FRAMEWORK FOR ASSESSMENT AND LIFE EXTENSION OF STRUCTURES AND INDUSTRIAL PLANTS

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1. Introduction

As existing facilities / structures are modified, as engineering knowledge advances and as the requirements to extend life increase, industries must demonstrate that operations can continue safely and economically. There is a general recognition across all industrial sectors that this reassessment process is different from the design process. As a minimum, the known conditions and specific functional requirements of existing facilities / structures need to be taken into account (with design 'uncertainty factors' removed where site-specific parameters are available from as-built information and inspections).

Workpackage 6 of SAFERELNET TN [1] has established a framework for the cost optimal assessment of existing structures in consistency with the available information and such that any requirement to the safety of the facility or structure is achieved. This framework is applicable to all industrial sectors.

The approach for the assessment of structures is given in Section 3. To asset a system, product, or process the reader is kindly referred to WP4 [2]. However, a short general conclusion is presented in Section 2.

2. General Approach of Assessment

If an object is designed and constructed, it can be assumed that it is efficient and fulfils the given requirements. However, this statement is strictly subjected to the condition that all assumptions underlying the codes and applied specifications are fulfilled throughout the anticipated service life. Therefore, if there is a doubt concerning the fulfilment of either the given requirements to the operating of an object or the assumptions underlying the design a reassessment of the structure is recommended.

Independent from the type of assessment and the kind of object, every assessment consists of 3 main parts: a) Triggering & Preliminary Investigation, b) In-depth Investigation & Assessment, and c) Conclusion & Consequences), according to Figure 1.

Within each main part, various decisions are necessary, which can result in a complex decision-making process. To avoid subjective decisions, a cost-benefit analysis is recommended, assigning each future event with all advantages and disadvantages in monetary units. These cost-benefit relations should be considered in each part and can be reused and updated within the assessment process. The quality and success depend on the current state-of-the-art (codes, standards, etc.), the individual expertise, and experience of the executor.

3. Framework for the Assessment of Existing Structures

Nowadays, many industrial sectors have established their own strategy for the assessment of existing facilities / structures and lifetime extension. A common approach is a step-by-step assessment from a crude visible inspection to a detailed structural reliability analysis. Each indus-

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trial sector has developed its own concept for the assessment. The most advanced and common guidelines and codes are JCSS, ISO 2394, and ISO 13822, described in WP6 [4].

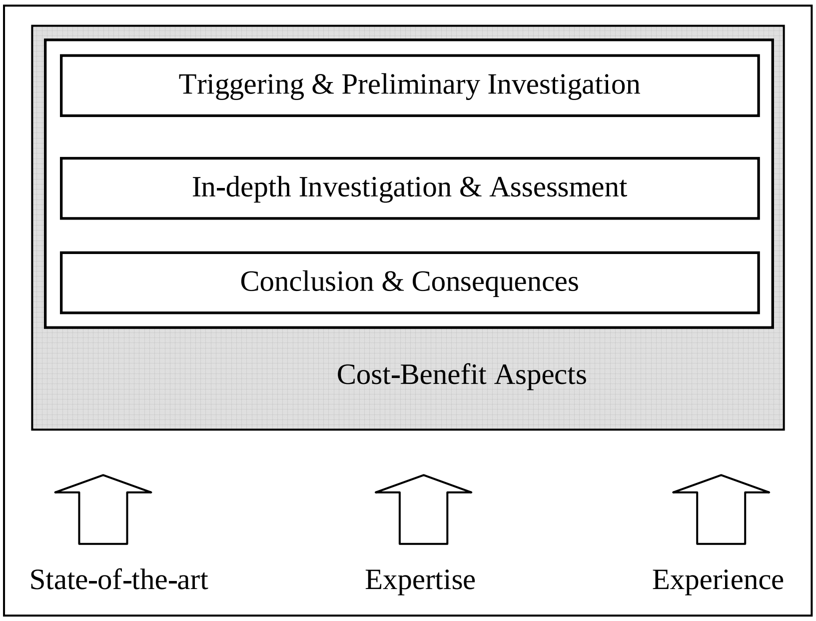

Figure 1 General approach of an assessment

The flow chart, shown in Figure 2, summarises the best practice of all industrial sectors to one framework for the assessment of existing structures and facilities, applicable to all structures of all industrial sectors. Additionally, special standards and codes should be established to reflect the special requirements of each industrial sector at the specific assessment stage.

The process of collecting information, updating structural performance through analysis and devising repair and strengthening activities is a decision process which aims to identify the most effective investigations and modifications required to satisfy new requirements to the use of the structure and to remove any doubts in regard to the condition and future performance of the structure. It is important that this process is optimised, considering the total service life costs of the structure by an integrated cost-benefit analysis.

Explanation of specific assessment steps:

(a) Assessment initiator: An assessment initiator, also called trigger, is the reason to activate the assessment procedure. The main initiators are described in WP6 [4].

(b) Review system, actions and condition: The current system, actions, and condition have to be compared with the original design performance. The information is available from original design data, construction data, history data (e.g., monitoring data, special events), and simple visual inspection and measurements (e.g., size of components). Changes regarding renewed codes should be considered.

(c) Assessment reasonable? In case the preliminary investigations show that a full assessment is not necessary, the procedure can be stopped; for example, if doubts are not confirmed or the knowledge from a similar object can be used.

(d) Refine system, actions, and resistances: If new information from the first review (b) is available, the assumptions of actions, resistances, model, and system have to be corrected. In advanced levels of numerical assessment it is possible to refine these assumptions by increased knowledge due to experimental assessments.

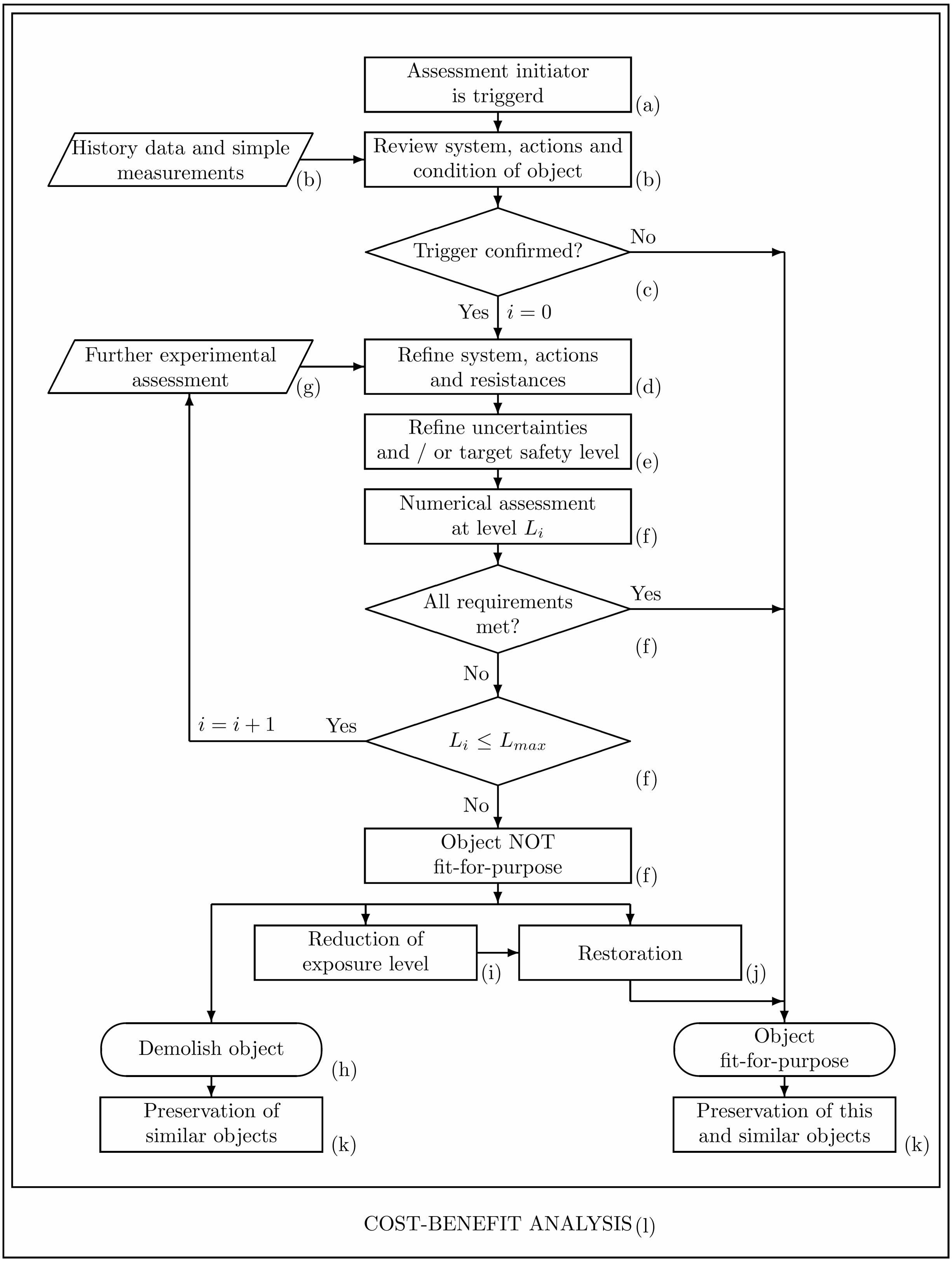

Figure 2 Flow chart of a structural assessment

(e) Refine uncertainties and / or target safety levels: In the first level of calculation L_0 newest common codes and standards shall be used to determine the uncertainties of exposure and resistance, as well as, the target safety level. Very often these codes use a partial safety factor approach. Within more advanced experimental assessments the uncertainties and safety levels can be corrected due to increased knowledge. The refinement of model and system assumptions has to be considered as well. WP6 [4] discusses this topic in detail.

(f) Numerical assessment: Numerical assessment is every calculation based on the refinements in (d) and (e) of the safety / reliability of the considered object. There are several possible levels, whereas the first one should be always using common codes.
If the object do not pass the requirements of the codes, a more advanced numerical assessment can be applied. Some possibilities are: considering linear or non-linear approaches, or investigating components or the whole structure. The most advanced method is the system reliability analysis based on a generic approach. Obviously, it is difficult to define a strong hierarchy of such methods. The range of more advanced levels depends on the object and differs from industrial sector to industrial sector. Risk analysis and cost-benefit aspects shall be considered as well.
Additional experimental assessments can be necessary to increase the knowledge of the exposure level, resistance level, and model and system assumptions of the investigated object, which finally yields to a loop with different levels L_i of increased accuracy. The highest level L_{max} depends on the available numerical and experimental assessment methods and cost-benefit relations. Assuming all tools are used and the object does not pass the numerical assessment, the loop ends and the object is declared as NOT fit-for-purpose.
A detailed description of advanced numerical assessment methods is given, for example, in WP5 [3].

(g) Experimental assessment: Experimental assessment includes the decision of what should be measured, which method has to be used and the subsequent interpretation of the results. Obviously, it depends on the next numerical assessment step and the cost-benefit relation. A detailed description of various methods is available in WP6 [4].

(h) Demolish object: The investigated object will be destroyed. Therefore, aspects of environment-friendly recycling or reuse of parts of the object have to be considered. The reused parts need an additional intensive experimental assessment and an advanced maintenance program (WP7 [5], [6]). The data of the assessment should be used to verify similar existing or further objects.

(i) Reduction of exposure level: The exposure level of the object will be limited. It has to be guaranteed that no higher exposure level is possible. Consequently, an additional modification of the object is necessary by restoration (j).

(j) Restoration: Restoration is defined as an essential or minimum set of retrofit steps such that the service or ultimate life can be extended for a specified time period. The main restoration methods are the increase of resistance or reduction of the exposure level. After a restoration an additional general assessment is necessary to verify the performance of the new object.

(k) Preservation: Preservation defines all activities, which allow keeping the system in a state such that a continuous safe and reliable operation is guaranteed during the entire service life. This is of paramount importance for systems, which are subjected to deterioration with usage and age, as well as for a further extension of lifetime. Preservation encircles different activities: information updating (WP5 [3]); reassessment (WP6 [4]); and, most notably, maintenance (WP7 [5] [6]).

(l) Cost-Benefit Analysis: The results of a cost-benefit analysis can be used as input to the decision processes. Such decisions have to be made during the whole assessment (e.g., should the object be demolished or restored, or what kind of experimental assessments should be performed). A cost-benefit analysis is a rational decision tool where the optimal decision is the one which maximizes the total expected benefits minus costs in the design or remaining lifetime. All benefits and costs have to be expressed in monetary units and are discounted to, for example, the time of decision. In the decision process all information and aims should be considered by weighting social, economical, and environmental aspects. The description of modelling a cost-benefit-function is described in Section 6 and in detail in WP6 [4].

4. Current Guidelines, Rules, and Codes

Table 1 gives an overview of the current state-of-the-art of common rules, codes, and standards sorted by industrial sectors and investigation topics. This list is not exhaustive.

Table 1 Overview of the state-of-the-art in several industrial sectors
(for more details see WP8 [7])

Industrial sector	Modification of Target safety levels or partial safety factors	Guidelines for assessment / reassessment of existing facilities / structures	Cost – Benefit – Aspects
Overall sectors	JCSS guide [16]; ISO 2394 [9]	JCSS guide [16]; ISO 2394 [9]	JCSS guide [16]
Offshore Oil and Gas	NPD [27]; Very crude suggestions by API [26]	ISO 19902 (DRAFT) [8]; ISO 2394 [9]; ISO 13822 [10]	
Marine Transportation	ANSI/ASME B31G; DNV RP-F101		ESREL03 paper [25]
Buildings	Reduction of partial safety factors [20]	ISO 13822[10]; ISO 2394 [9]; national guidelines	JCSS guide [16]
Motorways and Bridges	- Very, very crude assumptions by introducing a condition factor (BD21/93 [12], BD44/95 [13]) - Reduction of resistance to consider deterioration (limited to non visible deterioration) [11] - Rodriguez et al.[30]	- bridge management systems PONTIS [33], DANBRO [14]and BRIME - theoretical models ([18], [15]) - further special national guidelines - ISO 2394 [9]	JCSS guide [16]
Process Industry		Special company intern guidelines (e.g. Shell [32])	
Power Plants	Lower target safety level for existing nuclear power plants than for future INSAG-3 [22]/ INSAG-12 [23]	- Special company intern guidelines (e.g. CPPE) - for nuclear installations: Safety Guideline [21] and French rules RCC-M	
Aircraft		European (UK, France, Germany) guidelines ([17], [24])	

5. Experimental and Numerical Assessment Methods

For experimental, as well as, for numerical assessment methods several steps of different levels of detail and effort are possible. It is recommended to start from a very simple level with less work and crude assumptions, and to increase the level of detail step-by-step. The top level depends on the special task, expertise of the employees, the research status-quo, and the relation between costs and benefits. This decision has to be determined after each assessment step.

Fundamental numerical assessment methods sorted from a lower to an upper level are, for example:

- Linear analysis and component check (follow the code)
- Refined actions and resistances
- Linear elastic redundancy analysis
- Non-linear analysis and component checks
- Structural reliability analysis, using BAYESIAN event updating

Obviously, not each method is applicable for each task and for special problems additional methods are required. Sometimes, a higher level can only be obtained by additional knowledge about the structure using experimental assessment strategies. This increase of information can also be used to adjust the target safety level or uncertainties of exposures, resistances, and model and system assumptions (WP6 [4]).

With regard to the method, experimental assessment methods can be distinguished between:

- Inspections (i.e., simple sight views and measurements, sometimes this step is done within a maintenance process)
- Destructive techniques (DT)
- Non-destructive techniques (NDT)

Another classification relates to the object of assessment. It is possible to asset the:

- Resistance level (i.e., materials)
- Exposure level (i.e., determine the wind or waves by monitoring)
- Relation between resistance and exposure level (i.e., maximal loads for ultimate or serviceability limit states)

Table 2 gives an overview about possible experimental assessment methods, which are described in detail in WP6 [4].

Due to cost and time aspects, an excellent coordination between numerical and experimental assessment methods is required. Consequently, a precise preparation is recommended. Before starting with an experiment, the following questions should be answered:

- What do you expect from an experimental assessment?
- Are the expected results useful for the special task?
- What do you need for the next numerical assessment step?
- Which kind of experimental assessment is the optimal for this aim?
- Do the expected results justify the expected costs?

6. Decision Making and Cost-Benefit Analysis

Nowadays many decisions have to be made by people who are not specialists in all of the fields a decision will cover. In many cases this leads to arbitrary decisions, which are not optimal considering a global view. As an input to the decision process the results of a rational cost-benefit analysis can be used. A cost-benefit analysis is a rational decision tool where the optimal decision is the one which maximizes the total expected benefits minus costs in the design or remaining lifetime. All benefits and costs have to be expressed in monetary units and are discounted to, for example, the time of decision.

Basically, benefits $B(\mathbf{d})$ depend on the decision maker and the related preferences. Benefits can be related to:

- Serviceability / user benefits
- Disposition (total or partial)
- Individual benefits (prestige, maintenance of environment, saving of resources, historical maintenance, motivation of employers, etc.)
- Others

The costs are:

- $C_{IR}(\mathbf{d})$ - Initial repair / strengthening / demolition costs for the assessment (direct costs (i.e., material and employers costs), indirect costs (i.e., costs of detours)), i.e., costs close to the time of re-assessment T_R
- $C_{EI}(\mathbf{d},\mathbf{e})$ - Expected inspection costs (maintenance, monitoring, additional reassessment, preventive actions, experiments, etc.), i.e., costs after the time of re-assessment T_R

- $C_{ER}(\mathbf{d},\mathbf{e})$ - Expected repair and strengthening costs (direct costs (i.e., material and employers costs), indirect costs (i.e., costs of detours)), i.e., costs related to actions based on the results of inspections
- $C_{NS}(\mathbf{d},\mathbf{e})$ - Non-serviceability costs (production downtimes, etc.)
- $C_F(\mathbf{d},\mathbf{e})$ - Failure costs (in case of total collapse, i.e., damage of material, life, and prestige)
- Others

All benefits and costs have to be discounted by

- γ - real rate of interest

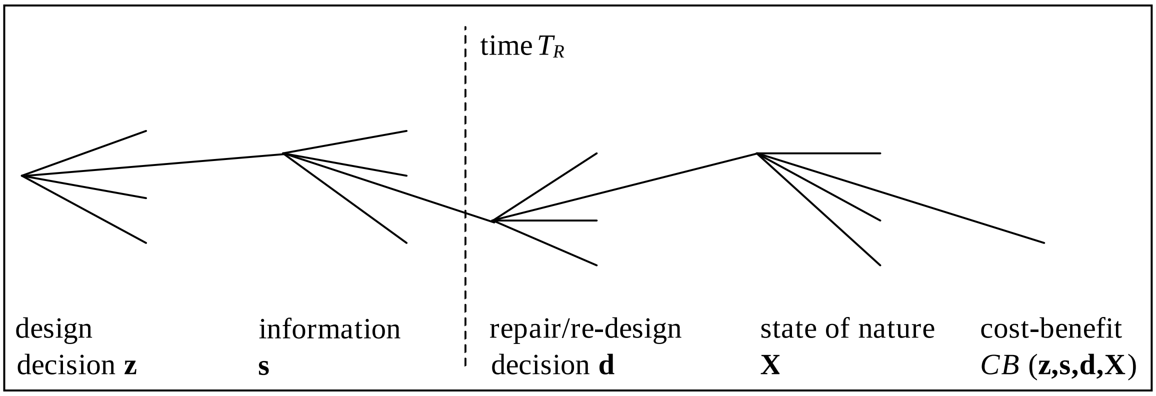

Figure 3: Time scale for decision-making procedure, T_R indicates the time of re-assessment

The preceding lists are generally applicable for the decision-making during the assessment process indicated in the flowchart in Figure 2, even though the main emphases are dissimilar for the different industrial sectors. The decision variables related to the actions at the time of re-assessment are denoted **d**, and the decision variables related to future inspections are denoted **e**.

A cost-benefit function *CB* can be defined by

$$\begin{aligned} \mathrm{E}[CB(\mathbf{d},\mathbf{e})] &= \mathrm{E}[B(\mathbf{d},\mathbf{e})] - \mathrm{E}[C(\mathbf{d},\mathbf{e})] \\ &= \mathrm{E}[B(\mathbf{d},\mathbf{e})] - \left\{E[C_{IR}(\mathbf{d})] + E[C_{EI}(\mathbf{d},\mathbf{e})] + E[C_{ER}(\mathbf{d},\mathbf{e})] + E[C_{NS}(\mathbf{d},\mathbf{e})] + E[C_F(\mathbf{d},\mathbf{e})]\right\} \end{aligned}$$ Eq. 1

The optimal decisions $\mathbf{d}^*$ and $\mathbf{e}^*$ are obtained by solving the optimisation problem

$$\begin{aligned} &\max_{\mathbf{d},\mathbf{e}} \quad \mathrm{E}[B(\mathbf{d},\mathbf{e})] - \left\{E[C_{IR}(\mathbf{d})] + E[C_{EI}(\mathbf{d},\mathbf{e})] + E[C_{ER}(\mathbf{d},\mathbf{e})] + E[C_{NS}(\mathbf{d},\mathbf{e}) + E[C_F(\mathbf{d},\mathbf{e})]]\right\}] \\ &\text{s.t.} \quad d_i^l \le d_i \le d_i^u, \qquad i = 1,\ldots,N \\ &\qquad \Delta P_{F,t}(\mathbf{d},\mathbf{e}) \le \Delta P_F^{\max}, \qquad t = T_R, T_{R+1},\ldots,T_L \end{aligned}$$ Eq. 2

where T_R is the time of re-assessment. The annual probability of failure in year t is $\Delta P_{F,t}$. The N future inspections are assumed performed at times $0 \le T_R \le T_1 \le T_2 \le \ldots \le T_N \le T_L$.
The total capitalised expected benefits are written

$$E[B(\mathbf{d},\mathbf{e})] = \sum_{t=T_R+1}^{T_L} B_t \left(1 - P_F(t,\mathbf{d},\mathbf{e}) - P_{NS}(t,\mathbf{d},\mathbf{e})\right) \frac{1}{(1+\gamma)^{t-T_R}},$$ Eq. 3

whereas the *t*-th term represents the capitalized benefits in year t given that failure has not occurred earlier, B_t is the benefit in year t, $P_F(t,\mathbf{d},\mathbf{e})$ is the updated probability of failure in the time interval $[T_R, t]$, and γ is the real rate of interest. The updating is based on the information **s**.

By assuming the probability of initial repair is equal to 1, the total capitalised initial repair costs are written

$$\mathrm{E}[C_{IR}(\mathbf{d})] = C_{IR}\,. \qquad \text{Eq. 4}$$

If inspections are foreseen, the total capitalised expected inspection costs are obtained by

$$E[C_{EI}(\mathbf{d},\mathbf{e})] = \sum_{i=1}^{N} C_{EI,i}(\mathbf{e})\left(1 - P_F(T_i,\mathbf{d},\mathbf{e})\right)\frac{1}{(1+\gamma)^{T_i - T_R}}\,. \qquad \text{Eq. 5}$$

The *i*-th term represents the capitalised inspection costs at the *i*-th inspection when failure has not occurred earlier, $C_{EI,i}(\mathbf{e})$ is the inspection cost of the *i*-th inspection.
The total capitalised expected reassessment costs are

$$E[C_{ER}(\mathbf{d},\mathbf{e})] = \sum_{i=1}^{N} C_{ER,i}P_{ER,i}(\mathbf{d},\mathbf{e})\frac{1}{(1+\gamma)^{T_i - T_R}}\,, \qquad \text{Eq. 6}$$

where $C_{ER,i}$ is the cost of a repair at the *i*-th inspection and $P_{ER,i}(\mathbf{d},\mathbf{e})$ is the probability of performing a repair after the *i*-th inspection when failure has not occurred earlier and no earlier repair has been performed.
Considering a serviceability limit state, the total capitalised expected costs due to non-serviceability are

$$E[C_{NS}(\mathbf{d},\mathbf{e})] = \sum_{t=T_R+1}^{T_L} C_{NS}(t)\Delta P_{NS,t}(\mathbf{d},\mathbf{e})P_{COL|FAT}(\mathbf{d})\frac{1}{(1+\gamma)^{t - T_R}}\,. \qquad \text{Eq. 7}$$

The total capitalised expected costs due to failure, excluding the non-serviceability, are estimated from

$$E[C_F(\mathbf{d},\mathbf{e})] = \sum_{t=T_R+1}^{T_L} C_F(t)\Delta P_{F,t}(\mathbf{d},\mathbf{e})P_{COL|FAT}(\mathbf{d})\frac{1}{(1+\gamma)^{t - T_R}}\,, \qquad \text{Eq. 8}$$

where $C_F(t)$ is the cost of failure at the time *t*. $P_{COL|FAT}(\mathbf{d})$ is the conditional probability of collapse of the structure given failure of the considered component.

Eq. 2 can equivalently be formulated as a reliability-constrained optimisation problem

$$\begin{aligned} &\max_{\mathbf{d},\mathbf{e}} \quad && \mathrm{E}[B(\mathbf{d},\mathbf{e})] - \mathrm{E}[C(\mathbf{d},\mathbf{e})], \\ &\text{subject to} \quad && \beta''(\mathbf{d},\mathbf{e}) \geq \beta^{\min}, \end{aligned} \qquad \text{Eq. 9}$$

where the generalised reliability index is defined by $\beta''(\mathbf{d},\mathbf{e}) = -\Phi^{-1}\left(P_F(\mathbf{d},\mathbf{e})\right)$. $\beta^{\min}$ is a code specified minimum acceptable reliability level related to annual or lifetime reference time intervals. How to choose $\beta^{\min}$ is considered in WP6 [4]. Other design constraints can be added to Eq. 9 if needed. If new information **s** is available, the BAYESIAN event updating can be applied.

Numerical solution of the decision problems requires solution of one or more optimisation problems. Since the formulated optimisation problems are generally continuous with continuous de-

rivatives sequential quadratic optimisation algorithms such as NLPQL [31] and VMCWD [29] can be expected to be the most effective, see [19]. These algorithms require that values of the objective function and the constraints are evaluated together with gradients with respect to the decision variables.
The probabilities in the optimisation problems can be solved using FORM techniques, see [28]. Associated with the FORM estimates of the probabilities also sensitivities with respect to parameters are obtained. If the decision problem includes analysis of a structural system, the finite element method in combination with sensitivity analyses can be used.

7. Summary and Conclusion

This study is aimed to review the different practice of several industrial sectors concerning the assessment of existing structures. Thus, the presented approach includes the best, cost-optimal assessment practice extracted from all industrial sectors by requiring the optimal level of safety. Nevertheless, further research work is inevitable to consider some aspects in detail.

However, it is a preliminary report of the final deliverable of Workpackage 6 of the SAFERELNET Thematic Network [1]. Please, feel free to contact the authors in case of comments and recommendations..

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