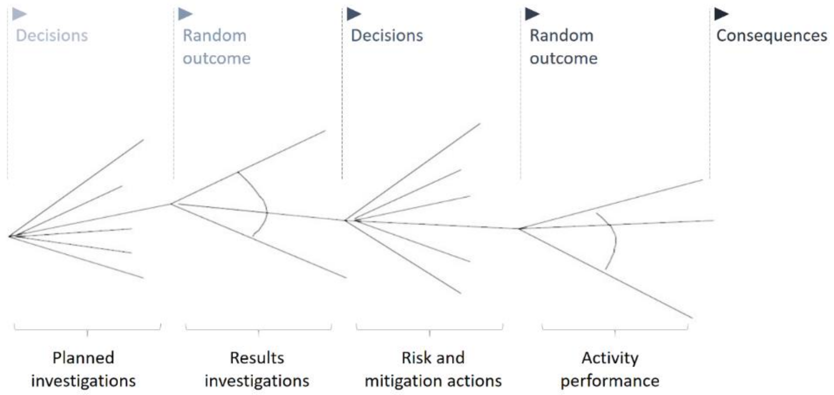
Quantifying the Value of Structural Health Information for Decision Support

GUIDE FOR PRACTISING ENGINEERS



Authors
Dimitris Diamantidis [1]
Miroslav Sykora [2]
Helder Sousa [3]

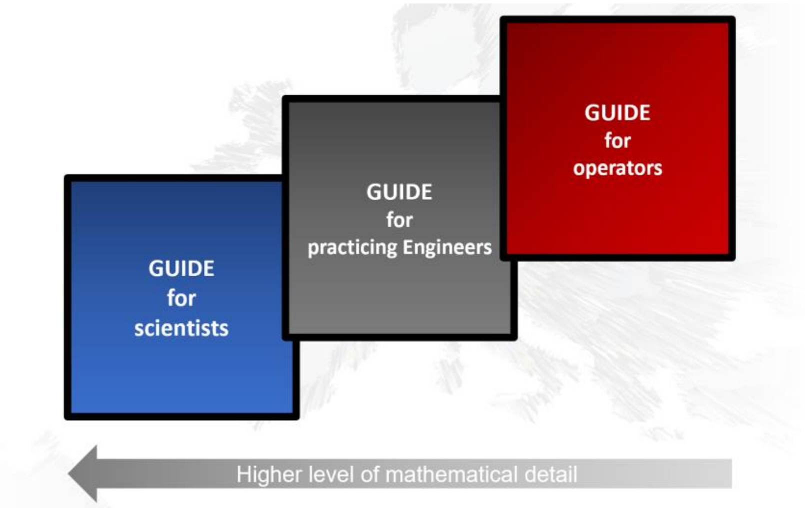
May 2019

[1] Ostbayerische Technische Hochschule Regensburg, Regensburg, Germany
[2] Czech Technical University in Prague, Prague, Czech Republic
[3] BRISA Group / HS Consulting, Portugal

Preface

The Guides for Operators, Scientists and Practicing Engineers on Quantifying the Value of Structural Health Information (SHI) for Decision Support have emerged from the scientific networking project COST Action TU1402 (www.cost-tu1402.eu) in the period from 2014 to 2019. The guides are the result of the TU1402 Working Group 5 on Standardisation in conjunction with the work of the Joint Committee on Structural Safety (JCSS – www.jcss.co).

The Guide for Operators contains recommendations for the use of SHI value analyses by infrastructure owners, operators and authorities aiming at an enhanced infrastructure performance and utility management in terms of costs, life safety and sustainability. The Guide for Scientists provides a consistent formulation of value of SHI decision scenarios encompassing probabilistic SHI system performance and cost models, probabilistic infrastructure performance and utility models and approaches for adapting infrastructure performance models with SHI. The Guide for Practicing Engineers aims to provide guidance in applying, implementing and using results of value of SHI analyses.



CONTENT

Nomenclature

List of symbols and abbreviations which are consistently used in this guide. Symbols which are not listed here are defined at their location of first use.

Roman & Greek symbols

B_0:	expected life cycle benefits without the utilization of any *SHM* strategy
B_M:	expected life cycle benefits by the utilization of a *SHM* strategy *M*
β:	reliability index
$C(\ )$:	consequences
C_{Ak}:	annual maintenance/operation costs
C_F:	present value failure costs
C_O:	annual operational costs
C_T:	total life cycle costs
d_j:	decision rule *j*
$\delta(\ )$:	discount rate function
E:	action effect
$f(\ )$:	model function (e.g. joint probability density function)
$E[\ ]$:	expected value
F:	failure event
$g(\ )$:	limit state function
p_f:	failure probability related to a reference period (typically one year)
q:	annual discount rate
R:	risk
R:	resistance
R_H:	human risk
R_F:	economic (financial) risk
t:	time
t_{ref}:	reference period
T_L:	service life of the potential safety measure
V:	value of information
$\boldsymbol{X}$:	vector of random variables
X_i:	monitored parameter *i* (also random variable *i*)

x_{lim}: threshold associated with the monitored parameter *i*

Acronyms and abbreviations

BIM: Building Information Modelling

BMS: Building Management System

CC: Consequence Class

FORM: First Order Reliability Method

LQI: Life Quality Index

LCC: Life-Cycle Costs

NDT: Non-Destructive Testing

PI: Performance Indicator

PoD: Probability of Detection

SHM: Structural Health Monitoring

SHI: Structural Health Information

SORM: Second Order Reliability Method

SWTP: Societal Willingness To Pay

VoI: Value of Information

Glossary

List of technical terms which are consistently used in this guide along with explanations of their meanings, which are based mainly on [1-3].

#	Technical term	Meaning
A	*Accuracy*	difference between the result of the measurement and the actual value of the measurand (this is frequently provided by manufactures)
	Asset	Infrastructure (resource) with economic value that an individual, corporation or country owns or operates
B	*Bayesian decision analysis*	probabilistic framework to quantify the utility and decision attributes (e.g. costs, benefits, consequences for human safety)
C	*Conjugate distributions*	prior and posterior distribution functions are from the same probability distribution family
C	*Consequence*	outcome of an adverse event including human, economic and environmental contributions
	Consequence Class	Categorization of the consequences of structural failure
D	*Damage*	Change in the condition of the structure that can affect the structural performance unfavourably
	Damage characterization	process of ascertaining the time of occurrence, physical location and the size of the damage
	Data acquisition	sampling and processing of monitored data
	Data analysis	transformation of data into an applicable information
	Decision tree	tree-like graph or model of decisions and their possible consequences, including probabilities and costs or utilities
	Deterioration	process that adversely affects the structural performance, including the reliability over time; it can be caused by various reasons, such as chemical, physical and biological actions.
E	*Error (systematic)*	value that remains constant when measurement is repeated under the same conditions
F	*Failure*	Insufficient load bearing capacity or inadequate serviceability of a component of the system or of the whole system.
	Filter	electronic device or mathematical algorithm to process a data stream by means of separating the frequency components of signals.

#	Technical term	Meaning
I	*Information*	knowledge gained by means of measurement(s), analytical, numerical or empirical methods related to the decision scenarios.
	Information (sample)	knowledge that describes a realization of the value or state of a random property
	Information (perfect)	knowledge that describes the true value/state of a deterministic property
	Inspection	On-site non-destructive examination aiming to assess the actual condition of the structure
	Inspection (qualitative)	On-site examination of parameters that relies primarily on words such as surface condition (good/bad), visible deformations (yes/no), crack patterns (diffuse/regular), etc.
	Inspection (quantitative)	On-site examination of parameters that relies primarily on numbers such as crack length, corrosion area, etc.
L	*Lifetime or lifecycle cost*	sum of all recurring and one-time (non-recurring) costs of the structure over the lifetime
	Limit state	state beyond which a structure no longer satisfies the design requirements
M	*Measurement*	process to determine a value (if quantitative) or status (if qualitative) of a parameter
	Model uncertainty	basic variable related to the accuracy of physical or statistical models
	Monitoring	procedure related to observation or measurement of structural conditions or actions or structural response
	Monitoring system	technical system (including hardware and software) that allows to collect information related to the parameters of interest
P	*Performance Indicator*	parameter describing a certain property of the structure or a certain characteristic of the structural behaviour
	Periodic monitoring	repeated action over time by means of a temporary monitoring system on a structure towards the collection of measurements for a short period of time
	Periodic monitoring (triggered)	collection of measurements by means of a programmed criterion, usually a predefined threshold related to a parameter that is being measured which triggers the data recording (e.g. observation of accelerations)

#	Technical term	Meaning
P	*Permanent monitoring*	continuous action over time by means of a permanent monitoring system on a structure towards the collection of measurements for a long period of time
	Portfolio	group of assets sharing a common set of characteristics (e.g. structures, in general, with a permanent monitoring system installed, bridges from a specific concessionaire, corroded metallic bridges)
	Posterior distribution function	probability distribution that expresses the knowledge about a parameter after relevant evidence (e.g. new data) is considered
	Prior distribution function	probability distribution that expresses knowledge about a parameter before some evidence is considered
	Probability of Detection (PoD)	chance of detecting a failure, which is generally expressed as a *PoD* curve that relates the likelihood of detection to a parameter related to the failure
	Proof loading	test to demonstrate the fitness of a load-bearing structure
S	*Sensors*	device that allows the observation of a parameter of interest by means of known correlation between the parameter and an electric/optic parameter (e.g. electric strain-gauge, *fib*re optic sensor)
	Structural performance	behaviour of the structure or one of its members usually quantified by means of a quantitative parameter (e.g. reliability index, ratio between resistance capacity and action effect)
R	*Reference period*	period of time used as a basis for assessing the statistical parameters of time dependent variables and of the target reliability
R	*Reliability*	ability of a structure or a structural member to fulfil the specified requirements, during the planned working life
	Reliability index	reliability indicator (substitute for the probability of failure)
	Risk	expected value of all undesired consequences (direct and indirect); it combines the probability of failure and related consequences
	Risk management	coordinated activities to direct and control an organization towards the minimization of occurrence of potential risks
U	*Uncertainty*	imprecision of a parameter which can be classified by its origin, namely (i) model uncertainty, (ii) statistical uncertainty, (iii) measurement uncertainty (error) and (iv) human and/or organization error.

#	Technical term	Meaning
U	*Uncertainty (epistemic)*	imprecision due to a lack of knowledge, which can always be reduced by means of new knowledge (e.g. acquired by measurements).
	Uncertainty (aleatory)	imprecision due to pure randomness, which is an inherent property of an uncertain parameter
	Utility	numerical (most often monetary) measure that corresponds with a certain procedure/decision that has been implemented
	Utilization ratio	Ratio between design action effect and design resistance
V	*Value of Information*	numerical difference between the expected benefit (utility) estimated with the implementation of the *SHM* and the expected benefit without implementation of the *SHM*
W	*Working life (design)*	assumed period for which a structure, or a part of it, is to be used for its intended purpose with planned maintenance but without major repair being necessary
	Working life (residual)	remaining period for which an existing structure, or part of it, is to be used for its intended purpose with the implementation of the maintenance plan

Supportive normative documents

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 [5, 6]. Table 1 summarizes the most relevant supportive literature for this guide (standards and guidelines).

Table 1: List of normative documents related to *SHM* and field of application.

Year	Title	Scope/Application Field	Ref
2017	EN 16991: Risk Based Inspection Framework	hydrocarbon and chemical process industries, power generation and other industries where risk-based inspection is applicable	[4]
2016	UNI/TR 11634: Linee guida per il monitoraggio strutturale	Civil Engineering structures by identifying the design criteria of the monitoring systems and methodologies, including methodologies for identifying the damage and material degradation.	[5]
2015	ISO 2394: General Principles on Reliability for Structures	structures of buildings in general by identifying the basis for decision making related to load-bearing structures relevant to the construction industry towards the systematic and rational treatment of risk to implementation of reliability-based design.	[6]
2014	GB50982–2014: Technical code for monitoring of building and bridge structures	monitoring technology for high-rise buildings, long-span spaces, bridges and seismic isolation structures and the corresponding analysis and early warning, to achieve advanced technology, reliable data and reasonable economy.	[7]
2014	ISO 55000: Asset Management Principles	overview of asset management and asset management systems, which can be applied to the broadest range of assets, in the broadest range of organizations, across the broadest range of cultures.	[8]
2013	ISO 16739: Industry Foundation Classes for data sharing in the construction and facility management industries	open international standard for Building Information Model (BIM) data that is exchanged and shared among software applications used by the various participants in a building construction or facility management project.	[9]
2012	RVS 13.03.01: Monitoring von Brücken und anderen Ingenieurbauwerken	monitoring of bridges and other engineering structures and is aimed at both the maintenance contractors and builders as well as the providers of monitoring systems	[10]

Table 1*: List of normative documents related to SHM and field of application.*(cont.)

Year	Title	Scope/Application Field	Ref
2011	EN 15331: Criteria for Design, Management and Control of Maintenance Services for Buildings	criteria and the general methods that can be used in the planning, management and control of maintenance in buildings and their surrounding area according to the applicable legal requirements, objectives of the owners and users and the required quality of maintenance	[11]
2010	GOST R 53778: Buildings and Constructions Rules of Inspection and Monitoring of the Technical Condition	regulatory basis for the control of mechanical safety degree and realization of design works aimed to increase a degree of mechanical safety of buildings and constructions, including general monitoring of technical condition of buildings and constructions to detect objects whose structures changed their stress and strain state and requires the examination of their technical condition	[12]
2010	ISO 13822: Bases for design of structures - Assessment of existing structures	general requirements and procedures for the assessment of existing structures (buildings, bridges, industrial structures, etc.) based on the principles of structural reliability and consequences of failure (based on ISO 2394)	[13]
2010	VDI 6200: Standsicherheit von Bauwerken - Regelmäßige Überprüfung	assessment criteria and practical instructions for the regular verification of structural safety and recommendations for the maintenance of buildings	[14]
2009	ISO 13824: Bases for design of structures - General principles on risk assessment of systems involving structures	general principles on risk assessment of systems involving structures, by facilitating and enhancing decision-making regarding monitoring, reducing and managing risks in an efficient, cost-effective and transparent manner.	[15]
2008	EN 31010: Risk management – Risk assessment techniques	guidance on selection and application of systematic techniques for risk assessment (supports standard ISO 31000)	[16]
2006	ISO 14044: Environmental management – Life cycle assessment	requirements and provides guidelines for life cycle assessment (LCA) including goals, scope, phases, impact, review, limitations and conditions for use of value choices and optional elements.	[17]

Table 1*: List of normative documents related to SHM and field of application.*(cont.)

Year	Title	Scope/Application Field	Ref
2004	ISO 16587: Mechanical vibration and shock - Performance parameters for condition monitoring of structures	stationary structures (buildings, bridges and tunnels, towers, masts and antennae, tanks and silos, retaining walls and dams, jetties and other shore-side structures, offshore platforms, pressure vessels, and pipelines), it describes performance parameters for assessing the condition of structures, including types of measurement, factors for setting acceptable performance limits, data acquisition parameters for constructing uniform databases, and internationally accepted measurement guidance.	[18]
2003	ISO 14963: Mechanical vibration and shock - Guidelines for dynamic tests and investigations on bridges and viaducts	guidelines for dynamic tests and investigations on road, rail and pedestrian bridges and viaducts (both during construction and operation), by providing provides general criteria for dynamic tests.	[19]
2002	Monitoring and safety evaluation of existing concrete structures	Summary of the most important inspection and measuring methods, with emphasis on non-destructive systems, lifetime monitoring, data evaluation and safety aspects	[20]
2002	EN 1990: Eurocode - Basis of structural design	structural design of buildings and other civil engineering works, including geotechnical aspects, structural fire design, situations involving earthquakes, execution and temporary structures.	[2]
2001	ISIS Canada: Guidelines for structural health monitoring	composition of *SHM* and the treatment of data, field testing, static and dynamic testing, the periodic monitoring, bridge case studies	[21]
2001	JCSS: Probabilistic Model Code	model code for full probabilistic design by covering basis of design, load models, resistance models and examples	[1, 22]
1999	DIN 1076:1999-11: Ingenieurbauwerke im Zuge von Straßen und Wegen	engineering structures in connection with roads - inspection and proof testing of bridges	[23]
1997	NORSOK N-005: Condition Monitoring of Loadbearing Structures	integrity management of offshore structures and marine systems throughout their lifetime, covering management of data, inspection and/or monitoring strategies, inspection and/or monitoring execution, integrity evaluation and integrity assessment	[24]

1 Scope

Structural Health Information (*SHI*) is understood in this guide as the process of measuring parameters related to conditions of a structural system and consequently related to its performance. These parameters can be (i) a single variable such as load (action parameter), (ii) a structural property or (iii) a function of variables such as strain or displacement (response). Information related to the global condition of the structure, such as records of signs/evolution of deterioration or even the whole capacity of a network of structures (for example through traffic monitoring), are also covered by this definition. Although visual inspection, non-destructive evaluation and proof loading are commonly understood as specific processes, here they are considered to be a part of *SHI*. In the concept of *SHI*, Structural Health Monitoring (*SHM*) plays a key role. The focus is on the quantification of the Value of Information (*VoI*) that results from the comparison of:

- the gain from obtained information and
- associated costs and risks.

The approach presented in this document is independent from material and structural system type. The *SHM* strategy is herein defined as the observation of a system at (i) specific points in time, (ii) periodically or (iii) permanently, with the main objective of providing in near real time, reliable information regarding the performance of the structural system.

The applications of current guides on *SHM* are often inconsistent mainly due to the fact that these guides are complementary. The unification with respect to the interpretation of the results and quantification of the value of additional information is thus urgently needed and is the main goal of this document. The present guide is basically referring to the accompanying guide for researchers [25] and is using results from the COST Action 1402 provided in [26-29] as well as the risk analysis principles given in [30, 31]. It is mainly addressed to practicing engineers and the providers of *SHM* systems by giving guidance on (Figure 1):

- *The decision on the SHI-based strategy* – definition of the main criteria to support the decision, which mainly includes the characteristics of the structure to be monitored (including environmental/loading conditions) and the specifications requirements in the context of monitoring.
- *The choice of the monitoring system* – definition of the characteristics of the monitoring system based on a set of criteria related to the structure, the environment/loading conditions and the monitoring system features/potentialities.
- *The VoI gained from SHI* – quantification on the benefit (or cost) derived from the collected information by means of the monitoring systems (i.e. *VoI*) based on probabilistic methods and a set of criteria related to costs of monitoring, safety measures and consequences (i.e. direct and indirect costs).
- *The decision-making process supported by the VoI* – effective integration of the *VoI* gained from the monitoring data into the protocols of decision-makers by means of a rational selection of inspection/maintenance or repair policy.

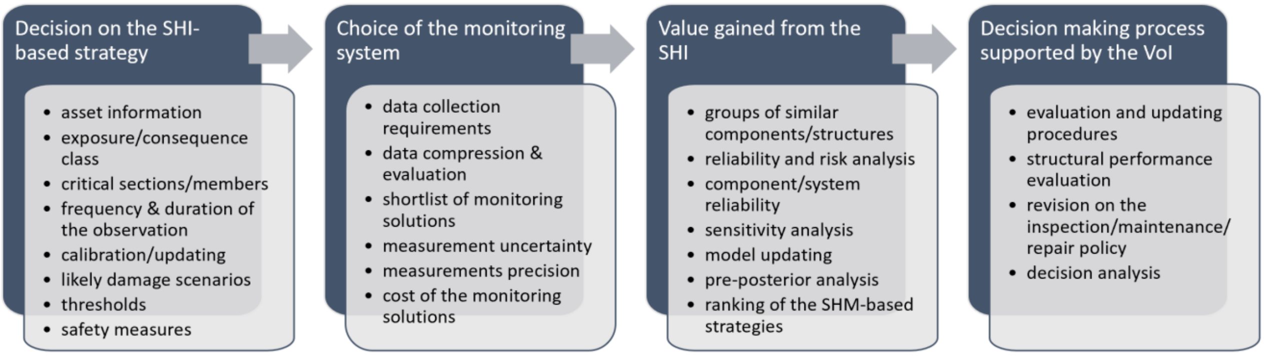


Figure 1: The four main pillars of the assessment of the *VoI* gained through *SHI*-based strategies.

Indeed, a planned and proactive implementation has been gaining interest, since it can be used together with standards to describe and verify structural performance [32]. With the objective of providing a holistic approach and credible recommendations (i.e. covering a wide field of applications), the *SHM* implementation is recommended according to [32].

Hence, and further to the concept presented in Figure 1, *SHM* can be effectively explored to assess the condition/performance of civil engineering structures and to provide data for infrastructure management and decision making. Potential benefits by using *SHM* include [32, 33]:

- reduction of uncertainties regarding critical parameters related to the condition/ performance of the structure,
- better estimation of the safety level of the structure and/or its critical components,
- updated and more accurate risk assessment related to the operational status of the structure along its lifetime,
- improvement and efficiency in the inspection and maintenance strategies,
- implementation of a risk-informed asset management.

Focusing on civil engineering structures, it becomes important to categorize, beforehand, the type of application due to specificities of each category. In this context, the field of application is subdivided into three main domains: (i) new structures, (ii) existing structures and (iii) group of (similar) structures (Figure 2). Regarding the latter, it is worth noting that the implementation of statistical sampling allows structures to be grouped into populations with similar characteristics. Hence, a prioritization of structures and/or structural members through sampling is thereby necessary.

New structures

- uncertainties related to resistance, load effects and/or structural performance are considerably larger compared to those inherent in codified safety formats
- use of new materials or innovative types of structural systems (i.e. limited experience)
- demanding structural geometry and/or environmental conditions
- specifications with unusual requirements (i.e. stricter compared to standards)
- planning of prototype structures (i.e. novel design), which are difficult to be assessed solely by means of numerical analysis
- expected value of adverse consequences (e.g. damage/failure), significantly exceeds the costs of a SHM-based warning strategy

Existing structures

- deviations from the original project description
- adverse results of a periodic investigation
- doubts about the structural safety caused by evidence of gradual damage or deterioration leading to inadequate serviceability
- concern regarding structural behaviour after a sudden incident or extreme event
- expiry of the planned service life and the requirement for a life time extension

Group of structures

- similar structures installed within a specific location
- similar structures designed with the same standard
- structures that due to their behaviour can be determined by similar characteristics and by a few statistically independent parameters

Figure 2: Categorization of the main fields of application of the *VoI* gained through *SHM*-based strategies.

2 Decision process

2.1 Basis for the decision on the implementation of a *SHI*-based strategy

The decision on the implementation of a *SHM* system, in the context of a *SHI*-based strategy, is based on the expected benefit resulting from its use. A fundamental principle in decision theory is that optimal decisions must be identified as those resulting in the highest expected utility. In this guide, the term *utility* is translated into consequences, which are represented by benefits and costs, such as economic, human losses, environmental impact, etc. [6] Hence, the optimal decisions are those resulting in the highest expected benefit or lowest expected total costs [30, 31].

The benefit can be reflected by means of the Value, V (a quantitative parameter, Eq. (1), gained due to the existence of a *SHI*-based strategy (e.g. a monitoring system on the structure). The value of *SHI* can be derived through the difference between the expected life cycle benefits with the utilization of a *SHI*-based strategy, B_M, and the expected life cycle benefits without a *SHI*-based strategy, B_0 [25].

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

where B_0 depends on the structural performance subjected to uncertainty, the decision rules and the adaptive actions, and B_M depends on the same set of parameters/conditions and additionally on a *SHI*-based strategy.

Since the assessment can be made before the implementation of a *SHI*-based strategy, V can be quantified, according to Eq. (2). In this case *V* is the difference between the expected value of the total life cycle costs, C_T, with and without the implementation of a *SHI*-based strategy [25]. It is worth mentioning that the assessment is made before the implementation of the *SHI*-based strategy and the benefit can be included as a negative component of the cost.

$$V = E\left[C_{T,0}\right] - E\left[C_{T,M}\right] \qquad (2)$$

where:

- 0: scenario without implementation of a *SHI*-based strategy
- M: scenario with implementation of *SHI*-based strategy

In order to normalize costs (or benefits), a relative *VoI*, $\Delta\bar{V}$, can be derived, according to Eq. 3, which allows also a rational basis for comparison among different analysis.

$$\Delta\bar{V} = \frac{E\left[C_{T,0}\right] - E\left[C_{T,M}\right]}{E\left[C_{T,0}\right]} \tag{3}$$

Using the expected value of the total life cycle costs, $E[C_T]$ can be estimated according to Eq. (4) which includes the expected value of the failure costs, $E[C_F]$, (section 6.5) and the expected value of the operational costs, $E[C_O]$ covering inspection and maintenance costs (section 6).

$$E[C_T] = E[C_F] + E[C_0] \tag{4}$$

It is important to highlight that the expected benefit of the adopted *SHI*-based strategy depends on several variables which can be determined by a pre-posterior analysis where the possible random outcomes from the *SHI*-based strategy under consideration are systematically included [25].

2.2 Background on decision making context

In order to specify decision alternatives corresponding to defined preferences, the effect of the decision has to be identified and represented. The level of detail of the system representation plays an important role, which in turn is highly influenced by *SHI*-based strategies. It also requires measurable parameters that reflect the changes of the decision variables for the purpose of optimal decision making. The knowledge about the decision context is, consequently, the fundamental factor for optimal decision making and is basically related to:

- decision maker (private or public authority),
- decision scenario (future use of the structure),
- decision time horizon and other time constraints,
- technical constraints such as code requirements or safety targets,
- complexity of the case study,
- socio-economic or political preferences,

On the other hand, the decision process and objectives are dealt with in the *VoI* for which the following aspects are the most important:

- decision strategy,
- parameters or group of parameters affecting decision,
- dependencies in the flow of information.

Figure 3 illustrates a high-level representation of the *VoI* analysis. Here, the dependencies in the process resulting from observations of Performance Indicators (PIs), through monitoring and from possible actions, to be taken (based on given constraints) are highlighted; see [32] for further details.

Under the scope of this guide, the decision analysis is performed in a Bayesian context. Thereby, prior analysis is referred to a scenario where decision is to be made based on available (often generic information). Using this prior information, probabilities are assigned to possible structural states/conditions. These assigned probabilities are called prior probabilities. On the other hand, posterior analysis corresponds to a scenario where new information (about the structural state) becomes available. The prior probabilities can be updated by means of the new information available. Hence, pre-posterior analysis provides a consistent framework for quantifying the *VoI* for an adopted/planned *SHM* strategy. In the context of practicing engineering this quantification, made before the effective implementation of a *SHI*-based strategy, helps to select an optimum *SHI* strategy. Commonly, decision trees are used for these analyses as they allow the identification of possible outcomes and their respective probabilities of occurrence for any action. In such a decision tree (further to the concepts introduced in Eq. (1) and (2)), two main branches can be distinguished: (i) with a *SHI*-based strategy (where *SHM* is considered as a component) and (ii) without a *SHI*-based strategy. The difference between both, in terms of expected costs, leads to the quantification of the *VoI*, which in turn can be used to support, on rational basis, the decision in investing (or not) into a specific *SHI*-based strategy. Further details can be found elsewhere [4, 5, 26-29].

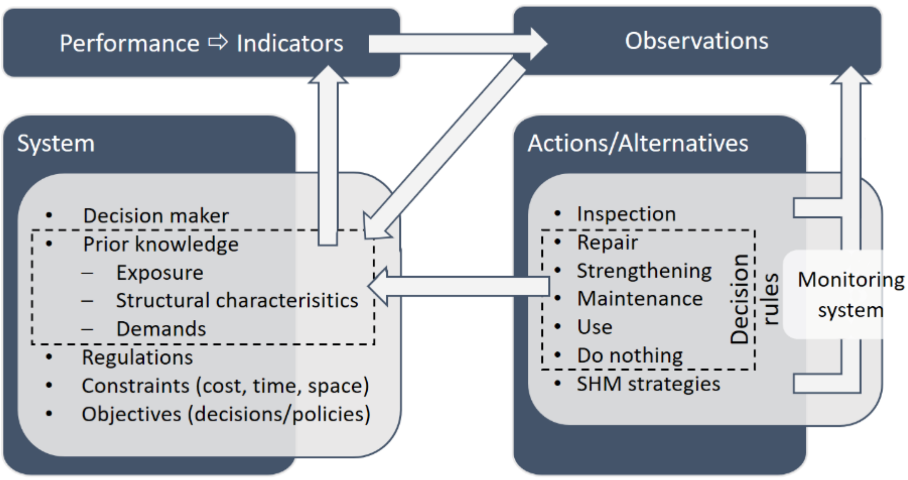


Figure 3: Representation of the *VoI* analysis highlighting the dependencies in the process [33].

2.3 Basic decision objectives

Aiming at a rational decision approach on the selection of an optimal *SHI-based* strategy, the decision tree for the pre-posterior analysis is shown in Figure 4. Four main consecutive steps are highlighted: (i) *SHI*-based strategy, (ii) chances of exceeding the thresholds, (iii) safety measures and (iv) optimization over a working life. The basic decision objectives can be thereby alternatively defined as:

- maximize the benefit (improve safety or serviceability through damage control),
- minimize lifetime costs through control of the structural performance.

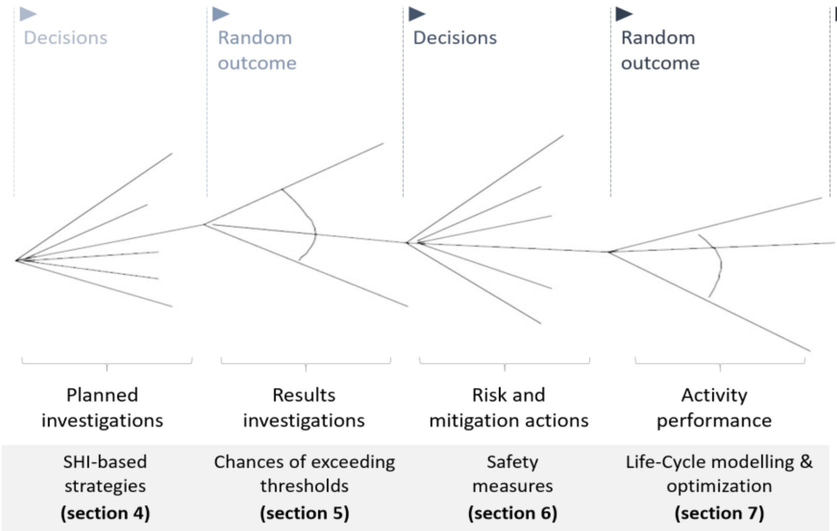


Figure 4: Typical decision tree used for the pre-posterior analysis and *SHI*-based strategy optimisation.

2.4 Decision variables

A decision set must be defined and should lead to a positive benefit V or ΔV (Eq. 2 and 3, respectively). The decision to be taken regarding a *SHI* strategy option can be categorized in the following 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).

The *SHI*-based strategy influences the results through its capabilities and characteristics such as accuracy, robustness, sensitivity and cost. Hence, and further to Eq. 2 where V is quantified, the maximum value that can be achieved, $\max V$ (Eq. 5), corresponds to the highest utility among the different *SHI*-based strategies, *i*, and subsequent decisions, *j*, (Figure 4).

$$max\ V_i = \max_{i,j}\{E[C_{T,0}] - E[C_{T,M,i}(d_j)]\} \tag{5}$$

The optimal decision minimizes the overall expected cost over all possible sequences of choices and chance outcomes, where:

- A typical choice could be the implementation of monitoring system *i* or *i* + 1.
- A typical chance outcome can be for example a damage detected or not.
- A typical decision can be whether or not to implement a safety measure given an outcome (e.g. a measurement from the monitoring system).

Decision rules are often specified by defining thresholds, the exceedance of which indicates the need for a measure (an example is given in Chapter 9).

The choice of the *SHI*-based strategy can be performed based on the expected benefit and by considering the requirements established for the measurements' uncertainty and precision (Figure 1). It should be kept in mind that the main goal of monitoring is to provide better information (i.e. with lower uncertainty) on the structural performance in order to support better decision making in terms of asset management [25]. In the decision process, either critical/representative structures an infrastructure park or critical components of a structure, the *SHI*-based strategy be implemented, must be beforehand selected. This can be done on the basis of critical factors, for instance, on the basis of respective utilization ratios provided in design documentation. The critical factors reflect the consequences of (i) failure of the structure (in the context of a network of structures) or (ii) structural failure of a component (in the context of a single structure). Performance may relate to different aspects, such as reliability, availability, serviceability, depending on the particular features of the problem under investigation. For instance, the sampling rate of the monitoring system (related to the data collection requirements in Figure 1) depends on the monitored parameters, the structural system and the available budget.

In practical terms typical questions which need to be answered by the practicing engineers can be one of the following ones:

- What is the actual condition of the structure?
- What *SHI*-based strategy is optimal?
- What inspection actions are needed?
- What type of analyses shall be performed?
- What are the risks associated with further use of the structure?
- What type of preventive actions shall be taken?
- What can be learnt for future design?

The answers to these questions are not provided by codes in a straightforward way [1]. This is due to the fact that those classical approaches do not consider the possibility of including new information (that in the future might become available) related to the condition/performance of the structure under investigation. Hence, updating information related to the effective condition/performance of the structure is thereby a key issue by means of statistical techniques (i.e. Bayesian updating methods).

3 Asset and portfolio information

3.1 General

In order to efficiently analyse the decision process (as presented in Figure 4 in section 2), it is of major importance to characterize the system (e.g. a network of structures), which might be comprised by a set of assets (e.g. a tunnel). This characterization is highly important and it should be done as precise as possible (see [31] for information on the level of detail). This characterization must consider, collect and validate information mainly related to:

- codes and standards used in the design/repair/retrofitting,
- structural typology and organisation,
- key components,
- geometric and material characteristics,
- structural model as it has been constructed,
- environmental data,
- geotechnical data,
- design and construction documents and other relevant existing documentation,
- operational data (if available),
- track record of known damage,
- knowledge about the effective material conditions,
- knowledge about the effective loading conditions,
- unitary costs of structural elements including discount rate,
- operation and maintenance costs,
- failure consequences including direct consequences of adverse states and subsequent consequences of failure (indirect consequences of adverse states).

In complement to this, the knowledge and *know-how* of experts is also highly relevant. Usually, this is found in the form of non-documented data such as expert judgements on:

- socio-economic importance of structure,
- general experience with the system or component,
- possible consequences of failure.

3.2 Specifications on the *SHI*-based strategy

In order to establish an efficient *SHI*-based strategy, the measuring points, the sampling rate and the respective period of time of observation associated with the monitoring system must be defined. This should be preceded by a preliminary analysis with the objective to identify critical zones and circumstances related to the structural system, either a structure or a specific component, under analysis. Hence, the *SHI*-based strategy should focus mainly on:

- structural members, which based on prior information (structural analysis, visual inspection), are identified as the critical ones. For this, the utilisation of ratios derived from design can be adopted;
- structural members that despite not showing evidence of significant degradation holds high impact into the overall system condition/performance in case of failure;
- structural members with serviceability problems or/and with identified damage;

– structural members or structural systems that due to their high degree of repetition in the contexts of an infrastructure park become critical to observe. For this, the sampling can be performed based on expert opinion, judgement and/or prior analyses.

4 Monitoring in the context of a *SHI*-based strategy

As part of the *SHI*-based strategy, the characterization of the monitoring system plays a fundamental role in the quantification of the *VoI* in Eq. (1). Hence, it becomes vital to understand the concept and characteristics of the monitoring system(s) under consideration within the *SHI*-based strategy. As aforementioned, Structural Health Information (*SHI*) is understood in this guide as the process of measuring parameters influencing the health of a structural system. More specifically, it is focused on new data that may influence, in a meaningful way, the knowledge about actual conditions of the structural system or some of its components. The meaningful way is basically related to the reduction of uncertainty related to a parameter of interest. This uncertainty is dependent on several aspects from the design of the monitoring system to data processing.

Monitoring comprises standard inspection techniques performed periodically, following a regular maintenance plan, and continuous/periodic long-term measurements of time variant measures with sensors installed at the structure [34]. Today, it is possible to continuously and remotely monitor highly instrumented structures, with a high degree of automation. Present solutions are versatile enough to allow for surveillance tasks to be remotely carried out in a cost-effective manner [35-37]. As an example of pro-activity and cutting-edge approach on this matter, monitoring is already being included as a standard mechatronic system in the design and construction of most large-scale and multi-disciplinary bridge projects in Hong Kong and China [38, 39].

There is a consensus among experts that monitoring can be designed and implemented as a complement to visual inspection, to enhance its effectiveness and mitigate its shortcomings. Bridge owners would decide to take advantages of this new paradigm during its whole lifetime, i.e. from construction to operation and/or to demolition [40-47]. In this context, three main phases are highlighted in this guide, mainly: (i) design & parameter selection, (ii) field implementation and (iii) data processing.

4.1 Design & parameters selection

The design of a monitoring system must be based on a set of structured documents, considering that these systems usually hold a level of complexity and specificities. The definition of milestones and a full vision of the system (in advance) that integrates different sub-systems and components is vital at further stages (e.g. implementation stage) [36].

From a conceptual point of view, the monitoring system is aimed to be able to display the collected measurements. For this, a design is needed which is able to synthesize into meaningful information beforehand, in an easy and understandable way towards effective application in a decision-making process.

In addition to the parameters that are intended to be monitored, the operational status of the monitoring system must be well understood, and training for the personal handling alarms or indications is crucial. These aspects needs to be properly considered in the design stage and reflected in the operational costs as part of the *SHI*-based strategy.

Regarding the requirements for the selection of a monitoring system, the following aspects need to be properly addressed at the design phase:

- parameter(s),
- sensitivity,
- reliability,
- robustness,
- sampling rate,
- observation period,
- costs.

The parameters must be related to the *PIs* selected to assist/support the decision process. If possible the direct monitoring of a PI should be conducted. Otherwise uncertainties related to indirect measurements must be accordingly considered. In order to calculate the PI from measured parameters $\boldsymbol{X}$, a relation through a model shall be applied and model uncertainty $\boldsymbol{\Theta}$ shall be considered, as presented in Eq. (6).

$$PI = \Theta f(\boldsymbol{X});\ or\ f(\boldsymbol{X}) + \Theta, \qquad \boldsymbol{X} = (X_1, X_2, \dots, X_n) \tag{6}$$

Model uncertainty should reflect the Probability of Detection (*PoD*) of a defect or damage, for instance a fatigue crack in the steel structure (EN 16991 [4]). The details on updating procedures considering *PoD* are provided in [25] and [48].

Eq. (6) assumes a multiplicative or additive format of model uncertainty. In some cases more complex formats can be appropriate [22, 49].

Commonly, the monitored parameters are used for validating structural models. This is conducted by adjusting parameter values that define material, geometry and boundary conditions. The adjusting should respect variability of the parameters and their relative importance with respect to PI(s). Such validation aims to minimise the discrepancies between data and simulated structural behaviour. Bayesian updating provides a consistent tool.

The aforementioned requirements can then be used when defining the architecture of the monitoring system. The following main components need to be properly designed:

- number/type of sensors,
- datalogger(s),
- computer(s)/server,
- connections,
- data pre-processing (malfunctioning identification),
- data storage service,
- data processing (diagnostics, new information).

4.2 Implementation

The implementation phase needs to consider the observation period defined in the aforementioned requirement list. For instance, the requirement on monitoring of the execution of the structure may lead to additional work (e.g. installation of the monitoring system on a temporary and evolutionary basis). This is very important and has a direct impact on the costs of the monitoring system. In addition, several tests are needed in order to consider the monitoring system ready for operation [36]. Hence, in order to satisfy the conditions during which the monitoring shall be considered in the data analysis procedure, the following shall be defined in the implementation phase:

- installation of sensors and related equipment/accessories,
- implementation of the measurement protocol (occasional, periodic or permanent),
- tests to identify and repair malfunctioning status,
- maintenance to ensure the required level of quality and reliability.

4.3 Data processing

The monitoring system included in the *SHI*-based strategy needs also to be able to (preferably by an automatic and protocoled approach) analyse and evaluate the collected measurements.

Mainly, the data processing needs to assess the collected measurements against specified criteria (*diagnostic analysis*) and give alert levels when respective *thresholds,* x_{lim}, are or will soon be reached. For a successful data processing, the collected measurements need to be subjected to a quality check control (in order to avoid false alarms due to, for example, a malfunctioning of the monitoring system) and an assessment related to uncertainties. Regarding the latter, this can be accounted for by suitable conversion or modification factors in the threshold levels. Such factors can be estimated from information provided by the manufactures and/or from previous experience with the specific type of monitoring system under use.

Finally, a user-friendly interface should be a part of the *SHI*-based strategy. Also, training of technical staff is advised in order to potentiate the effective organizational acceptance and adoption of practices involving monitoring systems.

Hence, the following shall be defined in the data processing phase:

- Definition of assessment criteria,
- Measurement uncertainty quantification,
- Integration of the monitoring in the *SHI*-based strategy (e.g. user-friend interface).

5 Structural performance modelling – exceedance of thresholds

5.1 Performance Indicators (PIs)

Often, the sensors used in *SHM* systems do not allow measuring, directly, the structural performance either at local or global level. In this case, the assessment of the structural performance relies on indirect inference. Therefore, *PIs* related to the structural/system performance need to be also based on *SHM* system characteristics [50]. PIs are used in the decision-making process and they can be classified with respect to the level of application mainly:

- performance of the network (system of structures),
- performance of structure (system of components),
- performance of a structural member (single component).

PIs can be used for screening purposes of critical parts in which *SHM* shall be considered for application. *PIs* can be also categorized with respect to:

- technical criteria,
- sustainability criteria,
- socioeconomic criteria.

With respect to the structural assessment the following categorisation of *PIs* is useful, mainly from the point of view of the degree of sophistication and analysis implementation:

A) *direct indicator* reflecting the structural behaviour related to a measurand such as:

- structural property such as material strength,
- strain,
- deflection or vibration.

B) *indirect indicator* (– exposure related) reflecting external factors that affect the structure performance such as:

- environmental actions (snow depth, wind velocity, wave height),
- atmospheric conditions,
- local traffic conditions,
- soil category or type.

C) *combined indicator* reflecting the state of the structural member or system by including both resistance and action characteristics such as:

- utility ratio or degree of compliance with a given standard,
- 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.

Uncertainties regarding performance levels including measurement, model and statistical scatter must be considered in a *PI* definition. As an example, the threshold levels for utilisation ratio or target reliability can be defined; other examples include limit strength or strain, maximum snow depth or load, or even acceptable risk value. For the purpose of the evaluation of additional information gained through *SHM* and respective decision making, it is recommended to apply state-of-the-art tools with respect to structural assessment. This includes reliability, robustness and risk analysis. The higher the degree of sophistication of the analysis, the more reliable are the results, and consequently, the confidence in associated decision.

5.2 General Framework

The characterisation of the structural system (either a network of structures or a structure) in terms of condition/performance plays a central role in the decision analysis. This is explained by the fact that the probabilities of failure depends on how well this characterization is made, following the importance related to the asset and portfolio information highlighted in section 3. There is a consensual agreement among the engineering community that modelling a structure can be a challenging and complex task. This becomes even more challenging in the context of decision analysis where the objective is to reduce total costs – i.e. take best decisions. Nevertheless, simplifications are inevitable and this is mainly dictated by the available information. In order to minimize (as far as possible) the impact of these simplifications, the following recommendations provide a preliminary check list:

- model of the structure (system behaviour),
- description of actions on the structure including loads and environmental factors,
- description of the structural condition (damage identification),
- definition of indicators,
- identification of key members,
- formulation of limit states $Z(\boldsymbol{X})$ and associated thresholds,
- description of the reliability analysis,
- procedure on the update of PIs,
- assessment of failure consequences and classification,
- risk of future use of the structure,
- required operational life and progress of relevant deterioration mechanisms.

Figure 5 illustrates a typical performance of the structure during its lifetime. One can consider the performance as a quantitative variable defining the behaviour of the structure. Once the structure is in use (even before), it starts to deteriorate and consequently, the value of the associated *PI* become decreasing. In general, the performance is dependent on key parameters, i.e. the resistance, R, and the action effect, E, or through an indicator (i.e. a *PI*) that depends on both R and E (e.g. crack width or deflection) , which can be time-dependent (Figure 5). Performance parameters are thus parameters affecting or describing the structural performance either related to mechanical properties of materials or the stiffness/bearing capacity of the structure. *PIs* are parameters that can measure the 'fit for purposes' of the structure and therefore can be used in the decision process. Failure occurs if the action effect exceeds the resistance or the indicator exceeds a prescribed limit. Finally, it is also clear to understand that R and E can be time-dependent variables as shown in Figure 5.

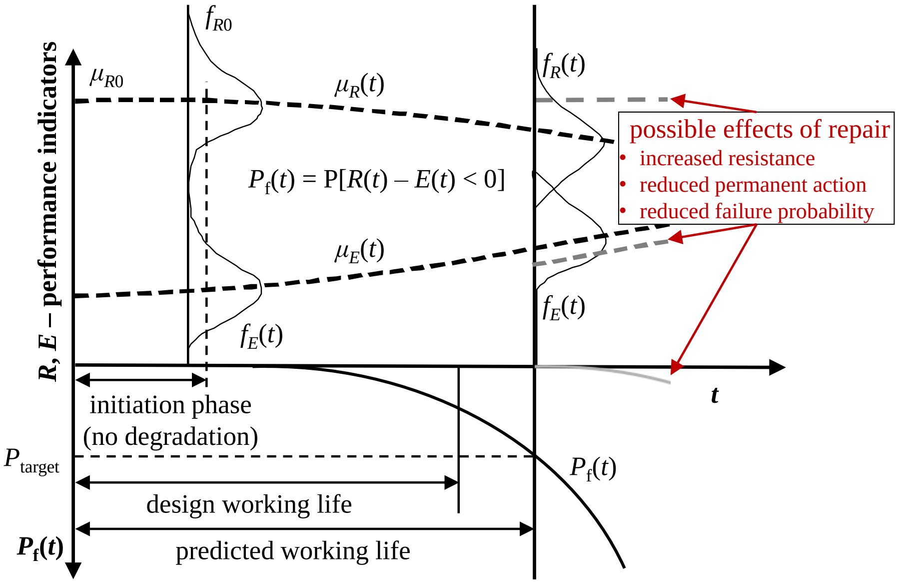


Figure 5: Working life with and without repairs.

5.3 Reliability analysis

In reliability analysis, basic variables $\boldsymbol{X}$ in the limit state function $g(\boldsymbol{X})$ include, commonly:

- time-invariant variables such as model uncertainties, initial resistance and geometry variables, and permanent actions;
- time-variant actions such as climatic and imposed loads that are often described by extreme values related to a specified reference period;
- deterioration parameters affecting resistance and geometry.

In addition, probabilistic models are used to describe the randomness nature of these basic variables and lack of knowledge related to failure modes under consideration. The probability of the failure event F associated with a structural system can be obtained by probabilistic reliability analysis as per Eq. (7).

$$p_f(t) = P(F(t)) = P[g(\boldsymbol{X}(t)) < 0] \tag{7}$$

with $g(\boldsymbol{X}(t)) < 0$ indicating failure and $\boldsymbol{X}$ being the vector of basic variables which can also depend on the time *t*. This is the case for time-dependent actions, dynamic effects or degradation mechanisms. The reference period, i.e. the period of time used as a basis for assessing the statistical parameters of the time dependent variables, is thereby of importance. The limit state function $g(\boldsymbol{X})$ may be alternatively formulated as the difference between an indicator and its limiting value (typically for serviceability criteria). The influence of the random variables is obtained through the sensitivity factors, taking absolute values between 0 and 1. The probability of failure p_f is given through the related reliability index β, which represents an enhanced *PI* The reliability index is updated based on the outcomes obtained from an adopted *SHI* strategy. It is further noted that the reliability of components is derived from Eq. (7). The reliability of the structure, or part of it, can be represented through the system reliability index. More information on probabilistic reliability analysis can be found elsewhere [1].

5.4 Updating

5.4.1 Random variables

Information collected from inspections and/or proof tests, which is directly related to realisations of random variables, should be used in the updating process. This is done by assuming the parameters of the distributions used in the probabilistic modelling hold (implicitly) some degree of uncertainty. Hence, new observations related to realisations of these should be further used to update the respective probability distribution functions.

Firstly, the parameters are modelled by so-called *prior* distribution functions. These *prior* distribution functions are then updated by Bayesian reasoning which, however, requires that a weight is given to the information conveyed by the *prior* distribution functions in terms of equivalent sample sizes, if conjugate *prior* distributions are used [1]. Although the latter are available for a few distribution functions, these belong to the set of most commonly applied models. Even so, and if no analytical solution is available (i.e. by means of a conjugate), *FORM* / *SORM* techniques can be employed [51]. By application of the Bayes theorem, the *prior* distribution functions, assessed by any mixture of frequentist and subjective information, are updated and transformed into *posterior* distribution functions. General information and practical applications can be found elsewhere [1].

5.4.2 Event probabilities

On the other hand, the failure probabilities, given an inspection or monitoring outcome, may be quantified by direct updating by using the definition of conditional probability as per Eq. (8).

$$P(F|I) = \frac{P(F \cap I)}{P(I)} \tag{8}$$

Going back to Eq. (7), it becomes now important to distinguish between the types of inspection outcomes and monitoring outcomes. In case of the survival of the structure under extreme load conditions, the outcome *I* can be defined by the event $h(\boldsymbol{X}) \geq 0$ [1], where the inequality may be elaborated in a straightforward way according to Eq. (9).

$$P(F|I) = \frac{P[Z(\boldsymbol{X}) < 0 \cap h(\boldsymbol{X}) \geq 0]}{P(h(\boldsymbol{X}) \geq 0)} \tag{9}$$

This procedure can be extended to complex failure modes and to a set of inspection outcomes by intersecting all possibilities, $\bigcap_i h_i(\boldsymbol{X}) \geq 0$. Proof loading can be used for updating purposes [52]. Software packages are available for computation purposes [1].

On the other hand, the outcome *I* can be represented, in the case of a monitoring outcome (e.g. measurements of deformation, crack width or strain) by a limit state function $h_i(\boldsymbol{X}) = 0$; see references [25] or [53, 54] for further details.

The information, $h_i(\boldsymbol{X}) = 0 \text{ or } h_i(\boldsymbol{X}) > 0$, should account for measurement and/or model uncertainty including *PoD*, particularly when *PI* is derived from indirect indicators; see also Section 4.1.

5.5 Risk analysis

The risk estimation is herein needed for the quantification of the *VoI*. The risk associated with an event is a combination of the probability of occurrence of the event and the associated consequences. The most sophisticated methods dedicated to risk analysis are able to consider all consequences relevant for the context and resolution of the decision problem. The basic relation for can be represented according to Eq. (10a), which needs to be consistent with the decision-making objectives.

$$R_{i,j} = \iint_{\dots} \int C_i\big(X_1, X_2, \dots, X_\mathrm{n} | d_j\big) f\,(X_1, X_2, \dots, X_\mathrm{n}) \mathrm{d}X_1 \mathrm{d}X_2 \dots \, \mathrm{d}X_\mathrm{n} \tag{10a}$$

where $R_{i,j}$ represents the risk related to a monitoring alternative i and decision rule(s) d_j, $C(\quad)$ the consequences (including possible benefits – see Section 2.1), and $f(\,)$ the joint probability density function of the basic random variables. In most of the cases, especially the case of time-dependent random variables, the calculation of R is only possible by means of numerical methods, [6], [15]. Nevertheless, it is worth noting that the simplest version of this function, which according to Eq. (10b), it relates the two fundamental constituents of risk, i.e. by multiplying the probability of failure, p_f , by the consequences of failure C_F. This represents the expected value for the failure consequences.

$$R = p_f \times C_F = E[C_F] \tag{10b}$$

As aforementioned, the calculation of the probability of failure can be done as discussed in sections 5.3 and 5.4, whereas the consequences may be calculated on the basis of monetary units or in terms of injured persons or fatalities per event, or even by some other indicator. Indeed, one of the key steps of risk analysis is the quantification of the cost of failure, C_F. A systematic procedure to describe, and if possible quantify, consequences is required. In general consequences related to the failure of civil engineering structures can be direct or indirect and may be grouped in (i) human including injuries and fatalities, (ii) economic and (ii) environmental. For a specific structure under analysis, the same consequence can relate either to direct costs or indirect costs. In order to combine the aforementioned types of consequences, a monetarization procedure needs to be adopted. Human consequences are thereby expressed by the Societal Willingness to pay (SWTP) (based on the *LQI* principle) [6]. These costs are then combined with initial costs and maintenance costs in order to find the optimal intervention solutions.

5.6 Classification of civil engineering structures

The classification of civil engineering structures can be based on (i) the exposure level (e.g. number of people at risk) or (ii) the consequence level, given structural failure. Direct and indirect consequences (e.g. fatalities, injuries or weighted fatalities) should be included. Recently, class categories given structural failure have been defined in standards [2, 6, 14]. This can be used for recommendations related to inspection intervals. Three Consequence Classes, *CCs*, are highlighted in this guide, according to [14], which is consistent with the EN 1990 [2]:

- *CC1* Low consequences in case of a failure event
- *CC2* Medium consequences in case of a failure event
- *CC3* High consequences in case of a failure event

In this context, a higher safety level is required for a structure classified with a higher *CC* and consequently, a better planned *SHM* strategy and inspection procedures shall be adopted. In order to better explain and illustrate the utility of this concept, typical examples for the CC classification are given in Table 2.

Table 2. Definition of CCs for buildings according to VDI 6200 [14].

Class	Characteristics	Examples
CC1	Low consequences for loss of human life, social and environmental consequences small or negligible	Agricultural buildings, silos, greenhouses, family dwellings
CC2	Medium consequences for loss of human life, economic, social or environmental consequences considerable	Residential and office buildings, hospitals, television towers
CC3	High consequences for loss of human life, or economic, social or environmental consequences very great	Stadia, congress halls

The recent version of ISO 2394 [6] makes distinction amongst five *CC*, taking into account (i) the economic losses related to failure, (ii) the environmental impact and (iii) the number of fatalities. The lowest *CC* in the ISO standard is deemed here to correspond to *CC1* in Table 2, whereas the second and third to *CC2*, and the fourth and fifth to *CC3*.

It becomes evident that monitoring and inspection become critical actions in order to guarantee the serviceability and safety levels of the structure. Moreover, inspection intervals may be either fixed in advance (i.e. based on a long-term plan) or flexibly defined and dependent on the measured condition at the current inspection.

6 Intervention actions – safety measures

In the context of the decision process, intervention actions based on *SHI*-based strategy and the related measurements collected by the monitoring system under consideration can include various options. It is important to choose an appropriate level of detail of the system comprised by interrelated constituents (in broad terms assets) [31] to facilitate the logical description and the effects of the intervention actions. All relevant parameters, including discounted costs, residual working life, along with their respective uncertainties shall be thereby considered. Hence, in this section a range of possible intervention actions are outlined, ranging from *no action* up to the demolition of the structure. In principle these actions are considered by the owner/ concessionaire during the whole working life.

6.1 Do nothing

This is perhaps the most frequent decision taken over time. Considering the lifetime period of a structure (for example), the owner/concessionaire will not take any intervention action most of the time. This is expected when the structure is well-designed and maintained.

6.2 Operational measures

There is normally a point in time (with certain periodicity depending on the reason for the action) when some interventions are needed:

- provide optimal inspection and maintenance plan;
- decrease exposure (limit number of persons at risk);
- reduce the load magnitude (e.g. by limiting the traffic on the bridge, re-routing the traffic or by limiting the loads in storage rooms or archives);
- operational utilization of the structure under constraints (restrict the traffic on the bridge or access of visitors of the observation tower in periods of strong wind);
- provide additional safety measures (protection measures such as protective barriers or mitigation measures such as appropriate escape ways);
- reduce the remaining working life and re-assess afterwards.

6.3 Structural interventions

Less frequently some actions might be taken to change structural resistance:

- repair to avoid/delay further degradation;
- upgrade to increase structural reliability.

Upgrade and/or repair can be required for various reasons such as:

- strengthening to improve reliability of specific structural elements or the overall structure,
- repairs to compensate for the effects of current or anticipated structural deterioration,
- preventative measures to avoid or minimize future structural deterioration,
- improvement of robustness.

6.4 Complementary measures

These actions do not affect structural resistance but may affect utilization of the structure:

- installation of temporary or permanent safety barriers,
- river management,
- road restraint systems,
- maintenance of the surroundings of the structure.

6.5 Insurance risk

When the risks become excessive, the owner can reduce a risk by involving another party, sharing a part of the risk with a trade-off of fixed cost, i.e. risk premium. By transferring the risk, the owner becomes less exposed although the total amount of the risk does not change for the whole society [15].

6.6 Demolition

The most unlikely decision – the demolition of the structure – is taken in an extreme case where the demolition and replacement costs and associated losses are lower than for any other alternative of repair or upgrade. In this case, it is important to consider the implications of the demolition (e.g. *Will a new structure be built to replace the existing one? What are the alternatives for the users in case of no replacement and what are the consequences?*).

7 Life-Cycle Cost modelling – optimization of working life

The total costs must include *SHI*-based strategy costs, operational costs (including the acquisition and maintenance of the monitoring system) and failure costs. The optimum *SHI* strategy is selected by minimising the expected total cost, using a Life-Cycle Cost (LCC) analysis. When benefits differ between *SHI* strategies *i* and related decision rules d_j, they can be subtracted from costs (included as *negative costs*).

7.1 Cost without *SHI* strategy

The total cost without any *SHI* strategy, $C_{T,0}$ can be expressed as:

$$C_{T,0} = C_F \cdot Q\left(p_f(x), t_{ref}, q\right) \cdot p_f(x) \tag{11a}$$

where:

C_F:	present value of failure cost,
Q:	time factor (defined in section 7.4),
$p_f(x)$:	prior or pre-posterior annual failure probability.

7.2 Cost for *SHI* strategy

Considering a *SHI* strategy *i*, the total cost $C_{T,i}$ are extended as follows:

$$\begin{aligned} C_{T,i} = {} & C_{A,i} + C_{0,i} \cdot Q\left(0, t_{ref}, q\right) + C_{safe} \cdot Q\left(P\left(x_{lim,i}\right), t_{ref}, q\right) \cdot P\left(x_{lim,i}\right) + \\ & C_F \cdot Q\left(p_f(x), t_{ref}, q\right) \cdot p_f\left(x_{1y.} | x < x_{lim,i}\right) \end{aligned} \tag{11b}$$

where:

$C_{A,i}$:	initial cost on the monitoring system associated with the *SHI* strategy, i, (including installation),
$C_{O,i}$:	present value of annual operational cost associated also with a *SHI* strategy i
Q:	time factor (defined in section 7.4),
C_{safe}:	present value of safety measure cost,
$P(x_{lim,i})$:	annual probability of exceeding a threshold ($x > x_{\mathrm{lim},i}$) for the *SHI* strategy,
$p_f\left(x_{1y.} \| x < x_{lim,i}\right)$:	prior or pre-posterior annual failure probability, given information obtained from the monitoring system; $x_{1y} \| x < x_{\mathrm{lim},i}$ denotes the distribution of the annual maximum of x provided that $x < x_{\mathrm{lim},i}$.

Regarding the probability of failure, the distinction between two cases – without and with a *SHI* strategy – needs to be made:

$$p_f = \begin{cases} p_f(x) & \text{, without } SHI \text{ strategy} \quad (12a) \\ p_f\left(x_{1y.} | x < x_{lim,i}\right) & \text{, with } SHI \text{ strategy} \quad (12b) \end{cases}$$

When using Eq. (11b), the following remarks should be taken into account:

1. The observed indicator x may be different for different *SHI* strategies, i.e. when a safety measure represents the structural upgrade, the safety and failure costs need to be accordingly updated to consider increased reliability after the upgrade.
2. The 4th term in (11b) describes the expected failure cost that may occur before a threshold (section 0) is reached. Such failure can hardly be fully prevented as a *SHI* strategy normally reduces only some uncertainties affecting the limit state function.
3. Relationship (11b) can be extended to account for imperfect *SHI* (e.g. *PoD*). As exceedance of the threshold may not be detected, in general with decreasing *PoD* the failure cost is increasing while the safety cost – the 3rd term in (11b) – is decreasing.
4. When determining $P\left(x_{lim,i}\right)$, it is normally assumed that the probability of two and more threshold exceedances in a year is negligible. Otherwise a multiple crossing analysis shall be performed.

For all strategies, the total costs, $C_{\mathrm{T},i}$, are then compared, an optimum *SHI* strategy is selected and the respective total cost, $C_{\mathrm{T,opt}}\left(x_{\mathrm{opt}}\right)$, are compared with the total cost for the no *SHI* strategy. The no *SHI* strategy can be optimal particularly in the cases of short working lives, relatively low failure consequences or relatively high *SHI* costs, or highly reliable structures.

7.3 Optimum threshold

For each strategy "*i*", an optimum threshold, $x_{\mathrm{opt},i}$, needs to be found. A simplified cost-benefit analysis can be conducted to specify the target reliability level related to a limiting value, x_{lim}, of the monitored parameter *x*. When x_{lim} is exceeded, reliability becomes unacceptable and a safety measure must be implemented. The cost-benefit analysis aims to balance safety measure cost and the expected failure consequences (accepted risk) and defines the rule for the decision on *risk and mitigation actions* (Figure 4).

A safety measure is implemented whenever the risk – failure probability, $p_{\mathrm{f}}(x)$, depending on the observed *x* multiplied by C_{F} – exceeds the safety measure costs , C_{safe}:

$$C_{safe} \geq C_F \cdot p_f(x) \quad (13)$$

Realistically assuming that $C_{safe} \ll C_F$, the target failure probability based on the economic optimisation, p_{ft}, is obtained according to Eq. (14), whereas the reliability index corresponding to the target probability, β_t, is given by Eq. (15).

$$p_f(x) \leq p_{ft} \approx C_{safe}/C_F \tag{14}$$

$$\beta_t = -\phi^{-1}(C_{safe}/C_F) \tag{15}$$

where Φ^{-1} is the inverse cumulative distribution function of the standardised normal distribution (see section 9.8.1 for further practical implementation).

For low thresholds the safety cost is high due to frequently applied safety measures while with increasing x_{lim} the failure cost may become excessive.

7.4 Time factors

In the context of the LCC modelling, all costs need to be expressed on a common basis and with respect to a reference period, t_{ref} in years in this guide (e.g. the working life of the structure). This can be achieved by converting the operational, safety and failure costs in Eq. (11a) and (11b) to the present value by using the time factors, Q, reflecting an annual discount rate q. This re-calculation is provided by Eq. (16a) and (16b) for the operational and safety cost, and failure cost, respectively.

$$Q(0, t_{ref}, q) = \frac{1 - \left[\frac{1}{1+q}\right]^{t_{ref}}}{1 - \frac{1}{1+q}} \tag{16a}$$

$$Q(p_f(x), t_{ref}, q) = \frac{1 - \left[\frac{1 - p_f(x)}{1+q}\right]^{t_{ref}}}{1 - \frac{1 - p_f(x)}{1+q}} \tag{16b}$$

where:

Q:	time factor based on the sum of a geometric series assuming independent annual events [55];
t_{ref}:	reference period considered here as the minimum of (i) the residual working life with respect to ultimate and serviceability limit states and (ii) a useful residual life determined by obsolescence with respect to physical, economic, functional, technological, social, legal or political aspects;
q:	annual discount rate.

The factor for failure consequences considers only one failure event (assuming a major repair/ strengthening after failure), whereas the factor for operational and safety costs takes into account multiple events during t_{ref}. All the time factors assume at most one event per year (one implementation of safety cost, one failure). If several events per year are expected, the time factors can be based on a shorter period, e.g. month or week.

Finally, it is worth mentioning that Eq. (11) and Eq. (16) apply for stationary cases, thus for no significant degradation or time-dependent changes in the load characteristics loads (e.g. due to climate change or increasing traffic). The equations can be adapted to account for non-stationary conditions. As an example, the failure cost for no *SHI* strategy in Eq. (11a) can be rewritten for time-dependent annual failure probability, $p_f(x,t)$ assuming negligible initial failure probability ($p_f(x,0)=0$):

$$C_F \cdot \sum_{i=1}^{t_{ref}} \frac{p_f(x,i)\prod_{j=1}^{i}\left(1-p_f(x,j-1)\right)}{(1+q)^{i-1}} \tag{17}$$

8 Decision and Value of the *SHI*-based strategy

8.1 Evaluation of alternatives

Based on the obtained *LCC* results, different *SHI* alternatives can be assessed by the decision maker. The approach introduced in section 7 provides the required methods and tools for this. In addition, a sensitivity analyses can be performed to investigate different scenarios/input values to better understand the impact of different alternatives.

8.2 Optimization

Among all possibilities, an optimal solution for *SHI*-based strategies can be defined by means of an objective function, considering the existence of structural-related constraints as well as budget and time constraints.

8.3 Risk-informed selection of safety measures

After the evaluation of the *SHM* outcomes in the investigated system, safety measures might be necessary in order to reduce the risk associated with a structural failure to an acceptable level. Acceptable risk levels are described and provided in [6], whereas the aforementioned safety measures shall be selected, by considering for each measure k, the following basic parameters:

C_{Ik}: investment costs,
C_{Ak}: annual maintenance/operation costs,
T_L: service life of the potential safety measure including the effect of obsolescence,
dR_k: risk reduction due to implementation of the safety measure *k*,
dR_{Hk}: fraction of dR_k concerning the reduction related to human risk,
dR_{Fk}: fraction of dR_k concerning the reduction related to economic (financial) risk,
dA_{Ek}: fraction of dR_k concerning the reduction of damaged area of the environment,
c_u: unit costs to recover the damaged area.

If a discount rate function $\delta(T_L)$ is taken into account and human losses are appraised by

the SWTP, the evaluation of each individual safety measure can be made according to Eq. (18), on the basis of the aforementioned considerations.

$$\frac{C_{lk} \cdot \delta(T_L)}{T_L} + C_{Ak} < SWTP \cdot dR_{Hk} + dR_{Fk} + c_u \cdot dA_{Ek} \quad (18)$$

It should be noticed, that the SWTP value in Eq. (18) is not the value of one life; the human life is beyond price. It is also not the amount of a possible monetary compensation for the relatives of the victims of the occurrence. It represents the monetary value for which society should be willing to invest for saving one life according to its ethical principles. The risk reduction is evaluated in most cases through project specific risk and decision analyses. Nevertheless, it is also commonly supported by engineering judgement and experience. Hence, the uncertainties in the influencing parameters of Eq. (18) should be investigated based on both the experience and available data.

8.4 Prognostic analysis

Based on the diagnostic results, prognostic analyses and respective algorithms (i.e. algorithms able to estimate the remaining lifetime of the structure) can be developed and applied. For example, such a procedure can support the assessment of the time development of a resistance function as shown in Figure 5.

8.5 Documentation

Monitoring results, calculations regarding decisions, among other similar information, must be well documented and consequently it shall be prepared and submitted as basis for decisions in accordance with valid regulations. The operator should assess the need for documentation in the various phases of the activities.

8.6 Integration with other control systems

The integration of the Value obtained from the monitoring information analysis (Value of *SHI*) with existing management systems such as *BMS* is highly beneficial and recommended. For example, *BIM* has been changing, substantially, the workflow of planning and operating engineering structures, in the most recent years. Typically, *BIM* is stored and exchanged via model files. Different schematic approaches towards modelling *SHM* information or a BIM-based representation are described in [56].

9 Implementation of the *VoI* – a case study

9.1 TU1402 cases study portfolio

Further to the tools and methods summarized in this guide, the TU1402 community has been exploring and applying these techniques on a set of real structures across Europe. This set of real applications is part of the *TU1402 case study portfolio* (part of the WG4 tasks and deliverables). The objective of this is to offer further insights into the implementation of the VoI, also, from a practical point of view. Table 3 presents the available portfolio, including details on the structure type, associated to each case, the country where the structure is placed and references with further details.

Table 3. Portfolio of case studies of the COST Action TU1402.

Structure type	Title	Country	References
Building	Condition assessment of timber structures – quantifying the value of information	Croatia	[57, 58]
	Optimizing in-situ testing for historic masonry structures	Czechia	[59-61]
Dike	Head monitoring for flood defences	The Netherlands	[62]
Bridge	The Söderström Bridge	Sweden	[63-65]
	Bridge maintenance strategy using SHM data	Croatia	[66-68]
	Emergency Management of Highway Bridges	Italy	[69]
	Value of Information of a pro-active SHM tool devoted to early damage detection on bridges	Portugal	[70, 71]
Offshore wind-park	Case Study on Offshore Wind Farm Foundation	Norway	[72, 73]
	Value of structural health information for the operation of wind parks	Denmark	[74]
Roof	Case study on the maintenance of a tendon supported large span roof	Poland	[75]
	Optimizing Monitoring: application to assessment of roof snow load risk	Italy	[61, 76, 77]

To support the reader of this guide, the case study *Optimizing Monitoring: application to assessment of roof snow load risk* illustrates the application of the presented concepts towards the quantification on the *VoI* regarding *SHI*-based strategies supported by monitoring systems.

9.2 Overview and relevance on the case study

The case under consideration is an existing stadium, erected at the beginning of the 1990s, in the Alpine region of Italy at an altitude of 190 m and subjected to snow loading conditions. Snow actions are important especially in northern and mountainous regions where heavy snowfalls and related accumulation result in considerable loads. In recent years, multiple major snowstorms resulted in numerous roof failures. The direct and indirect monitoring of the snow load and the impact on the structural performance and decisions regarding intervention actions are analysed based on the developed guide. Thereby refined levels of PIs such as reliability index and risk value (total cost) are considered to illustrate the selection of an optimal monitoring strategy. Further details on this case study can be found elsewhere [76, 78].

9.3 Asset information

The stadium can accommodate up to 4000 people and it is occasionally used to host sport events, concerts and shows in a winter season. Due to the structure location, it is subjected to snow loads and the assessment of its effective structural reliability became a critical issue to the owner after the recent roof collapses and the related investigations. Considering the nature of the problem under analysis, the analysis is performed under the Ultimate Limit State verification and therefore, the serviceability aspects are not addressed herein.

The analysis of past and present prescriptive codes reveals that the design snow load increased significantly over the last decades. The obtained values indicate that the present snow loads exceed those considered in design and the structure does not comply with the requirements of the Eurocodes.

More specifically, and with the objective on giving evidence on the *VoI* related to *SHM* strategies, the numerical example focuses on the roof of the stadium, which consists of cantilever steel beams IPE450 (Figure 6) spaced by 5 m. The inclination of the steel beam is negligible ($\alpha \cong 0^o$).

Figure 6. Scheme of the roof beam.

9.4 Structural performance modelling

In order to keep the reliability level of the stadium classified in the highest consequence class, *CC3*, according to EN 1990 [2], the reliability of the roof beam is analysed by means of the probabilistic methods mentioned in this guide. The objective is to support the decision regarding the use of the stadium and the implementation of a permanent online monitoring system. Thereby, the monitoring of the snow depth or, alternatively, the monitoring of the snow load on the roof of the stadium are critically compared with the alternatives to update the structural reliability using the information about the ground snow load.

The limit state function is based on the flexural resistance of the cantilever beam and the maximum bending moment due to the permanent actions and annual maxima of snow load:

$$\mathrm{Z}(\mathbf{X}) = R - \theta_E\,[G_{\mathrm{steel}} + G_{\mathrm{roof}} + \mu\,S + \Delta S] \tag{19}$$

The respective notations and associated probabilistic models for the basic variables are given in Table *4* considering the JCSS recommendations [22]. More details are provided in [76, 78].

Table 4. Models of basic variables.

Variable	Distribution	Mean / char. value	CoV in %
Flexural resistance including model uncertainty, R	LN	1.28	8.6
Load effect uncertainty, θ_E	LN	1	5
Moment due to self-weight, G_{steel}	N	1	1
Moment due to roofing, G_{roof}	N	1	5
Shape coefficient, μ - no monitoring on roof - monitoring on roof	N	1 $^{1)}$ 1	15 5
Bending moment due to snow load *S*: measured ground snow load (monitoring M_1; Table 5)	N	measured	$^{2)}$
Measured roof snow depth (M_2)	LN$^{3)}$	$^{4)}$	20
Measured roof snow load (M_3)	N	measured	$^{5)}$
Snow load predicted for next three days, ΔS	LN	$^{6)}$	50

$^{1)}$Shape factor of 0.8 to convert ground snow loads to roof loads. $^{2)}$Standard deviation of the measured value σ = 0.05 kN/m^2. $^{3)}$Affected by probabilistic model of snow density. $^{4)}$The mean snow load in kN/m^3 estimated as (1.09d + 2.4)d where d is a measured value in m. $^{5)}$$\sigma$ = 0.1 kN/m^2. $^{6)}$Expected increment of ground snow load characterising major annual snowfall in the upcoming three days - 0.3 kN/m^2.

The analysis is also based on selected parameters of the influencing random variables and the obtained annual reliability index β_{comp}, selected as a *PI* in this case study. The obtained β_{comp} = 3.83 (corresponding to annual failure probability 6.4 × 10^{-5}) is significantly lower than the annual target level of 5.2 given in the EN 1990 for *CC3* [2]. It is worth noting that this level may be deemed too strict for verifications of existing structures. The system reliability analysis and the updating based on past satisfactory performance could not provide evidence of better performance [51].

9.5 *SHM* strategies

Based on the available prior information, the obtained results give evidence that the snow load dominates the structural reliability. Therefore, it is proposed to apply a *SHI* strategy supported by continuous monitoring of the snow load magnitude. This will allow to update information related to the dominating variable. In order to justify, on a rational basis, the potential implementation of the monitoring system, the pre-posterior analysis (section 2.4) is conducted, considering failure costs, operation and acquisition costs.

When the monitored parameter exceeds a specified threshold, two decisions are considered: (i) the snow on the roof is removed or (ii) the stadium is temporarily closed. This is in full agreement with the concept of a safety plan provided in ISO 2394 [6]. Such plan specifies "*the performance objectives, the scenarios to be considered for the structure, and all present and future measures (design, construction, or operation, - e.g. monitoring) to ensure the safety of the structure*."

Three monitoring strategies under consideration, denoted as M_1, M_2 and M_3, are described in Table 5. To allow for early warning and timely removal of snow from the roof or temporary closure of the stadium, snow loads estimated from measurements are increased by an additional load ΔS, which is predicted by meteorologists for the following three days.

Table 5. Monitoring strategies for the roof beam.

#	Measured parameter	Description	Monitoring cost	Uncertainty
M_1	Measurement on the snow load on the ground at a nearest meteorological station ($S_{g,mon} + \Delta S$)	The decision maker is informed by the meteorological service about the actual ground snow load	No charges related (negligible personal costs)	Uncertainty in $S_{g,mon}$ is that adopted for $S_{g,sur}$. The major drawback is the considerable uncertainty related to the shape factor, μ_i, due to the conversion from ground to roof snow loads
M_2	Measurements on the roof by snow depth sensor ($\gamma_{snow}\, d\, +\, \Delta S$)	The decision maker is informed on the snow depths at two locations. The number of sensors on the roof can be optimised nevertheless, this is beyond the scope of this case study.	Acquisition cost: 3500 € / sensor; Annual operational cost (including periodical inspections in winter periods and replacement each 10 years): 800 €/year	The predicted roof snow load is highly uncertain due to the significantly variable estimate of snow density. The uncertainty in the shape factor is reduced as no conversion from ground to roof snow loads is needed
M_3:	Measurements on the roof by snow load sensor ($S_{r,mon} + \Delta S$)	Same for M_2.	Acquisition cost: 7000 € / sensor. Annual operational cost (including periodical inspections in winter periods and replacement each 20 years): 800 €/year	Accurate estimate of the roof snow load and reduced uncertainty in the shape factor

9.6 Intervention actions

When a specified threshold is exceeded, a set of actions is considered, mainly:

- cleaning of the roof by specialists, which involves a cost around 30 k€;
- temporary closure from one to two weeks (highly season-dependent), which slightly exceeds the cleaning cost when the stadium is fully utilised;
- do nothing (accept the risk).

9.7 Cost Modelling

Both the construction costs and the monitoring costs can be assessed based on available data from the industry [79]. The following estimates are considered when specifying failure consequences C_F:

- cost of repair or replacement of the roof and damaged structure of the stadium (≅ 5 % of the construction costs of the whole stadium);
- economic losses due to non-availability of the structure (≅ 35 % of the construction costs);
- costs of injuries and fatalities (≅ 7% of the construction costs, based on SWTP and taking into consideration the occasional use of the stadium during winter).

These estimates are based on available statistics and the authors' expertise. An upper bound on failure consequences was estimated at 7500 k€ [80].

9.8 Threshold levels

9.8.1 Cost-benefit optimisation

Based on the cost estimates, a simplified cost-benefit analysis is conducted to specify the target reliability level related to a limiting value x_{lim} of the monitored parameter *x*. When x_{lim} is exceeded, a safety measure is implemented. The cost-benefit analysis defines the rule for the decision on *risk and mitigation actions* in Figure 4 (section 2.3); see also Figure 8.

Focusing on the safety measure of snow removal, Eq. (13), (14) and (15) are applied. Figure 7 shows the variation of the target reliability index β_T with the cost ratio C_{safe} / C_F. The target level is approximately linearly proportional to the order of magnitude of the cost ratio; for realistic C_{safe} / C_F ≈ 30 / 7500 = 0.004 the target level β_t = 2.65 is obtained for threshold exceedance – warning level. For more details see [76].

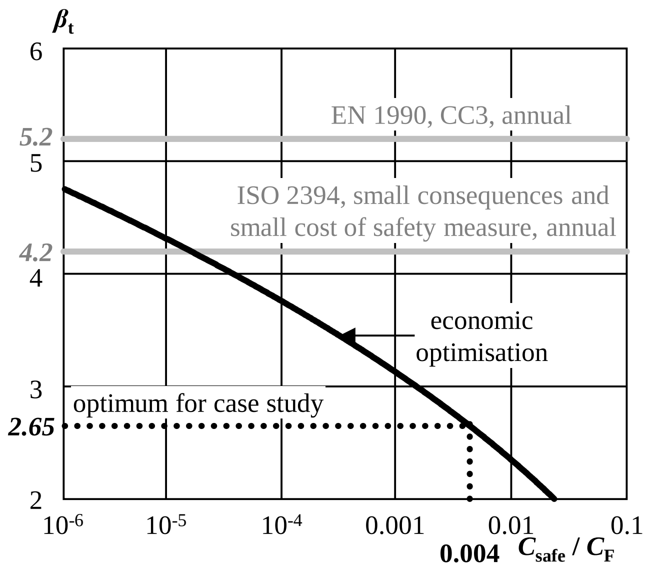


Figure 7. Variation of the target reliability index β_T with the ratio C_{safe}/C_F.

It is emphasised that β_t = 2.65 is not related to any reference period and no direct comparison to annual levels provided in codes is possible (for illustration purposes, Figure 7 shows the annual target reliability levels according to EN 1990 [2] and ISO 2394 [6]); see the discussion below.

9.8.2 Thresholds for monitoring strategies

Regarding the thresholds associated with the monitoring strategies, Table 6 summarizes the obtained values by using the limit state function, $Z(\boldsymbol{X})$, defined in Eq. (19). The probability of failure, p_{f}, is obtained by Eq. (20).

$$p_{\mathrm{f}}(x_{\mathrm{lim}}) = \mathrm{P}\{R < \theta_E \cdot [G_{\mathrm{steel}} + G_{\mathrm{roof}} + \mu\, x_{\mathrm{lim}} + \Delta S], \qquad \beta(x_{\mathrm{lim}}) = -\Phi^{-1}[p_{\mathrm{f}}(x_{\mathrm{lim}})] \qquad (20)$$

where the models of the basic variables are taken from Table *4* and x_{lim} is a threshold, the value of which is for each M_i found to achieve $\beta(x_{lim})$ = β_t = 2.65.

Table 6. Thresholds for the observed variables and the associated returning periods.

Approach	Parameter	M1	M2	M3
β_{opt} = 2.65 (exceed. threshold)	Threshold	1.68 kN/m^2	0.47 m	1.59 kN/m^2
	S [1)]	≅ 1.34 [=0.80 × 1.68]	1.37 [=(1.09 × 0.47 + 2.4) × 0.47]	-
	T [2)]	140	160	480
Partial factors [77]	Threshold	1.29 kN/m^2	0.37 m	1.03 kN/m^2
	S	1.03	1.04	-
	T	32	33	31
β_1 = 4.2 (Bounded annual distr., ISO 2394)	Threshold	1.61 kN/m^2	0.48 m	1.55 kN/m^2
	S	1.29	1.41	-
	T	110	190	390
β_1 = 5.2 (Bounded annual distr., EN 1990)	Threshold	1.06 kN/m^2	0.33 m	0.95 kN/m^2
	S	0.85	0.90	-
	T	13	18	21

[1)] *S* – corresponding roof snow load in kN/m^2;
[2)] *T* – return period in years

The values of equivalent roof snow loads obtained for β_t = 2.65 (Table 6) indicate the importance of reducing the measurement uncertainty, i.e. the threshold for M_3 exceeds those for M_1 and M_2 by about 15 %. Therefore, the M_3 threshold is associated with a very long expected return period, implying that a safety measure will unlikely be needed.

Note that the return periods are estimated on the basis of available ground snow load records from the location (1973-2015) from which the distribution of a single snowfall and an average number of snowfalls per winter season (three per year – typical for maritime and continental climate) was inferred. Further details can be found in [78].

The strict application of the Eurocode design rules with an annual β_1 = 5.2 leads to conservative thresholds (Table 6) while the thresholds obtained by the partial factor method are slightly less conservative. This is attributable to the well-known fact that snow-dominated structures, designed by the partial factor method, have lower reliability than the Eurocode targets. The values in Table 6 are obtained considering distributions of annual maxima of the roof snow load bounded by a threshold affected by measurement uncertainty.

Alternatively, β_1 = 4.2 can be considered according to ISO 2394 [6] for small relative cost of safety measures (cleaning) and "material damages and functionality losses of significance for owners and operators, but with little or no societal impact." The obtained thresholds are very similar to those based on the economic optimisation. This is confirmed by deriving annual values equivalent to β_t = 2.65 (acceptable failure probability $p_{f,t}$ = 4‰ given a threshold is reached). With reference to the expected return periods in Table 6, the annual probability of threshold exceedance for β_t = 2.65 is 7.1‰ for M_1, 6.3‰ for M_2, and 2.1‰ for M_3. Therefore, equivalent acceptable annual failure probabilities become 7.1‰ × 4‰ = 2.8 × 10^{-5} (β_1 = 4.03) for M_1, 2.5 × 10^{-5} (β_1 = 4.06) for M_2, and 0.8 × 10^{-5} (β_1 = 4.3) for M_3, i.e. close to the ISO 2394 target and lower than the EN 1990 level. It seems that the ISO 2394 target levels differentiated with respect to relative cost of safety measures are applicable for decision making related to the implementation of safety measures. However, further investigations are needed – see the note at the end of this section.

9.9 Decision and value of *SHI* Analysis

Reflecting the approach recommended in this guide (Figure 4), the general decision tree for the case study is shown in Figure *8*. An optimum monitoring strategy should be selected on the basis of the total cost of monitoring and safety measures over a specified reference period (i.e. the required remaining working life, t_{ref}).

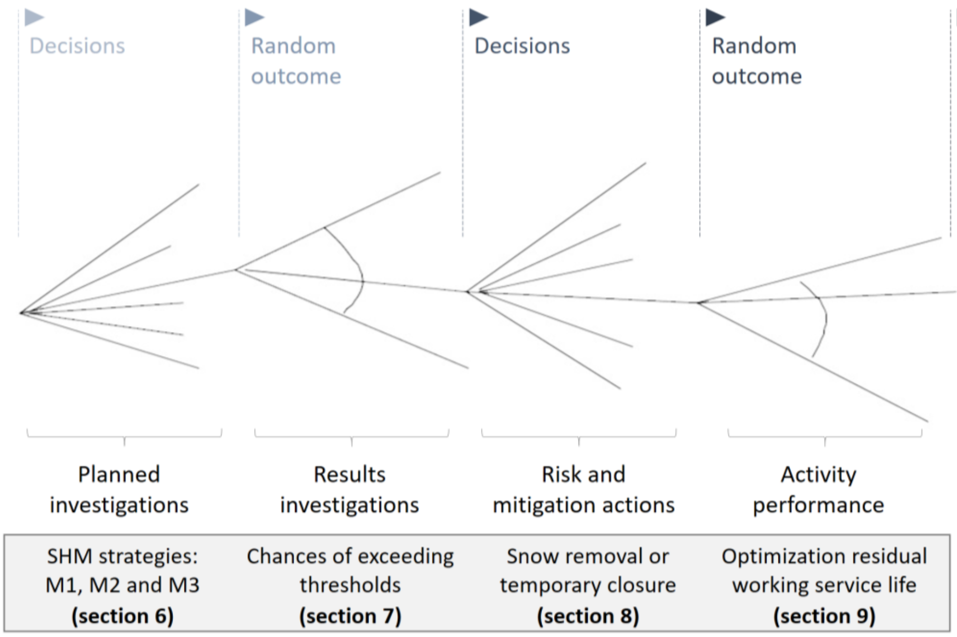


Figure 8. Decision tree for pre-posterior analysis and monitoring optimisation applied to the case study.

The cost-benefit optimisation [76] is based on minimising the expected total cost, $C_{T,i}$, of monitoring and safety measures over the specified reference period t_{ref}. Using Eq. (11b) minimum cost is compared with the total cost of no *SHI* strategy $C_{T,0}$ (Eq. (11a)). As an example, the total cost becomes for M_3, t_{ref} = 15 years and *q* = 3% (in k€):

$$C_{T,3} = 7\ per\ sensor \times\ 2\ sensors + 0.8\ per\ year \times 12.3\ y. + 60 \times 1.3\%\ per\ y. \times 12.3\ y. + 7500 \times 1.6 \cdot 10^{-5} \times 12.3\ y. \tag{21a}$$

$$= 14 + 9.8 + 0.8 + 1.5 = 26.1\ \text{k€}$$

$$C_{T,0} = 7500 \times 6.4 \cdot 10^{-5} \times 12.3 = 5.9\ \text{k€} \tag{21b}$$

where $p_f(x_{1y.}|x < x_{lim,3}) = 1.6 \cdot 10^{-5}$ is obtained from the reliability analysis considering a bounded distribution of the roof load and $p_f(x) = 6.4 \cdot 10^{-5}$ is the failure probability obtained in Section 9.3.

Figure 9 shows the expected total cost for M_1, M_2, and M_3 as a function of the reference period taken equal to the remaining working life. As the acquisition and running costs are clearly dominating, the total costs of M_2 and M_3 are high. The optimum choice is to select M_1 as:

- it is associated with no acquisition and running cost (in the simplified case study),
- it helps to reduce uncertainty in a dominating variable – roof snow load.

Note that M_3 represents in this case study the strategy with nearly perfect information.

It is emphasised that the obtained results are strongly case-dependent. To illustrate this, consider that the roof was designed using low partial factors so as its 50-year reliability is only 1.5 (approximately corresponding to annual β_1 = 3.0 and to flexural resistance reduced by 25%); this is the case of many structures in Central Europe. The thresholds in Table 6 then drop significantly (roof loads between 0.75-0.9 kN/m^2, return periods 8-15 years). The annual probability of threshold exceedance for β_t = 2.65 is 12% for M_1, 9.5% for M_2, and 6.4% for M_3. Equivalent acceptable reliability indices drop to β_1 = 3.3 for M_1, 3.35 for M_2, and 3.45 for M_3. These estimates are lower than the target levels given in ISO 2394.

Figure 10 shows the expected total cost for M_1, M_2, and M_3 as a function of the remaining working life. In this case any monitoring strategy is more efficient than no *SHI* approach. The optimal strategies are now M_1 or M_2.

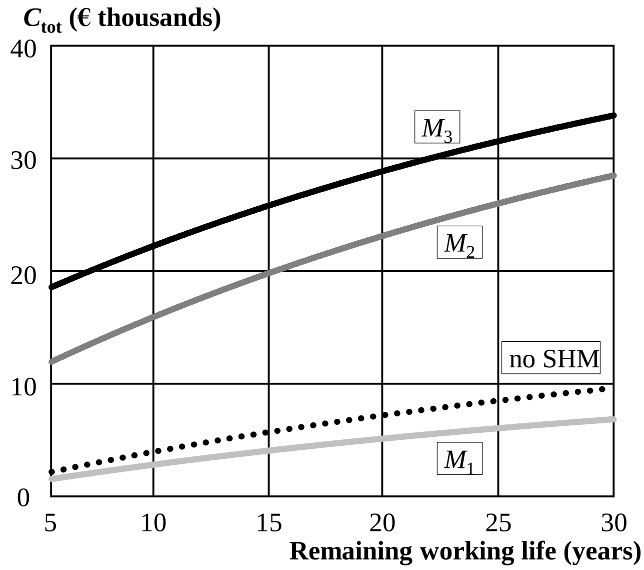


Figure 9. Variation of the expected total cost for strategies M_1-M_3 with a remaining working life (equal to a reference period).

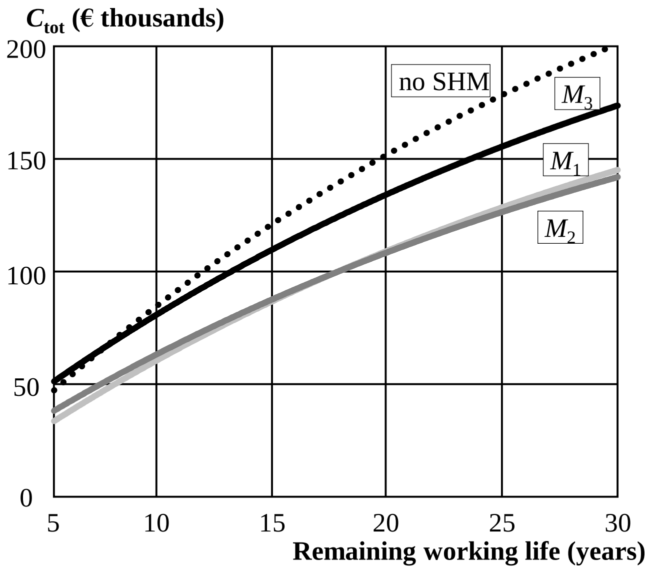


Figure 10. Variation of the expected total cost for strategies M_1-M_3 with a remaining working life (*flexural resistance reduced by 25%*).

References

1. Joint Committee on Structural Safety (JCSS) (edited by D. Diamantidis), *Probabilistic Assessment of Existing Structures*. 2001, RILEM Publications S.A.R.L.
2. CEN (European Committee for Standardization), *EN 1990 - Eurocode: Basis of structural design.* . 2002, Brussels, Belgium: CEN.
3. Limongelli, M. *Glossary (COST Action TU1402)*. 2017 22.02.2019]; Available from: www.cost-tu1402.eu/Resources-Downloads/Glossary.
4. European Committee for Standardization, *CEN Standard - EN 16991:2018 on Risk-based inspection framework*. 2018.
5. Ente Nazionale Italiano di Unificazione, *UNI/TR 11634:2016 Linee guida per il monitoraggio strutturale*. 2016.
6. International Organization for Standardization, *ISO 2394:2015 - General principles on reliability for structures*. 2015.
7. Ministry of Housing and Urban-Rural Development of PRC, *National Standard of the People's Republic of China: Technical code for monitoring of building and bridge structures GB50982–2014.* 2014.
8. International Organization for Standardization, *ISO 55000:2014 - Asset management: Overview, principles and terminology*. 2014.
9. International Organization for Standardization, *ISO 16739:2013 - Industry Foundation Classes (IFC) for data sharing in the construction and facility management industries*. 2013.
10. Österreichische Forschungsgesellschaft Straße - Schiene - Verkehr, *RVS 13.03.01 - Monitoring von Brücken und anderen Ingenieurbauwerken*. 2012.
11. European Committee for Standardization, *CEN - EN 15331: Criteria for design, management and control of maintenance services for buildings*. 2011.
12. National Standard of the Russian Federation, *GOST R 53778-2010: Buildings and constructions - Technical Condition Examination and Monitoring Rules*. 2012.
13. International Organization for Standardization, *ISO 13822:2010 - Bases for design of structures -- Assessment of existing structures*. 2010.
14. Verein Deutscher Ingenieure VDI Standsicherheit von Bauwerken, *Regelmäßige Überprüfung, Richtlinie VDI 6200*. 2010.
15. International Organization for Standardization, *ISO 13824:2009: Bases for design of structures -- General principles on risk assessment of systems involving structures*. 2009.
16. International Organization for Standardization, *IEC 31010:2009: Risk management -- Risk assessment techniques*. 2009.
17. International Organization for Standardization, *ISO 14044:2006: Environmental management -- Life cycle assessment -- Requirements and guidelines*. 2006.
18. International Organization for Standardization, *ISO 16587:2004: Mechanical vibration and shock -- Performance parameters for condition monitoring of structures*. 2004.
19. International Organization for Standardization, *ISO 14963:2003: Mechanical vibration and shock -- Guidelines for dynamic tests and investigations on bridges and viaducts*. 2003.

20. International Federation for Structural Concrete, *Monitoring and safety evaluation of existing concrete structures: State-of-art report*. 2003.
21. Mufti, A.A. and I. Canada, *Guidelines for Structural Health Monitoring*. 2001: ISIS Canada (Intelligent Sensing for Innovative Structures).
22. Joint Committee for Structural Safety (JCSS), *Probabilistic Model Code*. 2001.
23. German Institute for Standardization, *DIN 1076:1999-11 - Engineering structures in connection with roads - inspection and test*. 1999.
24. Standards Norway (NORSOK), *NORSOK N-005: Condition monitoring of loadbearing structures*. 1997.
25. Joint Committee for Structural Safety (JCSS), *Background document on Value of Information of SHM (in preparation)*
26. Faber, M.H., D. Val, and S. Thöns, *Value of Information in SHM- Considerations of the Theoretical Framework, 1st workshop of COST Action TU1402, Thöns (Eds), May 04-05, 2015*. 2015: Copenhagen, Denmark.
27. Brüske, H. and S. Thöns, *Domains of the Value of Information in Structural Health Monitoring,* , in *3rd workshop of COST Action TU1402, March 14-15, 2016*, Miraglia et al. (Eds), Editor. 2016: Barcelona, Spain.
28. Straub, D. and E. Chatzi, *Framework for SHM value of Information Analysis and computation*, in *3rd workshop of COST Action TU1402, March 14-15, 2016*, M.e.a. (Eds), Editor. 2016: Barcelona, Spain.
29. Straub, D., E. Chatzi, E. Bismut, W.M.G. Courage, M. Döhler, M.H. Faber, J. Köhler, G. Lombaert, P. Omenzetter, M. Pozzi, S. Thöns, D. Val, H. Wenzel and D. Zonta, , *Value of Information: A roadmap to quantifying the benefit of structural health monitoring*, in *2th international conference on Structural Safety & Reliability (ICOSSAR2017)*. 2017: Vienna, Austria.
30. Faber, M.H. and M.G. Stewart, *Risk assessment for civil engineering facilities: critical overview and discussion.* Reliability Engineering & System Safety, 2003. **80**(2): p. 173-184.
31. Joint Committee on Structural Safety (JCSS), *Risk Assessment in Engineering – Principles, System Representation and Risk Criteria*, ed. M. Faber. 2008.
32. Karbhari, V.M. and F. Ansari, *Structural Health Monitoring of Civil Infrastructure Systems - 1st Edition*. 2009: Woodhead Publishing.
33. Bismut, E., et al., *Framework and categorization of Value of Information Analysis, Factsheet WG3, Cost Action 1402*. 2017.
34. COST Action 345, *Procedures required for assessing highway structures, Joint Report of Working Groups 2 and 3: methods used in European States to inspect and assess the condition of highway structures*. 2004.
35. Chang, S.P., J. Yee, and J. Lee, *Necessity of the bridge health monitoring system to mitigate natural and man-made disasters.* Structure and Infrastructure Engineering, 2009. **5**(3): p. 173-197.
36. Sousa, H., et al., *Design and implementation of a monitoring system applied to a long-span prestressed concrete bridge.* Structural Concrete, 2011. **12**(2): p. 82-93.
37. Xu, Y.L., *Making good use of structural health monitoring systems of long-span cable-supported bridges.* Journal of Civil Structural Health Monitoring, 2018. **8**(3): p. 477-497.
38. Wong, K.-Y., *Design of a structural health monitoring system for long-span bridges.* Structure and Infrastructure Engineering, 2007. **3**(2): p. 169-185.

39. Standardization, C.A.f.E.C., *Design standard for structural health monitoring system (CECS 333:2012)*. 2012, China Architecture & Building Press.
40. Pines, D. and A.E. Aktan, *Status of structural health monitoring of long-span bridges in the United States.* Progress in Structural Engineering and Materials, 2002. **4**(4): p. 372-380.
41. Bas, S., et al., *Structural health monitoring system of the long-span bridges in Turkey.* Structure and Infrastructure Engineering, 2018. **14**(4): p. 425-444.
42. Zonta, D., B. Glisic, and S. Adriaenssens, *Value of information: Impact of monitoring on decision-making.* Structural Control and Health Monitoring, 2014. **21**(7): p. 1043-1056.
43. Vardanega, P.J., et al., *Assessing the potential value of bridge monitoring systems.* Proceedings of the Institution of Civil Engineers: Bridge Engineering, 2016. **169**(2): p. 126-138.
44. Enckell, M., *Lessons learned in Structural Health Monitoring of Bridges Using Advanced Sensor Technology*, in *School of Architecture and the Built Environment*. 2011, KTH Royal Institute of Technology: Stockholm.
45. Thöns, S., *On the Value of Monitoring Information for the Structural Integrity and Risk Management.* Computer-Aided Civil and Infrastructure Engineering, 2018. **33**(1): p. 79-94.
46. Sousa, H., J. Bento, and J. Figueiras, *Assessment and Management of Concrete Bridges Supported by Monitoring Data-Based Finite-Element Modeling.* Journal of Bridge Engineering, 2014. **19**(6): p. 05014002.
47. Sousa, H., J. Bento, and J. Figueiras, *Construction assessment and long-term prediction of prestressed concrete bridges based on monitoring data.* Engineering Structures, 2013. **52**: p. 26-37.
48. Dann, M.R. and M.A. Maes, *Stochastic corrosion growth modeling for pipelines using mass inspection data.* Reliability Engineering & System Safety, 2018. **180**: p. 245-254.
49. Holický, M., J.V. Retief, and M. Sýkora, *Assessment of model uncertainties for structural resistance.* Probabilistic Engineering Mechanics, 2016. **45**: p. 188-197.
50. COST Action TU 1406, *Performance Indicators for Roadway Bridges, Technical report of the Working group 1: Performance indicators. Editors/Autors: Strauss A., Mandić Ivanković A.* 2016.
51. Melchers, R., *Structural reliability analysis and prediction*. 1999: Chichester, John Wiley & Sons.
52. Faber, M.H., D.V. Val, and M.G. Stewart, *Proof load testing for bridge assessment and upgrading.* Engineering Structures, 2000. **22**(12): p. 1677-1689.
53. Ditlevsen, O. and H. Madsen, *Structural reliability methods*. 1996: John Wiley & Sons.
54. Straub, D., *Reliability updating with equality information.* Probabilistic Engineering Mechanics, 2011. **26**(2): p. 254-258.
55. Holický, M., *Optimisation of the target reliability for temporary structures.* Civil Engineering and Environmental Systems, 2013. **30**(2): p. 87-96.
56. Sternal, M. and K. Dragos, *BIM based modelling of Structural Health Monitoring (SHM) using the IFC Standard 28*, in *Forum Bauinformatik 19th –21st September 2016*. 2016: Leibniz Universität Hannover, Germany.

57. Stepinac, M., V. Rajčić, and D. Honfi, *Decision analysis and scenarios for the assessment of existing timber structures*, in *IABSE Symposium 2019*. 2019: Guimarães, Portugal, .
58. Stepinac, M., V. Rajčić, and D. Honfi, *Condition assessment of timber structures – quantifying the value of information*, in *IABSE Symposium 2018* 2018: Nantes, France.
59. Sykora, M., et al., *Assessment of compressive strength of historic masonry using non-destructive and destructive techniques.* Construction and Building Materials, 2018. **193**: p. 196-210.
60. Sykora, M., et al., *Optimizing in-situ testing for historic masonry structures: a case study*, in *2nd RILEM Spring Convention & International Conference on Sustainable Materials, Systems and Structures*. 2019: Rovinj, Croatia.
61. Diamantidis, D. and M. Sykora, *Implementing Information Gained through Structural Health Monitoring - Proposal for Standards*, in *13th International Conference on Applications of Statistics and Probability in Civil Engineering*. 2019: Seoul, Korea.
62. Klerk, W., et al., *Structural health monitoring in life-cycle management of dikes: a case study in the north of the Netherlands.* , in *Life-Cycle Eng. Syst. Emphas. Sustain. Civ. Infrastruct. Proc. 5th Int. Symp. Life-Cycle Civ. Eng. (IALCCE 2016)*. 2016: Gent, Belgium.
63. Honfi, D., J. Leander, and I. Björnsson, *Decision support for bridge condition assessment*, in *4th International Conference on Smart Monitoring, Assessment and Rehabilitation of Civil Structures (SMAR 2017)*. 2017: Zürich, Switzerland.
64. Leander, J., D. Honfi, and I. Björnsson, *Risk-based planning of assessment actions for fatigue life prediction. .* Procedia Structural Integrity, 2017. **5**: p. 1221-1228.
65. Leander, J., et al., *A decision support framework for fatigue assessment of steel bridges.* Engineering Failure Analysis, 2018. **91**: p. 306–314.
66. Skokandić, D., et al., *APPLICATION OF BRIDGE WEIGH-IN-MOTION MEASUREMENTS IN ASSESSMENT OF EXISTING ROAD BRIDGES*, in *ZAGREB JOINT WORKSHOP - The Value of Structural Health Monitoring for the reliable bridge Management*. 2017: University of Zagreb, Faculty of Civil Engineering, Croatia.
67. Mandić Ivanković, A., et al., *Bridge performance indicators based on traffic load monitoring.* Structure and Infrastructure Engineering, 2017: p. 1-13.
68. Skokandić, D., et al., *Quantifying the value of B-WIM: Assessing costs and benefits for Value of Information Analysis*, in *IABSE Symposium in Guimaraes*. 2019.
69. Giordano, P., M. Limongelli, and S. Miraglia, *The benefit of permanent monitoring for seismic emergency management*, in *SHMII-9 International Conference on Structural Health Monitoring of Intelligent Infrastructure*. 2019: St. Louis, Missouri (USA).
70. Sousa, H., A. Slobbe, and W. Courage, *A pro-active concept in asset management supported by the quantified Value of Structural Health Monitoring*, in *IABSE Symposium 2019*. 2019: Guimarães, Portugal.
71. Sousa, H. and W. Courage, *Value of Information of a pro-active SHM tool devoted to early damage detection on bridges - Factsheet*. 2018: Limassol, Cyprus. p. 8.
72. Espinosa, J. and J. Köhler, *Value of site-specific information for the design of offshore wind farms*, in *IABSE Symposium 2019* 2019: Guimarães, Portugal.

73. Espinosa, J. and J. Köhler, *Risk-based Design of an Offshore Wind Turbine using VoI Analysis*, in *13th International Conference on Applications of Statistics and Probability in Civil Engineering (ICASP13)*. 2019: Seoul, South Korea.
74. Thöns, S., M. Faber, and D. Val, *On the Value of Structural Health Monitoring Information for the Operation of Wind Parks*, in *12th International Conference on Structural Safety and Reliability (ICOSSAR2017)*. 2017: Vienna, Austria.
75. Maślak, M., M. Pazdanowski, and T. Howiacki, *Value of information in the maintenance of a tendon supported large span roof*, in *40th IABSE Symposium "Tomorrow's Megastructures*. 2018: Nantes, France. p. S27-19 – S27-26.
76. Diamantidis, D., M. Sykora, and D. Lenzi, *Optimising Monitoring: Standards, Reliability Basis and Application to Assessment of Roof Snow Load Risks.* Structural Engineering International, 2018. **28**(3): p. 269-279.
77. Diamantidis, D. and M. Sykora, *Optimizing monitoring – implementation of draft guideline and case study of roof exposed to snow loads*, in *40th IABSE Symposium - Tomorrow's Megastructures*. 2018: Nantes, France. p. 27-34 (S27).
78. Diamantidis, D. and M. Sykora, *Optimizing monitoring – implementation of draft guideline and case study of roof exposed to snow loads*, in *40th IABSE Symposium*. 2018: Nantes, France.
79. Diamantidis, D., M. Sykora, and D. Lenzi, *Optimizing monitoring: application to assessment of roof snow load risks, Factsheet WG4*. 2018: Cost Action TU1402 - Quantifying the Value of Structural Health Monitoring.
80. Holicky, M., D. Diamantidis, and M. Sykora, *Economically optimum structural design: methodology and case study*, in *HPSM/OPTI 2018 - the 2018 International Conference on High Performance and Optimum Design of Structures and Materials*. 2018: Ljubljana, Slovenia. p. 143 - 153.