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Lessons learnt

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Case studies for quantifying the value of structural health monitoring information: lessons learnt

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Abstract

This paper provides an overview, insights, results and a classification related to development and analyses of case studies within the scientific networking project COST Action TU1402 on the value of Structural Health Monitoring (SHM) information. With an outline of the framework and approaches, a procedure on how to quantify the value of SHM information on the basis of the Bayesian decision theory is described. Various case studies with different types of structures (e.g. stadium roof, timber structures, offshore wind parks), several types of SHM systems (e.g. structural measurements, damage detection) and with diverse decision scenarios (e.g. structural system properties, SHM system properties, different SHM systems for structural service life extension) are outlined. Approaches for value of SHM information analyses visualisation and classification, both for the purposes of development of decision scenarios and for the comparison of case study results are introduced and described. Whereas the development of value of SHM information analyses is focussed on the establishment of a decision scenario, the comparison of analyses should also include the identification of optimal SHM information acquirement strategies, actions and decision rules beside an indication on which methodological and technological readiness level the analyses has been performed. The paper concludes with open fields identified when applying the visualisation and classification tools.

Keywords: Value of SHM Information, Structural Health Monitoring, decision analysis, case studies

1. Introduction

Value of SHM information analyses (VoSHM) may be challenging to perform as experienced when implementing case studies within the COST Action TU1402. Many scientific approaches written from an analytical perspective on the basis of the original decision theory [1] and its introduction to civil engineering and extension to random processes according to [2] can be found. However, the implementation of VoSHM analyses requires more than the analysis perspective: It requires the systematic development of a decision scenario, which takes into account the infrastructure system, its reliability and risks performance; actions, which influence the system behaviour; SHM strategies, which provide information and reduce uncertainties of the system performance; and the benefits, cost and consequence, which are generated or caused by the infrastructure operation.

The decision scenario development can be supported by schemes for scenario visualisation and a classification, which is listing the main elements of a decision scenario leading to an overview about the set of required models and their interfaces. Moreover, a classification can be utilised to compare case studies for very relevant results such as e.g. VoSHM and readiness levels.

This paper focusses - after the introduction of the value of information theoretical basis - thus on the description of a decision scenario modelling and a classification and the exemplification of the scenario modelling with the description of two case studies.

2. Approach for the Quantification of the value of SHM

The framework for value of SHM analyses takes basis in the Bayesian posterior decision analysis [1] in conjunction with utility theory [3] and recent studies such as e.g. by Faber and Thöns [4], Straub [5] and Thöns [6] to illustrate the basic principles.

The quantification of the value of SHM requires the definition of a decision scenario that specifies the objective function, decision variables associated to the SHM system and its employment, and the temporal and spatial dimension of the decisions to be implemented.

Figure 1 shows the decision tree for a value of SHM information analysis distinguishing two basic branches. The (upper) branch without additional information from SHM represents a prior decision analysis; for the other (lower) branch, a pre-posterior analysis is required. The decisions are based on the quantification and maximization of the expected utility for each of the choices accounting for the uncertain outcomes of the chance nodes.

The utility u_0 with no consideration of SHM information depend solely on the choice of actions $a_k \in \mathbf{a}$ and the outcome of the system's life cycle performance variables $X_l \in \mathbf{X}_k$. The utility u_i considering SHM information is further dependent on the vector of the SHM strategies $i_i \in \mathbf{i}$ and the chance of its outcomes $Z_j \in \mathbf{Z}_i$.

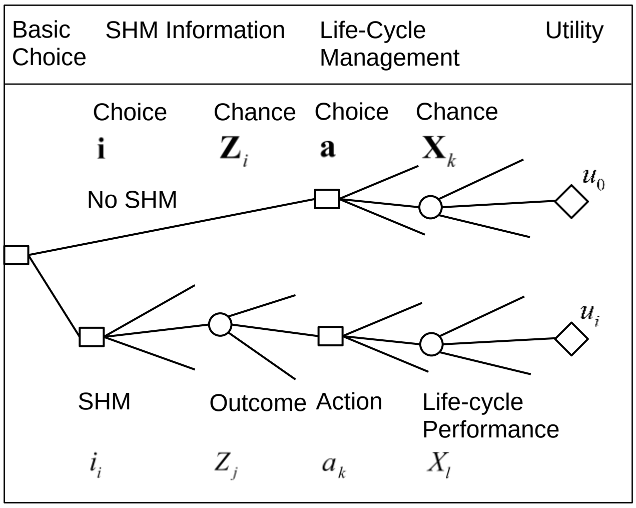

Figure 1: Decision tree for the assessment of the Value of Information containing decision nodes (rectangulars) and chance nodes (circles)

Two analysis types, namely the extensive form and the normal form analysis, can be used to quantify the expected utilities. In both forms the branch with no SHM is analysed in the same way. The expected benefit $U_0\left(a_k^{*,0}\right)$ considering the optimal action is calculated with

$$U_0\left(a_k^{*,0}\right) = max\, E_{X_l}\left[u_0\left(a_k^{*,0}, X_l\right)\right] \quad \text{and}$$

$$u_k^{*,0} = \underset{a_k \in \mathbf{a}}{arg\, max}\left(E_{X_l}\left[u_0\left(a_k, X_l\right)\right]\right). \tag{1}$$

In the extensive form, the decision tree is analysed from the right hand side of the decision tree, i.e. from the life cycle performance to the initial starting point: the choice of the information. For the purpose of calculating the expected utility $U_1\left(i_i^*, a_k^{*,i}\right)$ relating to the optimal information acquirement strategy and optimal action, first the expectation over the posterior life cycle performance are calculated by Bayesian updating (operator E''_{X_l}) and the dependency on the life cycle performance is then marginalized with the expectation in regard to the chances of the information outcome E_{Z_j} :

$$U_1\left(i_i^*, a_k^{*,i}\right) = E_{Z_j}\left[E''_{X_l}\left[u_i\left(i_i^*, Z_j, a_k^{*,i}, X_l\right)\right]\right] \quad \text{and}$$

$$\left(i_i^*, a_k^{*,i}\right) = \underset{i_i \in \mathbf{i}}{arg\, max}\, E_{Z_j}\left[\underset{a_k \in \mathbf{a}}{arg\, max}\, E''_{X_l}\left[u_i\left(i_i, Z_j, a_k, X_l\right)\right]\right] \tag{2}$$

The fundamental decision of considering additional and yet unknown information or not can then be based upon maximization of the Value of Information V, i.e.

$$V\left(i_i^*\right)=U_1\left(i_i^*,a_k^{*,i}\right)-U_0\left(a_k^{*,0}\right) \quad \text{with}$$
$$\left(i_i^*,a_k^{*,i}\right)=\underset{i_i\in\mathbf{i},a_k\in\mathbf{a}}{arg\,max}\,U_1\left(i_i,a_k\right)-U_0\left(a_k\right). \tag{3}$$

the Value of Information can be normalized in relation to the prior life cycle benefits U_0 resulting in the relative Value of Information, i.e.

$$\bar{V}\left(i_i^*\right)=\frac{U_1\left(i_i^*,a_k^{*,i}\right)-U_0\left(a_k^{*,0}\right)}{U_0\left(a_k^{*,0}\right)} \tag{4}$$

When the decision tree is applied sequentially, it may contain the information gathered in previous time steps and common influencing variables over the service life. The temporal modelling of the decision scenario should be allocated to the life cycle phases, which may be classified into planning and design, manufacturing, construction, operation and maintenance as well as decommissioning.

2.1 SHM information

SHM information can almost be directly used to update or adapt parameters of the structural system models describing the intact system, the deterioration process and the failure of constituent and system. Measurement information can be in form of physical, chemical and or empirical parameters. Measurements are obtained continuous or discrete and local or global, i.e. in relation to the response of the structural system. The probabilistic characteristic of measurement information is dependent of the measurement process, the amount of data and measurement period in comparison to the temporal boundaries of the decision scenario and human errors during installation, operation and data analysis.

3. Domains and case studies

3.1 Domains for potential SHM value

SHM can contribute to decision that enhance safety, improve economy and limit environmental impacts throughout any system states and in any life cycle phase of an infrastructure system. The domains where SHM can be of benefit maybe classified into:

1. Utility, integrity and risk management in the operation phase of an infrastructure system

There are various scenarios where the utilisation of SHM may be beneficial. These include the integrity management planning, the service life extension, the utilisation modification and functionality enhancement, damage progression monitoring and early damage warning.

2. Code and standard calibration

Code calibration for structural types may benefit from SHM when conducted systematically. The acquired information can be used to adapt the design basis in order to spare material and monetary resources while controlling safety, risk and reliability at the desired level. By measuring the relevant magnitudes in the operational structure, the model uncertainties in the design code equations may be reduced.

3. Structure prototype development and design by testing:

The production of larger quantities of identical structures can benefit from the optimisation processes supported by SHM. A prototype may be equipped with SHM systems in order to attain an optimized structural design before mass production. The SHM data may contain information to reduce uncertainties considered in the design model. Prediction of the response and performance of the prototype and mass produced structure may become more accurate with the use of SHM data. The optimized design may thus lead to an increased life-cycle benefit of the structure.

4. Targeted SHM system development

Similar to the benefit for the design of structures, new SHM systems may be designed and optimized using VoSHM concepts [5], [7]. The optimisation parameters may be the SHM strategy including the instrumentation as well as the number and placement of sensors.

3.2 TU1402 Case study portfolio

During the COST action TU1402 a case study portfolio have been developed. In total 7 case studies have reached an advanced stage and are documented by fact sheets and other publications. The types of structures range from concrete- and steel bridges, buildings and geotechnical structures. Fatigue, corrosion and creep had been considered as damage mechanism and both discrete inspection and continuous monitoring has been considered.

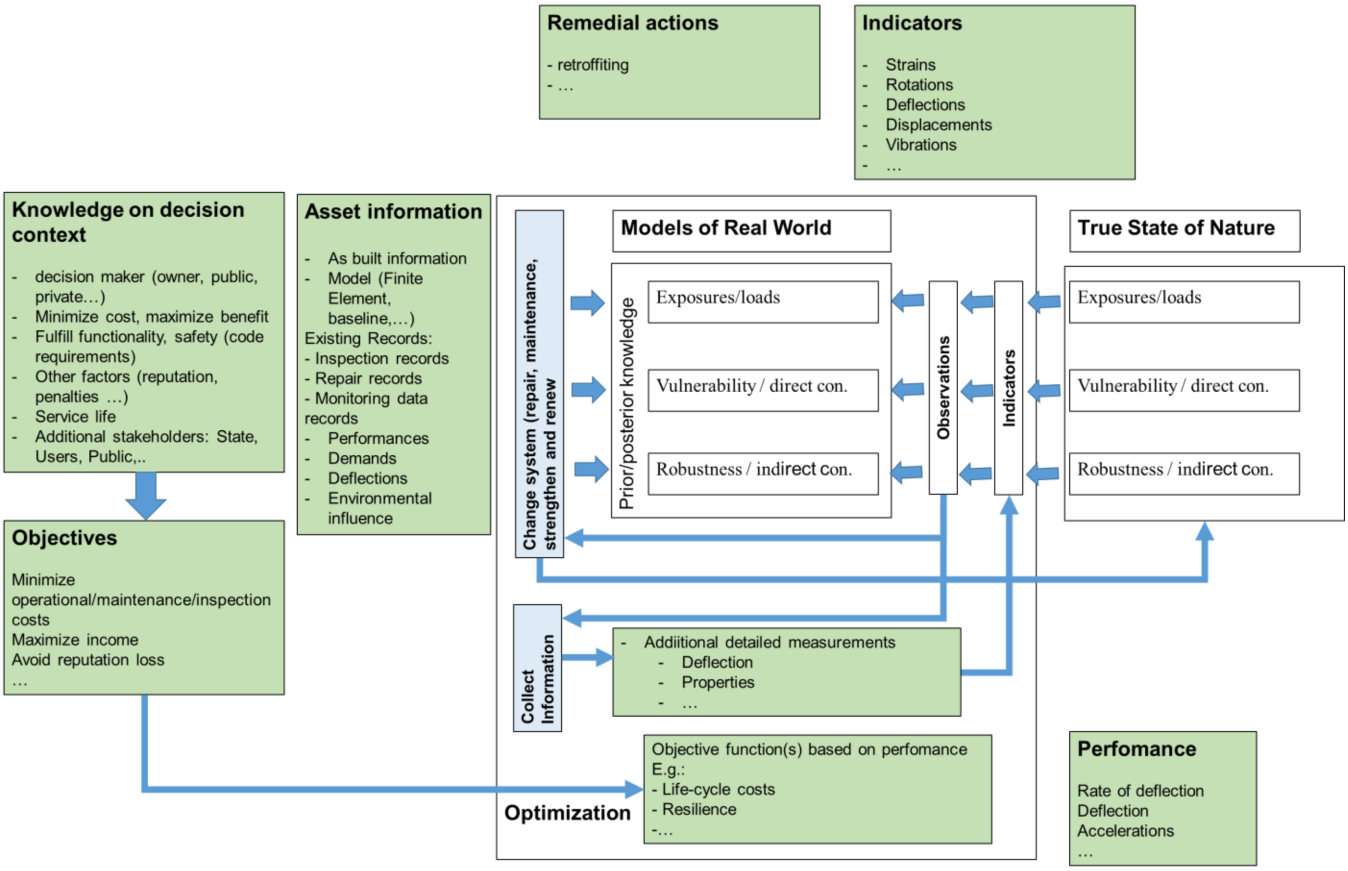

Figure 2. Flow chart for VoSHM analysis of engineering systems. Grey and white parts are general for all cases, green parts are case-specific inputs [13].

3.3 Definition and visualisation of decision scenarios

To enable drawing parallels between different case studies a consistent visualization and classification of the decision for a VoSHM analysis is required. Figure 2 presents a flow chart for VoI analysis for engineering systems. The consistent part for all cases are the white and grey areas. The white areas represent the understanding of the decision maker about the true state of nature, which is represented in his models of the real world. The grey areas show the actions available: the first option being system changes such as maintenance or renewal and the second the collection of information through measurements and monitoring of indicators.

In defining the decision scenario the first step is to define the decision context, which entails the of objectives are to minimize costs, but also less tangible objectives such as preventing the loss of reputation. Additionally, it is important to have insight in other stakeholders and the specific decision context. For example, if funding is only available for specific actions (e.g. only for retrofitting and not for monitoring) this can drastically change the optimal strategy from the perspective of the decision maker and lead to suboptimal decisions from an industrial and societal perspective or the perspective of other stakeholders. The context of the decision and the objectives by the decision maker should lead to an objective function that is optimized based on the performance for different actions. These actions consist of the application of SHM in combination with remedial actions such as maintenance or retrofitting (see Figure 1). SHM in this case is aimed at measuring indicators such as deflection, strains or cracks, which in turn give information on critical performance indicators that can be used to update the model of the real world by enriching the available asset information and reducing epistemic uncertainties. Such a performance indicator can for instance be the maximum rate of deflection, acceleration or the failure probability estimate based on the updated model. There must be a relation between indicators and the performance of the structure as given by the model, otherwise the SHM results cannot be translated to an improved model and more optimal actions. The actions taken can be defined as a single action (e.g. a single retrofitting decision [8]) or as a set of actions based on decision rules (e.g. retrofit if estimated failure probability drops below a critical level [9]). In addition, the type of SHM can be evaluated to decide upon less or more extensive (as e.g. investigated in [9]).

In summary, a decision scenario for VoSHM consists of a consideration between exploiting the current information on engineering behaviour as a basis for remedial actions, versus implementing actions without additional information. This consideration is evaluated based on an objective function derived from the objectives that follow from the decision context.

3.4 Classification and communication of case study results

Within COST TU1402 a classification is used to align and compare the case studies (Table 1). The classification is exemplified with two TU1402 cases namely the cases of flood defence monitoring and of soil testing for offshore windparks.

3.4.1 SHM of a flood defence

The case on SHM of flood defences was previously described in [10] and considered monitoring of an earthen sea dike in the Netherlands. After disapproval of a flood defence (i.e. the first part of the design phase), the question arose whether the results from the assessment model were realistic. It was decided by the asset owner to investigate monitoring, as it was deemed realistic that the outcomes could lead to a reduction of the societal costs for meeting the safety standards. The main reason would be a better characterization of the soil characteristics in the dike body, and their behaviour under extreme circumstances. In the analysis two decisions are considered: first whether monitoring is implemented, and second, based on the outcome of the monitoring, if and what amount of reinforcement is needed. The monitoring is mostly monitoring of groundwater levels during high water situations. In the analysis both the duration of the monitoring and uncertainty in measurements was varied. As the analysis was done after partly implementation of the project, we can distinguish both a posterior and pre-posterior VoSHM. As the monitoring showed that the flood defence was much stronger than initially estimated, the posterior VoSHM of the monitoring that was carried out are in the order of 60%. From the pre-posterior analysis it was found that, as the flood defence did not meet the standard at the initiation of monitoring, any delay in reinforcement would lead to very high failure costs. Therefore, we can distinguish two VoSHM values for the pre-posterior analysis: the first VoSHM value describes the case where monitoring translates to postponement of the reinforcement.

The second VoSHM value is based on a pre-posterior analysis where the reinforcement is not postponed due to the monitoring campaign (i.e. it is perfectly integrated in all the preparation work of the reinforcement). With postponement the VoSHM is found to be -42%, without postponement 2.5%.

	Type	**Description**
Structure	Life cycle phase	*Which phases are considered in the decision analysis: design, construction, operation, decommissioning …*
	Performance	*Extreme loading, deterioration, component or system*
Decision objective	Decision maker	*Who decides?*
	Decision point in time	*In which life cycle phase?*
	Objective	*Describe the objective function*
	Boundaries	*What boundaries e.g. for life safety apply?*
Decision variables	Actions	*E.g. Repair, maintenance*
	Action parameters	*Which parameters of the actions are varied?*
	Information acquirement strategies	*E.g. strain gauge measurements, damage detection etc.*
	Strategy parameters	*Which parameters of the information acquirement strategies are varied?*
Results	Value of Information	*What is the VoSHM resulting from the analysis?*
	Decision rules	*Which decision rules (information outcome - action relation) have been derived?*
	Readiness level	*In accordance with Horizon2020 TRLs*

Table 1. Classification for COST TU1402 case studies [14].

3.4.2 Soil testing for offshore wind parks

Monopiles are the most common solution for supporting wind turbines in offshore conditions. At the design phase of a monopile, a frequency check is to be performed to avoid the resonance hazard with the 1P and 3P excitations, i.e. the frequency domains at which the blades and the rotor provokes excitations. However, the estimation of the first natural frequency of the structure is associated with large uncertainties, especially due to lack of knowledge about the soil-structure interaction. Resonance induced phenomena leading to dynamic excitations results in a reduced fatigue life (see [11] and [12]). In this case study, the frequency check is addressed following a probabilistic formulation. A rational decision framework is formulated to find an optimum design, based on the evaluation of the expected consequences of failure using risk metrics. Furthermore, the value of acquiring further site-specific information on the soil characteristics is addressed by means of a value of information analysis. The system is represented by a Bayesian network that did facilitate the analysis. The results did provide insight on (1) the relation between design parameters and the risk associated with dynamic amplifications; and (2) how to efficiently distribute the resources at the design point in time between investments into the design and investments into additional soil tests.

The case study represents a full Value of Information analysis. However, some simplifications had to be taken. First, the optimum design was assessed utilizing available prior information. Insight regarding the optimum dimensions of the monopile support structure was provided. These results were then used to estimate the value of information of testing the site-specific soil conditions. The obtained net value of information was found to be significantly smaller than the cost of a typical offshore soil testing campaign. Nevertheless, the study considered a single OWT rather than an offshore wind farm. Taking into account the wind farm system effects may have a significant impact for the value of the experiments. Information could be used to update the spatial variability of the soil properties and the estimated prior correlation between the soil characteristics at different locations within the wind farm. Additionally, the comparison of the computed value of information and the costs of performing a soil campaign could be compared in a fair manner. It should be noted that the benefit of inspecting the soil conditions are broader than just updating the knowledge regarding the soil parameters. For instance, the value of hazard identification on the seabed should be included in the analysis.

4. Lessons learnt and conclusions

Value of information analysis can be a powerful concept to enhance operation and maintenance of structures. The case study portfolio developed in COST Action TU1402 has illustrated the applicability of the developed approaches, concepts and tools to provide decision support on the basis of structural performance, SHM performance and cost and consequences models to achieve a maximum utility for the decision maker. Throughout the case study work with the TU1402 network and in conjunction with several workshops the following lessons have been learnt:

1. A VoSHM analysis requires the identification and modelling of a decision scenario and its temporal and spatial boundaries in conjunction with a classification. The decision scenario includes the considered structural system and its performance, the decision objective and its boundary conditions, the decision variables associated to the choices of SHM and actions. The temporal modelling should include the decision point in time to distinguish between a pre-posterior and posterior VoSHM analysis and the service life or life cycle period of the infrastructure.
2. A complete representation of the a priori risk is necessary. This includes the (physical) representation of the events that lead to consequences as well as the quantification of the consequences in monetary units. Both is associated to uncertainties and the justified quantification of these uncertainties is often particularly challenging.
3. The information that can be gained by the measurements or by monitoring require a probabilistic description e.g. in the form of a likelihood. For many and especially scientific monitoring approaches in conjunction with and extensive data analysis further probabilistic models need to be derived including up- or downscaling in the system space, i.e. local measurements vs. global structural behaviour and vice versa.
4. There can be an enormous difference in posterior and pre-posterior Value of SHM Information as demonstrated with the flood defence case study.
5. It is important to identify and assess SHM opportunities in an early stage of an infrastructure's design life or - even better - in the design phase.

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