Rational maintenance of timber bridges

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Summary

The present paper provides some ideas about how decisions concerning maintenance of timber bridges should be made in a rational way. First, a brief discussion is provided concerning the evolution of maintenance strategies in general and it is suggested that maintenance of timber bridges should follow a risk-based approach. Then the discussion moves on to the condition assessment of timber bridges with a main focus on inspection and monitoring. The use of non-destructive testing methods and structural health monitoring is highlighted with regard to collecting useful information for maintenance decisions. It is argued that the information collected, should be used in a Bayesian decision analysis framework, which is especially useful in quantifying to value of information and thus the worth of various inspection and monitoring alternatives.

Keywords: structural timber, bridge maintenance, condition assessment, decision making.

1. Introduction

1.1 Background

Regular inspection and maintenance of timber bridges is essential due to their susceptibility to various types of deterioration mechanisms. Several inspection methods have been developed and applied to assess structural performance that cause minimum physical intrusion and disturbance of functionality of bridges. Similarly, maintenance is often carried out with as little disruption of traffic as possible. However, both the outcome and the costs of inspection and maintenance involve significant uncertainties [1].

Bridges are often owned by the public and the corresponding authorities manage large portfolios of many bridges. The authorities aim to allocate resources on operation and maintenance in the best possible way. Therefore a balance is needed between the expected benefits of functioning and the expected costs of maintenance including direct and indirect consequences of possible failures.

Rational decisions about maintenance and upgrading require reliable information about the performance of existing structures including exposures, structural response, associated uncertainties and costs of possible consequences. The current paper discusses how a rational decision making framework could be applied in relation to condition assessment of timber bridges with regard to the utilisation of the information collected through inspection and monitoring.

1.2 Rational maintenance approaches

Maintenance in general can be defined as the "combination of all technical, administrative and managerial actions during the life cycle of an item intended to retain it in, or restore it to, a state in which it can perform the required function" (EN 13306:2010 [2]). Determining appropriate maintenance actions require decisions on various issues, namely: how, when, by whom and at what cost an action should be carried out. These decisions should be supported by information about the actual condition and functional importance of the items (i.e. bridges). As such, the decision making process includes also decisions on how to collect and analyse new information.

How these decisions are made can differ depending on the industry in question and the expectations of the operating authority. Furthermore, during the last decades, a significant development has been made on available strategies and techniques to support maintenance. These improvements can be divided into evolving maintenance generations (see Fig. 1). In [3] this process is illustrated by defining three generations: corrective (or breakdown) maintenance, preventive maintenance, and condition-based (or predictive) maintenance. However, since the 2000s, a 4th generation maintenance – the risk/utility-based maintenance – has started to emerge in some industries; especially where maintenance costs are relatively high as, e.g. in oil and gas or off-shore, see e.g. [4] and [5].

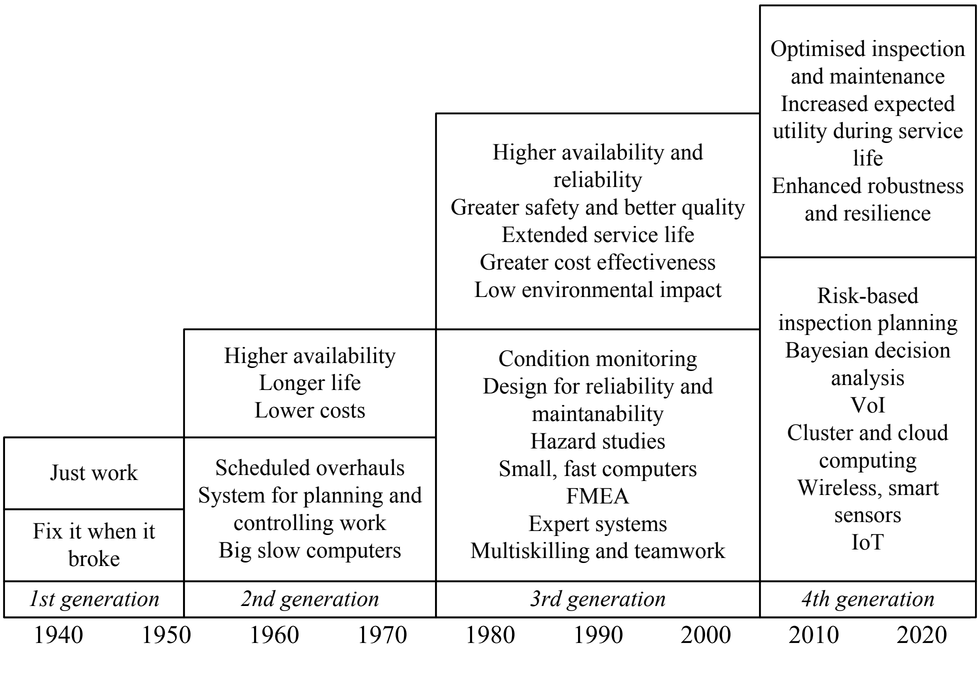

Fig. 1 Evolving maintenance goals and techniques, extended from [3]

The focus of the 4th generation approaches is to provide strategies to optimise inspection and maintenance activities; increase expected utility during service life; and enhance robustness and resilience of the structures and the network of interconnected assets. Techniques utilised to achieve these goals include risk-based inspection planning [4]; Bayesian decision analysis [6]; Value of Information (VoI) theory [7]; high performance computing infrastructures (cluster and cloud computing); wireless, smart sensors; and intelligent infrastructure as part of the Internet of Things (IoT).

Maintenance of transportation infrastructure, including timber bridges, is challenging for several reasons: they are exposed to a wide range of exposures, they are often owned and used by the public, the number of bridges is constantly increasing, consequences of reduced (or non-) functioning can be high, etc. These challenges have led to research projects exploring the possibility of the application of 4th generation maintenance strategies to bridge stocks. However these approaches have not been fully utilized in practice. One particularly interesting and important issue is how the condition assessment procedure of existing bridges can be rationalized given the practically endless methods and techniques available to obtain information on and analyse structural performance. This issue will be further discussed in the subsequent sections focusing on timber bridges.

2. Condition assessment

2.1 Procedure and levels of assessment

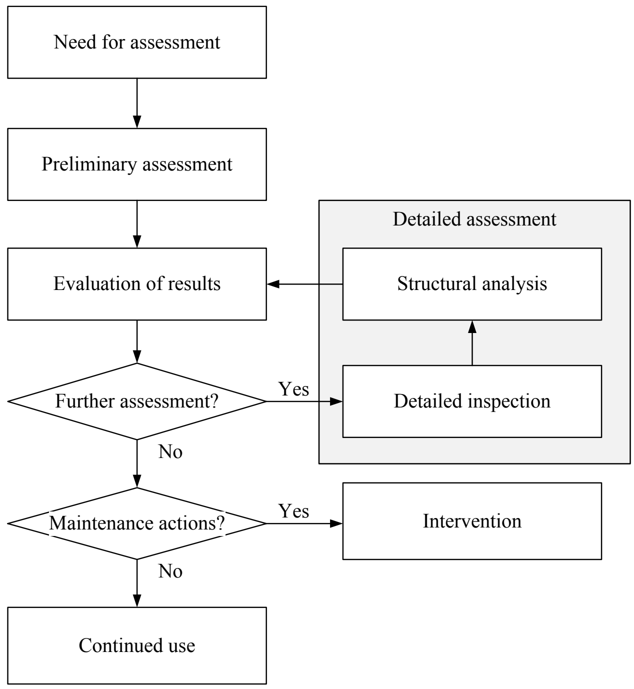

Fig. 2 Assessment procedure of timber bridges

There are several techniques and approaches available for the condition assessment of civil engineering structures. Here a general procedure for the assessment of timber structures is outlined.

The procedure is based on the general assessment framework for existing structures proposed in [8] and [9]; previous research projects on the assessment of existing bridges, e.g. [10] and [11]; ongoing and existing standardisation activities, e.g. ISO13822 (Bases for design of structures – Assessment of existing structures) [12], New European Technical Rules for the Assessment and Retrofitting of Existing Structures [13]; and the strategy suggested for assessment of timber structures in [14].

The methodology comprises the following steps (see also Fig. 2): 1) Identification of the need for assessment due to e.g. regular inspection, doubts about performance, change in requirements; 2) Preliminary assessment (document search, simplified analysis, visual inspection); 3) Evaluation of results; 4) Decision on further assessment; 5) Detailed assessment if needed, including e.g. material testing at critical sections, detailed structural analysis, reliability analysis; and 6) Decision on maintenance actions.

From Fig. 2 it is clear that there might be a loop in the condition assessment process concerning detailed assessment, i.e. the level of detailed assessment is gradually increased if doubts about structural performance continue to exist.

According to [15], the condition assessment of bridges can be performed at different levels. The 1st level is the regular, usually visual, field inspection, also called rating. It provides a qualitative (or semi-quantitative) and rather subjective description about the structural elements and/or the structure itself. The results often provide input data for the bridge management systems and used for prioritisation of actions. Rating based on visual inspection tends to be conservative, i.e. underestimates the capacity and/or remaining service life of damaged elements. On the other hand, some defects remain undetected as a result. The next, 2nd level is a more detailed assessment of the parts which are found problematic at the point of initial inspection. This usually involves some kind of calculation to better quantify the effects of the damage on the structural performance. The final, 3rd level is when the performance of the entire bridge is assessed based on thorough instrumentation and detailed modelling, which in this paper is discussed under monitoring.

There exist other classifications of such levels of condition assessment as described in [16]. These classifications commonly progress from simple to more detailed levels. The increase in the level of details can either be seen as increasing the level of modelling sophistication, the level of uncertainty/risk consideration, or the level of information incorporated.

2.2 Maintenance actions

If any doubt about the performance of a bridge arises several actions are available to ensure that the bridge fulfils relevant codified requirements related to structural safety and serviceability. The hierarchy of terms related to these actions is given in ISO 13822 [12] and presented in Fig. 3.

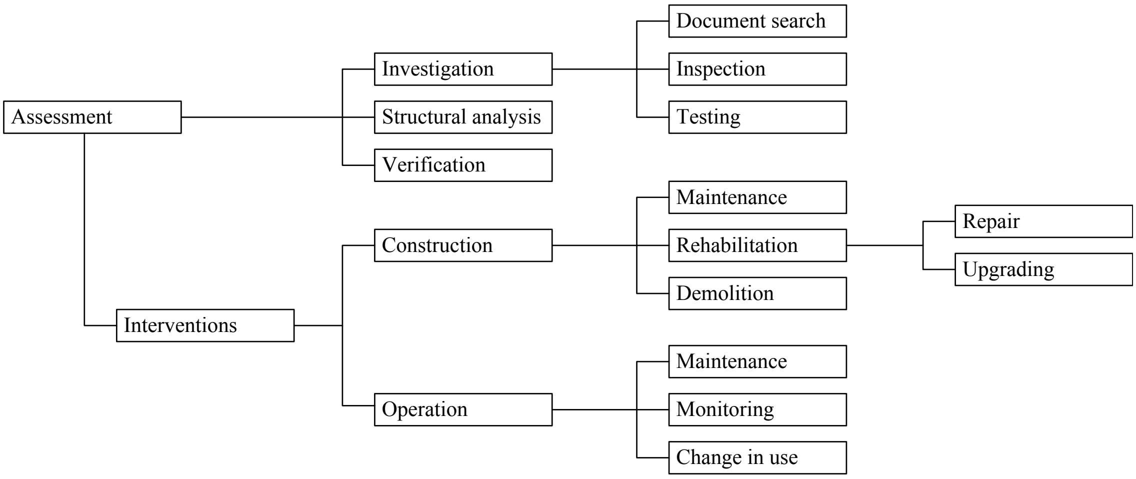

Fig. 3 Hierarchy of terms related to assessment of existing structures form ISO 13822 [12]

The challenge therefore is to select the most appropriate action considering the benefits it may bring to the decision maker, which is usually the public operator taking into consideration the preferences of the society including life-safety, economic and environmental issues.

As described before, the process of condition assessment starts with an initial assessment, i.e. visual inspection. A decision should then be made if: 1) no further actions are required; 2) a more detailed investigation is needed; or 3) interventions should be carried out. Any of these choices will lead to subsequent actions in the near future or the long run, which should optimally be taken into account when making a decision. However, the outcome of the choices can be uncertain; consequences of actions difficult to quantify; relevant information not available directly etc. Thus it is important to utilize a framework, which is able to deal with all these issues in a rational and consistent way.

In the current paper, we focus on inspection and monitoring as two major methods related to collecting information on the structural condition/performance of timber bridges. Various types of inspections include visual inspections, non-destructive and destructive testing typically of structural elements. In monitoring, the focus is on in-situ monitoring using sensors and concerned with the general structural behaviour of the bridge. Measurements of strains, displacements, accelerations, temperature, moisture content etc. are performed.

3. Inspection and monitoring of timber bridges

3.1 Performance of timber bridges

Since timber bridges are often exposed to harsh environments, in most cases this exposure leads to deterioration resulting in biological degradation processes, weathering and mechanical damage which reduces the performance of single structural components as well as the entire system [17]. Therefore it is important to identify the critical details, possible failure modes and deterioration mechanisms in an early stage of the assessment. A wide variety of inspection methods, both non-destructive testing (NDT) and semi-destructive testing (SDT) techniques, can be employed to locate damage and deterioration and obtain relevant characteristics of the structural elements to maintain the structural integrity and continuous functioning of the structure [18]. Often there is a need to combine several inspection techniques using a comprehensive assessment strategy that enables a confident estimation of structural condition and remaining service life.

As wood is an anisotropic material, the characteristics vary between the different directions, but, due to its natural characteristics, which cannot be fully controlled by the production process, the mechanical properties of new timber structural elements are uncertain and depend mainly on the wood species, moisture content, natural growth defects, load duration and geometry of the elements [19], [20]. For timber structural elements in use these uncertainties can, in principle, be reduced by new information that becomes available by inspection and monitoring.

Wood, if unprotected, is subject to different types of degradation processes. Usually, areas of high moisture content in the decking, girders, abutments and pilings cause appropriate conditions for biological damage such as mould, insects, fungi, bacteria, etc. Also mechanical damage of timber as well as mechanical fasteners (e.g. due to traffic, streams, corrosion) might be observed and are critical, especially since they might give way to further biological damage [21].

3.2 Inspection of timber bridges

Various methods exist and are used in practice to assess structural performance of timber bridges with minimum physical intrusion and disturbance to guarantee the continued function of the structure. Visual inspection, moisture content assessment, mechanical probing, drilling, resistance micro-drilling and stress wave or ultrasound-based technologies may all be used individually or in combination by inspectors. For example stress-wave techniques are used to evaluate the modulus of elasticity of bending members and resistance to drilling is used to gain knowledge of areas of changed density due to insect or moisture induced damages.

The following subsections provide a brief overview about some typical NDT/SDT techniques, which can be employed by an inspector in order to assess the condition of an aging timber bridge.

3.2.1 Enhanced visual inspection

Visual inspection is the starting point for any assessment of existing structures as it is the basis of any form of strength, performance grading on-site. It allows for a rather quick qualitative assessment of the structural integrity of individual structural members. In practice, visual inspections are supported by local NDT/SDT for the detection of damages, internal deterioration and degradation [17].

The standard tool equipment for efficient inspection of timber bridges is composed of a tape measure, a hammer, and an awl for the basic inspections, and a stress wave timer, a resistance micro drill and a moisture meter for the more advanced/detailed investigations [22].

3.2.2 Stress-wave timing

Stress-wave measurement is a simple and effective measurement technique to identify the internal soundness and condition of structural elements and also to estimate the modulus of elasticity (MOE) for structural analysis. In these tests, two piezoelectric probes are used to receive the longitudinal ultrasound wave. One-dimensional stress-wave transmission is the most commonly used technique to measure the time that is required to travel between the piezoelectric sensors [23].

There are several key aspects that influence the travel of the stress waves in timber. These are the effect of wood species, moisture content, temperature, biological and chemical degradation, decay, insect attacks, grain angle and measurement direction [24]. The technique requires an appropriate measurement strategy and approach in order to efficiently determine the structural performance of elements in-situ and successfully detect internal damage, as well as to quantify the extent of both external and internal damage.

3.2.3 Resistance drilling

Resistance drilling can be used to detect and quantify the internal condition and decomposition of the wood in timber structural elements [25].The drilling resistance is proportional to the relative variations in density, i.e. decreasing drilling resistance is followed by reduced torque in the drill. Areas that need less torque are therefore associated with reduced density. One of the main aspects in the use of resistance drilling is to apply appropriate drilling points and drilling direction to evaluate internal condition. The main principle is to drill perpendicularly with respect to the annual rings in order to be able to distinguish between intact wood and incipient decay from the relative density profiles [26]. The interpretation of the density profiles from the drilling-resistance measurements often requires expert knowledge of the composition and the inhomogeneity of wood structures [14].

3.2.4 Moisture meter

Measurements of the moisture content (MC) with resistive moisture meter at critical sections gives a good and fast indication over the risk of biological degradation. A more elaborate measurement method to track the condition of a timber bridge is to continuously measure the moisture content with a remote data transmission system to assess the condition over time, to identify moisture changes, dimensional changes and internal stresses caused by the change of moisture. The main advantage though is that early stage damage can be recognized in order to prevent further deterioration [26].

3.2.5 X-ray investigations

X-rays are short-wave electromagnetic radiation rays that rely on the mass density and the thickness when they penetrate an object. The primary benefit when using X-ray is the opportunity to determine the condition of structures on site without disturbance [27]. A low voltage/energy X-ray powertool can be used for the in-situ investigation of timber bridges for hidden defects and integrity of the structure. An overview of possible applications using X-ray equipment for the evaluation of timber structures is listed e.g. in [27] and [14] including: material loss quantification due to insect attack/decay, corrosion detection, cross section reduction, integrity/failures of mechanical connections, density identification, and mapping damage. As with any other method, X-ray investigations should be combined with other NDT/SDT methods.

3.2.6 Further methods

There exist several further SDT methods for the local condition assessment regarding strength and stiffness properties including e.g.: a) core drilling for internal condition of the timber at suspected deterioration; b) radial core drilling for determination of compressive strength; c) surface hardness test for local indication of the quality of the structural member; d) screw withdrawal resistance test for the indication of the quality of timber; e) thermography to detect voids/defects; f) videoscopy for the internal view of the extent of hidden deterioration; and g) ultrasonic pulse echo to detect e.g. delamination and check structural homogeneity.

3.3 Monitoring of timber bridges

Non-destructive inspection of individual members provides valuable information about the localized condition of bridge elements, but more information is required to assess the condition of a bridge as an entity. Furthermore, since timber bridges often require more frequent maintenance intervals than concrete and steel bridges, monitoring might provide promising opportunities for obtaining information for better decisions on maintenance activities [28].

In the monitoring of the structural condition of timber bridges the main focus is often on relative humidity, temperature and moisture content of the wood at different depths as moisture and temperature conditions are highly relevant for biological deterioration processes. The purpose of the measurements is often to verify models for prediction of long-term durability based on periods of surface wetting, on moisture conditions related to climatic loads, coatings, wood processing etc. [29].

Besides monitoring of deterioration mechanisms, the dynamic performance of some timber bridges, might be highly relevant and worth to monitor. This could be done e.g. to identify signs of damage of bridges with complex structural systems or to verify serviceability performance. Modal analysis is typically used to examine mode shapes of the vibrating structure and compares it either to previous experimental vibrational data on the structure or to data predicted by numerical modelling. Differences in dynamic characteristics can be used to diagnose damage in the structure [17]. Another use of analysing dynamic response could be e.g. to determine dynamic amplification factors for traffic loads [30]. A combination of different sensors in a comprehensive health monitoring system, i.e. continuous measurement of e.g. accelerations, displacements, strains, moisture contents and weather data could be useful to verify the structural design and the long-term behaviour of the timber bridges [31].

It should be noted that even diagnostic static load tests can be seen as a basic type of monitoring, even if a “real” continuous monitoring system is not implemented. Static load applied to a bridge provide valuable insight into the overall stiffness of the structural system and help verifying structural analysis models and thus the load bearing capacity of the bridge [17].

4. Decision making

4.1 Information and structural integrity management

As described e.g. in [32] engineering decision making can be interpreted as playing a game where the decisions aim to optimize the expected utility according to the decision maker's preferences and can be analysed by the game theory [33]. To be successful in the game the rules must be clear, i.e. the constituents of the decision problem must be known. According to [34] this means that information is needed about the system, its surrounding, the possible consequences of actions, the interrelation of different factors that affect system performance etc. Participating in the game is then carried out by "buying" physical changes in the system or "buying" knowledge about the system such that the outcome of the game should be optimized.

In the light of this, the main use of inspection and monitoring techniques concerning timber bridges, or any civil engineering structure in general, is that the information provided by these techniques can be utilized to reduce uncertainties concerning decisions about the structure. Unfortunately, collecting information comes with costs, which might or might not be in balance with the benefits gained by the reduced uncertainties and thus risks. In practical cases, the effectiveness of inspection and/or monitoring often becomes known only after the implementation. However, it is possible to develop a consistent decision procedure for maintenance in general, and for inspection and monitoring in particular, which aims to maximise the utility of the structure over its entire lifetime with due consideration of regulatory constraints (e.g. life safety and environmental requirements).

As it has been mentioned, these decisions usually need to be based on incomplete or uncertain information. To deal with this, Bayesian decision analysis [6] can be utilised where three different types of analysis are generally distinguished, namely, the prior- , the posterior- and the pre-posterior decision analysis. In a prior analysis the optimal action/decision is identified based on probabilistic models on relevant uncertain states of nature using existing information. In a posterior analysis new information (e.g. derived from inspection) are utilized to update the probabilistic models and the optimal action/decision is identified based on the updated models. In a pre-posterior analysis several possible inspection methods are considered as possible sources of information and it is analysed, given their costs, which one is the optimal to use. Based on the pre-posterior analysis it is possible to estimate the effectiveness of inspection and monitoring actions before they are carried out.

4.2 Quantification of the value of new information

Pre-posterior analysis could help quantifying the real benefits of inspection and monitoring and thus help the bridge operator to decide what price should be paid for such services. A decision problem is a choice among courses of action when [6]: 1) the consequence of any course of action will depend upon the state of the bridge structure; 2) the true state of the structure is as yet unknown; and 3) it is possible, at a cost, to obtain additional information about the state.

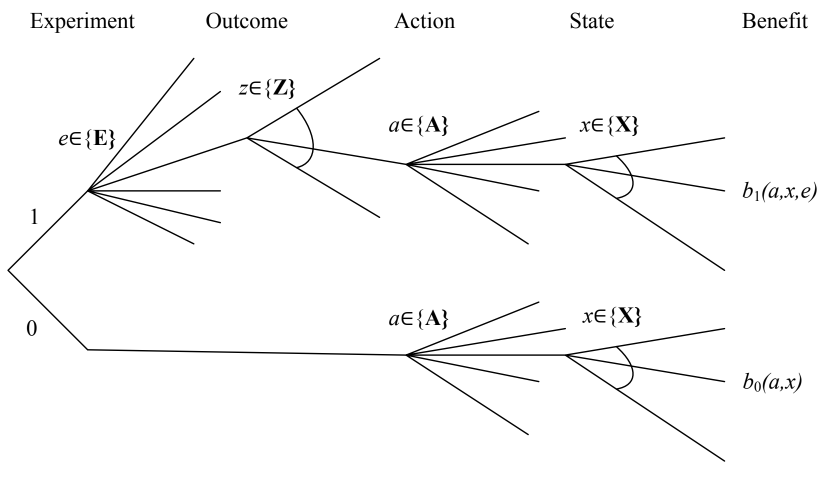

Fig. 4 Decision tree adapted from [35]

In bridge maintenance, the decision problem can be reduced to a limited number of alternatives (e.g. "do nothing", "inspect", "repair", "strengthen" and "reduce loads"). As described e.g. in [35], [36] and [37], the basic concept of pre-posterior analysis and VoI [7] analysis can be illustrated considering a decision tree, see Fig. 4. It is assumed that the the true state of the structure X is random with possible outcomes $x\in\{\mathbf{X}\}$ and various maintenance actions $a\in\{\mathbf{A}\}$ can be chosen, which will affect the probability assignment of the possible states of the structure.

Decision on collecting information about the structure through inspection or monitoring can be seen as the upper branch 1 of the figure, whereas the lower branch 0 can be seen as not collecting information. Considering the lower branch 0 of the decision tree, i.e. not collecting information, the decision analysis consists of choosing the maintenance action a, with maximizing the expected value of the benefit $b_0(a,x)$ resulting in the expected life cycle benefit B_0:

$$B_0 = \max_a E'_X\left[b_0(a, X)\right] \tag{1}$$

For the upper branch 1 in Fig. 4., i.e. opting for collecting information, a further decision has to be taken concerning the choice of the inspection method. This decision could be interpreted as an experiment $e \in \{\mathbf{E}\}$ with an outcome $z \in \{\mathbf{Z}\}$, where Z is a scalar valued random variable.

Applying Bayes' theorem the a-priori probability assignment of the true state of the structure $f'_X(x)$ can then be updated given the outcome of the inspection z:

$$f''_X(x|z) = \frac{L(x|z) f'_X(x)}{\int_{-\infty}^{\infty} L(x|z) f'_X(x) dx} \tag{2}$$

where $L(x|z)$ refers to the likelihood of the true state x given observation z.

The expected value of conducting the experiment e with subsequent optimization actions of the maintenance actions a is evaluated over the possible realisations of Z. Without providing all details here, it is possible to select the experiment e^* that leads to the maximum expected benefit:

$$B_1 = \max_e E_Z \left\{\max_a E''_X\left[b_1(a, X, e)\right]\right\} \tag{3}$$

The expected value of (collecting) information, i.e. the worth of inspection and monitoring, can be calculated as:

$$VoI = B_1 - B_0 \tag{4}$$

The above presented extended form of the pre-posterior decision analysis might, in some cases, be difficult to use and a so called normal form could then be applied. In the normal form of the analysis a decision rule d is defined specifying the action to be taken given the experiment outcome z, more details are given e.g. in [37].

5. Conclusions

Modern maintenance approaches in high-consequence industries are in their 4th generation utilising modern technologies and risk-based methodologies for decision making. It is here argued that these approaches will be used in the future for the maintenance of timber bridges as well.

Modern NDT and monitoring technologies in the condition assessment of timber bridges are already in use and their application is increasing. It is, therefore, expected that the utilization of information for decision making concerning structural integrity management will follow modern approaches as well. That is VoI analysis, which provides a consistent and rational way of making decisions about condition assessment of timber bridges with maximising the expected lifetime benefits of the structure.

The pre-posterior analysis takes into account the uncertainties during the decision making process; however, it might require significant efforts concerning statistical modelling and computation. This could be an obstacle for practical application and need to be further investigated in the context of maintenance of timber bridges.

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