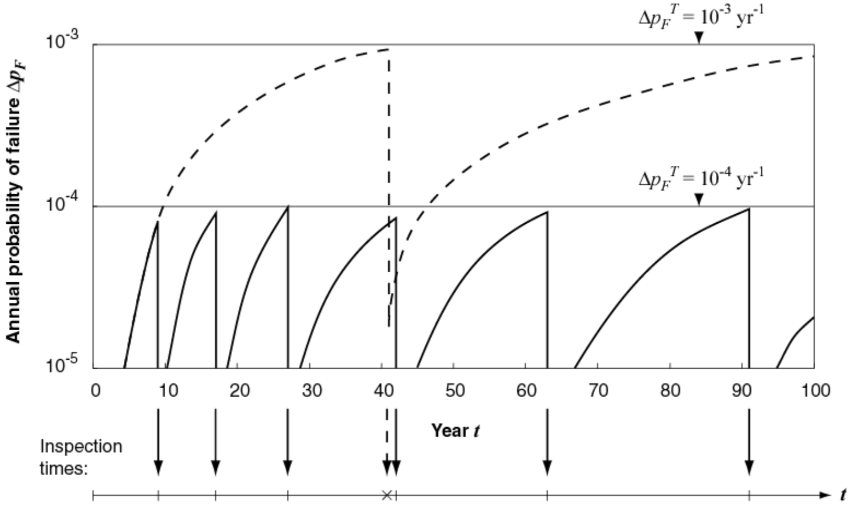
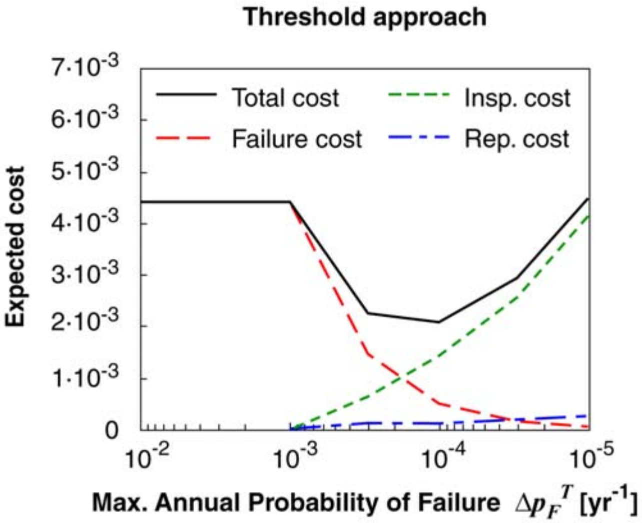




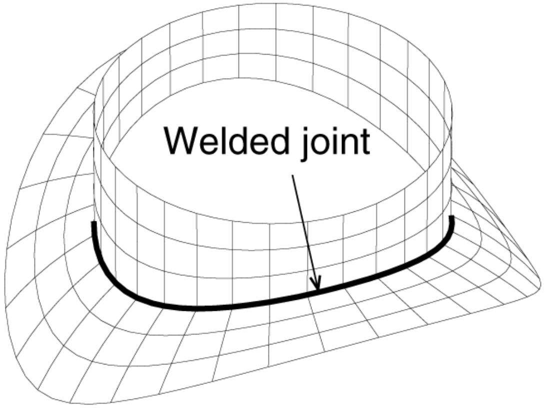
SHM for Steel Offshore Structures

Steel jacket structure subject to fatigue deterioration

The generic inspection planning approach is utilized

Calculate inspection plans for generic representations of structural details defined in terms of generic parameters using iPlan - Straub (2004).

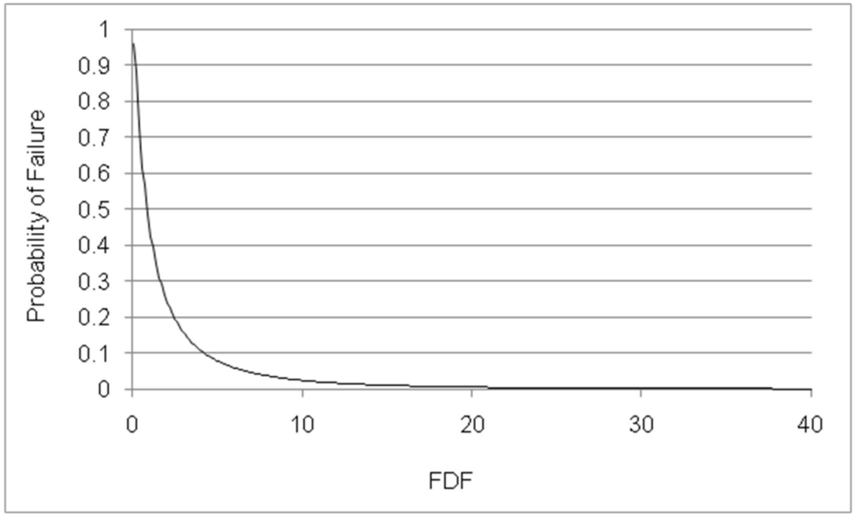
Detail type
Environment
Geometrical properties (thickness)
Loading characteristics
Fatigue Design Factor FDF (Resulting from standard deterministic fatigue evaluations)
Quality of fatigue calculations
Initial quality control

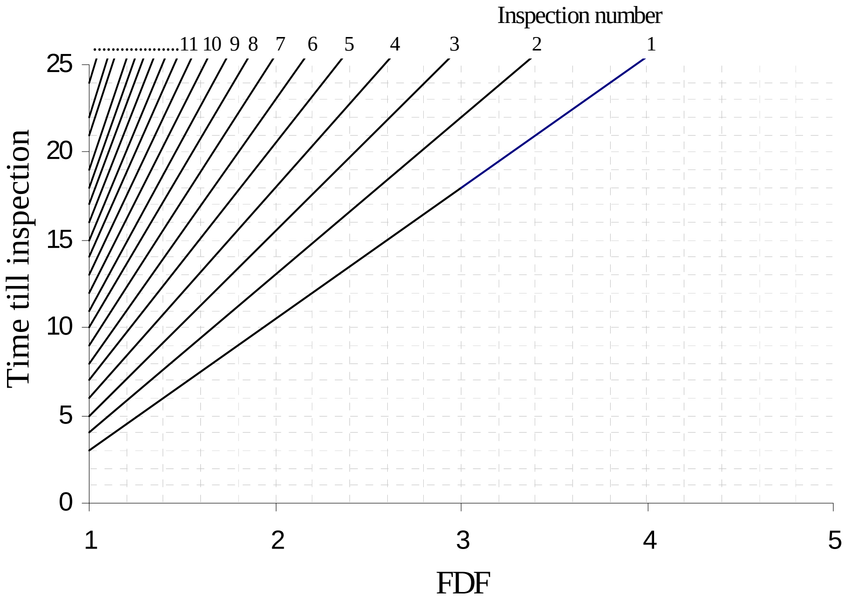


SHM for Steel Offshore Structures

Steel jacket structure subject to fatigue deterioration

The generic inspection planning approach is utilized





$$FDF = \frac{L_D}{L_S}$$

SHM for Steel Offshore Structures

Steel jacket structure subject to fatigue deterioration

Structural health monitoring is investigated for the purpose of better understanding the actual fatigue stress process

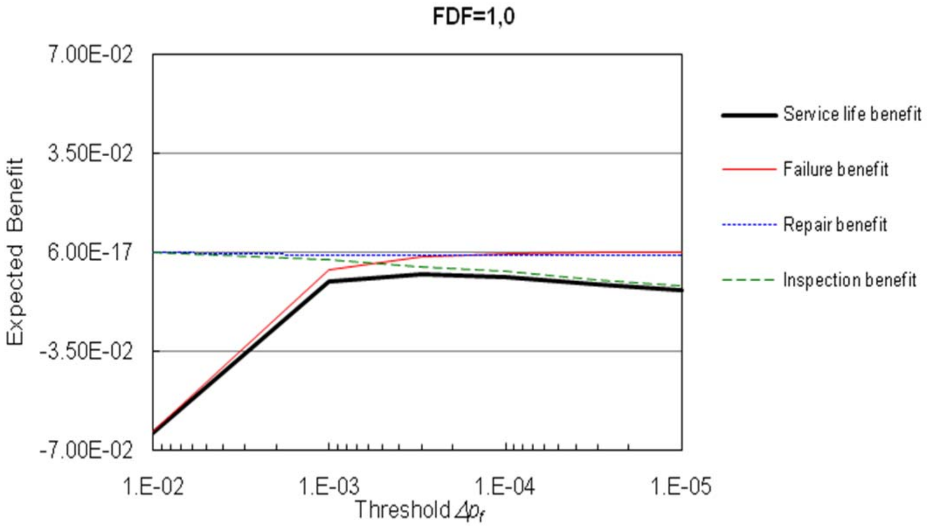
$$E\left[\Delta\sigma^{m}\right]=(M_{\sigma}k)^{m}\Gamma\left(1+\frac{m}{\lambda};\left(\frac{s_{0}}{k}\right)^{\lambda}\right)$$

M_σ: Model uncertainty – realization assumed to be determined by monitoring – strain gauges
k, λ: Parameters of the Weibull distributed long term stress ranges
m, S_0: SN curve parameters

SHM for Steel Offshore Structures

Steel jacket structure subject to fatigue deterioration

The expected benefit is calculated for the option of
not performing monitoring as function of the threshold



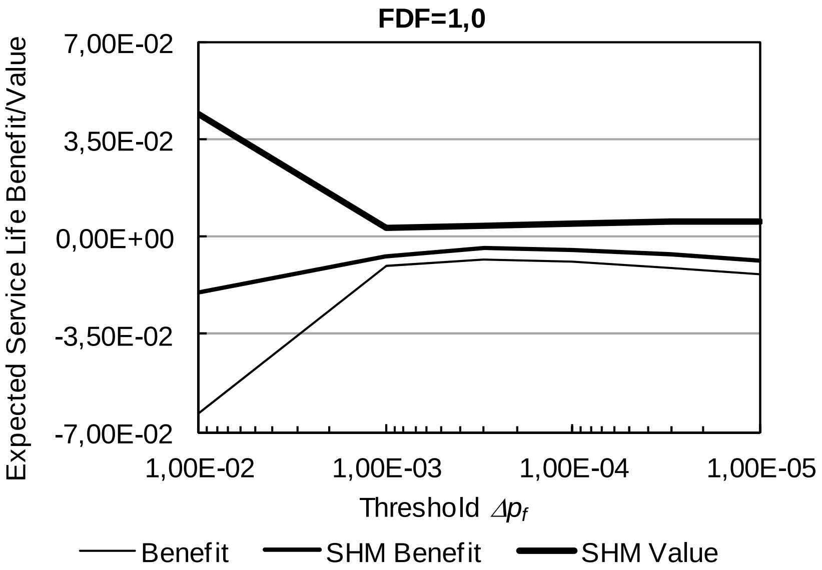
Failure costs = 1,0
Inspection costs = 0,001
Repair costs = 0,01.

Thöns

SHM for Steel Offshore Structures

Steel jacket structure subject to fatigue deterioration

The expected benefit is calculated for the option of **performing** monitoring as function of the threshold

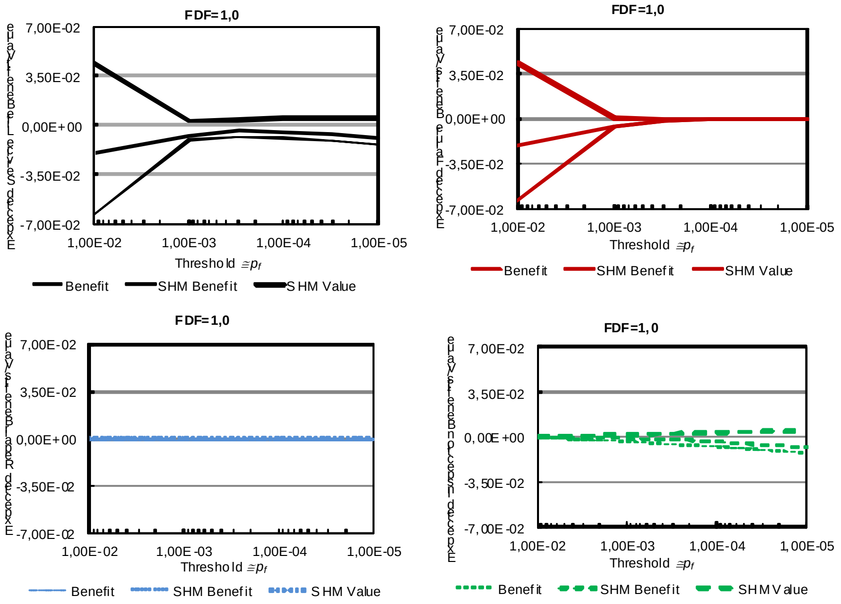


Thöns

SHM for Steel Offshore Structures

Steel jacket structure subject to fatigue deterioration

The expected benefit is calculated for the option of **performing** monitoring as function of the threshold



Thöns

Conclusions and Outlook

The value of Structural Health Monitoring can be quantified in consistency with the available knowledge (uncertainty)

The uncertainties which must be accounted for concern the epistemic and aleatory uncertainties associated with the structural performance and

The uncertainty associated with the accuracy of the SHE technique

The valuation of SHM facilitates an assessment of whether it is efficient to undertake SHE

Conclusions and Outlook

More work should be undertaken to quantify the value of SHM for different cases

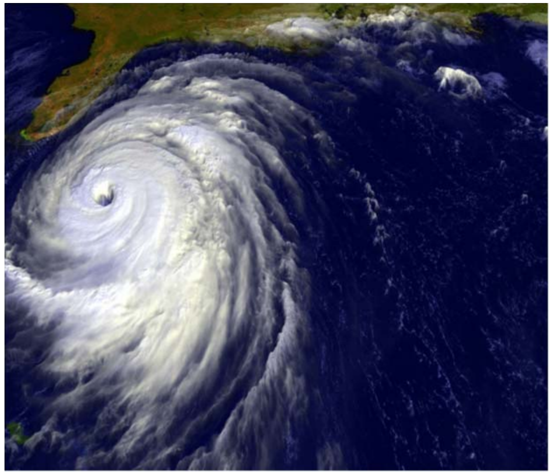
- different types of structures
- different types of decision situations
- different techniques of SHM

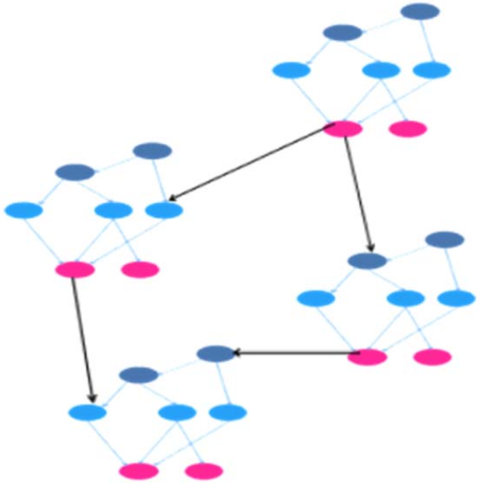
To undertake such a quantification necessitates a coordinated collaborative project

This could be a topic of future collaboration between DTU and BAM

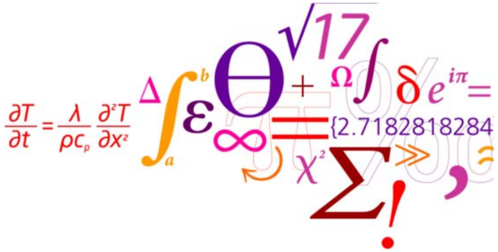
BAM, November 29, 2012

Kolloquium der Abteilung 7 “Bauwerkssicherheit”





On the Value of Structural Health Monitoring



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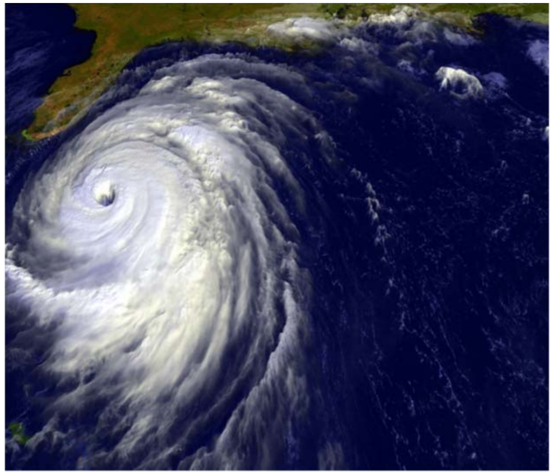
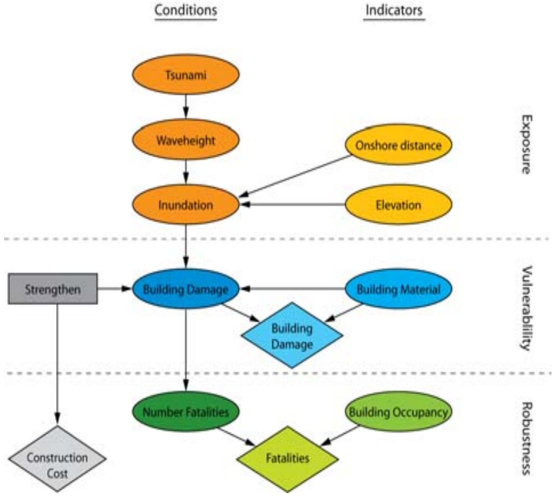
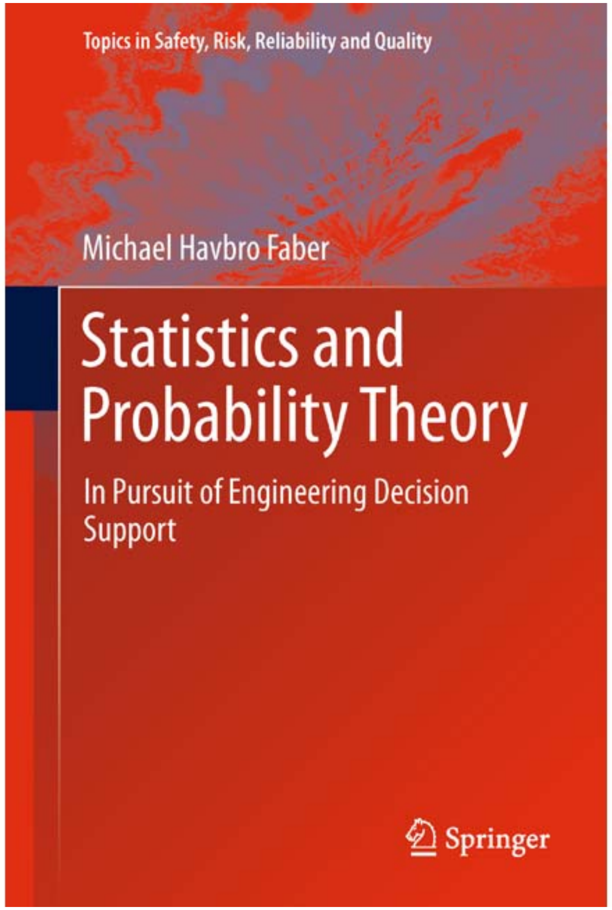






Topics in Safety, Risk, Reliability and Quality

Michael Havbro Faber

Statistics and Probability Theory

In Pursuit of Engineering Decision Support

Springer

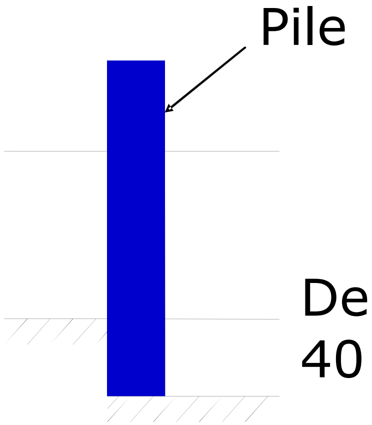
Decision Analysis in Engineering

Introduction to Decision Theory

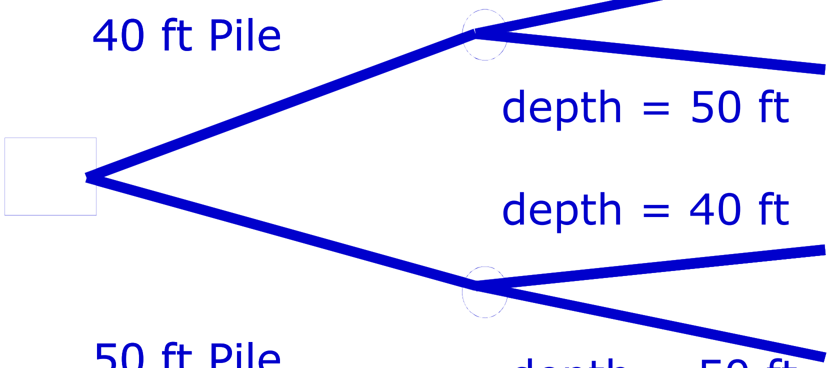
- The decision tree
- Prior decision analysis
- Posterior decision analysis
- Pre-posterior decision analysis

Decision Analysis in Engineering

The decision tree



Depth of rock bed
40 ft or 50 ft ?



Action alternatives	Outcome	Consequence	Utility(consequence)
40 ft Pile	depth = 40 ft	none	0
	depth = 50 ft	splice	400
50 ft Pile	depth = 40 ft	cutting	100
	depth = 50 ft	none	0

Decision Analysis in Engineering

The different types of decision analysis

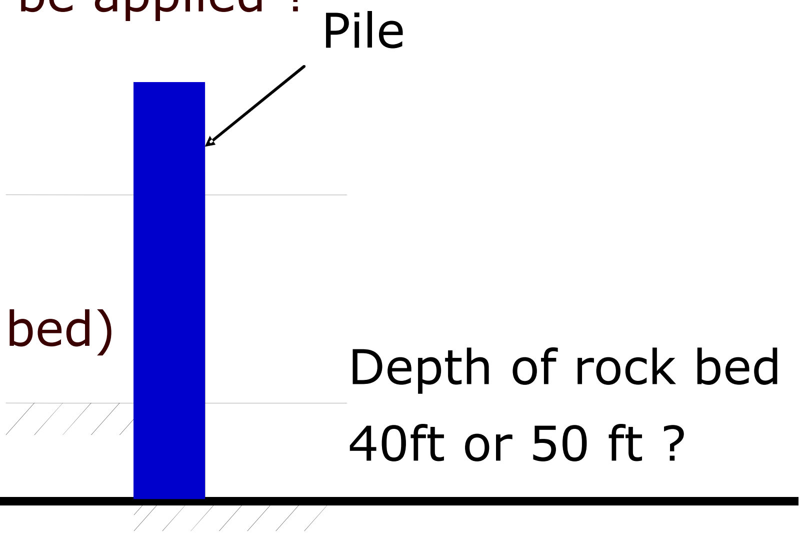
- Prior
- Posterior
- Pre-posterior

Illustrated on an example :

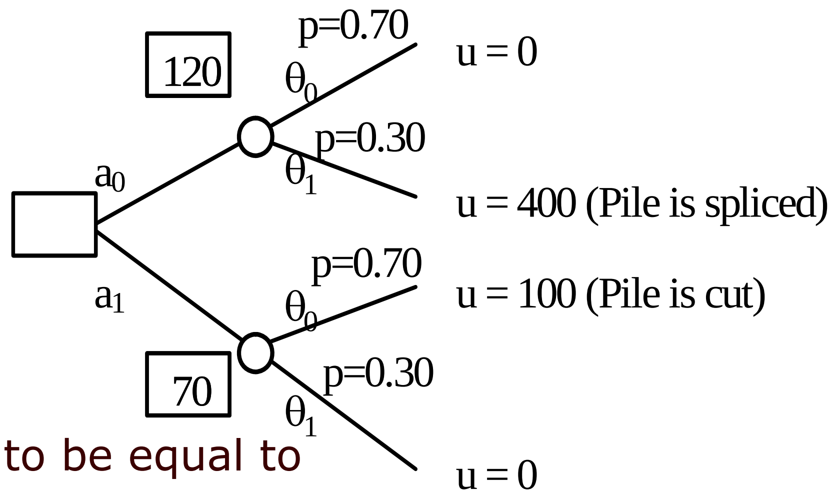
Question : What pile length should be applied ?

Alternatives :
a_0 : Choose a 40 ft pile
a_1 : Choose a 50 ft pile

States of nature (depth to rock bed)
θ_0 : Rock bed at 40 ft
θ_1 : Rock bed at 50 ft



Decision Analysis in Engineering



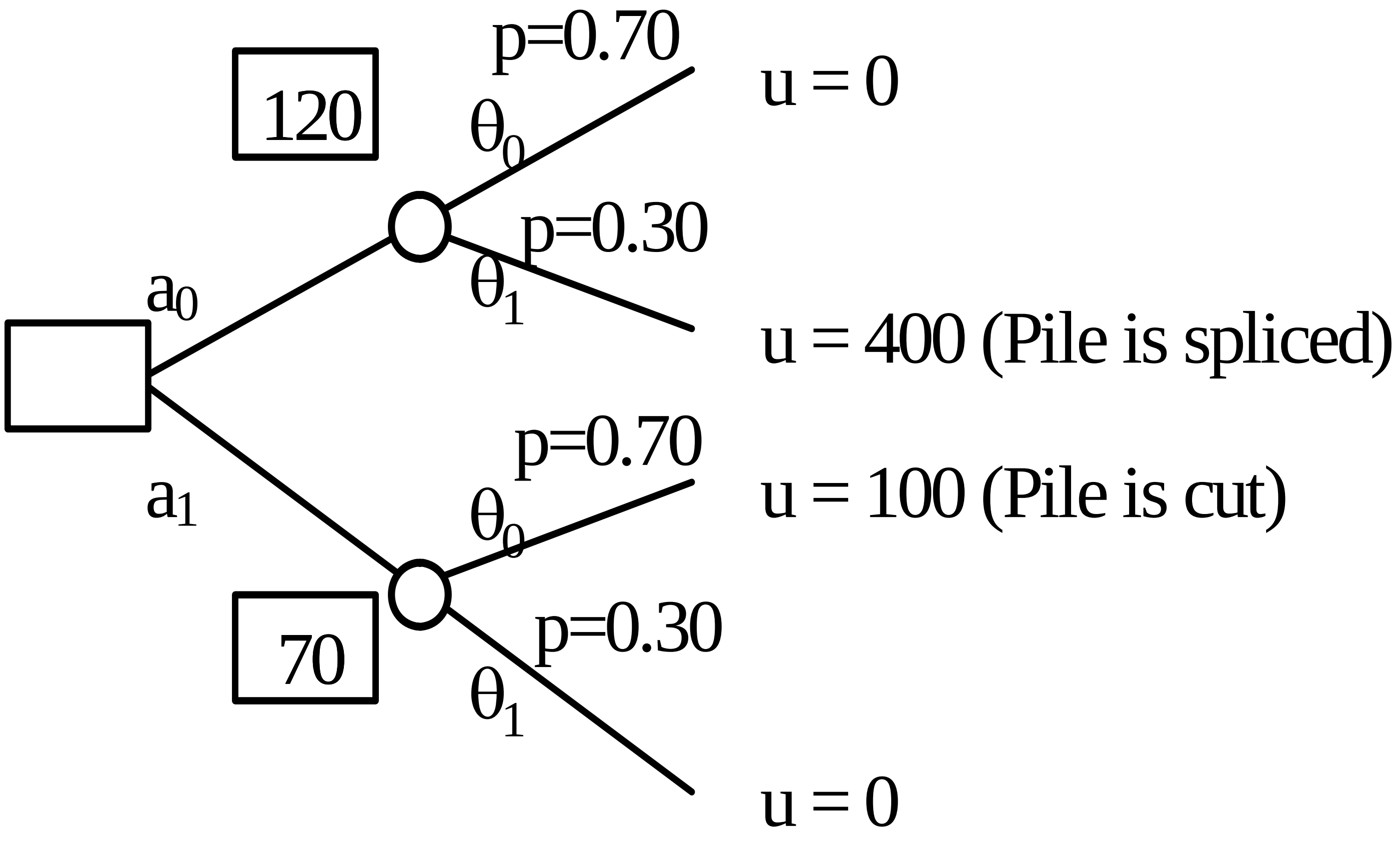
Prior Analysis

$P'[\theta_0] = 0.70$
$P'[\theta_1\ ] = 0.30$

The expected utility is calculated to be equal to

$$
\begin{aligned}
E'[u] &= \min\{u[a_0]\ , u[a_1]\} \\
&= \min\{P'[\theta_0]\times u[\theta_0|a_0] + P'[\theta_1]\times u[\theta_1|a_0]\ , \\
&\qquad P'[\theta_0]\times u[\theta_0|a_1] + P'[\theta_1]\times u[\theta_1|a_1]\} \\
&= \quad \min\{0.7\times 0 + 0.3\times 400,\ 0.7\times 100 + 0.3\times 0\} \\
&= \quad \min\{120, 70\} = 70 \quad \Rightarrow \text{ Decision for } \mathrm{a}_1 \text{ (50ft Pile)}
\end{aligned}
$$

Decision Analysis in Engineering



$\Longrightarrow$ Choice of pile a_1 (50ft Pile)

Decision Analysis in Engineering

Posterior Analysis

$$P''(\theta_i) = \frac{P\left[z_k \middle| \theta_i\right] P'\left[\theta_i\right]}{\sum_j P\left[z_k \middle| \theta_j\right] P'\left[\theta_j\right]}$$

Decision Analysis in Engineering

Posterior Analysis

$$P''(\theta_i) = \frac{P\left[z_k \middle| \theta_i\right] P'\left[\theta_i\right]}{\sum_j P\left[z_k \middle| \theta_j\right] P'\left[\theta_j\right]}$$

Ultrasonic tests to determine the depth to bed rock

True state / Test result	θ_0 40 ft – depth	θ_1 50 ft – depth
z_0 - 40 ft indicated	0.6	0.1
z_1 - 50 ft indicated	0.1	0.7
z_2 - 45 ft indicated	0.3	0.2

Likelihoods of the different indications/test results given the various possible states of nature – ultrasonic test methods $P\left[z_k \middle| \theta_j\right]$

Decision Analysis in Engineering

Posterior Analysis

$$P''(\theta_i) = \frac{P\left[z_k \middle| \theta_i\right] P'\left[\theta_i\right]}{\sum_j P\left[z_k \middle| \theta_j\right] P'\left[\theta_j\right]}$$

It is assumed that a test gives a 45 ft indication

$$P''[\theta_0] = P[\theta_0 | z_2] \propto P[z_2 | \theta_0] P[\theta_0] = 0.3\ x\ 0.7 = 0.21$$

$$P''[\theta_1] = P[\theta_1 | z_2] \propto P[z_2 | \theta_1] P[\theta_1] = 0.2\ x\ 0.3 = 0.06$$

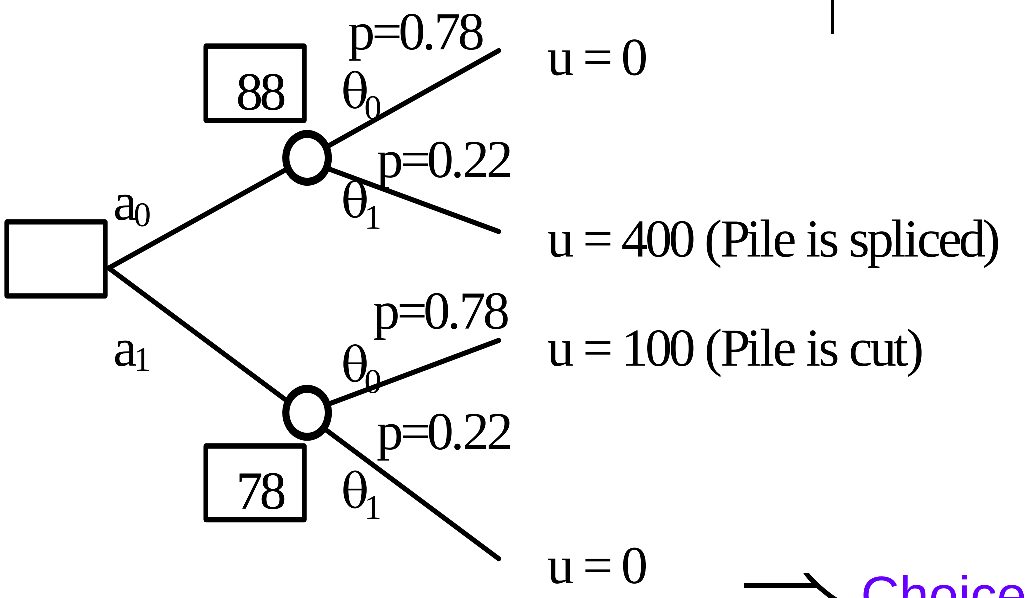
$$P''\left[\theta_0 \middle| z_2\right] = \frac{0.21}{0.21 + 0.06} \quad = \quad 0.78$$

$$P''\left[\theta_1 \middle| z_2\right] = \frac{0.06}{0.21 + 0.06} \quad = \quad 0.22$$

Decision Analysis in Engineering

Posterior Analysis

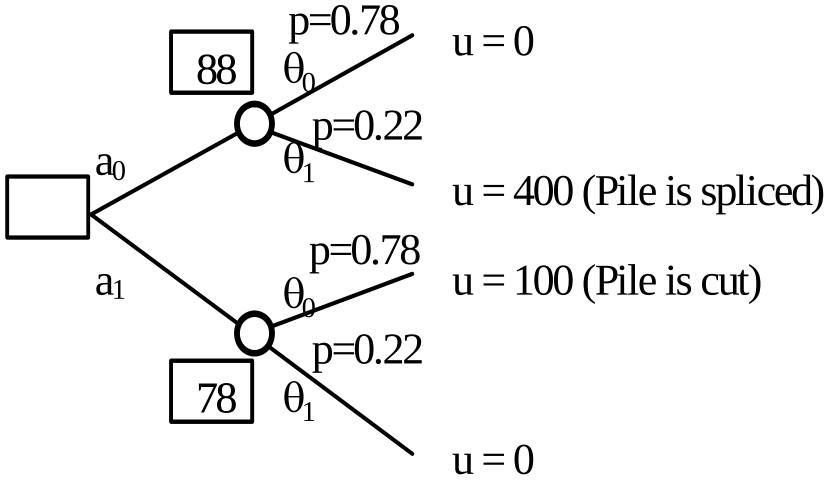
Test result indicates 45ft to rock bed



$\Rightarrow$ Choice of alternative a_1 (50ft Pile)

Decision Analysis in Engineering

Posterior Analysis



$$E''\left[u \middle| z_2\right] = \min_j\{E''\left[u(a_j) \middle| z_2\right]\}$$

$$= \min\{P''[\theta_0]\times 0 + P''[\theta_1]\times 400,\ P''[\theta_0]\times 100 + P''[\theta_1]\times 0\}$$

$$= \min\{0.78\times 0 + 0.22\times 400,\ 0.78\times 100 + 0.22\times 0\}$$

$$= \min\{88\ ,\ 78\} = 78$$

$\Longrightarrow$ Choice of alternative a_1 (50ft Pile)

Decision Analysis in Engineering

Pre-posterior Analysis

$$E[u]=\sum_{i=1}^{n}P'[z_i]\times E''[u|z_i]=\sum_{i=1}^{n}P'[z_i]\times\min_{j=1,m}\{E''[u(a_j)|z_i]\}$$

$$P'[z_i]=P[z_i|\theta_0]\times P'[\theta_0]+P[z_i|\theta_1]\times P'[\theta_1]$$

$$P'[z_0]=P[z_0|\theta_0]\times P'[\theta_0]+P[z_0|\theta_1]\times P'[\theta_1]=0.6\times 0.7+0.1\times 0.3=0.45$$

$$P'[z_1]=P[z_1|\theta_0]\times P'[\theta_0]+P[z_1|\theta_1]\times P'[\theta_1]=0.1\times 0.7+0.7\times 0.3=0.28$$

$$P'[z_2]=P[z_2|\theta_0]\times P'[\theta_0]+P[z_2|\theta_1]\times P'[\theta_1]=0.3\times 0.7+0.2\times 0.3=0.27$$

Decision Analysis in Engineering

Pre-posterior Analysis

$$E''\left[u|z_0\right] = \min_j\{E''\left[u(a_j)|z_0\right]\}$$

$$\overbrace{\textbf{do nothing} \qquad\qquad \textbf{splicing}}^{\mathbf{a_0}} \qquad \overbrace{\textbf{cutting} \qquad\qquad \textbf{do nothing}}^{\mathbf{a_1}}$$

$$= \min\{P''\left[\theta_0|z_0\right]\times 0 + P''\left[\theta_1|z_0\right]\times 400,\ P''\left[\theta_0|z_0\right]\times 100 + P''\left[\theta_1|z_0\right]\times 0\}$$

$$= \min\{0.93\times 0 + 0.07\times 400,\ 0.93\times 100 + 0.07\times 0\}$$

$$= 0.07\times 400 + 0.93\times 0 = 28$$

Decision Analysis in Engineering

Pre-posterior Analysis

$$E''\left[u\,\middle|\,z_1\right]=\min_j\{E''\left[u(a_j)\,\middle|\,z_1\right]\}$$

$$\overbrace{\textbf{do nothing}\qquad\textbf{splicing}}^{\mathbf{a_0}}\qquad\overbrace{\textbf{cutting}\qquad\textbf{do nothing}}^{\mathbf{a_1}}$$

$$=\min\{P''\left[\theta_0\,\middle|\,z_1\right]\times 0+P''\left[\theta_1\,\middle|\,z_1\right]\times 400,\ P''\left[\theta_0\,\middle|\,z_1\right]\times 100+P''\left[\theta_1\,\middle|\,z_1\right]\times 0\}$$

$$=\min\{0.25\times 0+0.75\times 400,\ 0.25\times 100+0.75\times 0\}$$

$$=0.25\times 100+0.75\times 0=25$$

Pre-posterior Analysis

The minimum expected costs based on pre-posterior decision analysis – not including costs of experiments

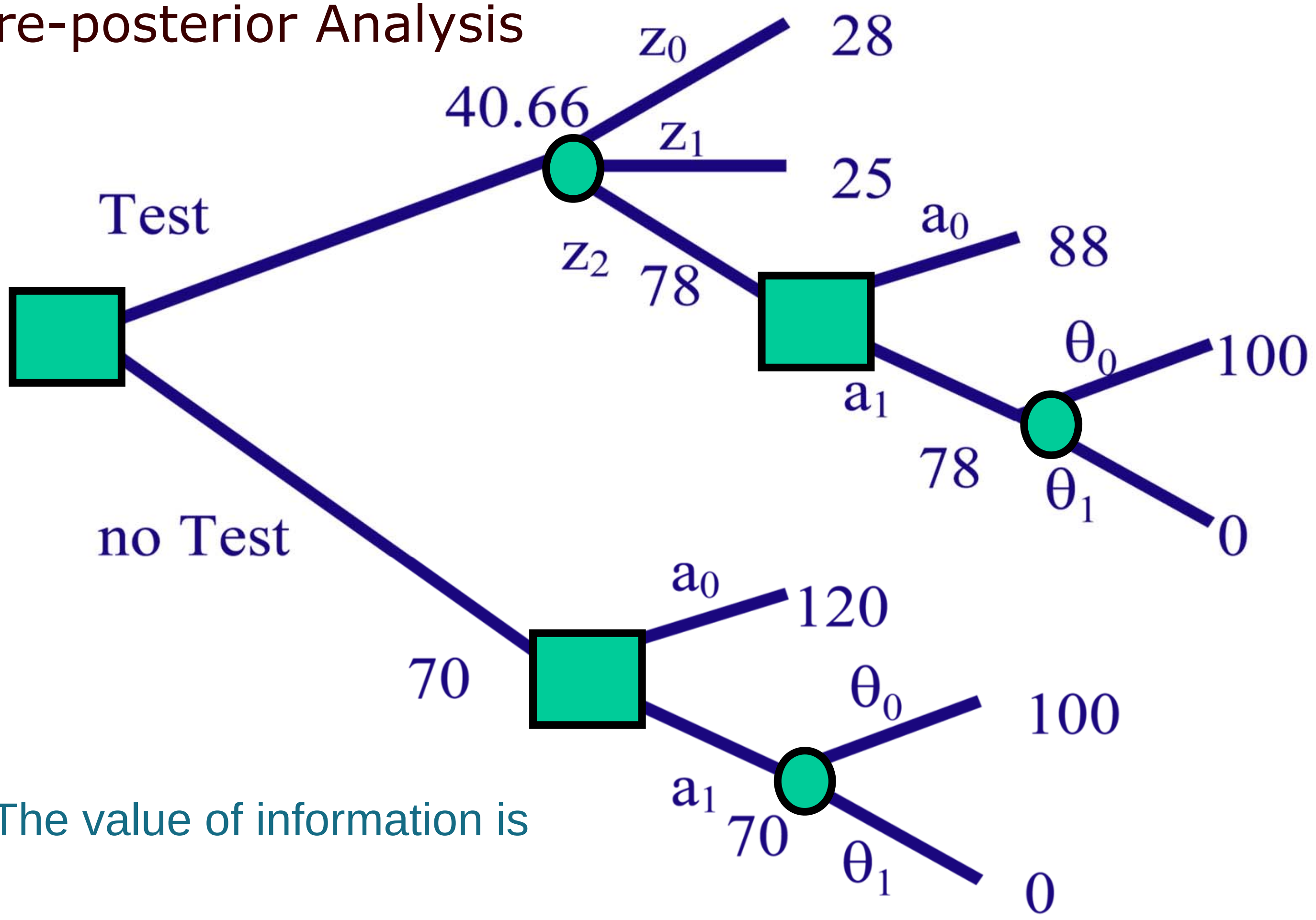
$$E[u]=\sum_{i=1}^{n}P'\left[z_i\right]\times E''\left[u\middle|z_i\right]=28\times 0.45+25\times 0.28+78\times 0.27=40.66$$

The value of the information is:

$$E'[u]-E[u]=70.00-40.66=29.34$$

Decision Analysis in Engineering

Pre-posterior Analysis

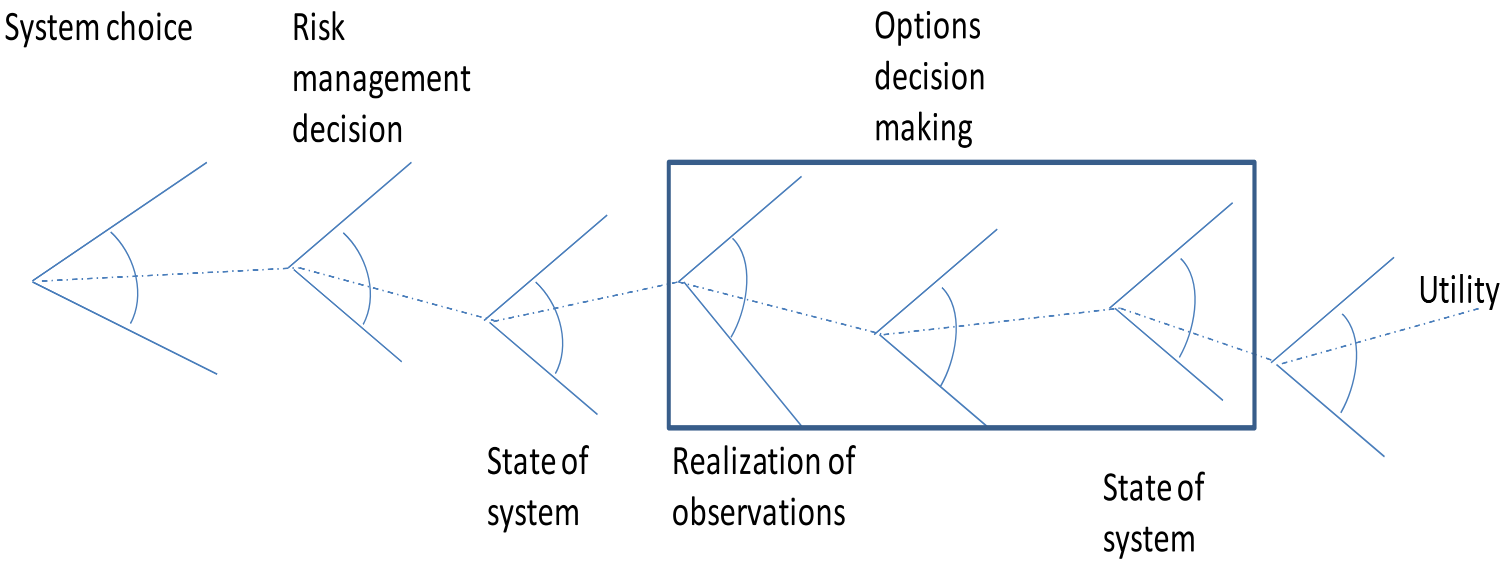


The value of information is

$$E'[u]-E[u]=70.00-40.66=29.34$$

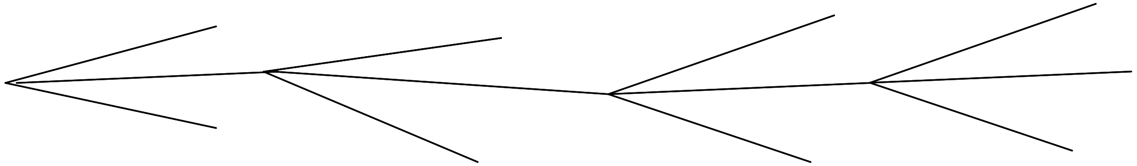
Decision Analysis in Engineering

Optimal decisions and available decision alternatives in general must be understood to depend on the actual system as it will be realized



Decision Analysis in Engineering

The decision problem is formulated as a joint optimization of which system to consider and how to treat risks



$s \in \mathbf{s}$	$\sigma \in \{\mathbf{\Sigma}\}$	$a \in \mathbf{a}$	$\mathbf{x} \in \{\mathbf{X}\}$	U
System choice	Realization of real system	Choice of activity	State of nature	Utility

$$\max_{\mathbf{a}} U^*(a) = \max_{\mathbf{a}} E'_{\mathbf{X}|s}\left[U(a,\mathbf{X})\right]$$

$$\max_{\mathbf{s},\mathbf{a}} U^*(s,a) =$$

$$\max_{\mathbf{s}}\left(\max_{\mathbf{a}} P(\Sigma = s)E'_{\mathbf{X}|s}\left[U(a,\mathbf{X})\right] + E'_{\mathbf{\Sigma}\backslash s}\left[E'_{\mathbf{X}|\mathbf{\Sigma}}\left[U(a^*,\mathbf{X})\right]\right]\right)$$

Facilitates for the assessment
of the robustness of the decision