COST Action
TU 1402

Quantifying the Value of Structural Health Monitoring

WG2

SHM Technologies and Structural Performance

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Final TU1402 Workshop

Contents

Introduction

- 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 2015-16 (1st to 4th Workshops) – resulting in more than 20 presentations

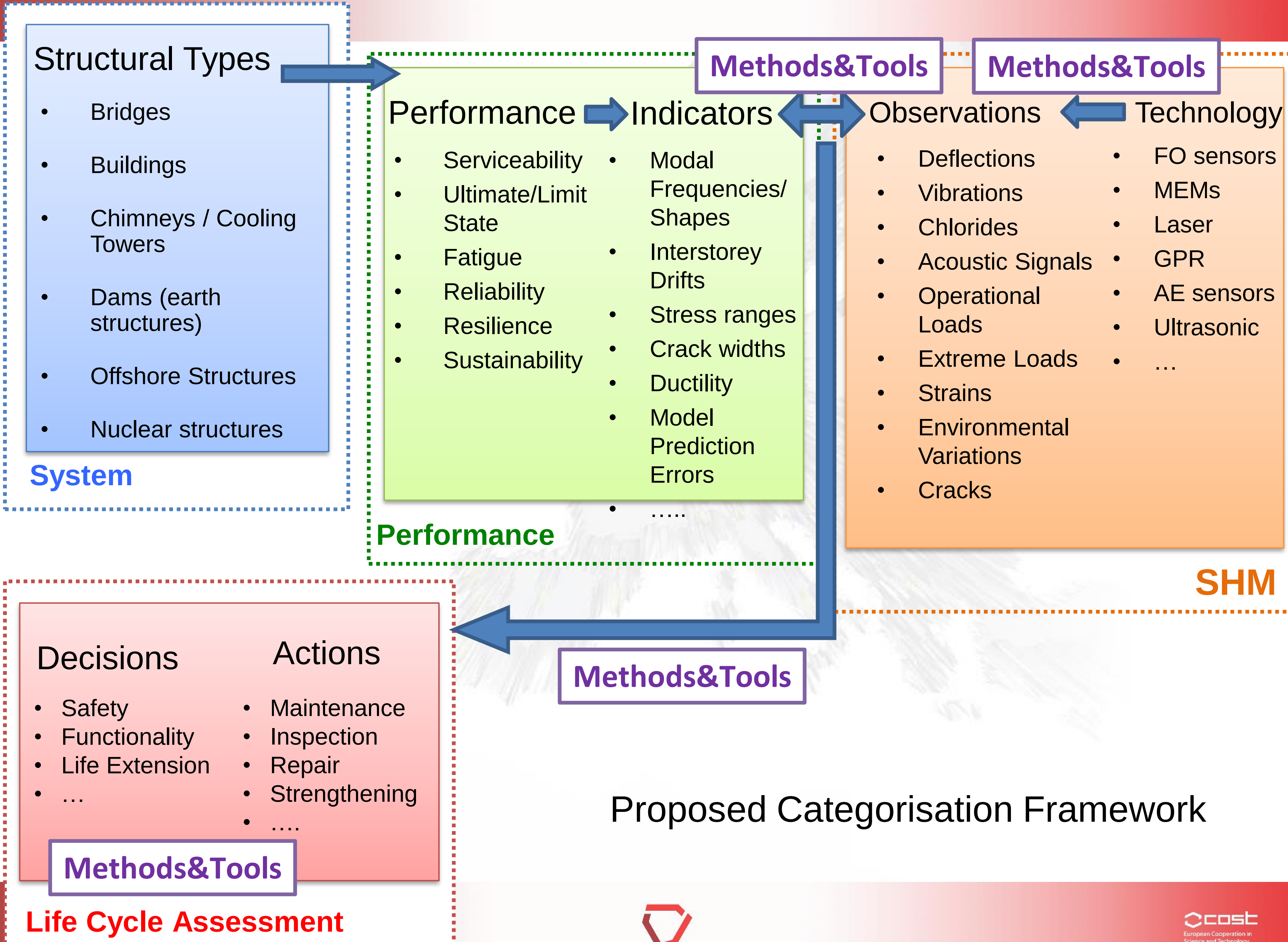
Aims

- Categorise available **SHM technologies** with regard to the **measured quantity** and the related **structural performance** – collect and represent “best practice”

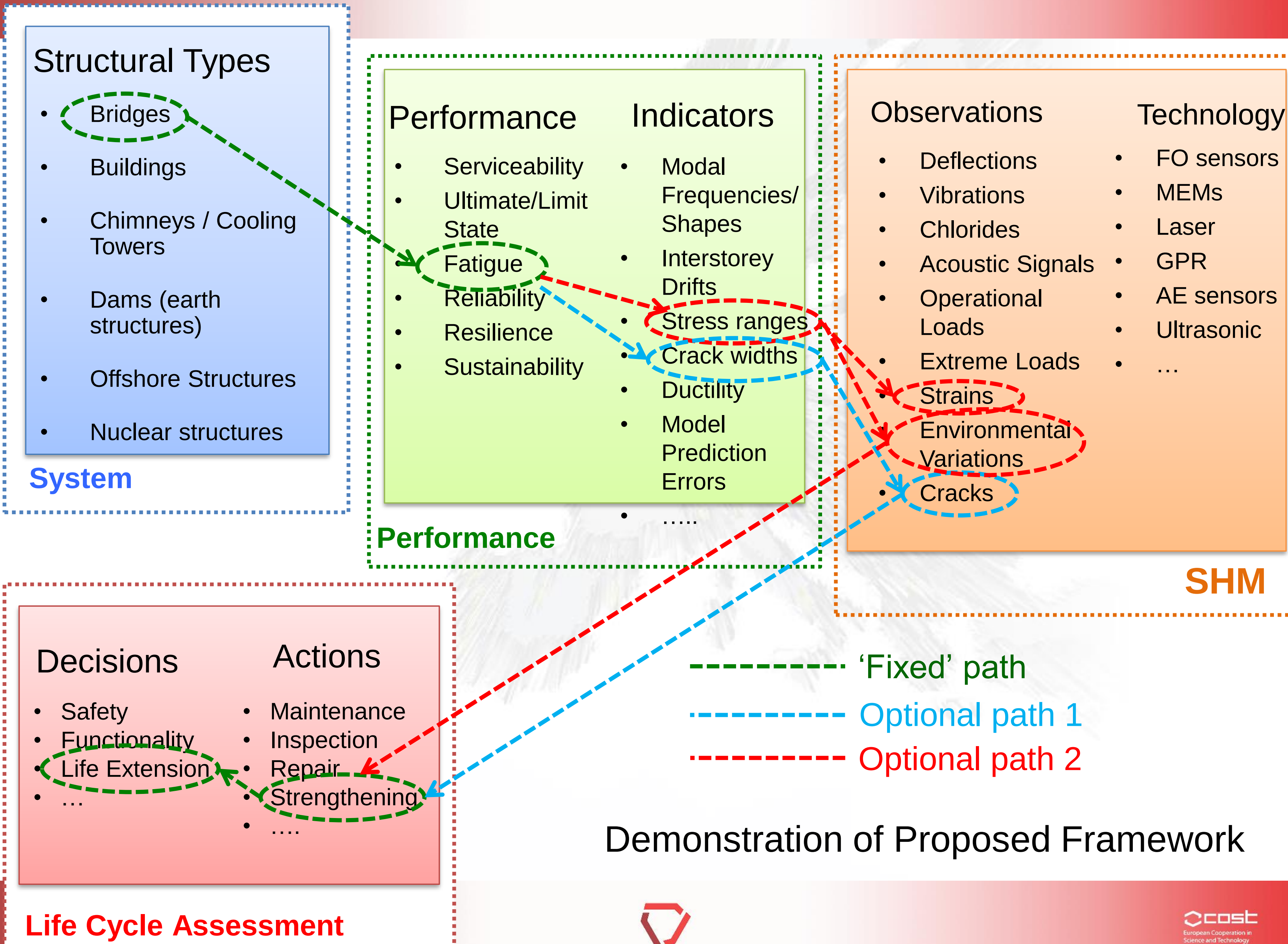
- Quantify links between measured quantities and structural performance of interest with consistent treatment of **uncertainties**.

Achievements

- Solicited factsheets (ca. 20) to record current practice in the implementation of SHM strategies in different sectors
- 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 the asset management process.
  - is linkable to the conceptualisations proposed by WG1 and WG3.
  - is developable to a greater level of detail.
- Launched a questionnaire to assess current practice in the **treatment of uncertainties** in SHM strategies.



Proposed Categorisation Framework


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

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.
- Questions 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
  - **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 and statistical models (random variables, random processes).
    - Distinguish between aleatory and epistemic?
    - Modelling uncertainty may be systematic.
    - Required information may not be available. Uncertainty on uncertainty?
  - 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

- How are the uncertainties taken into account? 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.

Treatment of uncertainties

Some remarks

- Presence of different kinds of uncertainties is acknowledged, but often methods for their quantification and treatment are missing
- Uncertainty of indicators is often (at least partly) quantified, but not used for monitoring
- Measurement uncertainty of SHM data is widely acknowledged, but few contributions on the resulting statistical uncertainty of the indicators
- Wide range of techniques used, scope for categorisation to improve consistency and transparency.

Dissemination

- Factsheets (in public domain?)
- Sessions organised at:
  - EWSHM 2016
  - IALCCE 2018
- COST action website
- COST action brochure

Concept for finalisation

- Finalise summary factsheet describing framework (draft ready)
- Continue work on treatment of uncertainties
- Prepare factsheet/paper on uncertainty treatment in SHM strategies for Final Conference

Lessons learnt

- Challenges with different approaches / technology readiness levels
- Improving links between monitoring data and performance indicators
- Defining suitable thresholds for performance indicators
- Assessing the benefits of SHM beyond the component level

Conclusions

- WG2 evolved in accordance with the objectives set in the MoU
- SHM applications are growing – exponentially?
- Frameworks can improve common understanding and achieve desired levels of transparency and consistency
- Treatment of uncertainties would benefit from directed research efforts

Thank you for your attention

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