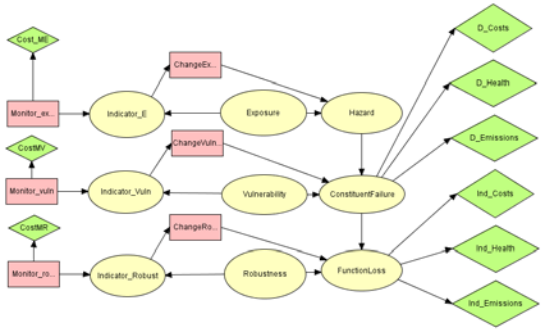
COST TU1402: Quantifying the Value of Structural Health Monitoring
Brussels, January 23-24, 2017



Observations and Suggestions on Research Strategy

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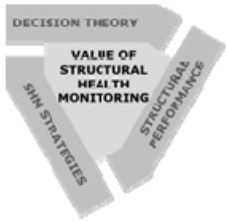


General Observations

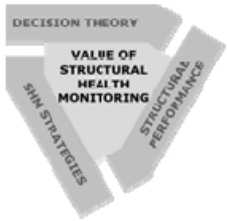
Basis

- Proc. from 1st workshop - DTU, May 4-5, 2015
- Proc. from 3rd workshop – Barcelona Tech, March 14-15, 2016
- Proc. from 4th workshop – Guilford, April 18-19, 2016

39 Fact-Sheets - addressing:

- Theoretical Framework
- SHM Strategies and Structural Performance
- Methods and Tools
- Case Studies

An Of course the presentations from last August at DTU



General Observations

The work till now has collected and presented very significant knowledge on:

- Frameworks
- Strategies
- Approaches
- Techniques & tools and,
- Case studies and example applications.

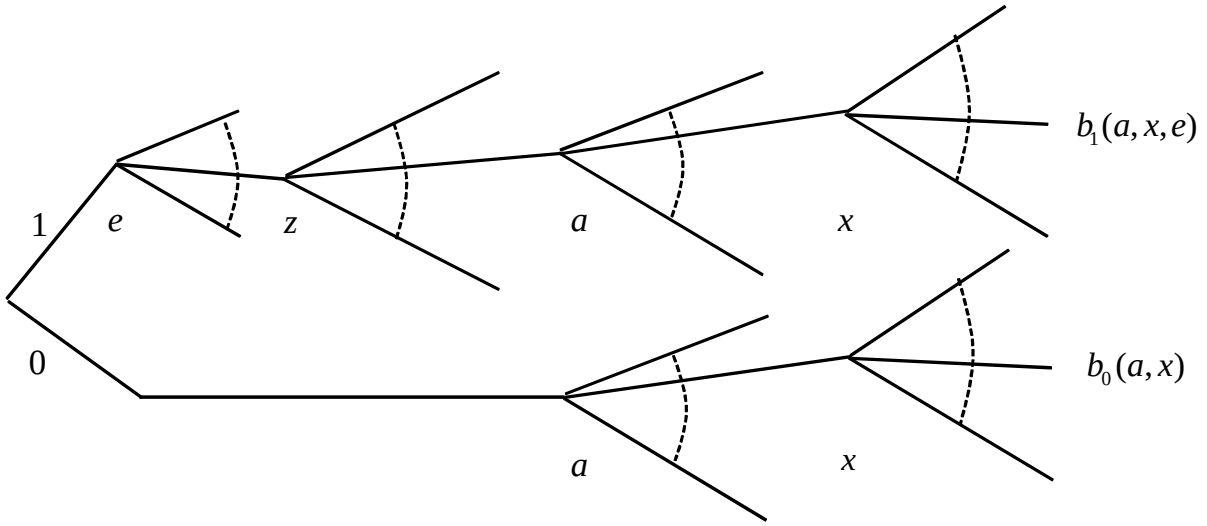
A strong achievement ! - an important stepping stone for adding value to already existing knowledge

How to proceed – putting order to the collected knowledge !

Targeted Processing

Generic Framework for VoI of SHM

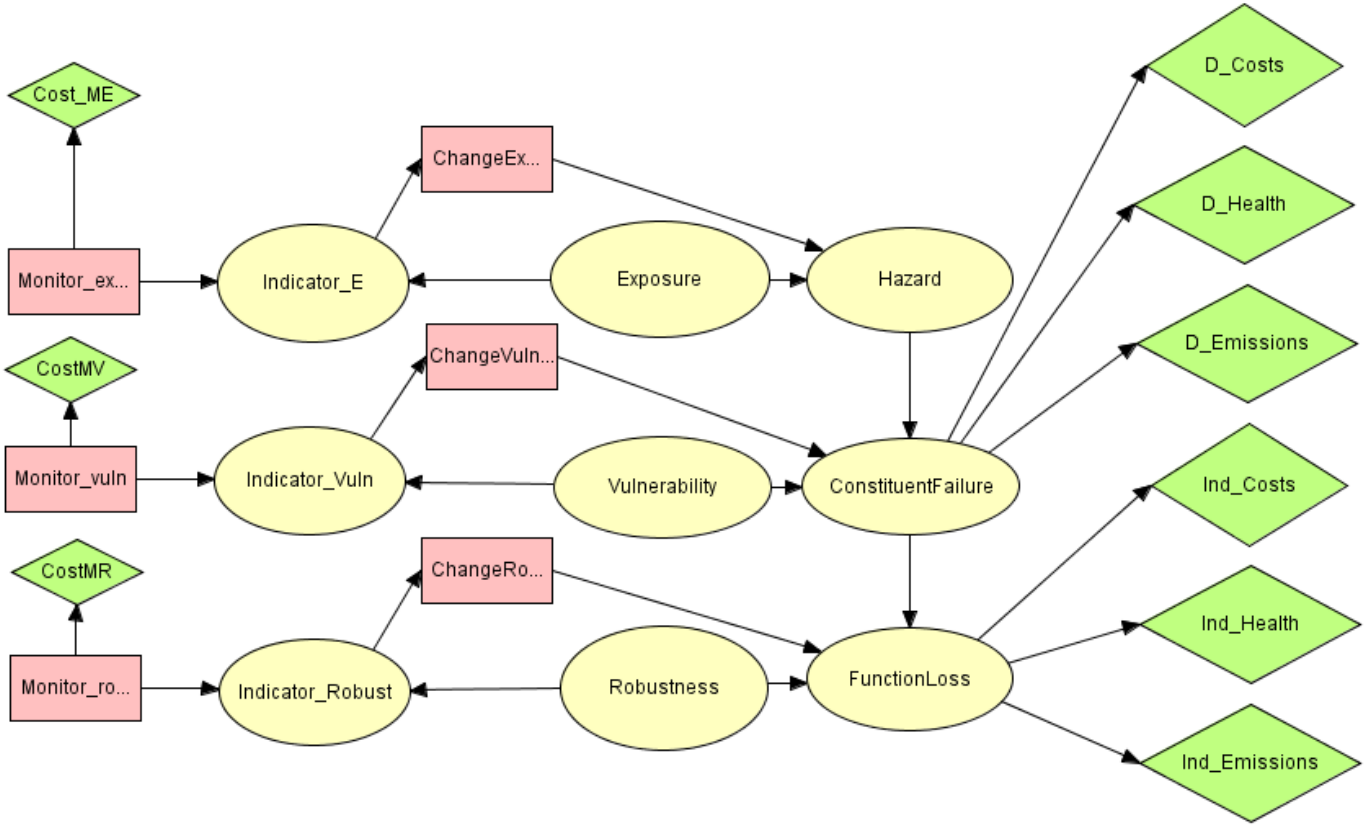
Value of Information

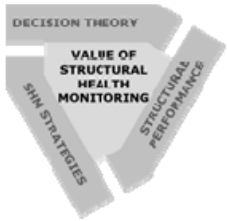


The value of information *VoI* is determined from:

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

Generic Framework for VoI of SHM



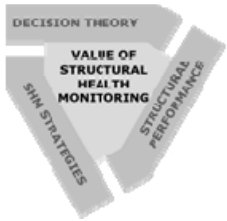


Way Ahead -

Focus efforts on categorizing :

1. VoI/SHM decision problems
2. Considered structures, components and materials
3. Deterioration processes
4. Possible measurable indicators
5. Uncertainty modeling of indicators/measurements
6. Relevant measure of (remedial) actions
7. Objective functions representing service life performance
8. Formulations of the pre-posterior decision problem
9. Uncertainty modeling and propagations tools

and 10. illustrate the approach and quantify the VoI for the most relevant categories

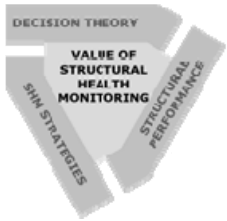


Categorizing….

VoI/SHM decision problems:

There are different decision problems involving structures where SHM could provide valuable information:

- Structural integrity management for deteriorating structures
- Load modeling purposes
- Prototype development/design by testing
- SHM prototype development
- Early damage/failure warning
- …



Categorizing....

VoI/SHM decision problems:

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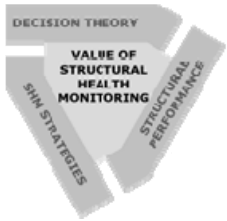
- Load modeling purposes
- Prototype development/design by testing
- SHM prototype development
- Early damage/failure warning
- ...

Suggested to focus on structural integrity management for structures subject to corrosion and fatigue



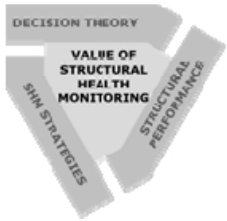
Categorizing….

Considered structures, components and materials:

There is a broad spectrum of different structures, components and materials for which SHM could be relevant, e.g.

- Offshore structures (steel, concrete)
    - members
    - hotspots (welded joints)
    - boat landings
    - anodes
    - ….
- Wind turbines (steel, concrete)
- Highway bridges (steel, concrete)
- Historical buildings/monuments (masonry, stone,…)
- Soil anchors

Suggested to focus on highway bridges (steel and concrete)



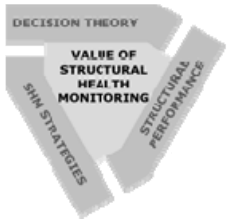
Categorizing….

Deterioration processes:

A number of different deterioration processes may be relevant depending on structure, materials and environment

- Alkali Silica Reaction
- De-passivation of concrete cover (ingress of chlorides, carbonation)
- Fatigue crack growth
- Corrosion
- Thaw / frost cycles
- Scour

Suggested to focus on corrosion and fatigue



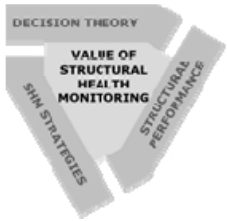
Categorizing….

Possible measurable indicators:

Different indicators may be relevant for different structures, components, materials and deterioration processes, e.g.:

- Spalling
- Rupture of reinforcement
- Rupture of cable wires
- Surface coloring
- Cracking
- Cross sectional stresses
- Hotspot stresses
- Dynamic responses

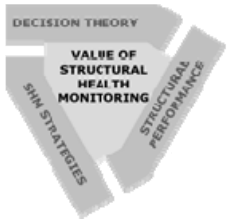
Suggested to focus on cracks, surface coloring, spalling, potentials, dynamic responses, stresses/strains



Categorizing….

Possible measurable indicators:

Concrete structures	**Corrosion initiation**	**Corrosion propagation**	**???**
	Chloride profile	Acoustics	
	HCP	Radar	
	Ladder measurements	??	
Steel structures	**Fatigue crack growth**	**???**	**???**
	ACFM		
	Dynamic response		
Loads	WiM		
	Temperature		
Environment	Humidity		
	Temperature		
	Salinity		

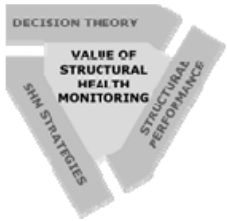


Categorizing….

Uncertainty modeling of indicators / measurements:

The uncertainty associated with the relationship between what is measured and the structural characteristics/conditions of interest must be quantified – accounting for the uncertainty associated with the measurements themselves.

Measured	**Condition**
HCP	Corrosion propagation
Strain variations	Stress variations/fatigue
Electron diffusion	Strain/stress
Chloride concentration	Initiation of corrosion
Acoustic emissions	Wire/reinforcement ruptures
…	…

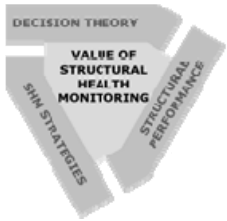


Categorizing….

Uncertainty modeling of indicators / measurements:

Models of real world		Decisions		Real world
Exposures/loads	⇦	Site investigations Load control Environment control ….	⇦	Observations/measurements
Vulnerability / direct con.	⇦	Materials Component design ….	⇦	
Robustness / indirect con.	⇦	System concept Maintenance/monitoring Evacuation strategy …	⇦	

Safety, risk and life-cycle costs



Categorizing….

Uncertainty modeling of indicators / measurements:

Models of real world

$p(\mathbf{EX})$

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

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

Safety, risk and life-cycle costs

Decisions

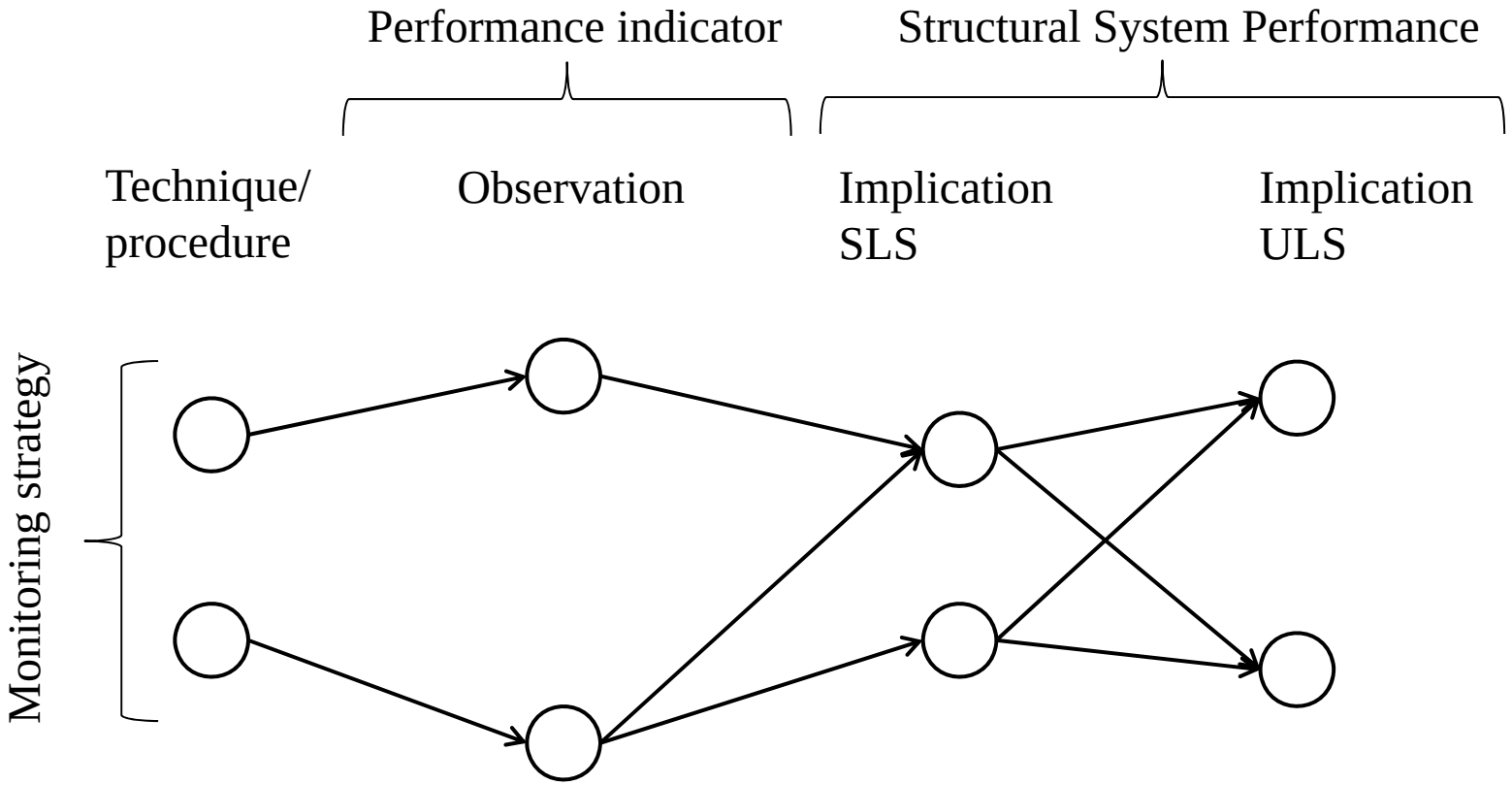
Site investigations
Load control
Environment control
….
Materials
Component design
….
System concept
Maintenance/monitoring
Evacuation strategy
…

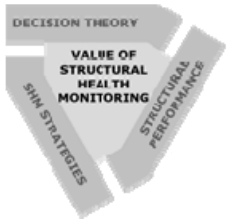
Likelihoods

Real world

Categorizing….

Uncertainty modeling of indicators / measurements:





Background

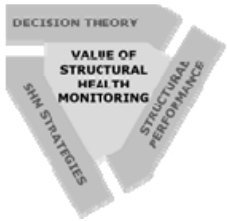
Posterior decision analysis

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

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

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

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



Categorizing….

Uncertainty modeling of indicators / measurements:

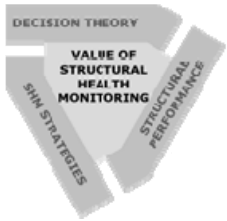
Structure described by system state variables $\mathbf{x}$

Performance of structure described as function of system state variables

$$Y = g(\mathbf{X})$$

Observed system characteristic

$$z = h(\mathbf{w}, \mathbf{x})$$



Categorizing….

Uncertainty modeling of indicators / measurements:

Updating of performance of system

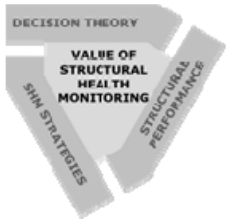
$$P(Y = y \mid z) \propto P(z \mid Y = y)P(Y = y) = P(h(\mathbf{W}, \mathbf{X}) = z \mid g(\mathbf{X}) = y)P(g(\mathbf{X}) = y)$$

Uncertainties must account for:

- Limited information/statistical uncertainty
- Inherent variability associated with SHM technique
- Model uncertainties

Time(s)/duration, location(s)/extent must be accounted for

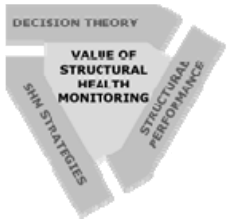
Different indicators may be associated with the same performance
Different performances may be associated with the same indicator



Categorizing….

Uncertainty modeling of indicators / measurements:

Technique	Time/duration	Space/location	Struc. charact.	Struct.perf.	SHM mod.
Strain gauges	Continuous	Hot spot i	Fat. stress	Fat.. damage	1
HCP	Time j	Surf. j	Corr. initi.	Cracking	2
ACFM	Time l	Hot spot k	Crack	Joint fail.	3
Accelerometer	Continuous	Plan j	Stiffness	Crack/failure	4



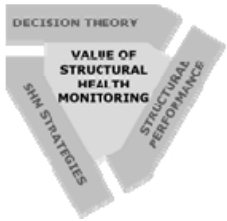
Categorizing….

Relevant measures of remedial actions:

Depending on the type of structures, components, materials and deterioration processes, and level of damage different remedial actions might be relevant e.g. (the case of integrity management):

- Concrete cover exchange
- Concrete cover sealing
- Exchange of reinforcement
- Exchange of membranes
- Stress release by drilling
- Patching
- Welding

Their effects must be modeled probabilistically

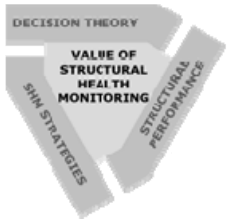


Categorizing….

Objective functions for service life performance:

Depending on the SHM decision problem, the type of structure, component and material, indicators and remedial actions different objective functions (utility functions) may be relevant

Such functions must account for – represent the consequences of – the quality of the monitoring results in terms of type 1 and 2 error probabilities



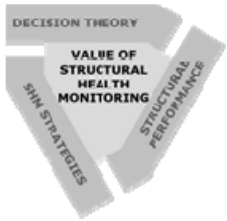
Categorizing….

Formulations of the pre-posterior decision problem:

For the different types of SHM decision problems different formulations of the decision analysis problem may be possible

It would be useful to establish a proposal on which of these possible formulations are adequate for which type of SHM decision problem

- Normal form decision analysis
- Extensive form decision analysis
- Combinations of the two



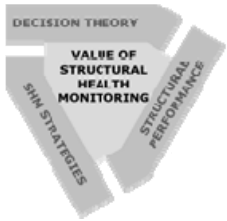
Categorizing….

Uncertainty modeling and propagation tools:

We need models and tools for the propagation of uncertainties to describe and assess:

- Structural performances
- Quality of measurement techniques
- Indicators of structural conditions/performances
- Expected value of utility

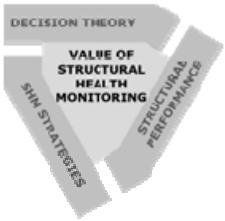
It would be very useful to establish an overview of which models and tools for uncertainty propagation are relevant/efficient in which of the categorized cases

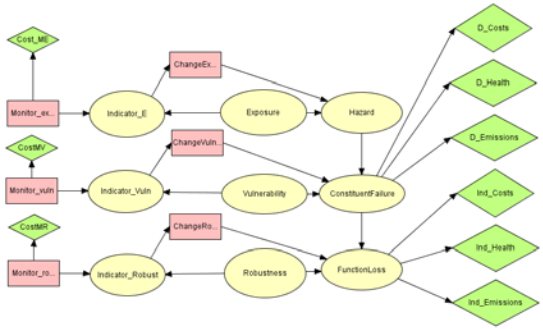


Summary

Main contributors to categorizations

1.	VoI/SHM decision problems	WG1
2.	Considered structures, components and materials	WG2
3.	Deterioration processes	WG2
4.	Possible measurable indicators	WG2
5.	Uncertainty modeling of indicators/measurements	WG3
6.	Relevant measure of (remedial) actions	WG2
7.	Objective functions for service life performance	WG1
8.	Formulations of the pre-posterior decision problem	WG1
9.	Uncertainty modeling and propagations tools	WG3
10.	Application examples	WG4





Thanks for your Attention!