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Scientific Paper

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IABSE Survey on implemented decision-making models at public and private owners/operators of road- and railway infrastructures

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Abstract

Infrastructure systems, such as bridges, are a driver for economic growth and sustainable development of countries. Similarly, development of operation and maintenance strategies for infrastructure systems may aim at optimal management using Key Performance Indicators (KPIs) such as reliability, redundancy, availability, safety, economy, environmental performance, and resilience. Recent research and development projects, such as COST TU1406, highlight that infrastructure managers make decisions based on a mix of qualitative and quantitative data from various sources paired with models of various level of complexity as well as expert judgement. Similarly, recent state-of-the-art from academia reports on a variety of different decision-making models applicable for optimal management of infrastructure systems. Within IABSE Commission 5 on Existing structures, Task Group 5.4 has performed a survey on implemented decision-making models among 23 infrastructure managers from 20 countries. It highlights some similarities in relation to KPIs, condition rating and limit state checks. This stimulated standardisation of decision-making. Application of risk-based methods, performance prediction and intervention modelling are somewhat more scattered and may call for further research and development as well as training. The need of bridging the gap between implemented decision-making models and research is of paramount importance.

Keywords: Decision-making models; Key Performance Indicators; Risk; Infrastructure systems; Bridges

Introduction

Infrastructure systems comprise bridges, tunnels, waterways, roads, railways, dams, power plants and transmission lines among many others. These infrastructure systems are a driver for economic growth and sustainable development of countries. Similarly, development of operation and maintenance strategies for infrastructure systems may aim at optimal management using Key Performance Indicators (KPIs) such as reliability, redundancy, availability, safety, economy, and environmental performance. Integration of these KPI's call for a risk-based approach addressing both probability and consequences of various lifetime scenarios. In recent years resilience as a KPI has been addressed by some infrastructure managers, ref. section 1.2.

Top level or executive asset management policies often address some or all the above KPIs. How these policies are translated within the owner/operator organisation into daily operation is not always transparent and for a good reason because this translation is not straightforward.

It may be argued that Infrastructure managers currently base their decisions on an implicit risk-based decision process. Often a combination of data from various sources is handled by models on various levels of complexity and paired with expert judgement. This process implicitly or explicitly addresses probability of structural failure, operational failure, or any other failure mode over the time alongside an assessment of consequences if these failures should occur. This process is more often qualitative rather than quantitative (in this respect management through condition rating is considered as a qualitative method).

The qualitative nature of current infrastructure management and the use of expert judgement for these uncertain systems introduce a level of subjectivity, but most importantly they do not allow for a fully transparent decision-making. The budget allocation needs to be performed objectively based on the goals and criteria set by the operators. All types of infrastructure objects should be considered. Transparent decision-making should be performed with different attributes (condition, costs, downtime etc.) that are either part of the objective function or constraints. The quality of these attributes is of utmost importance. Increasing the level of transparency will be a benefit for many stakeholders and not only for the operator.

Recent research and development projects such as COST TU1406[1] reveal that decision-making varies between countries and that performance assessment of roadway bridges (but also applicable to other infrastructure systems) should be standardised. Standardisation will allow for an easier exchange of knowledge and increase competition for the benefit of multiple stakeholders and society at large.

In parallel, recent state-of-the-art from academia reports on decision-making models applicable to optimal management of infrastructure systems, ref. Biondini and Frangopol[2], Sánchez-Silva et al[3], Frangopol[4], Thöns[23], Straub et al[24], Faber and Stewart[25], Straub and Faber[26] and Rackwitz et al[27] – journal papers that summaries more than 400 important references related to decision-making of infrastructure systems. Various decision-making models for infrastructure systems have been demonstrated in case studies in order to show their benefit. However, quite often, these models are not picked up by the industry. This can be due to various obstacles such as lack of data, reluctance to (or difficulties related to) deviate from their current modus operandi, lack of trust that these models really add to the specific engineering understanding, lack of skills within the infrastructure organisation and/or lack of standard provisions for their application. To advance the current level of infrastructure decision-making it is important to bridge the gap between implemented decision-making and current state-of-the-art.

To this end IABSE Commission 5 on Existing structures has formed a Task Group (TG) 5.4 dealing with decision-making models. TG 5.4 members represent various stakeholders such as owners/operators, consultants and academia covering the geographical area of America, Asia, Australia, and Europe.

TG 5.4 has performed a survey on implemented decision-making models among infrastructure managers. The survey is analysed in the following chapters. Figure 1 relates the structure of the paper, which to a large extend follows the questionnaire, to the decision-making process.

Finally, conclusions and outlook are presented with the aim of highlighting the current level of implemented decision-making models. Paired with current state-of-the-art from academia it should be possible to narrow the gap for the benefit of industry, academia, and the society at large.

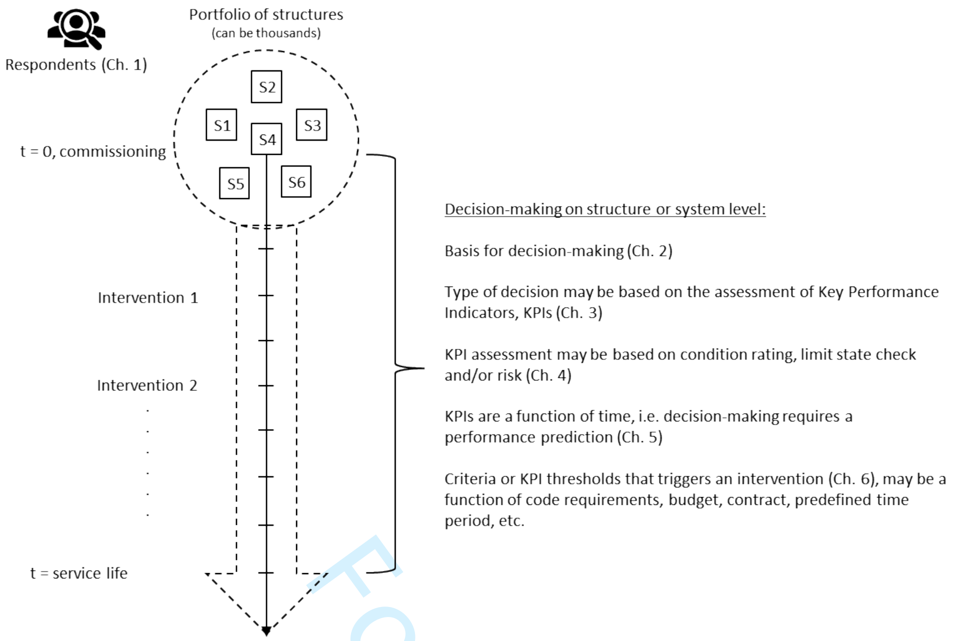

Figure 1 Relation between the structure of the paper (Ch. is Chapter) and the decision-making process.

1. Respondents

To explore currently implemented decision-making models, TG 5.4 has circulated a questionnaire to public and private owner/operators of road- and railway infrastructures - more than 60 questionnaires were sent to more than 50 countries. During the period of 2019-2020 a completed questionnaire from 23 respondents from 20 countries within America, Asia and Europe have been received.

The respondents represent both private and public owners/operators dealing with transport infrastructure systems such as bridges, tunnels, retaining walls, cuttings, embankments, and waterways. Some owners/operators are only managing roadway infrastructure systems, while others manage both road- and railway infrastructures.

Most of the questionnaires have been completed online directly by the infrastructure owner/operator. Other questionnaires have been completed through an interview between a TG 5.4 member and an owner/operator.

The participating countries and organisations have been anonymised in this paper in order not to favour specific countries or organisations that have the maturity and/or economic power to be quite advanced when it comes to implemented decision-making. The purpose of the paper is to present best practises and emerging improvements as well as their diversity. In this way the less advanced owners/operators may learn from the more advanced so that all are able to improve their approaches. Similarly, academia will get a firm view of the level of maturity within the owner/operator organisations. This may be considered when proposing state-of-the-art decision-making models or their further development.

The analysis of the responses related to decision-making models for infrastructure systems comprising bridges, tunnels, retaining walls, cuttings, embankments, among others, may be used as a blueprint to other sectors. When speaking of decision-making models, it is evident that different sectors can learn from each other.

2. Basis for decision-making

Decision-making is part of infrastructure managers' daily tasks. Decision-making is made on all levels within an owner/operator organization and often many years before the interventions. Decision-making may comprise e.g. the selection of an optimal intervention strategy that meets technical and financial considerations as well as current regulations. As basis for decision-making, infrastructure managers rely on data as well as systems/tools developed and operated internally within their organization or by external companies. The quality of information and the knowledge of the structures with their local peculiarities, damage process as well as the associated intervention cost and methods are crucial for good decision-making.

In the questionnaire, the respondents were asked about their structure management system and its basis. 21 out of the 23 respondents carry out the analysis internally to determine the interventions to be performed. Approximately half (11) of the respondents also use support (e.g. detailed inspection reports and measurements), which is provided by one or more consultants.

More than 50% of the respondents work with data provided by public or private companies in their decision-making process. In detailed reports external consultants provide structural assessments, cost estimates and different maintenance strategies to support the decision-making process defined and guided by the owners.

The decision-making process is also supported by a Bridge Management System (BMS) for 14 respondents and the remaining 9 respondents use databases for their decision-support. The large majority use proprietary software owned by the owner/operator and adapted to their own needs either in-house or with the help of a service provider. Only 3 respondents use a commercial management system, one of them customized to own needs. A summary from 2012 of BMS worldwide is provided by the IABMAS Bridge Management Committee[9]. In addition to the management systems described above, approximately half (12) of the respondents also use spreadsheets as a support for decision-making. These spreadsheets may deal with deterioration modelling, cost calculations, risk assessment, traffic simulations etc. In most cases MS Excel is used.

In summary, the manager controls the decision-making process for management of their structures. However, to a large extent external support is also used to form basis for the final decision.

3. Key Performance Indicators (KPIs)

The performance-based evaluation of engineering structures is becoming increasingly important and allows maintenance management and long-term planning to be carried out according to the needs of the user and owner. Often, performance evaluations make use of the term Performance Indicator (PI) which stems from economics and measures the success of an organization or of a particular activity (such as projects) in which it engages. The application of this term to physical objects is coupled to their fitness for purpose. The PI measures fitness for purpose of a physical object such as a bridge or its element. Since the fitness for purpose (i.e. quality) can change over time, so does the value of a PI. Maintenance interventions can also change the value of PI. It is obvious that bridge performance relates to safety and serviceability, but other performance criteria can be useful as well.

Generally, there is no clear distinction between PIs and Key Performance Indicators (KPIs). In this paper, like the COST project TU1406 WG3 report[16], KPIs relate to a whole bridge and are defined as follows (RASEE):

- Reliability is the probability that a bridge will be fit for purpose during its service life. It is the complement to the probability of structural failure (structural safety), operational failure (serviceability) or any other failure mode chosen by the infrastructure manager or required by other stakeholders.
- Availability is the proportion of time a structure is open for service. It does not include failure-related service outages but those due to expected maintenance interventions. Alternatively, the Availability for instance can be measured as additional travel time due to an imposed traffic regime on a bridge.
- Safety is the situation of life and limb being protected from harm during the service life of a bridge. Loss of life and limb due to structural failure is not included by this definition (since it would overlap with the Reliability).
- Economy is related to minimizing the long-term cost of maintenance activities over the service life of a structure. Herein the user costs for instance for bridges are incurred due to detours and delays are not included.
- Environment is related to minimizing the harm to environment during the service life of a structure.

In recent years resilience as a KPI has been addressed by some infrastructure managers. Resilience is associated with the ability of a structural system to deliver a certain service level even after the occurrence of an extreme event or series of events, and to recover the desired functionality as fast as possible. One can see that resilience may be seen as a combination of the above listed KPIs in function of time.

Following design provisions, the obvious choice for the Key Performance Indicators (KPI) for bridges would be safety and serviceability. Indeed, some suggestions for performance indicators (PI), e.g. in references[5, 6], include safety and serviceability and combine them with other performance indicators. As presented in Figure 2, the serviceability is combined with durability in performance category "Structural Condition" whereas safety is combined with stability to form the performance category "Structural Integrity". The performance category "Costs" include both agency and user costs. The user costs include delay, detour, and accidents costs. Finally, the performance category "Functionality" includes clearance, ride quality and load ratings and restriction on use.

Figure 2 Indicators related to bridge performance[5]

Some relevant indicators to bridge performance are included in Brown et al.[5], but the classification merits some further consideration. For instance, the structural integrity is related only to sudden events, mostly natural hazards such as earthquake and hurricane. The observable deterioration processes, although they may compromise structural integrity, affect only durability and serviceability. Durability seems to be understood as a span of time in which neither safety nor serviceability is compromised, and this understanding is adopted in the present paper as well. Within the COST Action TU1406[1], the Working Group 2 (WG2) elaborated the proposal for KPIs based on the Dutch RAMSSH€EP approach Rijkswaterstaat[7]. The following KPIs were defined:

- Safety, Reliability and Security (S, R, S) - a combined KPI
- Availability and Maintainability (A, M) - a combined KPI
- Economy € (i.e. Costs)
- Environment E
- Health and Politics (H, P) - a combined KPI.

One notes that whereas safety is directly considered, the serviceability is not. The overall performance is represented with a "spider net" diagram as in Figure 3. The most favourable value of a KPI is one (1), which means that if all KPI values are in the green area of the diagram, the bridge performs excellently. Hence, the larger the area in the diagram enclosed by the KPI values, the better is a bridge performance. Clearly, a similar diagram can be applied also for several bridges or even a whole bridge inventory.

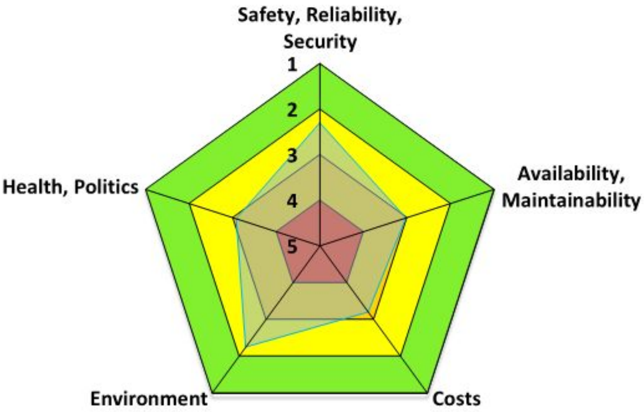

Figure 3 Example of "Spider net" diagram for bridge performance characterisation[8]

The evaluation of KPIs from performance indicators (PIs) and mere observations is still matter of vivid discussions. In addition, it seems that the KPIs from Figure 3 are not completely orthogonal (certain properties are participating in more than one KPI). In particular, the Reliability and Availability seem to be overlapping. Furthermore, some KPIs are difficult to assess at least on a bridge level, notably KPIs Health and Politics but also the Maintainability. The Maintainability is the ease with which a product can be maintained in order to repair damage or their cause, repair or replace faulty components without having to replace still working parts and prevent unforeseen maintenance interventions. This can be understood as a design aspect, and it is covered within Economy. The Security is the degree of protection against vandalism and may be coved within Maintainability. The protection against terrorism, which especially in the US belongs to security is not considered in this approach. The KPI of Health is absence of non-failure causes of illnesses (e.g. use of asbestos), which is in the most cases regulated. The KPI of Politics include elimination of causes for public outcry, image protection etc., it is a downstream performance indicator i.e. fulfilled if RASEE goals are met. Given the latter, the definitions of the RASEE KPIs are adopted to comply with the aforementioned TU1406 WG3 framework.

The primary goal of TU1406 WG3 was to develop a quality control plan that enables the systematic link between the best practice inspection systems and innovative asset management procedures.

Within a quality control framework, the KPIs will be evaluated for different maintenance scenarios, looking for the most feasible one. Here, it must be underlined that KPIs of Reliability and Safety can be evaluated based on the inspection and/or investigation at a point in time (i.e. static quality assessment) but can also be predicted over time (i.e. dynamic quality assessment). The KPIs of Availability, Economy and Environment can be only reasonably applied as a function of time. Several case studies on KPIs and decision making are referenced in the litterature[1, 29-31].

On the implemented survey, it was inquired upon the importance of different KPIs in the scheduling of maintenance and repair of structures. The inquired stakeholders were given the chance to indicate a level of importance between 1 (not important) to 5 (very important) regarding the following criteria: reliability, availability, safety, economy, environment, special/extreme cases of loading or any other criteria to be described by the respondent.

The criterion to which was given higher importance was safety closely followed by reliability. In both cases 15 out of 23 of the answers gave a ranking of 5 to these criteria. The third criterion considered most important was availability followed by economy and special/extreme cases of loading. From the given choices, environment was considered the least important, although in two cases a rank of 5 was given to this criterion. With e.g. the formulation of the United Nations Sustainability Development Goals in 2015[18] the importance of the environmental KPI may increase in the future. Comparing the criteria considered most important (safety and reliability) with the least important (special/extreme cases of loading and environment), it is seen that the first ones are given an importance value approximately 1.4 times higher compared to the least important ones. Figure 4 presents the comparison of attributed importance for the above-mentioned criteria.

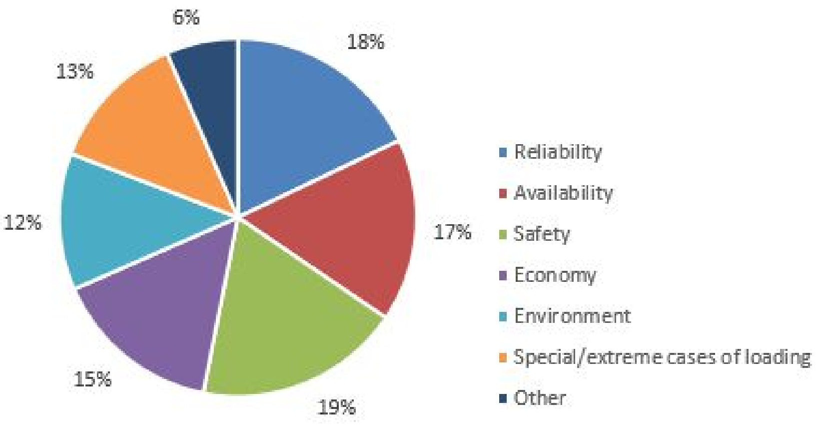

Figure 4: Importance of KPIs for scheduling of maintenance and repair of structures.

It should also be noted that 9 out of 23 respondents indicated other criteria used for scheduling maintenance activities, namely: feasibility, local community, redundancy, durability, consequences of failure (monetary consequences of failure compared to construction costs), reliability, network level availability related to structures (e.g. road category, annual average daily traffic), life cycle costs, maintainability, security, health and politics (National governmental interest in safe and predictable transportation). For 65% of the group who also consider these other criteria in their management framework, the very important class (5) was indicated.

This information also shows that the current RASEE KPI definitions given above are not yet fully recognized by the operators in their detailed and comprehensive meaning, since the other criteria mentioned to a large extent are indirectly contained in the defined ones. There is therefore still a need for training regarding the RASEE KPIs. Similarly, there is also a need for research regarding the RASEE KPIs.

4. Assessments

4.1. Condition rating

Condition rating seems to be the most available method for structural assessment of existing structures. This is due to its relatively easy deployment, mainly based on visual inspections, sometimes supplemented by some simple non-destructive testing in the case of standard bridges. In the case of complex, long-span and/or landmark bridges also permanent monitoring systems are becoming more used in order to perform a continuous monitoring of the bridge performance (Structural Health Monitoring).

The questionnaire evidences once again that condition rating (CR) is the most used assessment method regarding bridge performance. Therefore, it can be rated as a Key Performance Indicator (KPI). This is in accordance with the previously defined KPI. In fact, due to the difficulties in evaluating the KPI reliability, the CR has been used as a substitute in standard assessment. Also, a clear relation exists between condition and safety, another KPI and also, usually, CR has been used to quantify the safety related issues (condition of shoulder, parapets, handrails, expansion joints etc.).

Also, in all cases, they respond that the calculation of the condition of the whole bridge is based on the splitting into several parts (foundation, piers, abutments, deck) and these parts also split into different elements (for instance, the deck is divided into edge or interior beams, slab etc.). The maximum number of condition states for an element varies from country to country with a maximum of 22, with 5 condition states being the most common. The number of states of the structure is also variable, but with less variability, with a minimum of 4 and a maximum of 7. Again 5 is the most common value (43% of the cases). It is worth noting that 5 seems to be the optimum number of condition states, not only in the case of bridges, but also for other structural elements, structures (as buildings) and other scientific and technical fields[10].

Only 16 countries have answered to the question about the existence of a condition rating procedure for the bridge assessment (e.g. a formula or a standardized procedure) starting from the condition of the different elements, 9 of them use a formula or standardized procedure while 6 rely on the inspector´s assessment and engineering judgement.

In summary, although other KPIs are used in a small number of countries, condition rating is the most and widely used KPI by the stakeholders when looking to the assessment of capacity of existing structures. In fact, all the respondents to the questionnaire have answered that they use the condition rating in the inspection and assessment procedure. However, 6 countries declare that also a limit state check is performed for the assessment, whereas only 3 are using a risk assessment procedure (probability and consequences of failure). This is further analysed in the following.

4.2. Limit state checks

Design and performance assessment of structural elements, components and assets may be expressed in terms of limit state checks, allowing a more substantiated decision-making process. In that perspective, the performance evaluation may be defined by the probability of a limit state function to be violated. The failure, or non-acceptable performance, of an element is considered when the supply value (e.g. resistance, service limit) is exceeded by the demand value resulting from a loading scenario, on that specific element. Therefore, limit state checks are effective tools to assess the performance of an asset being commonly divided in ultimate and serviceability limit states, depending on the aim of the assessment. For instance, to design and assess for both ultimate and serviceability limit states, diverse target values for limit state violation are established for various structural situations by considering different consequences classes, reference periods of time and relative cost of safety measures.

In the survey, the stakeholders were asked what type of assessment they are employing based on inspection and inventory data. For that question, approximately 26% of all inquired have selected that limit state check was considered, whereas 100% considered condition rating and 17% considered risk concerning probability and consequence of failure. A combination of types of assessments was found in 39% of the cases. In all cases where limit state check was selected, condition rating was also part of the decision-making process.

The sample of inquired stakeholders that confirmed using limit state checks have a clear tendency to indicate reliability as the most important key performance indicators (KPI) for scheduling maintenance activities. Safety and availability are follow-ups on the importance scale coming before economy and environment. In this analysis, it was found that these stakeholders have determined the influence of extreme case loading as the least important factor for scheduling maintenance activities.

It is important to note that all stakeholders have indicated that, in the decision-making process they relied on assessment or analysis performed within their own organizations. In that respect, 83% of the stakeholders that confirmed using limit state checks referred to their use of simplified models and loading by design code or user specified limit states. Also 62% of them confirmed using detailed calculations for each structure or element. However, it is important to note that 50% confirmed using both procedures when needed. In one case, the limit state assessment based on detailed calculations is considered when the condition rating has reached its worst condition level. Also, a similar assumption is made for one case where the limit state assessment is performed when the observed condition state calls for a more refined analysis. Therefore, it was found that in those cases the limit state assessment is only considered when deemed necessary after analysis of the condition state (condition rating) of the asset. It was also found for one respondent that, although using the existing codes for limit state check, adaptations are made to the design factors for existing structures considering the condition state (or observed damages).

Only one entry, mentioned the use of advanced models based on proof loading and application of probabilistic methods to assess their assets. Nevertheless, also in this case simplified models are applied if the condition rating does not call for more complex analysis.

From the analysis of the results of the survey, it is concluded that limit state checks are generally considered to substantiate the decision-making process when condition rating indicates a bad condition state or inadequate performance of the asset. In that case, the level of complexity of the analysis may vary depending on its objective and adaptations may be made considering the assessment of existing structures.

4.3. Risk

Since resource scarcity is amplifying the requirements that funds should be used as efficiently as possible, there is a strong need to establish inspection and maintenance strategies depending on the magnitude of risk, to prevent the performance deterioration and/or enhance the durability of existing.

Risk is a concept which can be defined as a joint measure of the occurrence of a hazard and the consequences (direct as well as indirect related to safety, economy, environment etc.) induced by its realization[11, 28]. Risk assessment requires then to identify and characterize these hazards and their consequences. In practice, a risk-based methodology is useful to make the transparent and consistent decision on the priority for upgrade and/or repair actions considering multiple constraints. It should qualify and quantify risks in order to state proposals for further investigations, detailed structural assessment and maintenance/repair strategies. As an example, guidelines quantifying the value of structural health information for decision support have been developed for operators, practising engineers and scientists[29-31].

It is worth noting that four owners consider the following consequences in their management of structures:

- Casualty and injuries (3 respondents)
- Types of stakeholders affected (1 respondents)
- User availability (e.g. additional travel time for traffic infrastructure) (3 respondents)

- Additional operational costs (2 respondents)
- Repair costs (2 respondents)
- Environmental consequences (3 respondents)

Since failure of an element can cause severe consequences, it is important to establish the scenarios including the loss of functionality, the loss of lives or injury and the other economic and social impacts in structure management.

Only four out of 23 owners /operators from 20 countries filled out the questionnaires on the risk assessment performed in the management system. These four countries declare in the response to "Assessments performed in the management system" that risk assessment is performed based on inspection and inventory data. Three of them consider both interceptable and non-interceptable processes. Their interceptable processes include "damage processes (e.g. corrosion, alkali aggregate, carbonation)" and "demand (e.g. traffic volume, traffic loading, overweight)". Meanwhile, all four owners consider sudden events of the non-interceptable processes as man-made hazards (e.g. vehicle/ship impact, explosions and fire). In addition, sudden events as natural hazards (e.g. flood, earthquake and avalanche) and non-observable action (e.g. fatigue) are also considered by three owners. It is noted that no one selected demand associated with climate change, although climate change is becoming a critical issue in the field of structural engineering. Risk assessment incorporating the climate change effects seems still premature in the practical management system.

5. Performance prediction

5.1. Modelling of deterioration and effects of interventions

The wide range of processes that affect any infrastructure system during its lifetime leads to the requirement of periodic assessments based on inspection and sometime monitoring. When necessary, the performance of these infrastructure systems and their components is updated through carefully optimized maintenance interventions. Notwithstanding such control mechanisms and adjustment procedures, it is of utmost importance for the structure owner to be able to reliably predict both short-term and long-term behaviour in order to (a) efficiently assign both short term and long term interventions, (b) plan the relevant expenses, and (c) provide an acceptable degree of reliability throughout the structural lifetime as defined by the relevant standards and within the limits accepted by society. Hence, forecasting models for the prediction of an infrastructure's deterioration process plays a significant role in the estimation of optimal maintenance, rehabilitation, and replacement strategies.

For the modelling and representation of deterioration processes of structural components and systems, stochastic processes have gained increased interest and they offer a suitable approach for modelling the long-term performance of structures. The owners generally rely on statistical analysis of condition scores (obtained during inspections) and expert opinions to build some deterioration models[19]. The idea is to characterize a continuous deterioration process by the lowering of a discrete condition state. In practice, rather simple mathematical models are used to predict the future condition state based on inspection score database. Several management systems use Markov chains models for deterioration prediction, then assuming exponential distribution of the sojourn time in condition states. Other models have been investigated to better reflect that the transition probability is likely to increase with the sojourn time spent in a given condition state[20, 21]. One can cite in particular the semi-Markov (assuming a Weibull distribution for the sojourn time), and hidden Markov models together with artificial neural networks (ANNs), which have been reported in literature as reliable deterioration prediction models[12, 13, 22]. Gamma process representations also offer an alternative to the discrete Markov models for the description of degradation processes. Gamma processes are continuous-time stochastic processes with independent, non-negative increments that follow gamma distributions with typically identical scale parameters and a time dependent shape parameter. As such they are well suited for modelling damage that gradually accumulates over time in a sequence of small increments[14].

In addition to the above mentioned models based on condition scores, there are also physically based models for predicting degradation. For instance, there are fatigue, chloride-, carbonation- and corrosion prediction models used in specific situations for the remaining lifetime predictions. In parallel, new technologies were developed in the last years for identification of physical processes such as corrosion, fatigue, corrosion protection, creep, and shrinkage among others. In addition, the availability of data for calibration and validation, which can be gained through monitoring, is increasing rapidly. This also creates a solid foundation for reviewing the effectiveness of long-established inspection procedures for infrastructure systems, which are paramount to achieve the expected performance and safety of structural systems. The systematic collection of a wide range of site-specific data, if made available to the engineering community, is an essential element for the verification and improvement of current models and design concepts. In practice though, the use of physically based models requires the collection of more extensive model input data and cannot be operated solely from the information from visual inspections. Furthermore, questions such as spatial variability are still largely not standardized for such models, whose level of complexity prevents them to be largely used in management systems up to now.

Based on this previously outlined knowledge about model predictions, one focus of the survey was also on the modelling of deterioration and effects of interventions, see also chapter 6. The methods presented above and the data material available from the survey allow the following analyzes of the application of the models:

- A tool for modelling the deterioration of the asset on deterministic assumptions is used by 8 out of the 10 respondents who answered that question.
- Model of deterioration within an asset management system is included by 4 respondents, an independent expert software or tool is used by 5 other respondents, and in one case the model is mixed as it is partially within the system and partially using another expert software.
- Changes in the physical condition of the structure/elements are modelled by 9 out of 10 respondents, and only in 1 case, the changes in the KPI´s are used.
- The modelling of effects on the interventions are performed in 8 cases. The modelling is processed in a deterministic manner.
- From those countries modelling the interventions, in 38 % of the systems the model for intervention effects is implemented in it, and the other 50 % use external expert software/tool. Again 1 country (the same as for the case of deterioration modelling) reports a mixed system. In all cases the changes in the physical condition of the structure/elements are modelled.

In addition, the owners reported about budget and technical limitations associated with a comprehensive development of deterioration and intervention models for an effective use in practice. In particular, issues like the updating of old databases for compatibility with new software products are the limiting elements.

In summary, the agencies are willing to include a performance prediction module in their system, although this would require an expertise that is in some cases not yet available. In consequence, it also requires the service of external consultants and additional costs that must be accommodated in budget specifications and budget constraints.

6. Interventions

6.1. Intervention triggers

Infrastructure managers launch interventions (e.g. inspections, maintenance, repair and replacements) in order to keep their asset at a performance level that matches a given set of KPI's. These interventions may have different time horizons depending on their urgency, budgetary and/or network level considerations.

The first question was about intervention triggering. Almost all respondents mentioned that the main trigger for an intervention is the current condition state/rating of an asset. Only in second place (8 respondents) the theoretical condition, based on the damage process, is considered as an intervention trigger. This is probably because the damage process is explicit or implicit evaluated as part of the condition rating process and can give information on the urgency of the invention. It is highlighted that the respondents were not given a direct opportunity to choose financial resources as a trigger.

For 8 of the respondents, the time and thus the age of the asset was also stated as an intervention trigger. It can be concluded that interventions are launched due to a mix of triggers. Only one respondent reported that interventions would be executed based on the age of structure only. In this case, one or more interventions are defined independently of the condition using life cycle models.

The survey identified the following interventions:

- Element level – only some bridge elements will be maintained
- Structure level – for a better availability in the future, in most cases the whole asset will be maintained
- Multiple structure level (corridor interventions) – also for a better availability in the future, whole network sections (more than one structure) will be maintained

The idea behind this distinction is to show the different strategies on structure and network level. A multiple selection was allowed for this question.

About 80% of the respondents stated that the interventions would be related to the element level. Another approximately 65% said that the interventions would not only be related to the element level but also at the level of the asset itself.

However, 4 out of the 23 respondents informed that interventions are basically only implemented at the asset level. The idea is to maximize availability by implementing one large intervention rather than many smaller ones.

The network availability is considered by 8 out of the 23 respondents. The reduction of work sites is also a priority. This approach requires a very delicate comparison between the costs related to asset intervention and the costs due to network unavailability. Depending on the weighting of availability, different results can be expected. For example, interventions on elements that can be delayed involve additional long-term costs. However, if these costs are lower than the economic damage caused by disturbance of traffic, this intervention can still be beneficial.

6.2. Intervention strategies

An important step in the infrastructure management process is related to the identification of optimal intervention strategies. The interventions should be adopted minimizing some KPI's (e.g. cost, environmental impact) and maximizing others (e.g. availability, safety). In the last years, frameworks[1, 15, 17] to predict the intervention strategies, including inspections, monitoring, maintenance and/or repairs actions, for optimal management have been implemented and should be evaluated specifically for each asset. The developed approaches sometime integrate reliability or risk as well as life-cycle cost assessment - some even with multi-objective optimization techniques to determine optimum infrastructure, or infrastructure network, management plans to assist the decision-maker.

Optimization can be considered as an essential tool for providing optimal decision support in the management of infrastructure process[4]. All elements of this process (i.e. reliability, maintenance, condition, safety, structural health monitoring, inspection, cost, redundancy and robustness) interact and sometimes conflict. From all possible solutions, optimization should extract the best solutions that maintain the optimum compromises among these elements. For example, the role of optimization can be to identify the most effective retrofit strategy for aged bridges and the optimal times for retrofit actions. When performing optimization, the process needs to be transparent so that stakeholders understand the basis for budget allocation.

In this survey, 14 responses were available concerning the intervention strategies used by the respondents. In Table 1, a summary of the results about the intervention criteria is reported. The predefinition of a time horizon is used by almost all respondents. A relevant number of respondents are also evaluating life-cycle cost and/or performing risk analysis. One could argue that when the inspector formulates an intervention strategy as part of the inspection, the way of thinking is often somewhat similar to a risk analysis. 9 respondents use more than one criterion and 3 of these 9 respondents uses all three intervention criteria. 5 respondents report that they use some kind of optimisation process. Three respondents use only 1 criterion, being the definition of the time horizon in two cases and the life-cycle cost analysis in the other. In some countries, life-cycle costs analysis has been used for decades, where discounted maintenance costs over a certain time period are compared for different intervention strategies, e.g. the technical optimal strategy and a postponed strategy. Sometimes user-costs are monetized and included in the analysis.

The results of the questionnaire show the need to implement the intervention strategies based on optimization criteria in the management systems.

Table 1: Summary of intervention criteria.

Criteria	Responses	%
Time horizon predefined	10	71
Life-cycle costs	8	57
Risk analysis	8	57

6.3. Work programmes

Four different criteria were provided as the key drivers for the selection of the work programmes. These criteria were linked to the scheduled timeframe for the completion of the work (Predefined time period) and the allocation and types of work packages (Project packaging), while cost implications (Budget constraints) and the tools and techniques for optimization of the process (Optimization methods) were also considered. The main purpose of this part is to identify the most influential factors which should be taken into consideration for the development of work programmes as well as predictive models for the evaluation of the effectiveness of the examined strategies

17 responses were obtained concerning the criteria used to define the work programmes. Results are presented in **Error! Reference source not found.**. 5 respondents utilize at least 3 out of the 4 criteria, also 4 use 2 criteria at the same time and the rest (8) are only using the budget constraint, project packing or optimization methods to define the work programmes.

Table 2: Summary of criteria used to define the work programmes.

Criteria	Responses	%
Predefined time period	6	35
Project packaging	7	41
Budget constraint	15	88
Optimization methods	3	17

The results of Table 2 show that the most crucial parameters for the development of the work programs are the cost and the budget constraints which are the criteria included in nearly all the responses. The predefined time period and the project packaging are the next most important parameters (both roughly 40%).

In addition to these criteria, information was requested for the duration which is considered as ‘short time frame length’ for the development of the work programs. Also, an important parameter for the development of an improved decision-making process is the effective financial forecast and for this reason information about the ‘long time frame length’ for future budgets and development of management policies was also requested.

The short timeframe length for development of work programs ranges from 1 to 5 years, being 1 year in 57 % of the cases. The long timeframe length for prediction of future budgets and development of management policies varies from 1 to 50 years, being the most frequent the value of 5 and 10 years. It should be highlighted that the financial forecasting for the long-term budget predictions involves a high degree of uncertainty. Therefore, it is important to develop predictive models using appropriate tools and continuous updating forecast models where re-calibration of the models will be applied to consider recent data and the latest market conditions.

Conclusions and outlook

In this paper, IABSE TG 5.4 has performed an analysis of a survey on implemented decision-making models within owners/operators of infrastructure systems and bridges in particular. The main conclusions and outlook for the future are:

- The relative importance of different key performance indicators (KPI) is similar between the respondents with safety and reliability being the most important KPIs. This may promote standardization. Environment as a KPI is considered very important only for a few respondents. The orthogonal set of KPIs (reliability, availability, safety, economy, and environment) are not fully recognised as KPIs. Training as well as further research may stimulate this process.
- Infrastructure managers control the decision-making process for their structures. However, to a large extent external support is also used as basis. Some examples are structural assessments and cost estimates by public or private companies.
- Condition rating based on visual inspection and non-destructive testing is the most available method for structural assessment of existing structures.
- Limit state checks are overall considered to substantiate the decision-making process when condition rating indicates a poor condition state or inadequate performance of the asset. In that case, the level of complexity of the analysis may vary depending on its objective and adaptations may be made considering the assessment of existing structures.
- The respondents are willing to include a performance prediction module in the system, although this will require an expertise that in some owner/operator organisations is not yet available. In consequence, it also requires the service of external consultants and additional costs that must be accommodated in budget specifications and budget constraints.
- The results of the questionnaire show the need to implement the intervention strategies based on optimization criteria in the management systems. The respondents mention e.g. life cycle costs as an optimization criteria but other KPIs could be included.
- It should be highlighted that the financial forecasting for the long-term budget predictions involves a high degree of uncertainty. Therefore, it is important to develop predictive models using appropriate tools and rolling forecast models where re-calibration of the models will be applied to take into account recent data and the latest market conditions.
- Multi-attribute decision-making related to uncertain systems (based on KPIs) calls for a risk-based approach considering both probability of a failure mode whether structural, operational, or other and associated consequences. Risk assessment incorporating the climate change effects seems still premature in the practical management system.
- The decision-making process needs to be transparent, so that allocation of budget is understandable to all stakeholders. The decision-making process needs to be flexible, so that unstable budgets can be meet by change/update of strategies and assessment of possible impact. The decision-making process needs to be robust, so that application within owner/operator organisation is efficient and provide clear answers (unambiguous communication to various internal and external stakeholders). Decision-making varies between countries, between organisations and sometime also within organisations. Especially it may differ within an organisation dependent on the level, where decisions are made (from high level policy making to daily operation). Relating to decision-making models, it is evident that different sectors can learn from each other.
- There is a need for bridging the gap between implemented decision-making models and research models and methods.
- Data-driven asset management is high on the agenda within owner/operator organisations. This comprises application of BIM, Artificial Intelligence (AI) and other subjects. A transition from qualitative condition indicator towards quantitative or semi-quantitative data informed risk-based decision-making will be a natural next step for many owner/operator organisations. Researchers should play an important role, when identification and prioritisation of data collection is discussed by the industry. The concept of Value of Information[29-30] could be implemented but needs substantial refinement to be practice ready.

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