COST Action TU1402
Workshop on Standardization of VoI in SHM,
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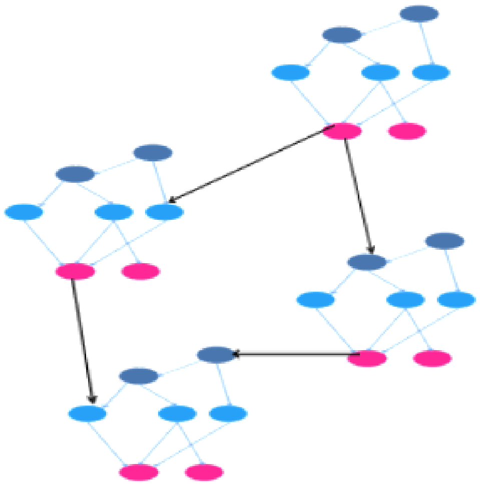

Aspects of Standardization of VoI in SHM

Michael Havbro Faber

Professor in Risk Informed Decision Support for Structures
Department of Civil Engineering, Aalborg University

AALBORG UNIVERSITET

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- **Structural Health Monitoring (SHM)**
- **JCSS PMC Topics / List of Contents**
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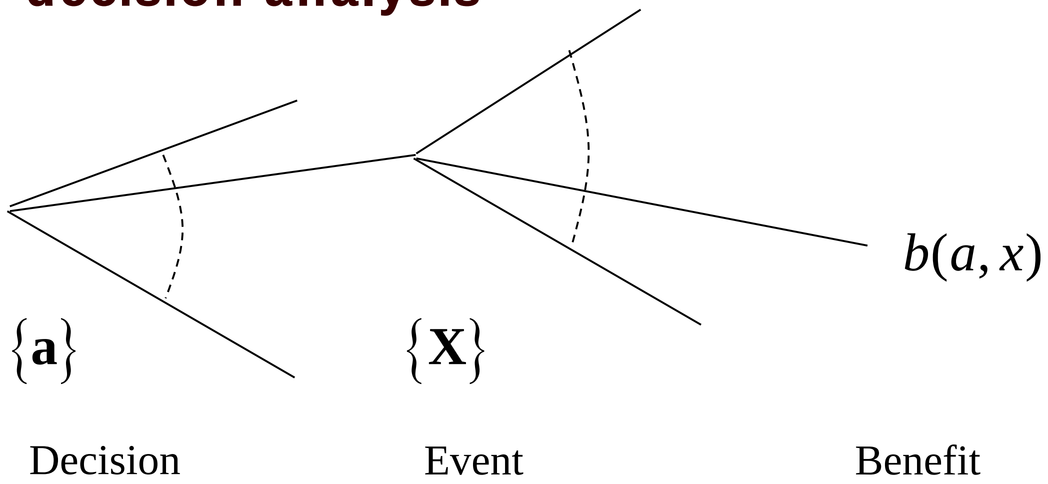
Engineering Decision Making

Prior decision analysis

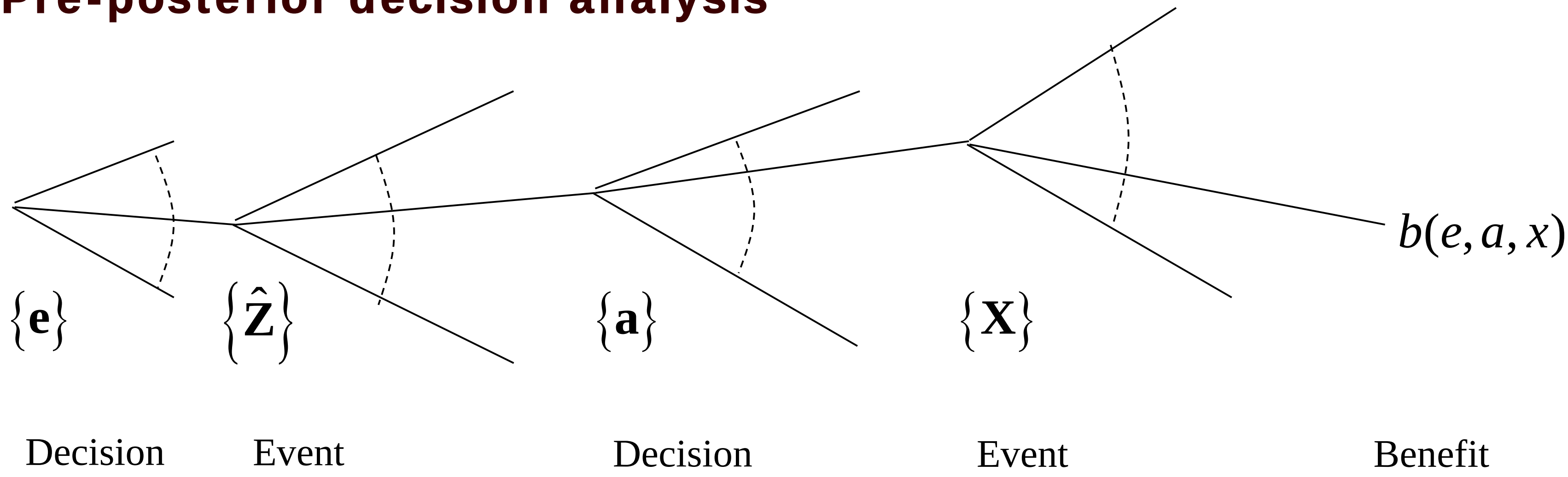


Optimal decision maximizes the expected value of benefit
(von Neumann & Morgenstern)

$$B_0^* = \max_a E'\left[b(a, X)\right] = \max_a \int b(a, x) f_X'(x, a) dx$$

Engineering Decision Making

Pre-posterior decision analysis



The optimal experiment e may be found from

$$B_1^* = \max_e E_{\hat{\mathbf{Z}}}\left[\max_a \int b(e,a,x)\, f_X''(x,a\left|\hat{\mathbf{Z}}\right.)dx\right]$$

Engineering Decision Making

Principal engineering decisions

Any design decision may be supported by the prior decision analysis

- a choice concerning structural system, materials, dimensions corresponds to a choice of the (prior) probabilistic model of $\mathbf{X}$

Any decision on assessments, inspections or monitoring may be supported by the pre-posterior decision analysis

- a choice concerning assessment method, inspection method and monitoring scheme will influence the (posterior) probabilistic model of $\mathbf{X}$

Engineering Decision Making

Principal engineering decisions

<u>Choices during the service life of structures:</u>

- Structural concept (static system, materials,..)
- Site investigations (characteristics, amount/extent)
- Design methods (analysis, codes,..)
- Construction concept (process, phases, interim structures,..)
- Quality control (design, manufacturing, construction,..)
- Maintenance strategy (inspection, repair, quality,..)
- Monitoring strategy (characteristics, techniques, quality,..)
- Decommissioning concept (process, assessments,..)

The choices define the prior knowledge concerning structural performances, i.e. risk, safety and service life costs, but also the options to influence these over time.

Engineering Decision Making

Structural safety and information management

Models of real world

Exposures/loads

Vulnerability / direct con.

Robustness / indirect con.

Decisions

Site investigations
Load control
Environment control
….
Materials
Component design
….
System concept
Maintenance/monitoring
Evacuation strategy
…

Observations/measurements

Real world

Engineering Decision Making

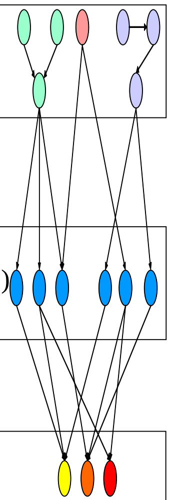
Structural safety and information management

Models of real world

$p(\mathbf{EX})$

$$R_D = \sum_{k=1}^{n_{EXP}} \sum_{l=1}^{n_{CSTA}} p(\mathbf{C}_l \mid EX_k) c_D(\mathbf{C}_l) p(EX_k)$$

$$R_{ID} = \sum_{k=1}^{n_{EXP}} \sum_{l=1}^{n_{CSTA}} \sum_{m=1}^{n_{SSTA}} c_{ID}(S_m, c_D(\mathbf{C}_l)) \times p(S_m \mid \mathbf{C}_l, EX_k) p(\mathbf{C}_l \mid EX_k) p(EX_k)$$



Decisions

Site investigations
Load control
Environment control
....
Materials
Component design
....
System concept
Maintenance/monitoring
Evacuation strategy
...

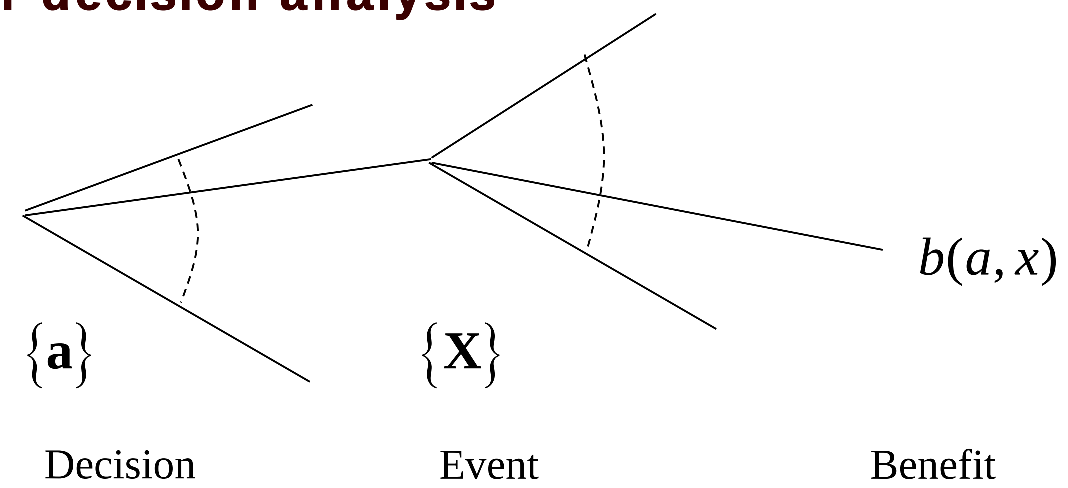
Likelihoods

Real world

Decision and VoI analysis

Prior decision analysis

Information is bought by choice of prior density



Optimal decision maximizes the expected value of utility (benefit)
(von Neumann & Morgenstern)

$$B_0^* = \max_a E'\left[b(a,X)\right] = \max_a \int b(a,x) f_X'(x,a)dx$$

Basic principle of Value of Information

Posterior decision analysis

By sampling information $\mathbf{z}$ from the sample space $\{\mathbf{X}\}$ using an experiment e we may update the probabilistic description of X

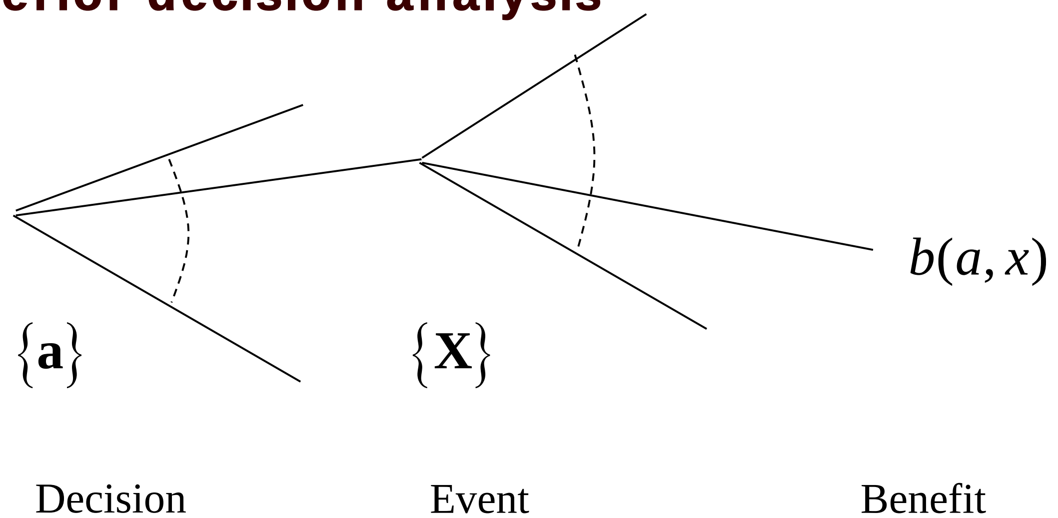
$$f''_X(x,a|\mathbf{z}) = \frac{L(x|\mathbf{z})\, f'_X(x,a)}{\int L(x|\mathbf{z})\, f'_X(x,a)}$$

Of course the likelihood of the sample $\mathbf{z}$ depends on the experiment e why we write

$$L(x|\mathbf{z}) = L(x|\mathbf{z}, e)$$

Basic principle of Value of Information

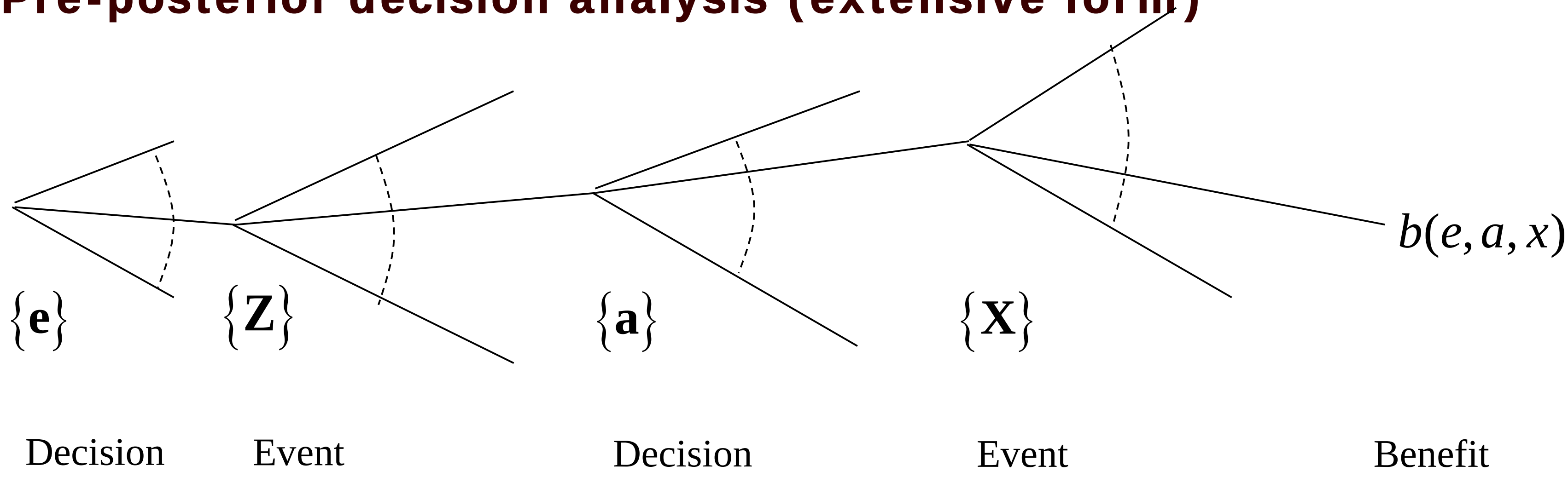
Posterior decision analysis



$$\max_a E''\left[b(a,X)\right] = \max_a \int b(a,x)\, f''_X(x,a\,|\,\hat{\mathbf{z}})\,dx$$

Basic principle of Value of Information

Pre-posterior decision analysis (extensive form)

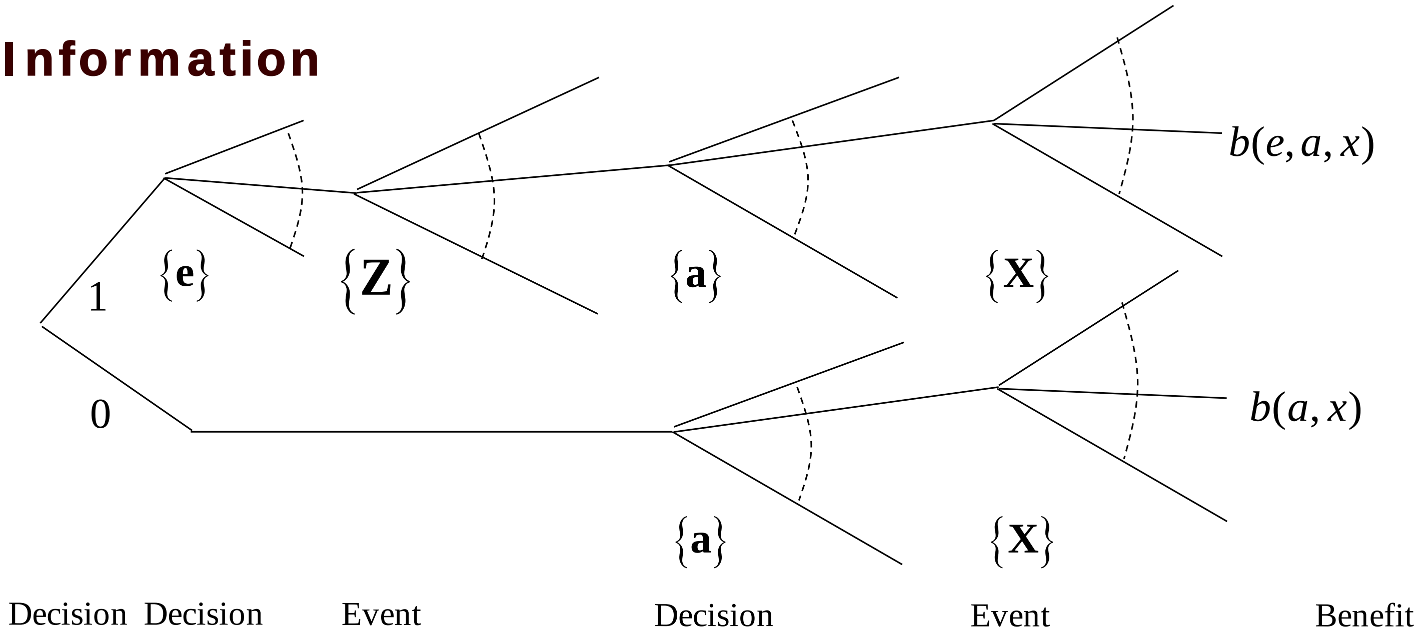


The optimal experiment e may be found from

$$B_1^* = \max_e E_{\mathbf{Z}}\left[\max_a \int b(e,a,x)\, f_X''(x,a\,|\,\mathbf{Z})\,dx\right]$$

Basic principle of Value of Information

Value of Information



The value of information *VoI* is determined from:

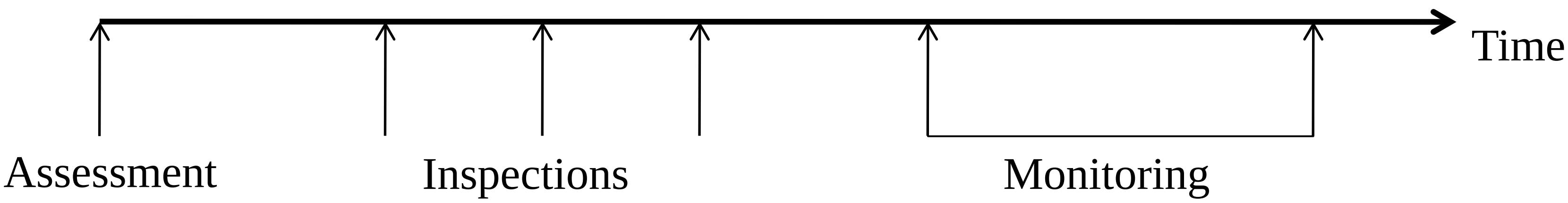
$$VoI = \max_{e} E_{\mathbf{Z}}\left[\max_{a}\int b(e,a,x)\, f_X''(x,a\,|\,\mathbf{Z})dx\right] - \max_{a}\int b(a,x)\, f_X'(x,a)dx$$

Shows the coupling between buying prior and
pre-posterior information (design/insp. and monitoring)

Engineering Decision Making

Principal engineering decisions

In the decision analysis structure there is no principal difference between assessment, inspection and monitoring activities



The only difference concerns the number of times at which information is collected and utilized for updating the prior probabilistic model

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 may perform unreliably
- For the optimization of maintenance strategies

Structural Health Monitoring

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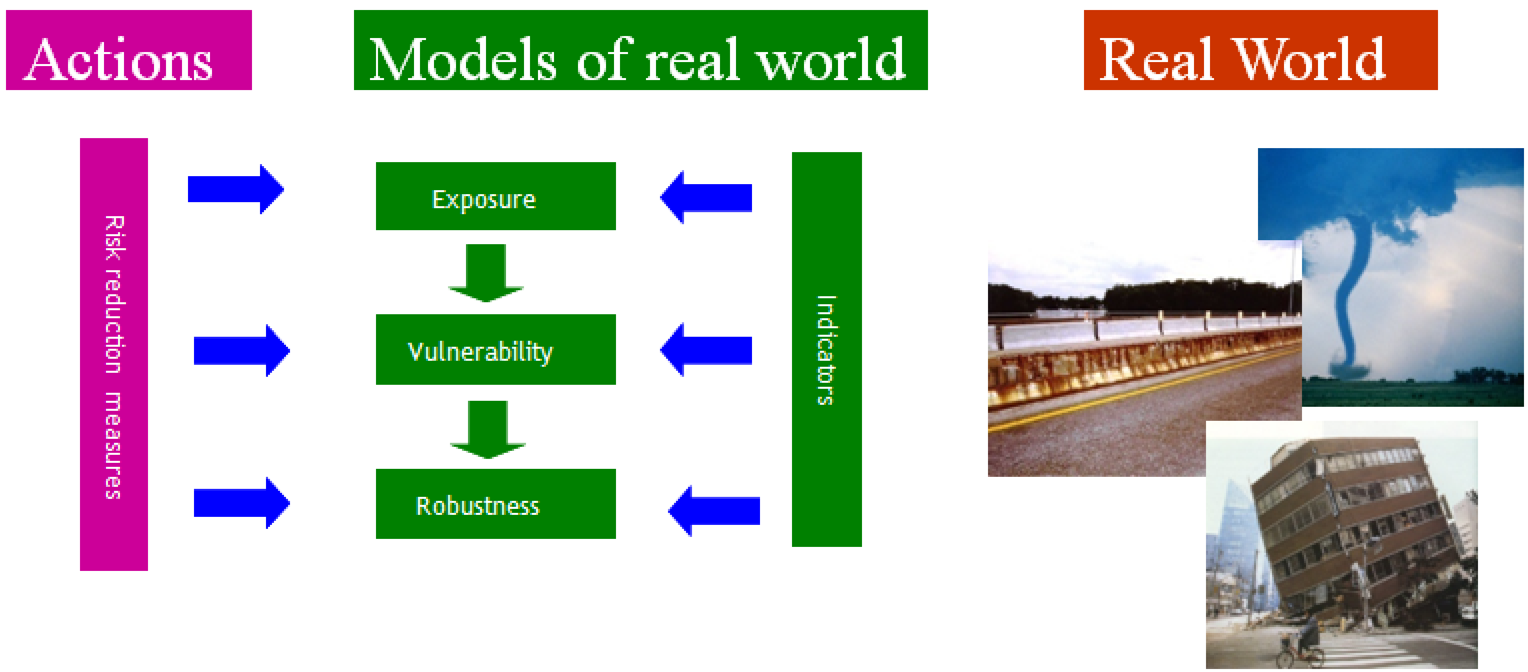


Structural Health Monitoring

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 may 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. Could also relate to approaching hazard event.
The value of monitoring would relate to the possibility of loss reduction by evacuation, shutting down the function or reducing the exposure of the structure, before human lives, environment and structure are lost and/or damaged excessively.

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

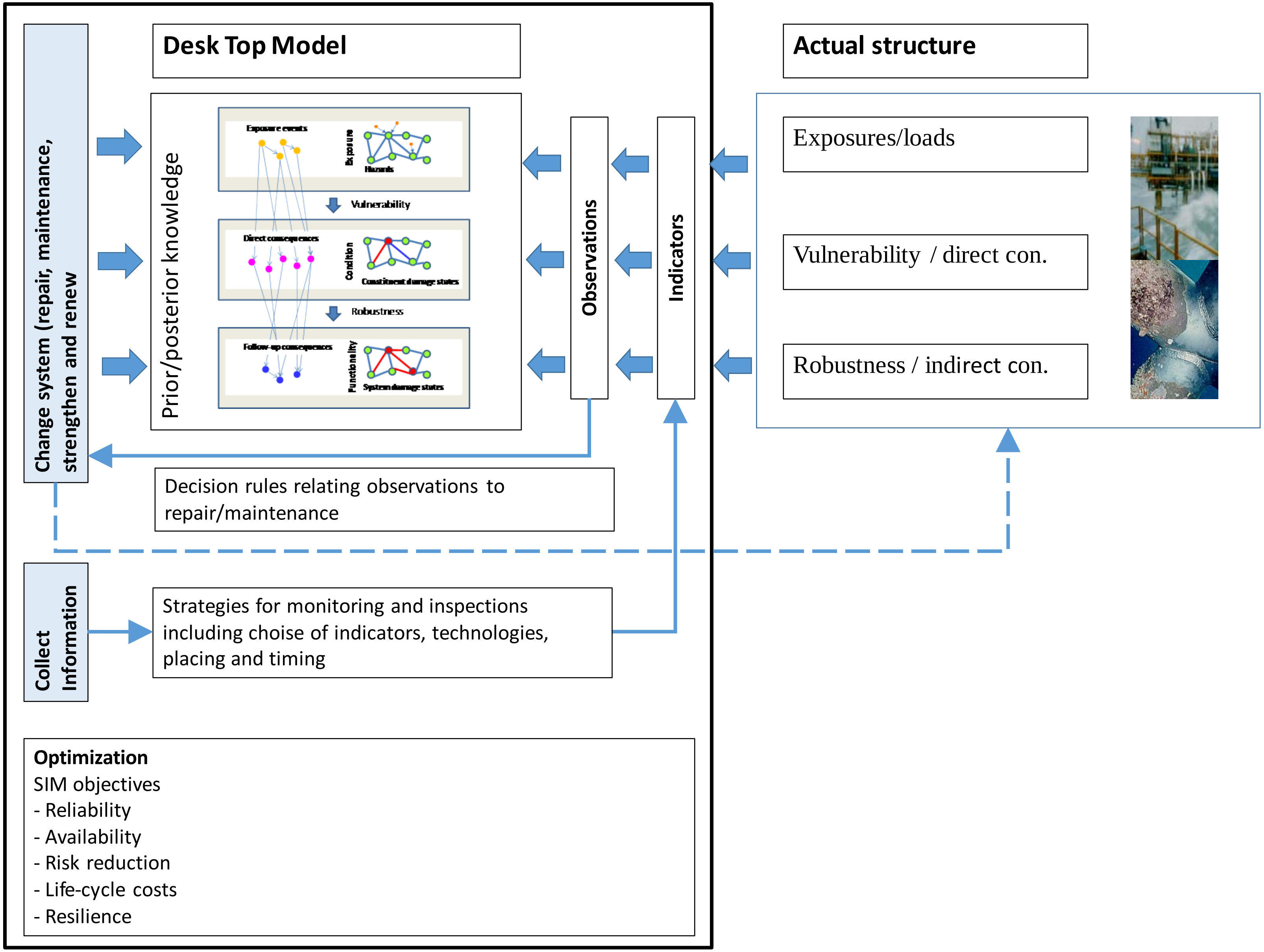
Structural Health Monitoring

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


Desk Top Model
Actual structure
Change system (repair, maintenance, strengthen and renew
Prior/posterior knowledge
Exposure events
Exposure
Hazards
Vulnerability
Direct consequences
Condition
Constituent damage states
Robustness
Follow-up consequences
Functionality
System damage states
Observations
Indicators
Exposures/loads
Vulnerability / direct con.
Robustness / indirect con.
Decision rules relating observations to repair/maintenance
Collect Information
Strategies for monitoring and inspections including choise of indicators, technologies, placing and timing
Optimization
SIM objectives
- Reliability
- Availability
- Risk reduction
- Life-cycle costs
- Resilience

Topics / List of Contents

- General framework
- SHM decision situations / decision-event tree modeling
- Principal probabilistic SHM indicator modeling
- Decision rules relating observations / indicators to actions
- Strategies of SHM (indicators / techniques / timing / placement)
- Example library

Eurocode Revisions

- SHM and VoI should be foreseen/facilitated as a means for Structural Integrity Management

  - Design by testing (e.g. prototyping)
  - Early warning/evacuation
  - Assessment planning
  - Inspection and maintenance planning (NORSOK)
  - Quality management (design, execution, operation,...)