COST Action
TU 1402

Quantifying the Value of Structural Health Monitoring

WG2

SHM Technologies and Structural Performance

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Aims

- Categorise available **SHM technologies** with regard to the **measured quantity (observation)** and the related **structural performance (indicator)** – collect and represent "best practice"

- Quantify links between measured quantities and structural performance of interest with consistent treatment of **uncertainties**.

Achievements

- WG2 attracted a **wide range of interest** from practitioners and researchers covering different:
  - Structural types
  - SHM technologies
  - SHM data analytics
  - SHM-Performance interfaces
  - Performance assessment / prediction models
  - Life-cycle asset management decisions
- Significant activity in the 1st upto 4th Workshops, resulting in more than 20 presentations and factsheets **recording current practice** in implementation of SHM in different sectors

Achievements

- Developed a **categorisation framework** which:
  - promotes the use of common language/terminology.
  - proposes common ‘start’ and ‘end’ to improve transparency – these are *‘performance’* and *‘decisions’.*
  - allows generic paths to be formed that cover the wide range of efforts made by practitioners and researchers in introducing SHM into asset management.
  - is linkable to the conceptualisations proposed by WG1 and WG3.
  - is developable to a greater level of detail.

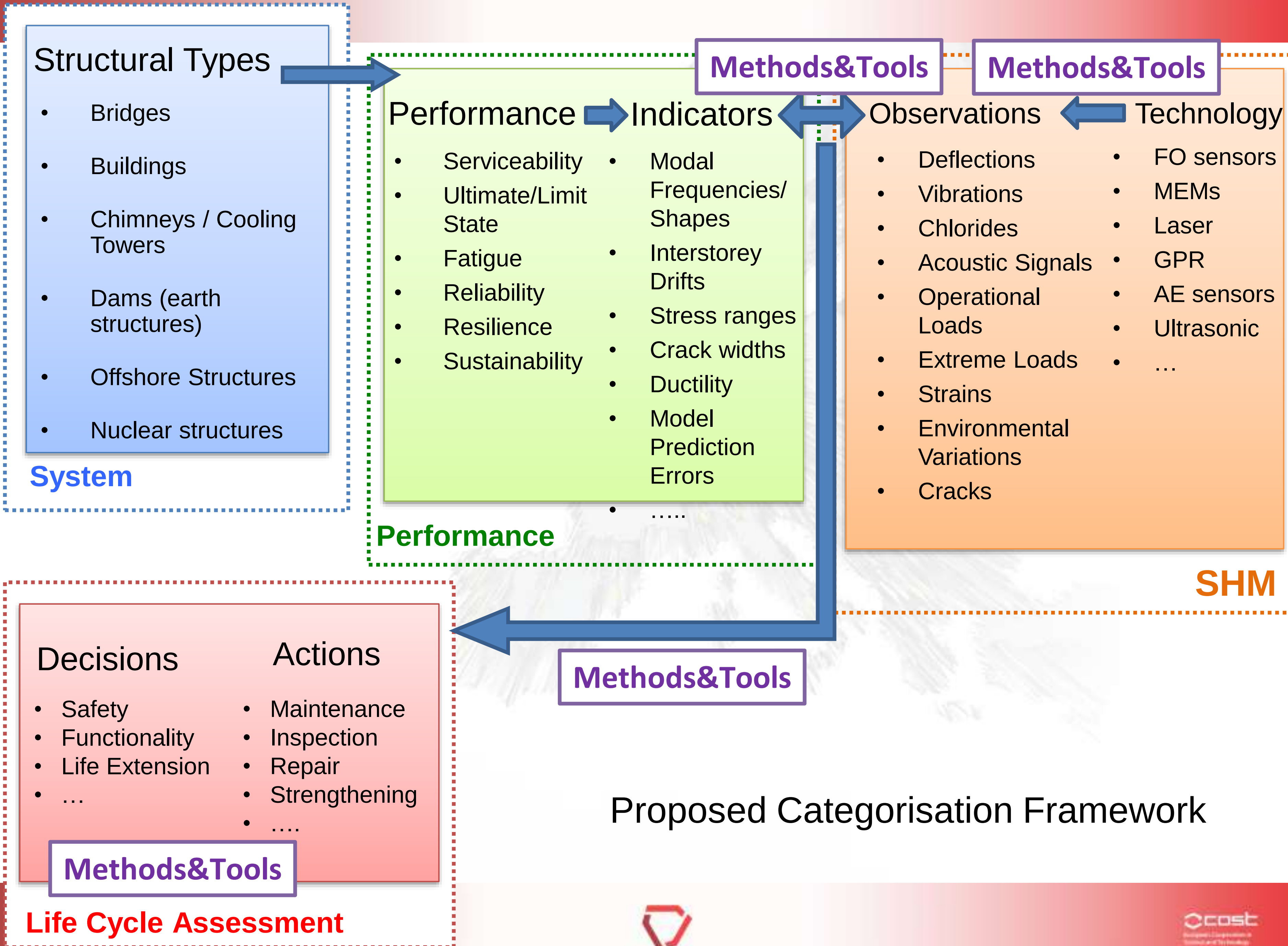
➢ **WG2 Summary Factsheet “SHM Technologies and Structural Performance**”

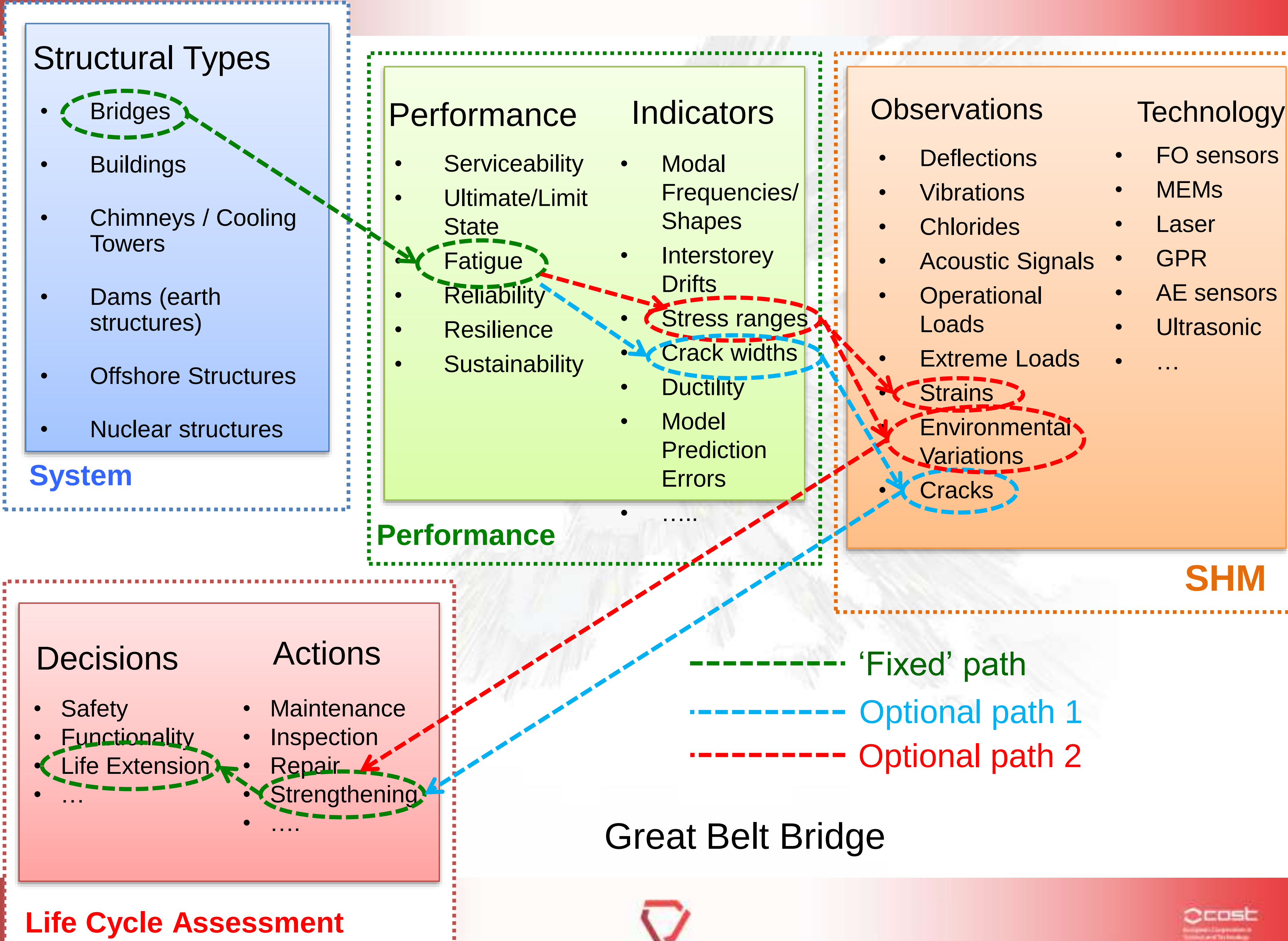
- Launched a questionnaire to assess current practice in the **treatment of uncertainties** in SHM strategies.

➢ **WG2 Summary Factsheet “Classification and Treatment of Uncertainty…**”

Dissemination

- Factsheets (6 from 1st workshop, publicly available, 13 in proceedings from 3rd and 4th workshop, limited access).
- Sessions organised at:
  - Eight European Workshop on Structural Health Monitoring (EWSHM 2016), July 2016, 15 presentations.
  - Fifth International Symposium on Life-Cycle Civil Engineering (IALCCE 2018), October 2018, 9 presentations.
- COST Action website
- COST Action brochure


Structural Types
Bridges
Buildings
Chimneys / Cooling Towers
Dams (earth structures)
Offshore Structures
Nuclear structures
System
Methods&Tools
Methods&Tools
Performance
Serviceability
Ultimate/Limit State
Fatigue
Reliability
Resilience
Sustainability
Indicators
Modal Frequencies/ Shapes
Interstorey Drifts
Stress ranges
Crack widths
Ductility
Model Prediction Errors
…..
Performance
Observations
Deflections
Vibrations
Chlorides
Acoustic Signals
Operational Loads
Extreme Loads
Strains
Environmental Variations
Cracks
Technology
FO sensors
MEMs
Laser
GPR
AE sensors
Ultrasonic
…
SHM
Decisions
Safety
Functionality
Life Extension
…
Actions
Maintenance
Inspection
Repair
Strengthening
….
Methods&Tools
Methods&Tools
Life Cycle Assessment
Proposed Categorisation Framework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• …
SHM
Decisions
• Safety
• Functionality
• Life Extension
• …
Actions
• Maintenance
• Inspection
• Repair
• Strengthening
• ….
Life Cycle Assessment
'Fixed' path
Optional path 1
Optional path 2
Great Belt Bridge

Structural Types

- Bridges
- Buildings
- Chimneys / Cooling Towers
- Dams (earth structures)
- Offshore Structures
- Nuclear structures

System

Performance

- Serviceability
- Ultimate/Limit State
- Fatigue
- Reliability
- Resilience
- Sustainability

Indicators

- Modal Frequencies/ Shapes
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- …..

Performance

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- Acc.
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SHM

Decisions

- Safety
- Functionality
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- …

Actions

- Maintenance
- Inspection
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- ….

Life Cycle Assessment

Z24 Bridge

Uncertainty modelling in structural reliability

(a) Physical → Aleatory

(b) Statistical → Epistemic

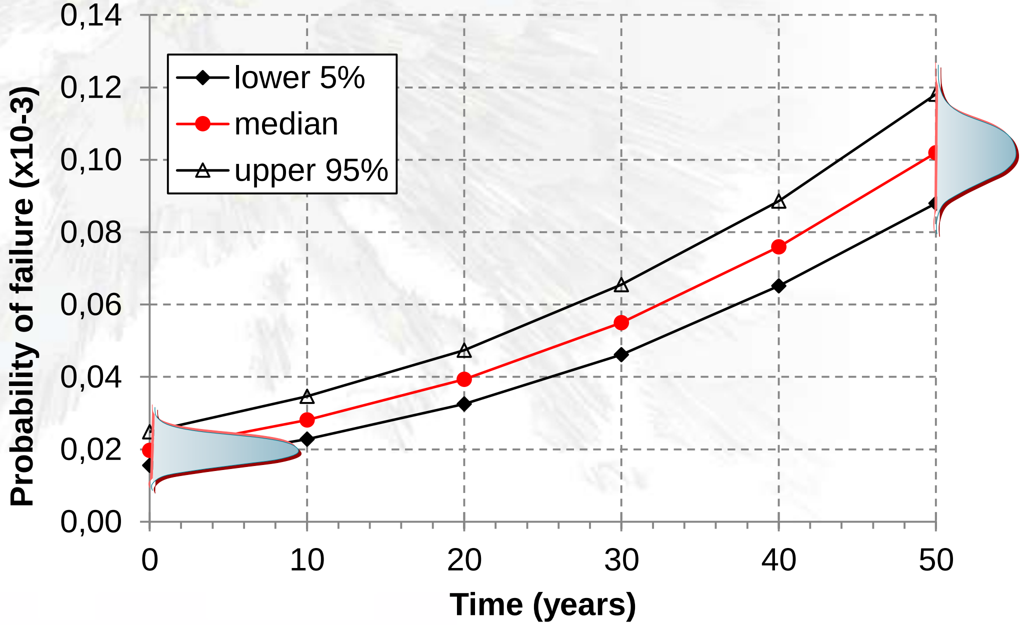
(c) Model → Epistemic

Evolution of a failure probability estimator

$$P_f(\theta) = \int_{g(\mathbf{x},\theta)\leq 0} f_{\mathbf{X}|\Theta}(\mathbf{x}|\theta)\, d\mathbf{x}$$

$$\bar{P}_f = E[P_f(\theta)] = \int_{\theta} P_f(\theta) f_{\Theta}(\theta)\, d\theta$$

How do SHM related uncertainties fit into this framework?



Model calibration uncertainties (indirect link obs.-ind.)

- Predictions rely on models which often contain a number of unknown or uncertain parameters.
- Data obtained from a sensor network can be used to ‘update’ models or predictions.
- Natural frequencies and mode shapes can be extracted from the dynamic response under ambient vibration and often used for updating.
- Usually formulated as a non-linear least-squares problem, solved using gradient-based optimization methods.
- Problem is inverse and often ill-posed (existence, uniqueness, and stability).

Model calibration uncertainties in SHM

Uncertainty quantification through Bayesian inference

- Many uncertainties involved: parameter uncertainty, model inadequacy, residual and parametric variability, observation errors, code uncertainty.
- Distinguishing between these uncertainties and taking them all into account is highly challenging…
- Mostly, focus is on one or a few and a highly simplified representation of the uncertainty is adopted.

Model calibration uncertainties in SHM

Uncertainty quantification through non-probabilistic methods

- Non-probabilistic models have emerged in response to the (assumed ?) inadequacy of probabilistic models when applied for epistemic uncertainty.
- Examples include interval-based approaches, convex modelling, and fuzzy set theory.
- All of these methods come with their own drawbacks…
- Little or no consensus exists on the subject, with the preferred method mainly determined by the background of the person.

Statistical uncertainties in SHM (direct link obs.-ind.)

- **Sources of statistical uncertainty**:
  - Measured observations with any SHM technology are only noisy versions of the desired physical quantities due to **measurement noise**
  - Observations are obtained only in a **finite time window**, while the exact computation of indicators requires sometimes infinite time series
  - **Insufficient information**: In some cases, the exact computation of an indicator would be possible if some additional information was available, and only assumptions on its statistical properties are made.
- Thus, nearly all indicators that are computed from data are **random variables,** having a probability distribution – statistical uncertainty
- Quantification and treatment of uncertainty crucial for monitoring:
  - Is a change in an indicator due to natural statistical variability?
  - Is a change significant, indicating abnormal behavior of the structure?

Statistical uncertainties in SHM

Uncertainty quantification

- In majority of cases indicators are assumed to be Gaussian distributed
  - Can often be justified through convergence properties (CLT)
  - Covariance contains all uncertainty information
  - Computation e.g. directly as a sample covariance, or sensitivity-based propagation of a sample covariance
- In other cases, e.g. for indicators originating from pattern recognition or statistical time series analysis, distributions may be more complex

Statistical uncertainties in SHM

Uncertainty treatment

- Confidence intervals
  - Gaussian case: 99.7% probability to be in interval $[x - 3\sigma , x + 3\sigma]$
- Mahalanobis distance
- Control charts
- Hypothesis tests, e.g. generalized likelihood ratio tests, compute test statistics and thresholds for decisions

Treatment of uncertainties

- A questionnaire was launched among the participants to assess current practice in the treatment of uncertainties in the links between measured quantities and structural performance.
- The following questions were asked:
  – Context of the work
  – What sources of uncertainties are present in this work?
  – How are these uncertainties best described?
  – Are these uncertainties currently taken into account in SHM data processing and/or the performance analysis in your work?
  – What methods are used to quantify or to propagate the uncertainties?

Treatment of uncertainties

- Received 18 responses, covering many different aspects in the proposed framework
- Main context of contributions:
  - Analysis of measurement uncertainties of the used technology
  - Uncertainties in data-driven performance indicators (damage detection)
  - Model-based performance indicators with uncertainties due to unknown material characteristics
  - Fatigue/reliability analysis with performance model uncertainties and measurement uncertainties
  - Decision making

Treatment of uncertainties

Analysis of measurement uncertainties of the used technology

Contributors	Title	Context of work	Uncertainty types	How quantified/treated?
Barrias & Casas; BarcelonaTech	Distributed optical fiber sensing for the SHM of concrete structures	Analysis of measurement technology	Measurement uncertainty due to strain transfer between the monitored structural component and the optical fiber itself	Regression error analysis by comparing the performance of distributed optical fiber sensing with other sensing techniques
Schoefs; University of Nantes	Uncertainty of measurements on the on-site quality of detection	Analysis and treatment of inspection uncertainties in general	Measurement (and inspection) uncertainty	Establishment of probabilistic model

Treatment of uncertainties

Uncertainties in data-driven performance indicators

Contributors	Title	Context of work	Uncertainty types	How quantified/treated?
Masciotta, Ramos, Lourenço & Matos; Minho	Development of key performance indicators for the structural assessment of heritage buildings	Monitoring of crack opening rate, towers tilting, modal frequencies	Measurement uncertainties, change of ambient conditions (temperature, humidity)	Sample variance of static and dynamic parameter estimates; no quantification related to ambient condition changes
Moughty & Casas; BarcelonaTech	Damage sensitivity evaluation of vibration parameters under ambient excitation	Damage detection using vibration measurements	Ambient excitation	Sample covariance of damage features in outlier analysis
Hoell & Omenzetter; University of Aberdeen	Optimal damage sensitive feature projections for enhanced damage identification in wind turbine blades	Damage detection using vibration measurements	Estimation uncertainty of damage features (due to ambient excitation + measurement uncertainty); uncertainty due to choice of model describing the data	Statistical hypothesis tests

Treatment of uncertainties

Uncertainties in data-driven performance indicators

Contributors	Title	Context of work	Uncertainty types	How quantified/treated?
Omenzetter & de Lautour; University of Aberdeen	Vibration-based structural damage detection via statistical pattern recognition	Damage detection using vibration measurements	Estimation uncertainty of damage features (due to ambient excitation + measurement uncertainty)	Statistical hypothesis tests
Reynders, Chatzi, Döhler, Lombaert	Monitoring the structural health of the Z24 Bridge	One year ambient vibration monitoring	Estimation uncertainties due to ambient excitation and measurement noise, model uncertainty of baseline model describing range of environmental conditions	Variance estimation of modal parameters, damage indicator definition through Polynomial Chaos Expansion approach using the distribution of temperature parameters

Treatment of uncertainties

Model-based performance indicators with uncertainties due to unknown material characteristics

Contributors	Title	Context of work	Uncertainty types	How quantified/treated?
Sienko, Howiacki, Maslak & Pazdanowski; Cracow University of Technology	Structural Health Monitoring for Kościuszko Mound in Cracow	Monitoring of soil behavior in combination with numerical model	Uncertainty of soil properties (heterogeneous soil structure), change of ambient conditions (humidity), measurement uncertainties	Sample variance of estimated parameters
Omenzetter; University of Aberdeen	Analysis of in-situ strain and temperature data from post-tensioned bridges	Strain monitoring, calibration of creep and shrinkage models	Estimation uncertainty due to ambient excitation + measurement uncertainty; model uncertainties after calibration from measurements	Sample statistics, analysis of model errors
Pakrashi, O'Donnell, Wright & Cahill; University College Dublin and Cork	Instrumentation and Modelling of the 'Shakey Bridge' in Cork, Ireland	Vibration monitoring due to concern of bridge performance	FE model uncertainty due to existing damage in bridge and unknown material strength	
Rizzo & Gaggero; University of Genoa	A posteriori monitoring of still water hull girder loads	Estimation of shear forces and bending moments	Data (weight and position of cargo are very roughly recorded), model uncertainties	Statistical hypothesis testing

Treatment of uncertainties

Fatigue/reliability analysis

Contributors	Title	Context of work	Uncertainty types	How quantified/treated?
Leander; KTH	Monitoring and fatigue assessment of a critical railway bridge in Sweden	Fatigue assessment in combination with numerical model	Estimation uncertainty of load effect through stress range spectra, uncertainty of material resistance (physical)	Variance analysis of measured response for fatigue analysis; FORM to consider uncertainties in service life estimations
Strauss, Slovik, Novak, Novak; BOKU Vienna, Univ. Brno	Shear resistance of prestressed girders	Probabilistic design of precast structural members	Measurement uncertainties, modelling and model uncertainties, material uncertainties	Probabilistic inverse analyses techniques and neural network approaches
Sykora, Markova & Diamantidis; CTU Prague, OTH Regensburg	Structural health evaluation of heritage structures	Update of performance models with monitoring results	Uncertainties in resistance parameters, dimensions, loads, model uncertainties, measurement uncertainties	Bayesian techniques for treatment

Treatment of uncertainties

Fatigue/reliability analysis

Contributors	Title	Context of work	Uncertainty types	How quantified/treated?
Alcover, Andersen & Chryssanthopoulos; COWI, Univ. Surrey	Outlier detection and fatigue life prediction based on structural health monitoring of a long-span bridge deck	Development of data-based models for asset integrity management	Data-based uncertainties due to variation of temperature and traffic, fatigue model uncertainties	Autoregressive model to quantify uncertainties in de-seasonalized time series, Monte Carlo simulation for evaluation of failure probability
Zonta, Verzobio, Cappello; Univ. of Trento	Parameter Estimation Based on Bayesian Inference: Application to a Constitutive Model for Intact Rock	Measurement of radial strain and axial stress of quartz phyllite due to axial strain	Measurement uncertainties, material inhomogeneity, model uncertainty	Bayesian inference, taking into account the estimated covariance of the likelihood functions

Treatment of uncertainties

Decision making

Contributors	Title	Context of work	Uncertainty types	How quantified/treated?
Zonta, Tonelli, Cappello; Univ. of Trento	Determination of a decision rule concerning the temporary closure of Colle Isarco Viaduct based on the Expected Utility Theory	Detect possible excessive deflections of the main span	Measurement uncertainties of prisms (also influence of temperature), structural model uncertainties	Bayesian inference, taking into account the estimated covariance of the likelihood functions
Smith, EPFL	Uncertainty estimation for asset-management decision support	Static or dynamic monitoring	Measurement and model uncertainties	Estimations from practising engineers

Treatment of uncertainties

- Sources of uncertainties:
  - **Modelling uncertainties**: underlying the choice and computation of an indicator is often a model implying an idealized representation of the system's behaviour. Examples:
    - unknown material properties
    - imperfect models for changing environmental and operational conditions
    - imperfect models for soil-structure interaction, etc.
  - **Measurement uncertainties**: observations extracted from data by SHM technology are characterized by measuring (data processing/human inspection) uncertainties.
  - **Estimation/statistical uncertainties:** an indicator computed from SHM observations is a random variable (measurement uncertainties, finite time window) with properties depending on the applied method.

Treatment of uncertainties

- **How are these uncertainties best described?**
  - Probabilistic models and statistical inference (random variables, random processes)
    - Majority of contributions
    - No distinction between aleatory and epistemic
    - Modelling uncertainty may be systematic
  - Fuzzy or interval based models.
    - Easier to define bounds on uncertain variables than distributions?
  - Scenario based models.
    - Uncertainty can not always be expressed in numbers.

Treatment of uncertainties

- **What methods are used to quantify or to propagate the uncertainties?**
  - Quantified through statistical methods and Bayesian inference.
  - Propagated through structural reliability methods (probabilistic models).
  - Practising engineers are used to cast uncertainties in bounds, though not strictly based on probabilistic principles.

Treatment of uncertainties

- **Are the uncertainties taken into account?**
  - Presence of different kinds of uncertainties widely acknowledged
  - Few contributions on the resulting statistical uncertainty of the indicators
  - Though often (at least partly) quantified, uncertainties are often not explicitly taken into account
  - Lack of consistency how the uncertainties are classified
  - Methods for their quantification and treatment only on a case specific basis
  - Concept of confidence levels should play a more prominent role, given the varied sources of uncertainties present in SHM
  - Wide range of techniques used, scope for categorisation to improve consistency and transparency

Conclusions with regard to uncertainty

- A formal, holistic and consistent treatment of the uncertainties in life-cycle asset management of structures is required, regarding in particular
  - Observations from diverse SHM technologies
  - Propagation of SHM data to indicators
  - Decisions
- Questionnaire among the COST TU1402 Action participants has shown that the importance of various types of uncertainties is widely recognized
- Formal decision theory tools (such as VoI) should include uncertainty quantification and treatment – decisions with confidence levels

General conclusions

- WG2 evolved in accordance with the objectives set in the MoU

- Participant presentations / factsheets revealed:
  - SHM applications in civil infrastructures growing fast
  - Different technology readiness levels in different sectors
  - Significant effort is being invested in improving links between monitoring data and performance indicators
  - Assessment of SHM benefits beyond component level still in its infancy

- Frameworks can improve common understanding and achieve desired levels of transparency and consistency

- Treatment of uncertainties is patchy

Thank you for your attention

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