COST ACTION TU1406

QUALITATIVE SPECIFICATIONS FOR ROADWAY BRIDGES, STANDARDIZATION AT A EUROPEAN LEVEL (BRIDGESPEC)

José C. Matos
University of Minho
jmatos@civil.uminho.pt
Guimarães, Portugal

Sérgio Fernandes
ANSER, Lda.
sergio.cd.fernandes@gmail.com
Santo Tirso, Portugal

Resumen

Durante la implementación de estrategias de gestión de activos se requieren acciones de mantenimiento para conservar las infraestructuras a un nivel de rendimiento deseado. En el caso de los puentes de carretera, se establecen indicadores de rendimiento específicos para sus componentes que, cuando se combinan, permiten evaluar el rendimiento general. Estos indicadores pueden ser cualitativos o cuantitativos y pueden obtenerse durante inspecciones principales mediante examen visual, ensayos no destructivos o mediante sistemas de vigilancia temporales o permanentes. A continuación, se comparan los indicadores obtenidos con los objetivos de desempeño, para evaluar los planes de control de calidad. En Europa existe una gran disparidad de país a país cuanto a la forma como se cuantifican los indicadores de rendimiento y se especifican los objetivos. COST Action TU1406 pretende reunir, por la primera vez, tanto las comunidades investigadoras como las practicantes, con el fin de establecer una guía europea en esta materia, abordando nuevos indicadores relacionados con el desempeño sostenible y económico de los puentes viales. La aplicación de esta norma dependerá en gran medida de los cambios en la filosofía y los métodos operativos (inspección, ensayos, ...) que las nuevas especificaciones requieren en el futuro como resultado de su aplicación. Por lo tanto, para reducir al mínimo la posible reticencia de las agencias de gestión de carreteras a cambiar los indicadores de rendimiento actuales y los métodos para obtenerlos y también aprovechar los antecedentes, conocimientos y bases de datos existentes, es obligatorio que la nueva especificación de calidad homogeneizada sea más o menos basada en la práctica actual.

Palabras Clave: calzada; puentes; desempeño; indicadores; metas

Keywords: roadway; bridges; performance; indicators; goals

Abstract

During the implementation of asset management strategies, maintenance actions are required in order to keep infrastructures at a desired performance level. In case of roadway bridges, specific performance indicators are established for their components which, when combined, allow to evaluate the overall performance. These indicators can be qualitative or quantitative based, and can be obtained during principal inspections through visual examination, non-destructive testing or by temporary or permanent monitoring systems. Then, obtained indicators are compared with performance goals, in order to evaluate if quality control plans are accomplished. In Europe, there is a large disparity from country to country regarding the way performance indicators are quantified and goals specified. COST Action TU1406 aims to bring together, for the first time, both research and practicing communities in order to establish a European guideline in this matter, addressing new indicators related to sustainable and economic performance of roadway bridges. The application of this standard will be highly dependent on the changes in philosophy and operational methods (inspection, testing, …) that new specifications require in the future as a result of their implementation. Therefore, to reduce to a minimum the possible reluctance of highway managing Agencies to change the actual performance indicators and the methods to obtain them and also to take advantage of existing background, knowledge and databases, it is mandatory for the new homogenized quality specification to be more or less based on current practice.

Introduction

The primary requirement of bridge asset management is to ensure that users' expectations and needs are met or exceeded. It is a challenging task for owners and operators as it involves vital assets to the community. From the owner's point of view, this means that assessment and management are closely connected to quality control (QC) and, consequently, the system is developed so that product requirements are met. From the QC side it is necessary to define the goals to be achieved and to identify the investment needs and priorities based on Life Cycle Cost (LCC) analysis. From the assessment and management side it is important to support the decision-making process regarding their preservation.

To keep structures safe throughout their life, they require regular maintenance actions. It becomes therefore important to define strategies to maximize societal benefits derived from the investment made in these assets. This investment should be planned, effectively managed and technically supported. The planning of maintenance strategies consists not only in the definition of goals to be achieved, but also in the identification of investment needs and priorities based on LCC criteria. The need to manage roadway bridges in an efficient way led to the development of bridge management systems (BMS) in Europe. Although, they present similar architectural frameworks, several differences constitute divergent mechanisms that may conduct to different decisions on maintenance actions. Therefore, a discussion at a European networking level, seeking to achieve a standardized approach in this subject, will bring significant benefits. Accordingly, COST Action TU1406 started in Europe in 2015 with the aim of standardizing the establishment of QC plans for roadway bridges *(COST, 2014)*.

The scientific program of COST Action TU1406 is divided in different tasks through Working Groups (WG). The first task – WG1. Performance indicators – consisted in the assessment of relevant performance indicators for the determination of roadway bridges overall state condition. A second task – WG2. Performance goals – would be the definition of standardized performance goals, which include the definition of threshold types to specific key performance indicators. Thirdly, a guideline for the establishment of QC plans in roadway bridges would be developed – WG3. Establishment of a QC plan. Additionally, the guidelines will be tested with real results – WG4. Implementation in a Case Study – and recommendations to practicing engineers will be given – WG5. Drafting of guideline/recommendations (Matos et al 2017).

The additional beneficial side of the Action is to connect asset owners, consultants and academics in order to improve the overall framework of existing road bridges.

In this paper the main outcomes achieved so far by COST Action TU1406 are presented.

Bridge assessment through Performance Indicators

As structures are aging, the assessment of bridges and other industrial structures is becoming increasingly important. Structural codes have been developed only for new design, but they often are not appropriate for assessment since there are significant differences between design and assessment. Design uncertainties arise from the prediction of load and resistance parameters of a new structure. These uncertainties represent the variability of a large population of structures caused by unequal qualities of material, different construction practices and the variability of site specific live loads. Also a conservative design does not result in significant increase in structural cost while a conservative assessment may result in unnecessary and costly repairs or replacement (Rücker et al. 2006).

Within the last years, significant research has been developed worldwide regarding the condition assessment of roadway bridges, namely through the use of non-destructive tests, monitoring systems and visual inspection techniques. Obtained values, which will provide information regarding the assessed bridge state condition, were then compared with previously established goals. As a result, there are nowadays several ways of evaluating a bridge condition. More recently, the concept of performance indicators was introduced, simplifying the communication between consultants, operators and owners. However, large deviations are still verified on how these indicators are obtained and, therefore, specific actions should be undertaken in order to standardise this procedure *(COST, 2014)*.

As mentioned before for the assessment of existing bridges, as well as for the evaluation of maintenance strategies, life cycle analysis is used. Management systems, capturing different degradation processes, are very often used in relation to such life cycle analyses methods. Such management systems, developed for structural condition assessment, are usually based on deterministic performance prediction models which describe the future condition by a functional correlation between structural condition attributes, such as the structural age, and the mechanical, chemical and thermal loading processes. The practical implementation of such models requires detailed information about its variables (Strauss et al. 2016).

Deterioration could lead to a decrease of performance to such an extent that a structure could not be able to satisfy the basic serviceability and safety requirements before the design life has expired. In order to prevent premature failure, structural codes provide several practical principles and application rules such as the use of protective systems for material exposed in aggressive environment, construction detailing aimed at avoiding the initiation of degradation, maintenance actions to be regularly performed, etc. (Strauss et al. 2016).

Each construction, during its life cycle, will face with deterioration depending on several factors such as the environmental condition, the natural aging, the material quality, the execution of works and the planned maintenance. Therefore, several design procedures based on deterioration prediction that will likely act on the structure will be developed in the framework of COST Action TU1406. Additionally, performance indicators for the present and future structural conditions on deterministic and probabilistic level will be defined and determined (Strauss et al. 2016).

In the work of COST Action TU1406 WG1, the objectives were the collection and analysis of practical and research based performance indicators (Matos et al. 2017):

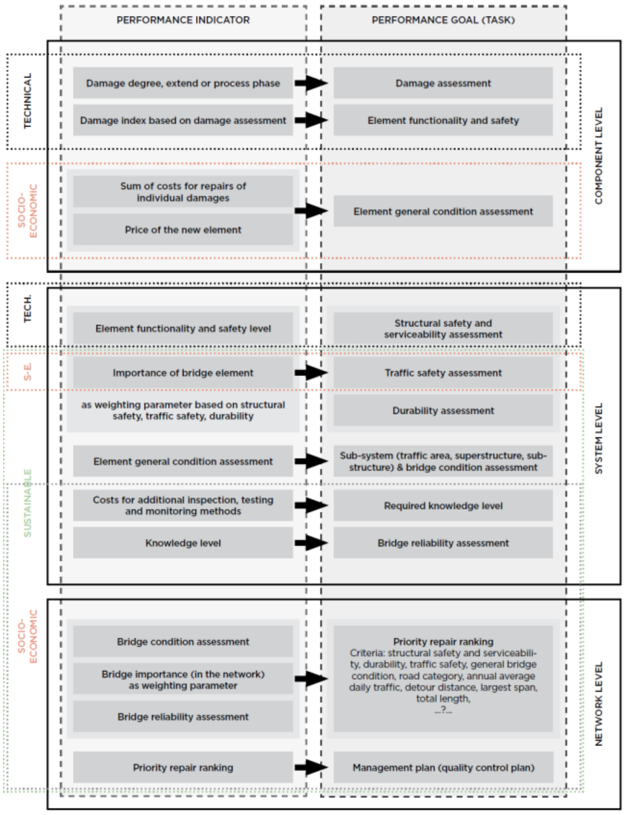
(a) Technical indicators: the goal in the first step is to explore, in the course of international research cooperation, those bridge performance indicators which capture the mechanical and technical properties and its degradation behaviour. These properties are already partly covered by norm specifications but not their complex time variable performance. Moreover, environmental condition, natural aging and material quality regarding to determined indicators will be investigated and evaluated in their meaningfulness. These considerations, however, also include service life design methods, aimed at estimating the period of time during which a structure or any component is able to achieve performance requirements defined at the design stage with an adequate degree of reliability. On the basis of the quality of input information (mainly concerning the available degradation models), as sketched in the above description, it is possible to distinguish among deterministic methods, usually based on building science principles, expert judgment and past experience, which provide a simple estimation of the service life, and probabilistic methods;

(b) Sustainable indicators: in addition to technical performance indicators, which characterize the ultimate capacity as well as serviceability conditions, sustainability indicators, environmental based, will be also formulated. These variables characterize the environmental impact of a structure in the course of its total lifecycle, expressed in terms of total energy consumption, carbon footprint (CO2 emission), balance of raw materials, etc. These indicators can be separated into direct and indirect indicators, where the former are related to the construction/ maintenance itself and the latter are caused e.g. as a consequence of limited functionality;

(c) Other indicators: other sustainable indicators, economic and social based, may be used to evaluate a bridge performance. These indicators capture, based on the technical performance of a structure, additional aspects that may influence the decision process and typically represent the discounted (accumulated) direct or indirect costs associated with construction and maintenance. Summed up over the full lifetime, they represent part of or the full LCC. They can, in the context of multi-objective optimization, be understood as a weighting scheme to arrive to a single objective function that is to be minimized.

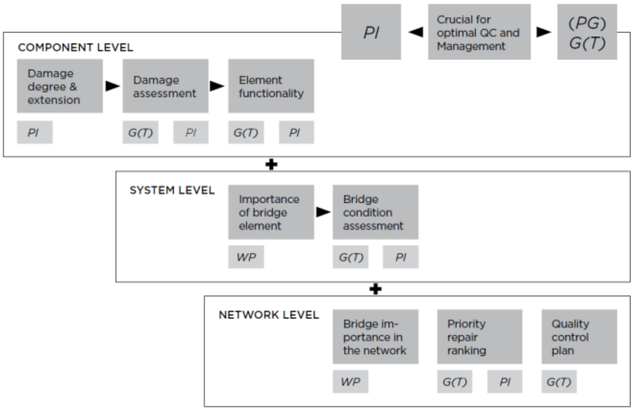
With this kind of collection it is possible to address a general description on how performance indicators of existing structures are assessed, with what frequency and what values are obtained. It is also possible to draw out the most common procedures and give recommendations to prevent unnecessary actions. Additionally, performance goals may be considered as characteristics to be satisfied during its lifetime. According to different levels of a bridge, it is also important to reach the goals at different levels (Figure 1).

Figure 1. Interaction of indicators and goals (tasks) related to structural performance within bridge management (Strauss et al. 2016).



Although different performance indicators interact (Figure 1), their categorization into technical, sustainable and socio-economic indicators through component, system and network level is required in order to identify methods for their quantification and their level of influence to a certain performance goal. A more detailed categorization with evaluation process (Figure 2) of damages as performance indicators should be related to detection methods, performance thresholds and evaluation methods, and finally the level and extend of their influence to a certain performance goal quantifiable in terms of monetary units (Strauss et al. 2016).

Figure 2. Interaction of indicators - PI, goals (tasks) - G(T) and weighting parameters - WP within bridge management (Strauss et al, 2016).



Indicators in existing bridge management

Management of road bridges comprises coordinated activities to realize their optimal value involving the balance of costs, risks, opportunities and goals. Performance goals may be considered as a type of bridge property or behavior required during its lifetime. Different types of performance goals need to be reached at different levels of roadway bridge assets as part of its efficient and effective maintenance strategy (Strauss et al. 2016).

The objective within COST Action TU1406 is also to deliver a set of performance goals varying from technical, environmental, economic and social factors. These goals, to be established for the collected performance indicators, will be linked to key performance indicators to summarize bridge state condition. In particular, it will be established:

(a) Technical goals: it will be analyzed what goals are actually used for technical performance indicators in roadway bridges and its components (e.g. bearing, joint, etc.). It will be also evaluated which are being defined in the course of international research cooperation. There will be an open discussion within the experts' network in this field, in order to determine the most important factors for the definition of such goals as well as the most suitable threshold values. It will be established goals, both for deterministic and probabilistic methods, for time-varying indicators and for different assessment procedures (e.g. visual inspection, non-destructive tests and monitoring systems);

(b) Sustainable goals: specific goals will be defined for sustainable indicators, environmental based. This task is much more difficult to perform than for technical indicators, as the historical data basis is much smaller. Nevertheless, an open discussion will be established within a network of experts in this field, in order to identify the most important factors for the definition of these goals as well as the most appropriate threshold values;

(c) Other goals: the definition of goals for other sustainable indicators, economic and social based, is extremely difficult as it largely depends on the established agreement between the owner and the roadway operator (concession model). Nevertheless, it will be important for the future of Europe to define such goals, or at least to provide some recommendations, so that standardized procedures can be implemented. In order to achieve this objective, an open discussion will be developed among a network of experts.

Performance goals are usually defined at different levels, from high-level strategic decisions to low-level, object-specific objectives. Functionality of a specific bridge element is a performance goal at the component level. Adequate performance of a complete bridge structure is a goal at the system level, but taking into account the relative importance to the network and the consequences of its collapse it may become a goal at the network level. Whether the goal will be (or is) achieved or not, may be assessed through the evaluation of various performance indicators, which additionally implies knowledge of their respective levels of influence to an observed performance goal. Performance indicator may then be defined as a superior term of a bridge characteristic which translates the condition of a bridge. It can be expressed in the form of a dimensional performance parameter or as a dimensionless performance index (Strauss et al. 2016). The former is a measurable/testable parameter that quantitatively describes a certain performance aspect and the second one is a qualitative representation of a performance aspect (e.g. importance of a bridge component in the whole bridge structure or importance of a bridge in the complete network). To evaluate performance indicators, performance thresholds or criteria must be set. A threshold value constitutes a boundary for purposes such as: a) monitoring (e.g. an effect is observed or not), b) assessing (e.g. an effect is low or high), and c) decision-making (e.g. an effect is critical or not). A criteria is a characteristic that is relevant for the choice between processes e.g. such as maintenance actions or others (Strauss et al. 2016).

A more detailed example on how these indicators can be used in bridge management can be seen in Figure 2. If divided into stepwise procedure then the steps would be:

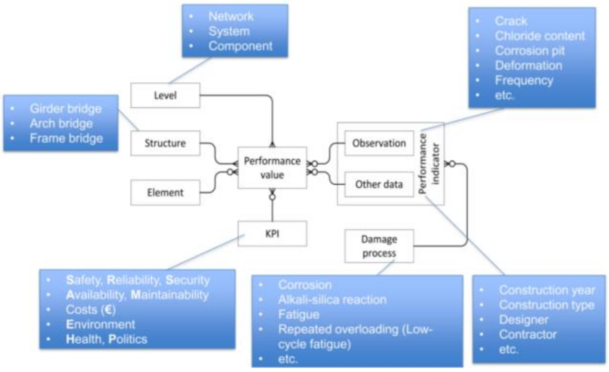
1. Assessment of damage at component level. Upon damage assessment of a particular bridge element, damage index becomes an indicator for the next goal – evaluation of component functionality level.
2. At the same time the element functionality is an indicator at the system level, together with the importance of a bridge element as weighting parameter. These are important input for the following goal ‐ bridge condition assessment.
3. From system level to network level it is important to add the bridge importance in the network as a weighting

parameter to bridge condition assessment. The next goal would be priority repair ranking.

4. Priority repair ranking may be considered as an indicator for a QC plan.

Before going into this procedure it is necessary to select the most important indicators for achieving the goals which are crucial for optimal QC and to allocate them with appropriate weights. A common framework for the development of QC plans for structural systems was proposed by Hajdin in 2016 (Figure 3).

Figure 3. Common framework for the development of QC plans (Hajdin, 2016)



This framework presents relationships between the entities considered fundamental for bridge management throughout their lifetime, including information referred to structure, elements, observations, damage process and performance values. Performance values are used to determine Key Performance Indicators to be compared with Performance Goals. By including time into performance indicators it is possible to plan short and long-term management activities.

Bridge performance goals can be set in order to ensure bridge performance is in line with network level performance goals. When defining bridge performance indicators, some difficulties may present themselves. First, the timescale for which network performance goals are set is typically much shorter than the estimated service life of a bridge. Therefore bridge performance goals should not only enable meeting the short term performance goals, but also facilitate life cycle optimization. Furthermore, where bridge management is traditionally focused on evaluating the condition of the bridge, the desired condition now needs to be expressed or translated into goals reflecting network performance.

Consequently, Performance Indicators for structures must be defined. The considered approach, a risk-driven maintenance concept, is based on the Dutch model RAMSSHEEP, which is the acronym for Reliability, Availability, Maintainability, Safety, Security, Health, Environment, Economic and Politics, respectively. Each criterion is defined as follows:

- Reliability: the probability that the required function of the system can be carried out under the given conditions for a given time interval;
- Availability: the probability that the required function of the system can be carried out under the given circumstances during a given arbitrary time;
- Maintainability: the probability that the maintenance activities are possible within the specified time and under circumstances that the required function continues to run;
- Safety: related to the freedom from unacceptable risks in terms of injury to people;
- Security: related to the safety of a system regarding to vandalism and unreasonable human behavior;
- Health: being related to physically, mentally and socially defined aspects;
- Environment: concerns the physical environment requirements;
- Economics: regarding the relationship between cost and value;
- Politics: concerning political-administrative and social requirements.

This grouping makes it simpler to present the necessary information, in particular by means of multi-criteria plots, thus facilitating the analysis of possible scenarios for assessing bridge performance.

Performance predictive models

Management systems rely in deterioration and maintenance models to predict assets future performance. These models can be either deterministic or probabilistic. A major disadvantage of deterministic models is that they do not consider uncertainties. This can be overcome by using probabilistic models. The most common probabilistic models for modelling deterioration are the Markov chains (Fernando et al. 2013). Markov chain is a random process that undergoes transitions from one state to another on a state space. The Markov property states that the next state only depends on the current and not on the sequence of preceding states. The transition between states is defined by Eq. (1):

$$P^{\Delta t} = \begin{bmatrix} p_{11} & p_{12} & \cdots & p_{1n} \\ 0 & p_{22} & \cdots & p_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & p_{mn} \end{bmatrix} \qquad (1)$$

where p_{ij} is the transition probability between states i and j from instant t to $t+\Delta t$. Although Markov chains can predict deterioration, these models are incapable of taking into account exceptional events, including manmade and natural hazards.

A decision is made based on the analysis of predictions. Thus, the rational decisions depends to a large extent on its ability to collect information about the behaviour of the system and to make relevant inferences. There are three important aspects that influence predictions (Sánchez-Silva, Klutke 2015): (i) time horizon; (ii) ability to make inferences; (iii) evolution of knowledge.

First, the accuracy of predictions depends on how far into the future we want to go. Clearly, the ability to predict diminishes as the time horizon increases. For example, under normal conditions, it may be possible to make a reasonable estimative of tomorrow's variations in the stock market, but very difficult to predict what would be its state in 5 years' time.

Secondly, the ability to make predictions is generally based on past experiences and observations; predictive models rely to a large extent on observed data. One may be unable to envisage events that have not been previously observed, which does not mean that such events will not occur. Predictions often rely on the notion of causality; however, inferences about causality that are not properly scientifically grounded should be carefully analyzed.

Finally, making predictions is a dynamic process. It changes permanently as new information and new technological developments become available. Furthermore, predictions may possibly change as the understanding of the system performance evolves. Despite the practical and conceptual difficulties in making predictions, they are unavoidable in decision making.

Good predictions require the appropriate understanding and management of uncertainty. Thus, in most engineering problems, the stochastic nature of the "laws" that describe the system performance (e.g., stochastic mechanics) plays a major role (Sánchez-Silva, Klutke 2015).

Investment decisions for engineered systems are based on predictions about the system's future performance. Within this context, life-cycle cost analysis (LCCA) is the study of a system's performance over a specific time period. LCCA provides a framework to support long-term decisions about resource allocation related to the design, construction, and operation of infrastructure systems. LCCA focuses mainly on finding the expected discounted value of a cost–benefit relationship $Z(\mathbf{p},l)$ at time t = 0 as written in Eq.2.

$$E[Z(\mathrm{p},l)] = E\left[\int_0^l B(\mathrm{p},\tau)\delta(\tau)d\tau - \sum_{i=1}^{N(l)} C_i(\mathrm{p},t_i)\delta(t_i)\right] \quad (2)$$

where p is a vector parameter used to describe the system performance. $B(\mathrm{p},\tau)$ represents the benefits derived from the existence and operation of the project, $\delta(\tau)$ is the discount function used to compute the net present value of future gains and investments and $C_i(\mathrm{p},t_i)$ describes all costs incurred (e.g., failure, repair, maintenance) throughout the lifetime t of the system. Note that $N(l)$ is the number of interventions in the time interval l, and is usually a random variable (Sánchez-Silva, Klutke 2015).

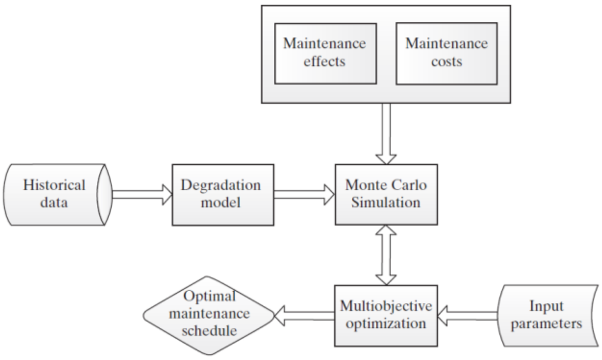
The use of predictive models allows infrastructure managers to plan maintenance strategies (Mirzaei, Adey 2015) and by integrating models with LCC to make objective decisions. To support the decision-making process, optimization of maintenance schedules is commonly employed. Some early studies for maintenance scheduling are based on single objective optimization (Miyamoto A. et al 2000). Such works often seek to find a maintenance schedule that minimizes the total cost, whereas the performance is considered a constraint (Estes, Frangopol, 1999; Yang, Frangopol, 2006). Single objective optimization results in a single optimal solution, which may provide the asset manager a little or no insight into the decision process. The task of maintenance planning naturally involves multiple conflicting objectives, as maintenance plans resulting in less deteriorated infrastructure assets also lead to higher costs. Multi-objective formulations have the potential to capture the complexity of the problems by exhibiting a set of solutions that represent trade-offs between several objectives (Neves et al. 2006). A major advantage of multi-objective optimization is that the infrastructure manager can be provided with a set of optimal maintenance alternatives that are equally important without any preference information. Then, the manager can look to all the generated solutions and identify the most preferred, based on his/her preferences (experience, aspirations, available funds, etc.). Moreover, if the Pareto set is successfully approximated, it also includes the least cost solution.

A generalized framework for optimum inspection and maintenance planning was introduced by Kim et al in 2013. Such framework covers: (a) the damage occurrence, propagation and service-life prediction; (b) the relation between degree of damage and probability of damage detection; and (c) the effects of inspection and maintenance on service life and cost.

As budgets are usually defined for a network in order to distribute the available funds among all components, system-based approaches to maintenance management are of great importance. A framework for bridge network maintenance scheduling was proposed by Bocchini and Frangopol in 2011. This framework addresses optimal maintenance scheduling by minimizing the cost and maximizing the reliability based network performance indicator.

In Figure 4 is presented the computational framework for asset maintenance scheduling based on Denysiuk et al (2016) work. This process begins with constructing degradation model based on historical data and the intervention module is developed on the basis of maintenance effects and costs. Optimal results can be achieved by performing a multi-objective optimization.

Figure 4. Flowchart of interactions among modules in maintenance scheduling (Denysiuk et al, 2016)



Intervention or maintenance actions can be either programmed or applied if the performance of the asset is inadequate. The former is usually referred as preventive, whereas the latter is denoted as corrective. When the action is applied, its impact on the asset performance can be modelled by the following effects: (a) improvement in performance at the time of application; and (b) delay and/or reduction in deterioration rate for a period of time after application. Since owners may have different preferences then optimization will be done according to provided parameters, which can be influenced by uncertainties due to a wide range of factors.

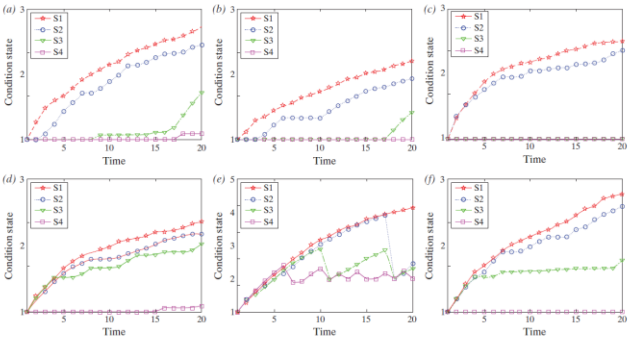
Nevertheless, an effective maintenance strategy must ensure adequate level of safety. These requirements can be expressed by imposing an upper bound on the asset condition state, which also guarantees the user specified threshold. To guarantee the feasibility of generated solutions during the optimization, a constraint handling technique based on a repair method is developed (Denysiuk et al. 2016).

Optimization models

Several bridge management systems have been developed in the last decades with the purpose of optimizing the selection of maintenance actions to maximise the benefits and to minimise the costs (Frangopol et al. 2001). As previously shown, there are different levels for performance indicators and to improve maintenance planning is important to optimize management at all levels.

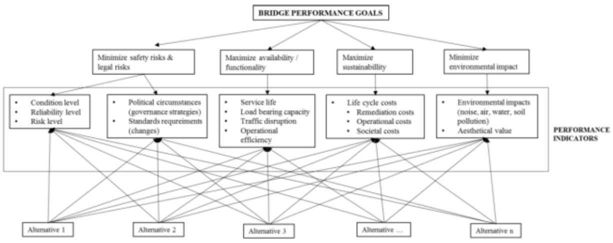
In an efficient management of single bridge it is important to develop a consistent framework for all components including degradation and maintenance models. In most bridge management systems it is possible to develop plans over time and to identify possible maintenance alternatives. Based on the alternatives, LCC can be calculated and compared. By expressing the possible futures, the concept of a “candidate” is suggested (Patidar et al. 2007). It consists of a sequence of future time periods of agency activities. Activities mainly include do nothing scenarios, but there are also a number of specified actions that must be done on different components of a bridge such as cleaning of bearings, replacement of expansion joints, etc. An example of road bridge optimization model is provided in Figure 5 from the work of Denysiuk et al. (2016) where four different solutions (S1, S2, S3 and S4) are highlighted to analyse maintenance scenarios of different parts. The least cost solution (S1) corresponds to do-nothing scenario and more expensive solutions involve more maintenance actions. The optimization at the bridge level will most likely lead to different maintenance scenarios.

Figure 5. Performance profiles of bridge components for 20 years. The plots illustrate the degradation process under different optimal maintenance scenarios, represented by the solutions located in different regions. (a) bearings, (b) piers, (c) abutments, (d) railings, (e) expansion joints and (f) deck.(Denysiuk et al. 2016)



On the other hand, in network-level bridge management, where a variety of objectives and constraints are faced, it is necessary to identify a set of goals and a set of performance indicators for each goal, as it is shown in Figure 6. According to previous work of COST Action TU1406 WG1 (Strauss et al. 2016) decision can be made based on different indicators which have separate goals. In a network of bridges the decision has to be made implicitly, so that alternatives can be ranked and best alternative selected. The ranking may be based on temporal alternatives or on a cost-minimization rule, where preference order is adequately represented. If there are more criterions, then multi-criteria decision-making (MCDM) should be considered.

Figure 6. Multi-objective bridge performance goals and performance indicators (Rashidi, M., Lemass, B. 2011)



MCDM provides a systematic approach to evaluate multiple conflicting criteria in decision making as shown in Figure 6. It is normally used to identify and quantify decision-maker and stakeholder considerations about various non-monetary factors, in order to compare alternative courses of action (Kabir et al. 2014). An example of MCDM has been provided in the framework of COST TU1406 by Bukhsh et al. (2017), in using analytical hierarchy process and multi-attribute utility techniques. Possible result of multi-criteria assessment of different bridge maintenance alternatives is shown in Figure 7, which can be used for a decision making about the optimal maintenance or design alternative.

Figure 7. Spider plot as a possible result of multi-objective assessment of different maintenance alternatives against different performance aspects.

An important class of decision-making techniques that attempt to construct the preference order by directly eliciting the decision maker’s preference is predicated on what is known as utility theory. This, in turn, is based on the premise that the decision maker’s preference structure can be represented by a real-valued function called a utility function. Once such a function is constructed, the selection of the appropriate alternative can be done using an optimization method. Broadly speaking, this technique involves three steps (Patidar et al., 2007):

1. Weighting: this assigns relative weights to the multiple criteria.
2. Scaling: because the performance criteria can be of different units, scaling provides a common scale of measurement and translates the decision maker’s preferences for each performance criterion on a 0–100 scale. This involves developing single-criterion utility functions.
3. Amalgamation: is combining the single criterion utility functions using the relative weights into one measure based on mathematical assumptions about the decision maker’s preference structure. This involves deriving the functional forms of multi-criteria utility functions.

Some of the weight factors are available in some countries (for example weight factor for traffic delays, noise, injuries etc.), depending on the selection of criteria, some weight factor may still need to be developed. In the development of the weight factors the starting point can be taken a qualitative approach from which the apparent relative weight can be deducted. Once the possible outcomes have been brought to a single scale, the best decision can be found as a formal optimised decision process, in which option with the maximum “utility” shall be selected as the recommended decision.

Analytic Hierarchy Process

The Analytic Hierarchy Process (AHP) is a structured technique for organizing and analyzing complex decisions, based on mathematics and psychology. It has particular application in group decision making, and is used around the world in a wide variety of decision situations, in fields such as government, business, industry, healthcare, shipbuilding and education.

Rather than prescribing a "correct" decision, the AHP helps decision makers identify the decision that best suits their goal and their understanding of the problem. It provides a comprehensive and rational framework for structuring a decision problem, for representing and quantifying its elements, for relating those elements to overall goals, and for evaluating alternative solutions.

The AHP aims to arrive at the relative weights for multiple criteria in a realistic manner while allowing for differences in opinion and conflicts that exist in the real world. The analytic hierarchy process can handle quantitative, qualitative, tangible, and intangible criteria. The process is based on three principles: decomposition, comparative judgments and synthesis of priorities. It constructs a hierarchy and uses pairwise comparisons at each level to estimate the relative weights.

The procedure for using the AHP can be summarized as (Saaty, 2008):

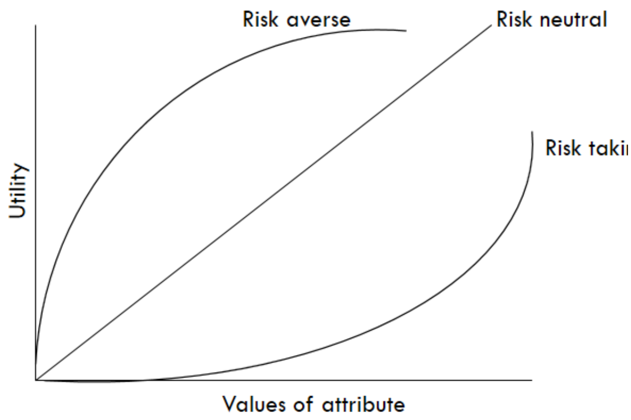
1. Model the problem as a hierarchy containing the decision goal, the alternatives for reaching it, and the criteria for evaluating the alternatives.
2. Establish priorities among the elements of the hierarchy by making a series of judgments based on pairwise comparisons of the elements. For example, when comparing potential purchases of commercial real estate, the investors might say they prefer location over price and price over timing.
3. Synthesize these judgments to yield a set of overall priorities for the hierarchy. This would combine the investors' judgments about location, price and timing for properties A, B, C, and D into overall priorities for each property.
4. Check the consistency of the judgments.
5. Come to a final decision based on the results of this process.

Multi-attribute Utility Functions

Utility theory provides a measure of preferences of a decision maker over a group of alternatives (Ishizaka & Nemery, 2013). Based on the six axioms of utility theory, Multi-attribute utility theory (MAUT) is introduced by Keeney and Raifa (1993). MAUT provides a systematic approach to reduce the qualitative values of various attributes (i.e. performance indicators) into utility functions. The obtained utility scores are then aggregated based on the relative importance of attributes. The final score assign a ranking to each alternative based on either minimization or maximization function. In other words, MAUT assigns the relative importance of performance indicators (e.g. condition, cost, etc.), while comparing number of bridges. These bridges are often referred as alternatives in MAUT.

MAUT involves the single decision maker who is willing to make certain trade-off among the performance indicators while exposed with uncertainty and risk (Keeney and Raiffa, 1993). The uncertainty is usually originated because of unavailable and dynamic nature of data, and involvement of number of stakeholders. For instance, in the bridge planning the exact estimation on number of users affected due to maintenance activity is difficult to define. MAUT integrates a body of mathematical utility models and a range of decision assessment methods in order to assist in decision ranking problem (Thevenot et. al., 2006). The single attribute utility function is calculated for each performance indicator, which reflects the risk attitude of the decision maker. The risk attitude is categorized into risk-taking, risk averse, and risk neutral. Figure 8 shows the resulting utility graph based on risk attitude of decision maker. The utility values can be calculated by plotting the attribute values in x-axis and utility values on y-axis ranging from 0 to 1.

Figure 8. Risk Attitude of decision maker



The mathematical formulation of MAUT is represented as follows:

$$U(x) = k_1 U(x_1) + k_2 U(x_2) + \cdots + k_n U(x_n) \tag{3}$$

where $U(x)$ is the overall utility value of each alternative, k is a scaling constant that provides the relative importance of each performance indicator, $U(x_i)$ is a utility value of each performance indicator i for the alternative x.

$$U_i(x_i) = A - B^{e^{(RT/x)}} \tag{4}$$

Where A and B are scaling constants and RT is risk tolerance.

The general steps to apply MAUT on decision-making problem e.g. maintenance planning are summarized as follows:

1. Identify the decision objectives and define the attributes relevant to the problem
2. Quantify the attributes in a form that structures and represent the defined decision objectives and goals in utility functions
3. Calculate the single utility function for each attribute by estimating the indifference point(s) and risk attitude of a decision maker(s). This steps will establish a relationship between the attributes values and their utility scores based on preferences structures of the decision maker(s).
4. Determine the relative importance of attributes build on the weighting assigned by the decision maker(s).
5. Compute the aggregative utility score for each alternative by either multiplicative form of addictive form. The total aggregative score will rank the alternatives, where an alternative that is the perfect fit in a realization of decision objective is ranked at highest.

Conclusion

During the implementation of asset management strategies, maintenance actions are required in order to keep assets at a desired performance level. As the focus on an efficient delivery of network performance increases, so does the interest in the relations between societal goals, performance indicators for both the road network and bridges or bridge elements. The implementation of asset management will increase the integration of network and structure performance requirements. In doing so, bridge managers and road agencies face a number of challenges:

- How to quantify the performance goals and related performance indicators?
- How to translate from network to the object level and vice versa?
- How to set a complete set of performance indicators?

Network or even societal goals tend to be rather broad in their definition. Furthermore, there is often no exclusive relationship between performance indicators set at a lower level and goals at a higher level. An important notion is that in many countries, the main focus of bridge management is still the condition assessment of the particular objects or elements thereof.

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