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Implementing Information Gained through Structural Health Monitoring - Proposal for Standards

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ABSTRACT: With exception of a few issues such as design by testing, current standards do not include guidelines on the use and the quantification of value of additional information gained through Structural Health Monitoring (SHM). This contribution summarizes a recently developed draft of the guideline for practicing engineers in the framework of the EU-COST project 1402 and illustrates its application in engineering decision-making. Besides continuous and periodic monitoring, visual inspection, non-destructive evaluation and proof loading are included herein as a simple form of SHM. The guideline is independent of a type of structure, construction materials, loading, and of environmental conditions. It aims at a wide field of application including design of new structures, assessment of existing structures and type specific monitoring of a population of structures. The decision process related to the use of SHM is presented first together with relevant decision objectives and variables. Performance indicators are summarized and discussed with respect to the performance objectives. The evaluation of monitoring strategies based on life cycle costs is exposed and the selection of optimal intervention actions including safety measures is shown in representative case studies. The results demonstrate the potential of the use of monitoring to support engineering decisions and reflect though the practical benefits from the application of the guideline.

1. INTRODUCTION

With exception of a few issues such as design by testing, current standards do not include guidelines on the use and the quantification of value of additional information gained through Structural Health Monitoring. This contribution summarizes a recently developed guideline for practicing engineers (Diamantidis and Sykora 2019) in the framework of the EU-COST project 1402 and illustrates its application in engineering decision-making.

Standardization of SHM in the civil engineering sector is an important topic which needs to be developed to contrast the actual fragmentation and to increase its applications and related benefits. A summary on activities related to standardization of SHM was provided by Del Grosso (2013) and Wenzel (2013). Structural Health Monitoring (SHM) is understood in the in this contribution presented and discussed guideline as the process of measuring parameters affecting the performance of a system and of possibly identifying the presence and quantifying the extent of damage in the structural system based on information extracted from the measured system or its members. Thereby the investigated parameter can be a single variable such as a load or a structural property, a function of variables such as strain, vibration, crack width or displacement, the global condition of the structure such as recording (scanning) of signs of deterioration or even a whole capacity of network of structures for example through traffic monitoring.

Possible changes to the load, material and/or geometric properties of a structural system, including changes to the boundary conditions and system connectivity, which adversely affect the system performance, are considered. Although visual inspection, non-destructive evaluation and proof loading are commonly understood as different processes they are included herein as a simple form of monitoring since the focus of the guideline is the Value of Information (VoI).

Besides continuous and periodic monitoring, visual inspection, non-destructive evaluation and proof loading are included herein as a simple form of SHM. The guideline is independent of a type of structure, construction materials, loading, and of environmental conditions. It aims at a wide field of application including as shown also by Catbas (2009):

- Design of new structures
- Assessment of existing structures
- Type specific SHM of a population of structures

The major topics covered in the guideline include:

- Decision process
- Asset portfolio information
- Structural performance modelling
- Monitoring strategies
- Intervention actions
- Life cycle cost modelling
- Decision and Value of SHM

The aforementioned topics are briefly discussed in this contribution. The evaluation of monitoring strategies based on life cycle costs is exposed and the selection of optimal intervention actions including safety measures is shown in representative case studies. The results demonstrate the potential of the use of monitoring to support engineering decisions and reflect though the practical benefits from the application of the guideline.

2. ASPECTS IN THE DECISION PROCESS

The decision on the implementation of a SHM system depends on the expected benefit from its use reflected in the VoI, V, gained through the SHM. As introduced for example by Thöns and Faber (2013), the value of SHM can be obtained through the difference between the expected value of the life cycle benefits B_M utilizing SHM and the expected value of the life cycle benefits B_0 without SHM:

$$V = B_M - B_0 \quad (1)$$

The life cycle benefits B_0 depend on the structural performance subjected to uncertainty, the decision rules and the adaptive actions. B_M depends additionally on the SHM strategies which deliver the uncertain SHM information.

The value of information V can be therefore practically quantified as the difference between expected costs (negative benefit), i.e. expected total life cycle costs C_T with and without implementation of SHM – see for example Thöns et al. (2015):

$$V = \mathrm{E}[C_{T,0}] - \mathrm{E}[C_{T,M}] \quad (2)$$

where “0” denotes the scenario without implementing SHM, and “M” scenario with SHM, assessed before its implementation. A relative VoI can be derived as:

$$\Delta V = (\mathrm{E}[C_{T,0}] - \mathrm{E}[C_{T,M}]) \,/\, \mathrm{E}[C_{T,0}] \quad (3)$$

Total expected life cycle costs include the expected failure costs C_F and the expected operation costs C_O (the latter includes inspection and maintenance costs – operational cost):

$$C_T = C_F + C_O \quad (4)$$

Figure 1 illustrates a high-level representation of the VoI analysis highlighting the dependencies in the process according to Bismut et al. (2018).

Decision analysis can be performed in a Bayesian context. Thereby *prior analysis* is referred to as a situation when decision is to be made based on previously available, often generic, information.

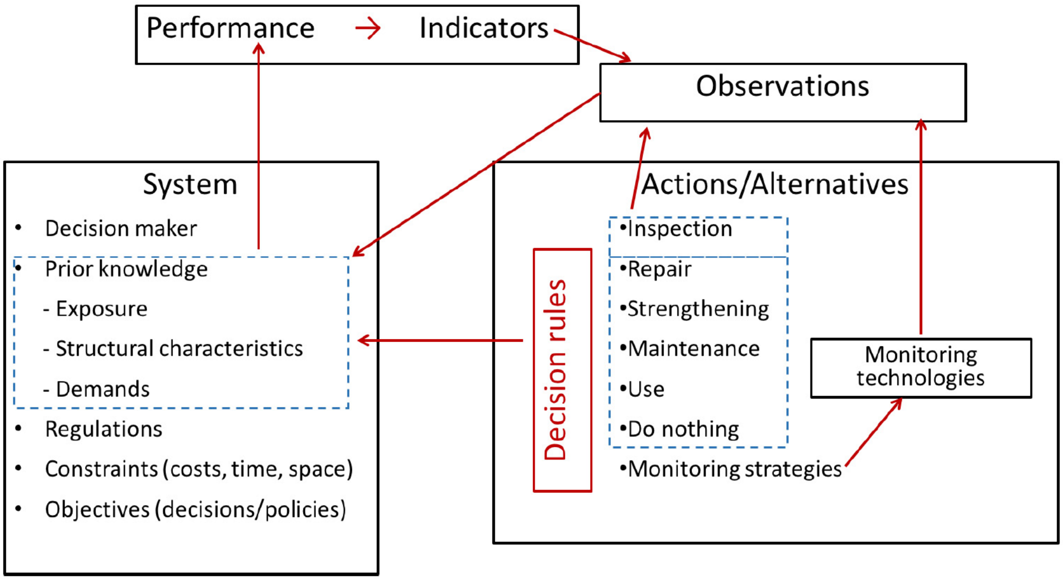

Figure 1: Representation of the VoI analysis highlighting the dependencies in the process (Bismut et al. 2018).

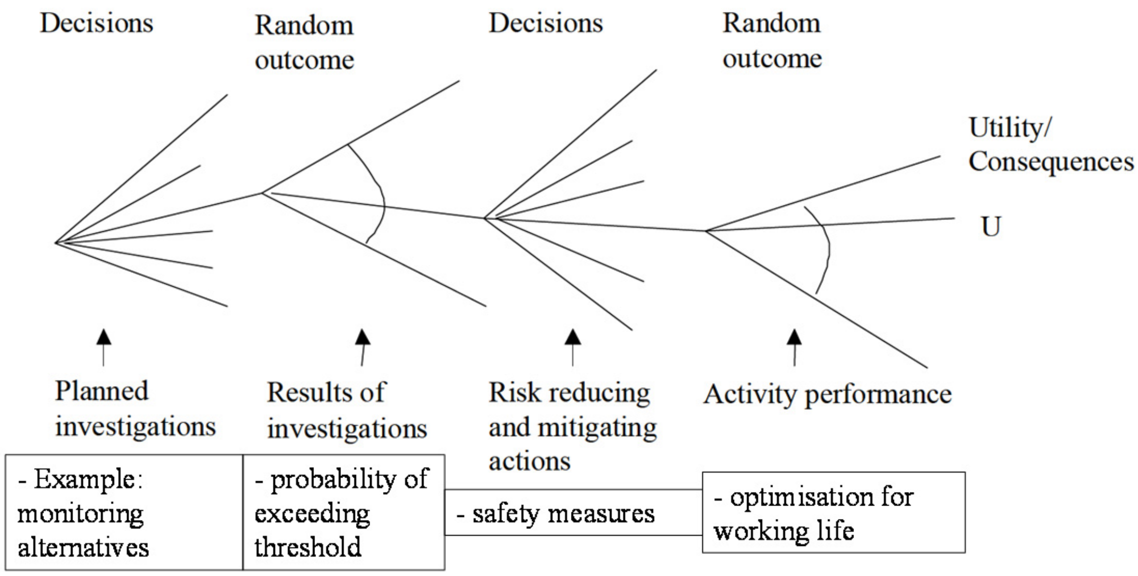

Figure 2: Decision tree for pre-posterior analysis and monitoring optimisation.

Using this prior information, probabilities are assigned to possible structural states/conditions. These assigned probabilities are called prior probabilities and designated. *Posterior analysis* corresponds to a situation when new information about the structural state becomes available for example through tests but a decision whether to carry out this inspection is not included in the decision process. Using the new information the prior probabilities assigned to the different structural states/conditions can be updated (JCSS 2018).

Pre-posterior analysis provides the framework for the consistent quantification of the VoI through SHM before it has become available. Decision trees are used which allow for any action the identification of possible outcomes and their probability of occurring. In a decision tree two main braches can be distinguished i) use of SHM and ii) no use of SHM. The difference in the expected values of benefits in both decisions trees represents the VoI.

Figure 2 shows the decision tree for pre-posterior analysis and monitoring optimisation including the various steps of this guideline as described herein. The basic decision objectives can be thereby alternatively defined as:

1. Maximize the benefit in accordance to specified preferences (improve safety or serviceability through damage control)
2. Minimize lifetime costs through control of the structural performance

A decision set must be defined which lead to a positive monitoring benefit represented by the VoI, V. The decisions D_i to be taken regarding SHM can be categorized in a hierarchical form:

- Choice of the monitoring system
- Selection of locations for SHM (space factor including local or global monitoring)
- Selection of respective time frames (frequency of monitoring, time of initiation of monitoring, duration of monitoring)

3. PERFORMANCE ASSESSMENT

The structural system characterisation is a key issue for its performance assessment. The modelling of the structure is a complex procedure and simplifications might be necessary. SHM typically cannot measure directly the structural performance at a local or global (major part of the structure) level and relies on indirect inference. Therefore, performance indicators related to the structural/system performance need to be defined or even calculated based (also) on SHM (Strauss et al. 2017). Performance indicators are used in the decision making process and they can be classified with respect to level of application:

1. Performance indicator of the network (system of structures)
2. Performance of structure (system of components)
3. Performance indicator of a structural member (component)

The indicators can be classified as follows:

1. *Direct* indicator reflecting structural behaviour and corresponding to a measurand such as material strength, strain, deflection or vibration
2. *Indirect* (for example environmental) indicator reflecting environmental and consequently mainly conditions such as actions (snow depth, wind velocity, wave height), exposure (atmospheric conditions), local traffic, soil category or type
3. *Combined* indicator reflecting the state of the structural member or system i.e. including resistance and action characteristics such as: utility ratio, damage level (for example percentage of decrease of cross section area), reliability index (based on reliability analysis including updating, see below), robustness index, expected risk value

4. MONITORING STRATEGIES

The selection of a monitoring system depends on:

1. Parameter to be measured: the direct monitoring of the interesting parameter is recommended; in case of indirect monitoring model uncertainties shall be taken into account
2. Sensitivity of monitoring system and especially of the sensors
3. Reliability of monitoring system
4. Robustness of monitoring system
5. Cost of monitoring system (lifetime including maintenance)

The monitoring system architecture includes sensors (number and specifications), sensor connections, processor/memory requirements, datalogger for transformation of the signals, computer for measurement analysis, warning system for disturbance identification, monitoring central station for data storage, sensor diagnostics.

The monitored parameters shall be related to the structural performance indicators. The direct monitoring of the interesting parameter is recommended; in case of indirect monitoring respective uncertainties shall be taken into account. In order to calculate the performance parameter from measured parameters X_i a relation through a model shall be applied and model uncertainties shall be taken under considerations:

$$Y = \mathrm{f}(X_1, X_2, \ldots X_n, \theta) \tag{5}$$

where Y denotes the performance indicator; f( ) is the model function; θ is the model uncertainty.

Monitored parameters maybe used for the calibration of structural models. The calibration is conducted by adjusting parameter values that define material, geometry and boundary conditions until the discrepancies between measured data and simulated structural behaviour are minimized with respect to an objective function.

The following shall be defined related to the execution of monitoring: location of measurements, number of measurements per time unit (static or dynamic loading), duration of measurement (spot, periodic or permanent monitoring), number of measurements, identification of disturbances, quality control and reliability of results.

The system should be able to analyse and evaluate measurement data, compare obtained results with specified criteria (*diagnostic analysis*) and give alert when respective *thresholds* $x_{\lim}$ are reached. Obtained data are subjected to quality control and to assessment of related uncertainties. Such uncertainties should be accounted for by suitably determined conversion or modification factors in the threshold levels. Such factors can be estimated from information provided by the supplier and from previous experience.

A user friendly interface shall be provided together with training for the human operators for successful organizational acceptance and adoption.

5. INTERVENTION ACTIONS BASED ON LIFE-CYCLE COST MODELLING

Intervention actions based on the monitoring results can include: do nothing, optimal inspection and maintenance plan, strengthen the structure, provide additional safety measures, reduce the residual service lifetime; use the structure under constraints or demolish the structure.

All relevant parameters including costs (considering discounting), residual working life etc. together with their uncertainties shall be thereby taken into account. The estimation of failure cost is a very important, but likely most difficult step in the cost optimisation. For consistency, all the costs need to be expressed on a common basis. Sensitivity analyses can be in addition performed to investigate different scenarios/input values.

Based on the SHM diagnostic results prognostic analyses and respective algorithms, i.e. algorithms able to estimate the remaining life of the structure can be developed and applied. Monitoring results, calculations regarding decisions etc. must be well documented and consequently documentation shall be prepared and submitted as basis for decisions in accordance with valid regulations. The operator shall assess the need for documentation in the various phases of the activities.

The integration with possible existing structure management systems such as BMS (Building Management System) is beneficial. In the past years, building information modelling (BIM) has substantially been changing the workflow of planning and operating engineering structures. Different schematic approaches towards modelling SHM information or a BIM-based representation were described by Sternal and Dragos (2016).

6. REFLECTIONS FROM SELECTED CASE STUDIES

The guideline has been developed by considering over 20 case studies developed in the COST Action TU1402. The studies vary in many aspects such as a type of the structure, SHM strategies or decisions to be taken. The implementation of the guideline is illustrated by two case studies dealing with 1) an existing stadium under snow load in the Alpine region of Italy (Diamantidis and Sykora 2018; Diamantidis et al. 2018) and with 2) a historic masonry structure (Sykora et al. 2019).

6.1. Stadium roof

Periodic (in winter periods) monitoring of the roof snow load on a stadium in the Alpine region is optimised. Monitoring strategies include M1) information on snow load on the ground at a nearest meteorological station, M2) measurements on the roof by snow depth sensor, and M3) measurements on the roof by snow load sensor. The monitoring strategies are associated with different efficiency (uncertainty) and acquisition and operation costs. When a specified threshold is exceeded, various interventions can be considered:

1. Cleaning of the roof by specialists
2. Temporary closure for one or two weeks – highly season-dependent decision; the loss slightly exceeds the cleaning cost when the stadium is fully utilised
3. Do nothing (accept the risk)

The key steps of the case study include:

- Demonstrating insufficient system reliability for the critical Ultimate Limit State verification using the partial factor method and probabilistic assessment considering the target reliability in EN 1990;
- Estimating costs using data from the industry and expert judgements (failure, safety measures, SHM operation); costs due to a partial collapse of the roof would total about 50% of the building cost of the whole structure; see Holicky et al. (2018) for details;
- Defining thresholds for M1 to M3 by economic optimisation, balancing a safety measure cost and accepted risk when no intervention is adopted in the situation with snow on the roof; the thresholds consider a three-day weather forecast so as to provide an early warning;
- Pre-posterior analysis of total cost related to M1-M3: based on ground snow load records for the site, roof snow loads are simulated for a considered lifetime; failure cost (failure before reaching the threshold) and safety measure cost (depending on an expected number of exceedances of the threshold) are estimated.

Figure 3 shows that an optimum monitoring strategy can be selected on the basis of the total cost of monitoring and safety measures over a specified reference period – the required remaining working life. It appears that M2 is associated with the highest costs as snow depth monitoring is not a low-cost approach and, more importantly, is associated with excessive uncertainties in snow density. Preferences between M1 and M3 depend on the required remaining life. For periods shorter than 14 years, M1 is optimal while the initial investments into the accurate snow load sensors (M3) are outweighed by reduced uncertainty and thus by reduced expected intervention costs for longer periods.

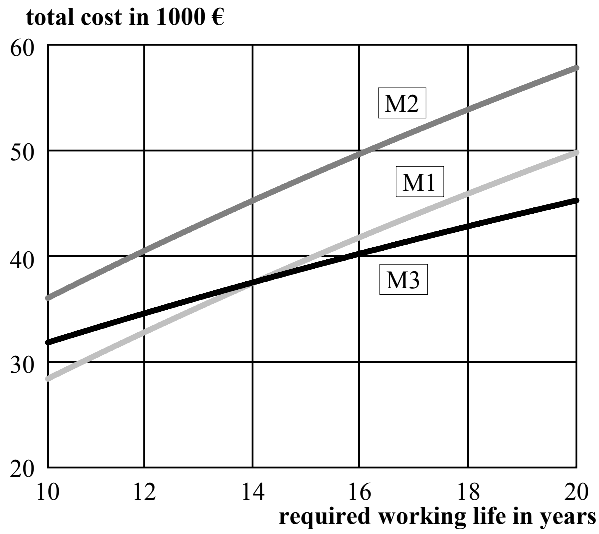

Figure 3: Variation of the expected total cost with a required working life for the three monitoring alternatives.

6.2. Historic building

In the second case study spot monitoring in terms of testing the material strength is considered. The case study of a historic building illustrates how the number of destructive tests (DTs) used to calibrate non-destructive tests (NDTs) can be optimised to provide the basis for the reliability assessment of a particular structure. Calibrated NDTs are used to establish the probabilistic model for compressive masonry strength and estimate its design value.

The preliminary assessment is based on non-calibrated NDTs. The number of DTs for calibration is then optimised by means of a probabilistic cost optimisation, considering also possible subsequent actions – 'do nothing' or 'strengthen the structure'. It is shown that the estimates of masonry unit strength based on NDTs are associated with a large dispersion and may be significantly biased. This is why it is often beneficial to conduct at least one DT.

A practical tool to determine optimum number of DTs, n_{opt}, for different outcomes of a NDT survey and different failure consequences is provided by Figure 4. The figure displays n_{opt} as a function of:

- φ_0 – the ratio of masonry strength based on non-calibrated NDTs to the masonry strength to comply with the reliability condition (e.g. the design value in the partial factor method)
- Failure consequences, considered relatively to upgrade costs; see Sykora et al. (2019) for details.

The figure suggests that no DTs are needed for $\varphi_0 < 0.2$; i.e. the NDT survey indicates the true strength be five times lower that the required strength and an upgrade is needed. Otherwise, the distinction amongst various failure consequences needs to be made:

- For low relative failure consequences: $n_{opt} = 1$ for $\varphi_0 < 1$ and $n_{opt} = 0$ for $\varphi_0 \geq 1$
- For medium consequences: $n_{opt} = 1$ for $\varphi_0 < 2$ and $n_{opt} = 0$ for larger φ_0
- For high consequences: $n_{opt} = 1$ for $\varphi_0 < 2.5$ and $n_{opt} = 2$ for larger φ_0

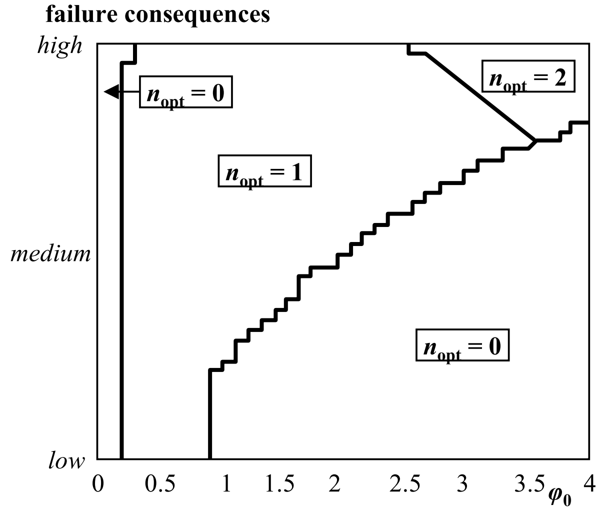

Figure 4: Optimum number of DTs as function of the ratio φ_0 for various failure consequences.

Obviously, the larger failure consequences are, the higher number of DTs should be taken. While it might seem alarming that a few DTs are needed for structures with high consequences, it is important to realise that in the case study:

- DTs are used to reduce uncertainty in NDTs
- DTs and NDTs are combined to assess a mean value of masonry unit strength (and not a low fractile like for other materials)
- Reliability of the masonry structure is predominantly affected by model uncertainty and thus it is inefficient to minimise uncertainty in material strength at high cost

7. CONCLUDING REMARKS

Current standards do not include recommendations on how to use and quantify the value of additional information gained through Structural Health Monitoring (SHM). The guideline developed within COST Action TU1402 fills this gap. However, further practical verifications and interactions with standardisation committees (e.g. within *fib* or CEN) are needed to provide user-friendly guidance covering all important theoretical aspects. This contribution discusses the background philosophy and basic steps when selecting an appropriate SHM strategy:

- Formulating decision context, objectives and variables
- Collecting asset and portfolio information
- Structural performance modelling and reliability analysis
- Updating of random variables and/ or of event probabilities
- Monitoring system design
- Data interpretation – specifying thresholds
- Selecting intervention actions
- Life-cycle cost modelling and optimisation

The guideline includes the aspects resulting from different case studies focused on the implementation of the guideline in a periodic and spot SHM. The first case study presented in this contribution shows the complexity of the decision process and indicates that an optimum monitoring strategy may depend on a reference period. The second case study demonstrates the potential of the pre-posterior analysis, allowing optimising an extent of an invasive survey based on the outcome of non-destructive tests.

8. ACKNOWLEDGEMENTS

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