System representation

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System representation

Scope of the fact sheet

- Outline the basic principles of system representation in the context of risk-based decision making framework.
- Highlight the most important aspects related to Structural Health Monitoring (SHM).

Abstract

To be able to quantify the value of SHM, the system in consideration needs to be identified and appropriately modelled. Therefore a general representation of the system is needed, which incorporates the identification of various scenarios of events i.e. exposures, damages, failures and associated consequences. Furthermore, it should be decided which of these to be considered and/or suited for monitoring. Thus the evaluation of expected utilities and risks with and without the application of the SHM system is possible. This fact sheet gives an overview about some of the important aspects of system representation.

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System representation

Basis / theory / methods

Structural reliability methods; Engineering risk assessment; Statistical decision theory and Bayesian analysis; Value of Information theory.

Application areas

The treatment of system representation in a consistent manner is important for achieving a decision, which is not biased due to poor system representation.

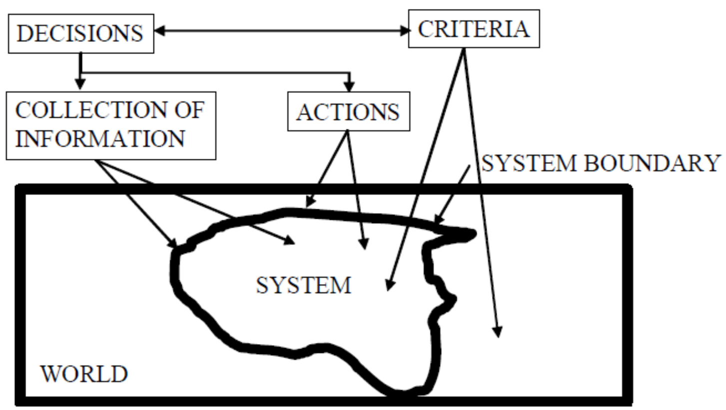
Critical appraisal

A consistent and convenient system representation in a risk-based decision framework is essential for the VoI analysis of SHM. However, the framework is relatively straightforward, often simplifications are needed, otherwise the computational efforts for the VoI analysis may become inconveniently large. When doing so, i.e. making simplifications, one should keep in mind “the principle of consistent crudeness”.

1 Introduction

- Inspection and monitoring techniques → information can be utilized to reduce uncertainties concerning decisions about the structure.
- Additional information has a price which might or might not be in balance with its benefits
- In practice the effectiveness of the monitoring system first becomes apparent after it has been installed and used.
- Mathematical framework for quantitatively assessing the benefit of a monitoring system before it is actually installed and operated does exist:
    - Bayesian statistical decision theory by Raiffa and Schlaifer (1961)
    - Value of Information theory by Howard (1966)
    - Structural reliability methods (e.g. Madsen, 1987)
- Several reliability- and risk-based approaches for inspection planning in the past decades.

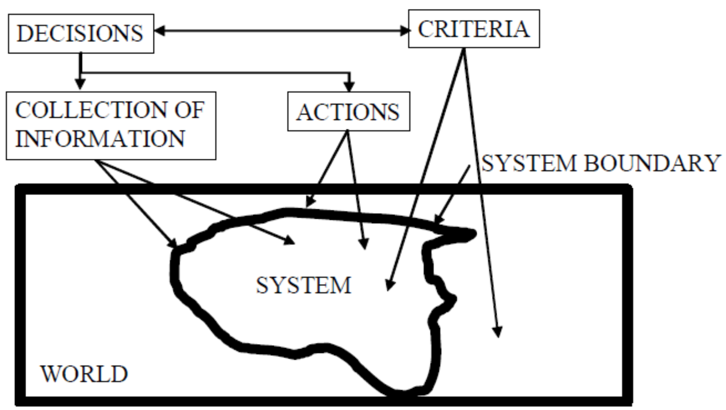
2 System identification



Main constituents in risk based decision analysis (Maes and Faber, 2008).

- Engineering decision making: "playing a game" where the decisions by the decision maker aim to optimize the expected utility
- To "win" the game the rules must be clear.
- Information is needed about: the assets, its surrounding, the possible consequences of actions, the interrelation of different factors that affect system performance etc.
- Participating in the game:
    - "buying" physical changes in the system or
    - "buying" knowledge about the system

2 System identification



Main constituents in risk based decision analysis (Maes and Faber, 2008).

- SHM context: uncertainty of the occurrence of future exposures/hazards, the system behaviour, system components, degradation mechanisms, observations etc. should be accounted for.
- Clear definition of several constituents of the decision:
  - the system (definition and identification),
  - the rationale of decision ranking (and acceptance criteria),
  - perception of risks and consequences (with probabilities of occurrence).

2 System identification

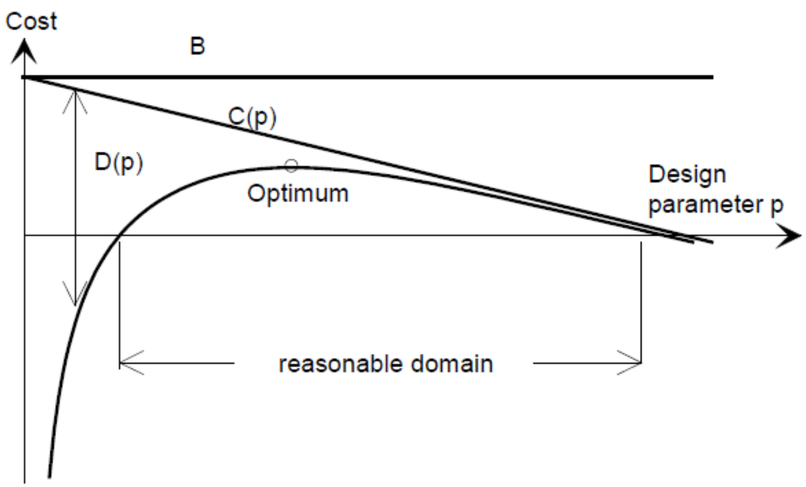
- Risk-based decision making enables:
  - the ranking of decision alternatives (consistent with available knowledge);
  - updating of risks (according to knowledge available in the future);
  - responsive decision making in the future (depending on future knowledge).
- SHM: continuous/regular updating of knowledge is available, therefore the latter two attributes of the model are utterly important.
- The system can be modelled at different levels of detail:
  - sufficiently describe the logical relationship between events and scenarios;
  - information about the system components can be incorporated (updating system performance);
  - uncertainties are treated consistently (different type of risks can be integrated and aggregated).

2 System identification

- Bayesian probability theory: incorporation of both subjective information and available evidence.
- SHM context: identify the components of the system, which are relevant to monitor, along with the identification of the individual components of the system and their interrelation. Different monitoring schemes should be identified in a consistent manner and be used as input in the decision making.

3 Utility/Risk

$$Z(p) = B(p) - C(p) - D(p)$$



Cost and benefit over design parameter p
(Rosenblueth and Mendoza, 1971)

3.1 Utility

- *Objective of DM: maximise the expected utility (often substituted by economic benefits)*
- *B(p)* is the benefit derived from the existence of the structure
- *C(p)* are the construction cost
- *D(p)* the expected cost of failure, whereas *p* is a parameter vector with which cost and reliability can be controlled.

3 Utility/Risk

3.2 Risk

$$R = P \cdot C$$

- Technical risk: expected consequences associated with a given activity.

$$R_A = \sum_{i=1}^{n_E} R_{E_i} = \sum_{i=1}^{n_E} P_{E_i} C_{E_i}$$

- Risk associated with a given activity R_A relating to all possible events n_E

4 Uncertainty

- The degradation of the performance of structures over time is subject to a number of uncertainties, which include material properties, environmental exposures, mechanical loading, operational conditions, etc.
- Types:
  1) aleatory variability which stems from natural randomness and
  2) epistemic uncertainty associated with lack of knowledge (or data).
- Limited statistical basis for the assessment: “statistical” epistemic uncertainties
- Epistemic uncertainties can be represented in the model by introducing auxiliary non-physical variables
- SHM context: auxiliary variables capture information obtained through gathering more data (or use of more advanced scientific principles),
- These variables define statistical dependencies (correlations), which arise among different components that have common uncertainties, in a clear and transparent way.

4 Uncertainty

- Probabilistic description: random variables, stochastic processes and/or random fields depending etc., temporal and spatial dependencies might be taken into account.
- SHM context:
  - deterioration processes acting on structures are highly uncertain (underlying processes rarely are fully understood and/or influenced by several parameters).
  - Probability of failure (both components and system) will increase in time without maintenance actions
  - The probabilistic models for deterioration processes: a mixture of physical understanding, observations and experience → observations can reduce the uncertainty in predictions
  - Inspection and maintenance actions themselves are subject to significant uncertainties. The quality of inspections: ability to detect and quantify the dimension of the defects in consideration. → Different inspection methods and techniques might be useful for different deterioration processes.

5 Ranking

Decision problem is a choice among courses of action when:

- the consequence of any course of action will depend upon the “state of the world”,
- the true state is yet unknown,
- it is possible (at a cost) to obtain additional information about the state.

SHM context: it can be assumed that the problem is reduced to a limited number of alternatives (e.g. do nothing, inspect, repair, strengthen, reduce loads). It can be further assumed that the decision maker wishes to choose among these alternatives in a way which will be logically consistent with:

- the decision maker’s basic preferences concerning consequences, and
- his/her basic judgments concerning the true state of the world.

5 Ranking

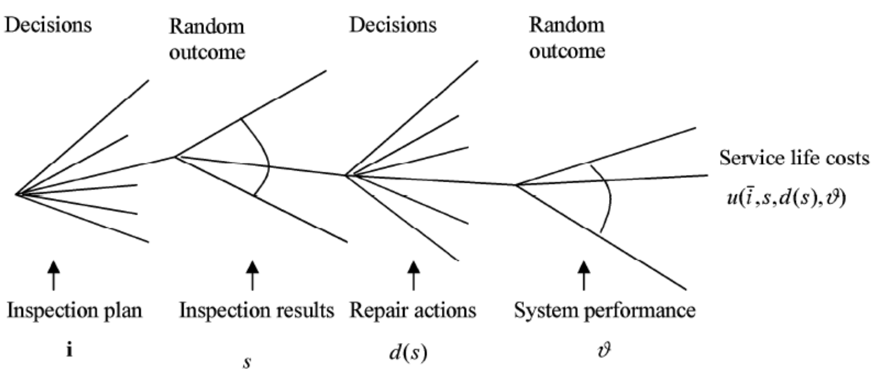
$$E\left[U(A)\right] = \sum_{i=1}^{n_O} p(i|A)u(A,O_i)$$

The basic principle of ranking alternatives *A* is based on their expected utility *E[U(A)].*

- n_O is the number of possible outcomes associated with alternative *A*,
- $p(i|A)$ is the probability that each of these outcomes will take place (given *A*) and
- $u(A, O_i)$ is the utility associated with the set (A, O_i).

The analysis of the utility function can be used for:

1) the prediction of the behaviour of the decision maker and
2) provide a basis for rational decision making.

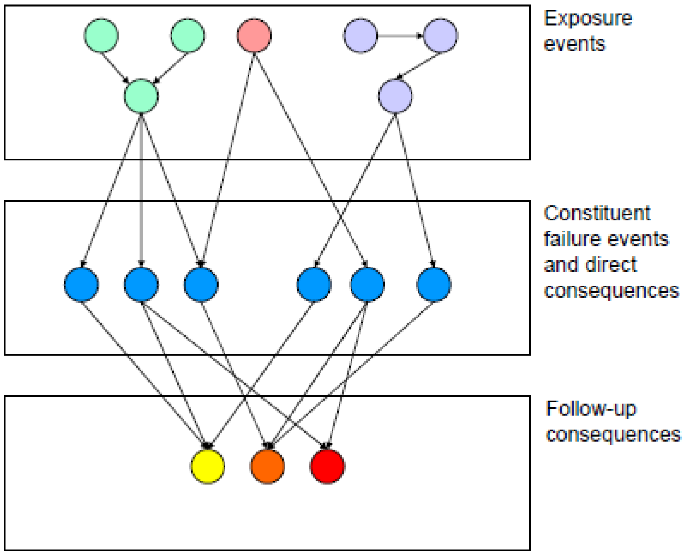


Inspection planning decision tree (Faber, 2002)

6 Acceptance criteria

- Usually: normative targets (implemented by the partial safety factors).
  - Not necessary the same for planned and existing structures, because the relative effort to control reliability and potential consequences is different.
- Acceptable p_f should based on an optimisation where the consequences of failure are assessed in terms of preferences expressed in monetary terms.
  - Value of the individual to society could be addressed by means of the LQI.
- Individual decision-makers might have considerably different preferences and accepted level of risk.
  - Risks unacceptable for the society should be avoided → maximum acceptable p_f → target reliabilities
- ALARP: all reasonable measure must be taken to reduce the risk. However, in some situation the actions required to reduce the risk is gross-proportional to the risk itself, if this can be well documented and ensured that all possible hazards and consequences are considered the risk picture is said to be ALARP.

7 Consequences



Generic representation of consequences (JCSS, 2008)

- System representation should facilitate the identification of scenarios of events.
- Repair and failure events of system components may have significant consequences on safety and economy.
- Inspections, repairs and failures have immediate consequences on costs; the event of failure may in addition have consequences on the potential loss of lives.
- Assessment of consequences related to an inspection plan can be assessed e.g. using decision/event trees.

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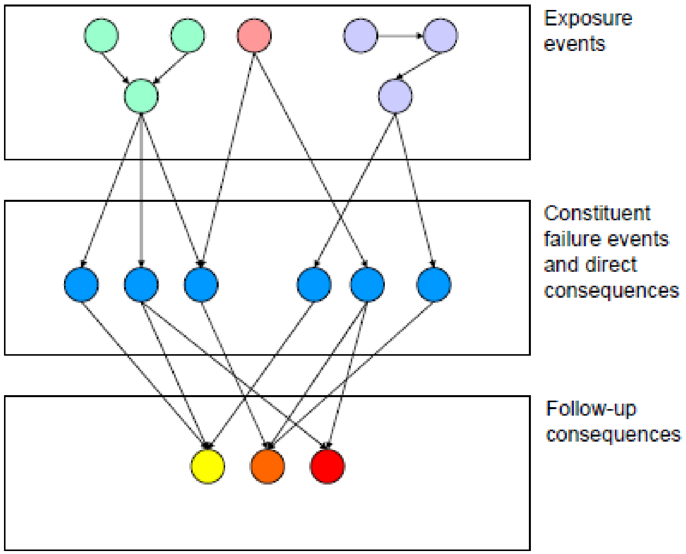
7 Consequences



Generic representation of consequences (JCSS, 2008)

- Scenario representations (possible sequences of events affecting the performances, taking into account probabilities and consequences).
- Risk indicators e.g. vulnerability and robustness → distinguish between direct and indirect consequences.
- C_D: associated with damages or failures of the system constituents;
- CI_D: associated with the loss of the functionalities of the system and by any specific characteristic of the joint state to the constituents and the direct consequences themselves.