VISUAL INSPECTIONS AND KPIS – BRIDGING THE GAP

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ABSTRACT

The service quality of a bridge- measured by key performance indicators (KPIs) - is considered insufficient if they do not meet performance goals. Widely recognized KPIs are safety and serviceability. A bridge is regarded as structurally safe if the probability of failure during its service life is not expected to exceed some nominal value. Similar approach applies to serviceability.

Whereas in the design phase the safety and serviceability concerns are addressed directly in quantitative manner, in the service phase, based on inspection results the condition state is determined, which is a qualitative performance indicator. The condition state is actually a vague measure for the deviation of inspected bridge from the "as new" condition. The direct assessment of safety and serviceability is regarded as not practicable. In this paper, the approach to determine KPIs based on inspection results is proposed.

The KPIs are subject to observations obtained by visual examination and simple non-destructive testing. Typically, they are related to bridge components and indicate existing or expected bridge dysfunctionality that can result in insufficient KPIs. The challenge is to establish a procedure that connect observations with KPIs.

The papers suggest Bayesian networks to this end. The à priori values of KPIs i.e. the ones of the intact bridge are assessed as a baseline for the assessment during the service life. The à posteriori assessment of KPIs based on inspection results is performed using Bayesian networks that model observations and its uncertainties. The proposed approach is illustrated in a simple example.

Keywords: Key performance indicators, Bridge management, Visual inspections, Safety, Serviceability

INTRODUCTION

There is a broad consensus that the benefits of road infrastructure for the society cannot be overestimated. The investments in road infrastructure raise the growth potential of a national economy, which is realized by efficient utilization of the road infrastructure. The road infrastructure enables road users to be involved in various productive activities that yield private, public and social goods. Maintaining these benefits on the long run in economically efficient, environmentally responsible and socially reconcilable manner is the fundamental task of road authorities. **Bridges** are critical components of the road infrastructure as they ensure fast safe passages over otherwise hardly surmountable obstacles. From the users' perspective, it is irrelevant whether a road is carried by the bridge or being in tunnel or merely resting on the soil, so long it provides the safe and fast travel from origin to destination. In this context, it is necessary to define what is meant by fast and safe.

Key performance indicators and performance goals

There are standards that apply to the design of a road infrastructure, which **affect road users** and they are related to clearance, speed and weight allowance. The design travel speed defines the minimum travel time on an arbitrary road link. In reality, this minimum travel time can be achieved only in the case of unrestricted traffic flow i.e. if road capacity is sufficiently higher than traffic volume. Based on the real or predicted traffic one can choose some value of travel time – larger than minimum travel time - to define the "fast travel". This value can be regarded as **performance goal**.

The safe travel however is somewhat difficult to define since it doesn't imply the accident free traveling. There is always the basic accident rate, which is a function of traffic volume but not related to the condition or to the design of infrastructure. This accident rate defines the "safe travel" and can be regarded as **performance goal**. Correspondently, the measured or predicted travel time and the accident rate are performance indicators that are compared with performance goals. Both travel time and accident rate belong to **user related performance indicators**.

Additional standards are used in road design aim to protect general public and abutter from negative effect of road traffic. These include but are not limited to noise and pollution. These can be measured as well and comprise the **society related performance indicators**. For these indicators performance goals, can be also defined, but this is out of the scope of this paper.

In context of bridges the above-mentioned performance indicators are not used directly. Instead, as in bridge design, the primary concern is **safety** and **serviceability**. The safety includes both traffic or user safety as well as structural safety. A bridge is regarded as structurally safe if the probability of failure during its service life doesn't exceed some nominal value. Similar approach applies to serviceability in which the exceedance probability of some service limits has to be sufficiently low. In addition to it the bridge riding surface also fulfills the performance goals that apply for the pavement, one can regard that the bridge meets performance goals for road users i.e. sufficient quality of service. It appears that **serviceability** and **safety** can be chosen as adequate key performance indicators (KPI) for bridges.

In (1) performance "issues" are suggested that may be interpreted as performance indicators as represented in

FIGURE 1. Herein, the serviceability is combined with durability in performance issue "Structural Condition" whereas safety is combined with stability to form the performance issue "Structural Integrity". The performance issue "Costs" includes both agency and user costs. It should be noted that the user costs include delay, detour and accidents costs. Finally, the performance issue "Functionality" includes clearance, ride quality and load ratings and restriction on use.

The most indicators relevant to the bridge performance are included in (1), but the classification merits some further consideration. For instance, the structural integrity is related only to sudden events, mostly natural hazards such as earthquake, hurricane and fire. The observable deterioration processes, although they may compromise structural integrity affect only durability and serviceability. The “durability” seems to be understood as a span of time in which neither safety nor serviceability is likely to be compromised. The “costs” include also user costs that may be also included in “user safety” and “serviceability”.

FIGURE 1 Bridge performance according to (1)

The consideration of agency costs is clearly reasonable if the broader definition of performance applies. The bridge performance is considered better if the same safety and serviceability level can be achieved with lower costs. According to the narrower definition of performance only user and societal perspectives are considered. The agency costs are to be minimized for the given performance goals. Indeed, the agency goal to minimize its costs may be regarded as their optimizing performance goal.

Maintenance planning

It can be assumed that at the time of commissioning the bridge meets the performance goals. Based on the design data that can be both performance indicators e. g. material properties as well as other relevant data the KPIs for a bridge can be evaluated at the commissioning. This evaluation on virgin bridge, even if performed at some later point in time, is a reference information needed to evaluate KPIs at some later time instance. In course of time, the road infrastructure is subject to damage processes in addition to increasing traffic volume. Both damaging processes and increasing traffic volume can result in performance indicators that fail to meet performance goals. These performance indicators can be assessed based on observations obtained by visual examination, non-destructive testing or permanent monitoring systems. Typically, they are related to bridge components e.g. girders, abutments, cross beams and indicate existing or expected bridge dysfunctionality that may result in one or more insufficient performance indicators. At some point in time the safety and/or serviceability goals are not met anymore as presented in FIGURE 2.

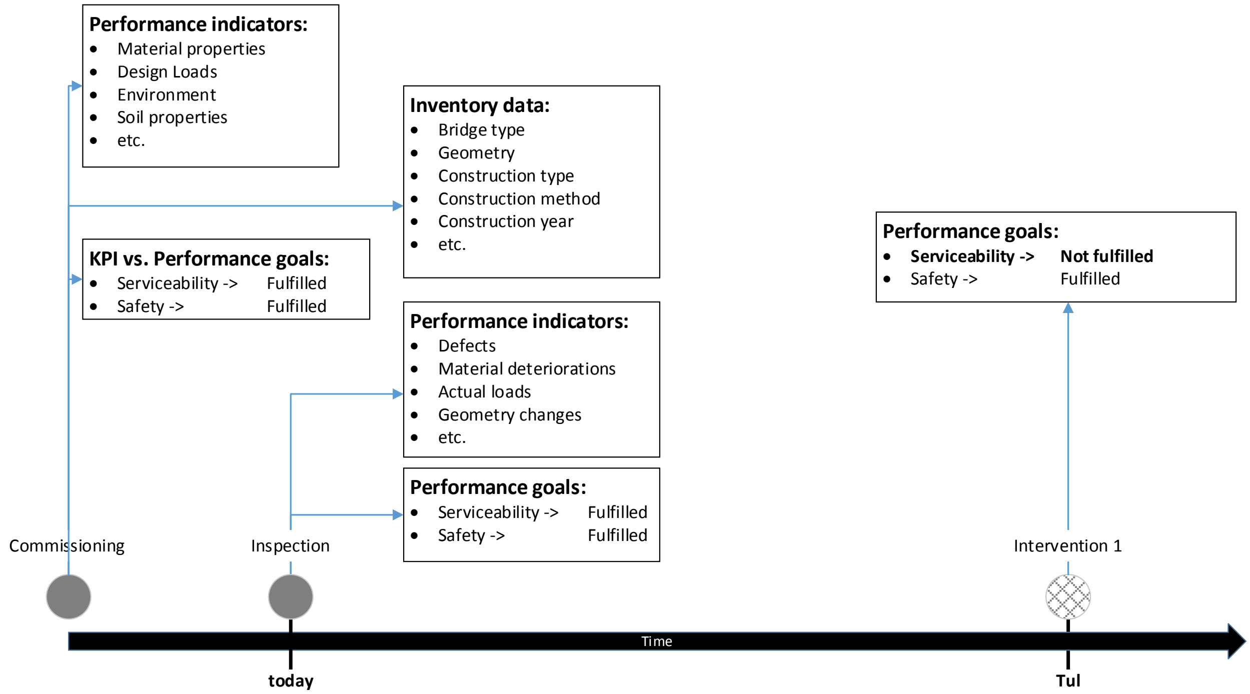

FIGURE 2 Road users' related performance over time - principle

It is assumed that an inspection is performed today as presented in FIGURE 2. The results from the inspection revealed some damages that in conjunction with the actual loads lead to worsening of the KPIs. They however, still meet the performance goals. Based on inspection results the serviceability and safety are forecast, yielding that serviceability criterion will be not fulfilled at the time instance marked "Tul". This means that the intervention needs to be executed at the latest at this point in time in order to comply with performance goals. It should be noted however that even bridges with no deterioration or dysfunctionalities may fail to meet performance goals. The reason for this can be found in an increase of traffic volume, the obsolete code of practice used for bridge design, new insights with regard to detailing, natural hazard, climate change etc.

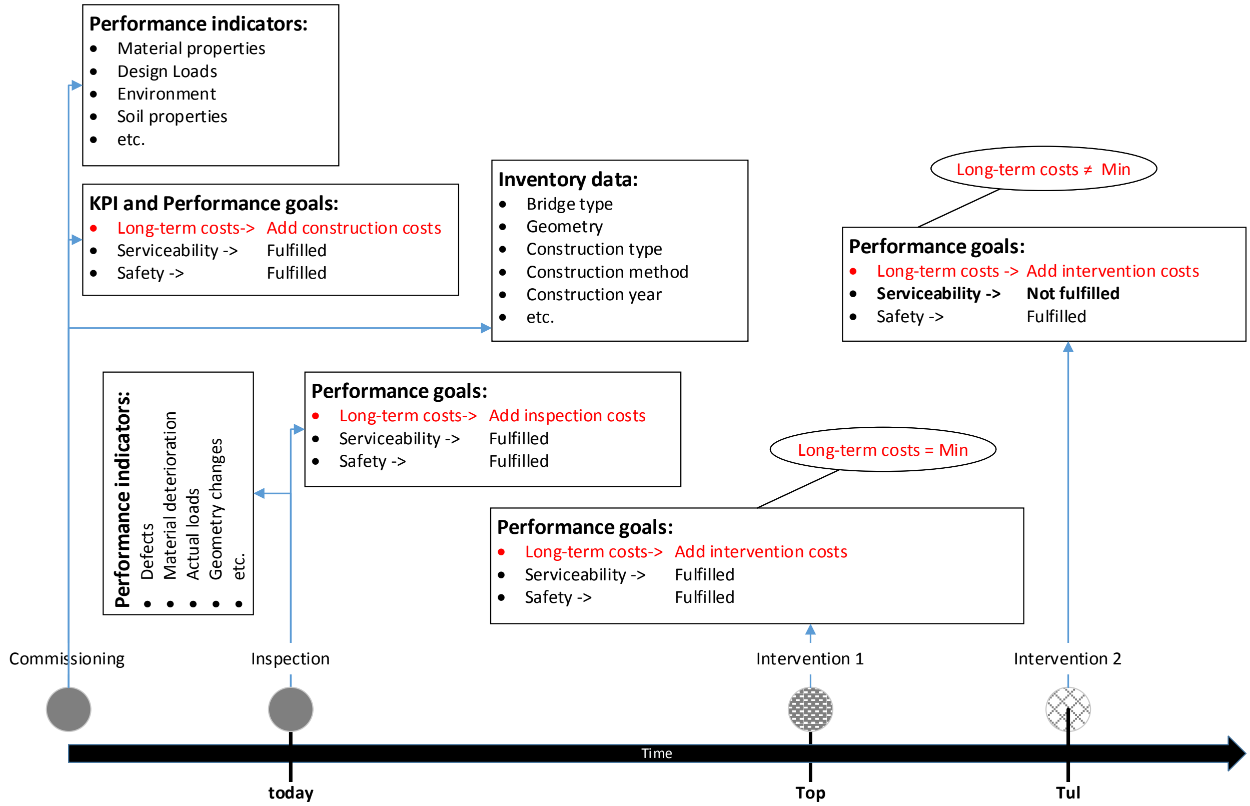

FIGURE 3 Road users' and owner's / operator's related performance over time

The owner's / operator's performance goal is to minimize his/her long-term costs. From owner perspective, the road users' performance goals can be regarded as optimization constraints. The general approach is presented in FIGURE 3. The intervention is planned prior to the instance in time at which road users' performance goals are not fulfilled i.e. "Tul". At the time instance "Top" the long-term costs are at their minimum and therefore the maintenance intervention should be planned at the time instance "Top". It is a matter of operator's methodology whether user cost should be added to agency costs in order to minimize them. In this case, the performance goal with regard to travel time and accidents costs should be revisited.

In principle, the same approach can be applied to societal and environmental performance goals. Depending on adopted modelling of related performance indicators these can be treated as optimizing or satisfying goals.

In practice, there is a serious obstacle to the approach presented above. Whereas in the design phase the primary concern is to meet safety and serviceability goals in quantitative manner, in the service phase condition state is determined, which is a qualitative performance indicator. The condition state is actually a vague measure for the deviation of a deteriorated bridge from the "as new" condition. The quantitative assessment of KPIs based on inspection results is regarded as not practicable. In this paper, the approach to determine performance indicators based on inspection results is shown.

GLIMPSE INTO THE FUTURE

It is foreseeable that in not so distant future Building Information Models (BIM) of both newly built and existing bridges will be available (see e.g. (2) and (3)). These models will be included into the Bridge Management System (BMS) and will significantly enhance the quantity of useful information in BMSs. A BIM can embed the structural system of the bridge as well as the relevant load cases. The evaluation of the KPIs would be therefore possible quasi on-the-fly within the BMS.

The inspection results can be directly captured in the BIM using photogrammetry or some other procedure. Cracks, spalling, deformation and other defects will be a part of BIM, which in most cases alter the BIM geometry.

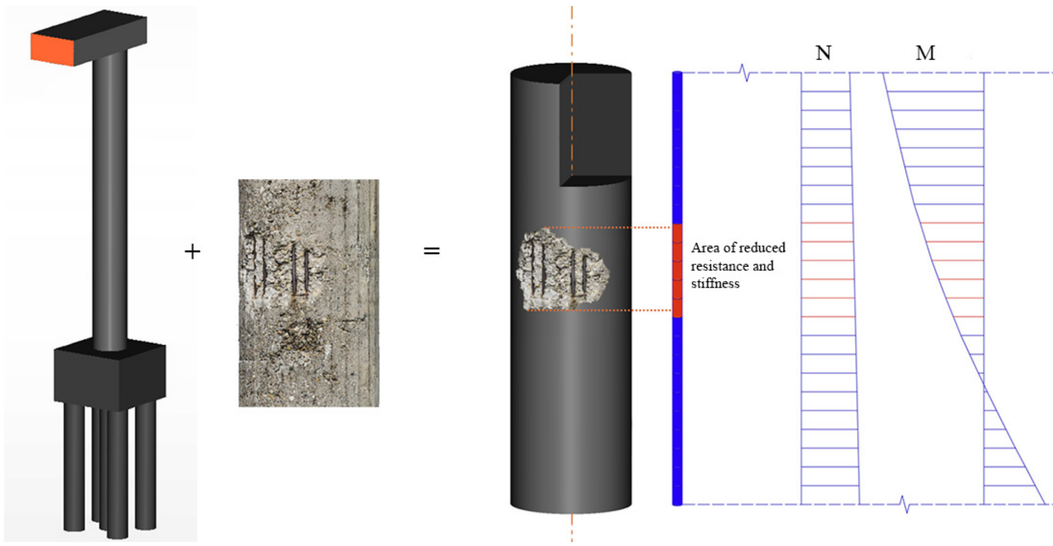

FIGURE 4 Integration of damage area into BIM

FIGURE 4 shows a column (far left) as a part of a BIM. On this column, a spalling area is observed (second from left). This spalling area is captured as 3D model and merged with the BIM of an intact column. The result is shown in FIGURE 4. The embedded structural system is also updated: The resistance of the column can be reduced due to spalling and the internal forces i.e. bending moment (M in FIGURE 4) and axial force (N in FIGURE 4) can be compared with the reduced resistance (e.g. interaction diagram). In this manner, the safety factor can be updated. Clearly, also the uncertainty of the material properties and spalling effect on resistance can be taken into account, so that the probability of failure can be determined.

The damaged BIM can be used as the basis for the deterioration simulation, which can provide significantly more accurate forecast that the current methods. The reasons for this are twofold:

- The resistance and loads i.e. probability of failure of an intact structure is duly taken into account.
- The exact location of a defect is known so that its effect on the safety and serviceability can be assessed in more accurate manner. A defect in a so called “hot area” i.e. highly stressed area would have a different impact on safety and serviceability.

Even if one has to wait for quite some time for the universal availability of BIMs, the above arguments can be seen as a guidance for the more advanced maintenance planning. In particular, data from original design can be used more extensively in bridge management. In this manner, the original weaknesses of the bygone design codes and design practices can be taken into account. Furthermore, apart from dividing bridges into their constitutive elements one can also identify “hot areas" i.e. areas in which damages can be particularly dangerous.

ENHANCEMENT TO CURRENT PRACTICE

The above reasoning can enhance both the qualitative and quantitative estimation of KPIs. The corresponding suggestion will be described in following chapters.

À priori assessment of KPIs

The safety and serviceability of an intact bridge under current traffic loading or some other action is the result of à priori assessment. This assessment can be – disregarding whether quantitative or qualitative - performed by means of Bayesian networks. The Bayesian networks for qualitative assessment of KPIs can differ from the one for quantitative assessment.

The Bayesian network for qualitative à priori assessment is presented in FIGURE 5. The effect of the construction year, type of structure (e.g. simply supported beams, continuous beam, frame, arch etc.) and code of practice used in the original design influence the resistance and serviceability limits based upon the experience and known deficiency related to the combination of these parameters. The actual traffic loads that are perhaps more aggressive, are also captured and conveyed into a load effect. The basis for the computation of load effects is a structural system i.e. the type of structure. The result is a safety and serviceability rating that is in a general stochastic variable. Clearly, it can be transformed in a single value by taking the expected value of its dis-tribution.

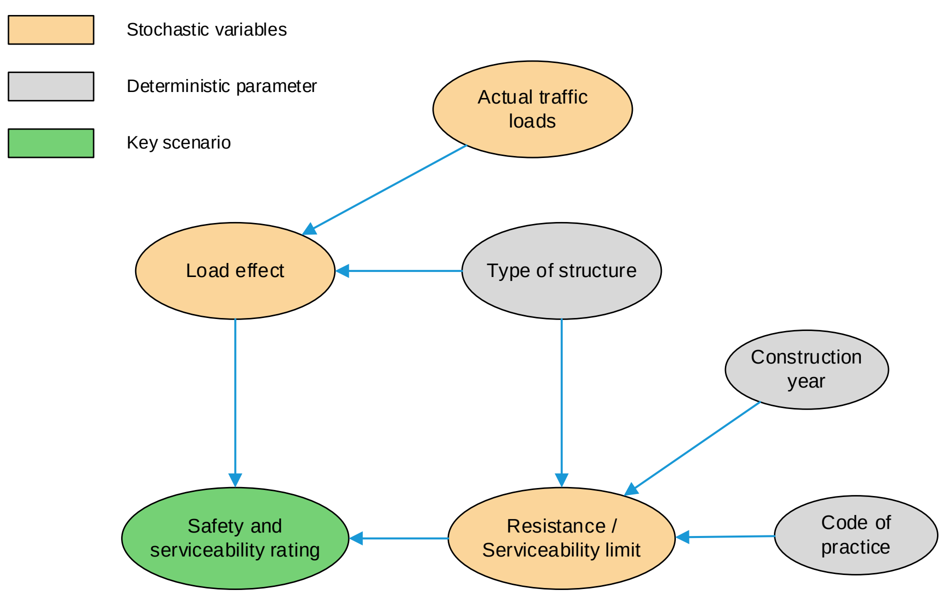

FIGURE 5 Simplified Bayesian network for qualitative KPI assessment

For practical purposes this diagram has to be enriched with additional information on elements, construction flaws, etc. The safety and serviceability rating is qualitative and can be chosen based on the existing scale of condition states.

In the quantitative approach one has also to include a structural system. The structural system can be simplified following the basic rules for preliminary design of bridges. For instance, for vertical loads the majority of "normal" bridges can be sufficiently well modelled with simply supported beams if the spans and the effective width are chosen properly. In (4) the possible simplification, albeit in a different context is explained in detail. Bayesian network for quantitative à priori assessment is presented in FIGURE 6. The simplified structural system is assumed to comprise a series of simply supported beams. The resistance and the serviceability limits can be approximated by the load effect of the original design code on simplified structural system. The construction year can reveal some inherent weaknesses of original design or the deficiency in the code of practice. The ratio of permanent to traffic load is necessary to correctly estimate the probability of failure or probability of exceeding the serviceability limit.

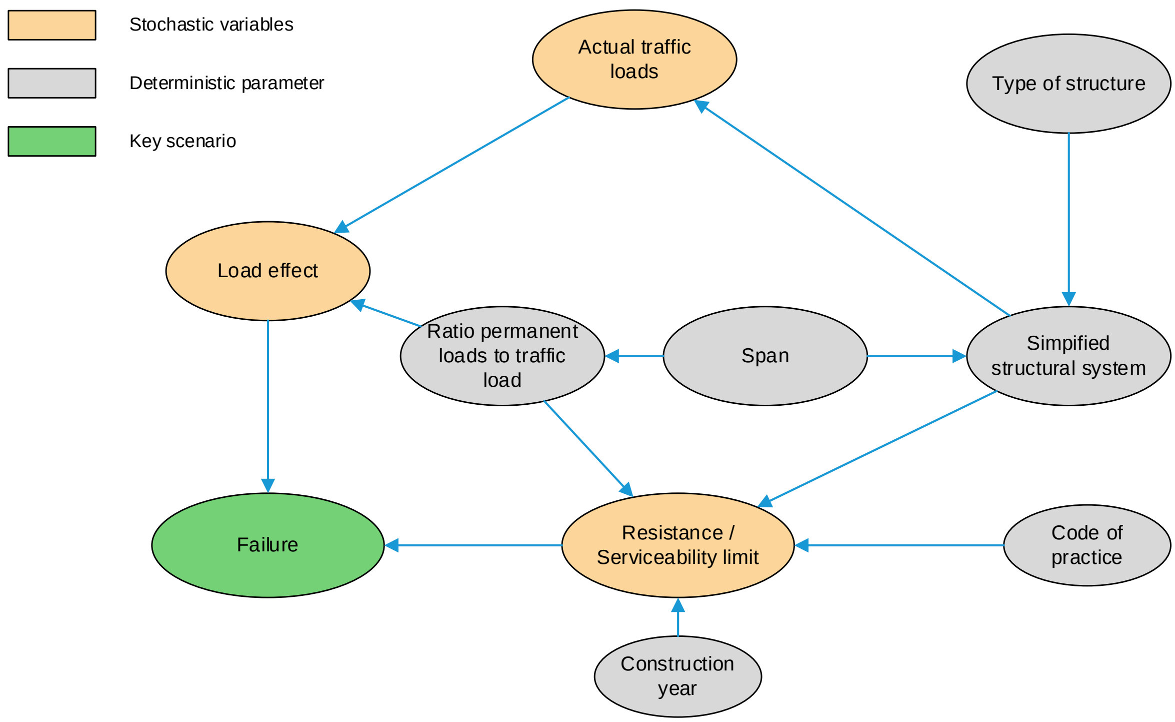

FIGURE 6 Example of a Bayesian network for quantitative KPI assessment

In order to illustrate the presented approach, the safety of an existing bridge that is modeled as simply supported beam (node “Simplified structural system” in FIGURE 6) is assessed. It is assumed that the safety is given if the probability of failure doesn’t exceed $5.0 \cdot 10^{-4}$.

The simply supported beam is presented in FIGURE 6 and the traffic load (node “Actual traffic load” in FIGURE 6) is modelled as a normally distributed point load with a mean value of *100kN* and standard deviation of *15kN*. Permanent loads are neglected in this example. It is assumed that the bending resistance (node “Resistance” in FIGURE 6) is constant along the beam and is normally distributed with a mean value of *500kNm* and standard deviation of *50kNm*. The span (node “Span” in FIGURE 6) is *10m*.

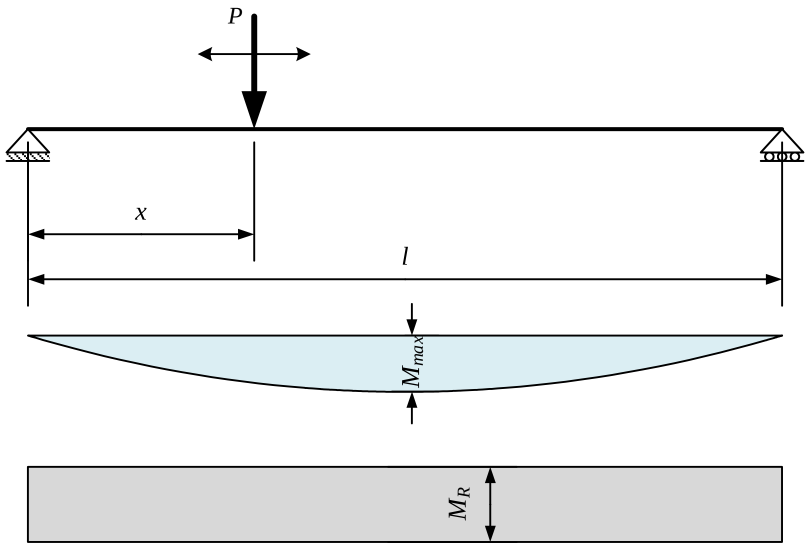

FIGURE 7 Simplified structural system and traffic loading

Due to the fact that both load effect and resistance are normally distributed, the safety index, which means also the probability of failure can be computed as follows:

$$\beta = \frac{\mu_{M_R} - \dfrac{\mu_P \cdot l}{4}}{\sqrt{\sigma_{M_R}^2 + \left(\dfrac{\sigma_P \cdot l}{4}\right)^2}} = \frac{500 - 250}{\sqrt{50^2 + \left(\dfrac{150}{4}\right)^2}} = \frac{250}{50 \cdot \sqrt{\dfrac{25}{16}}} = \frac{1000}{250} = 4.0 \tag{1}$$

$$P_f = 3.17 \cdot 10^{-5}$$

According to this assessment the virgin bridge meets the safety criteria.

À posteriori assessment of KPIs

The à posteriori assessment of KPIs is performed after an inspection or a detail investigations. The à priori values, either qualitative of quantitative are updated based on the observations and the actual traffic load. Similar to à priori assessment, the Bayesian networks for qualitative, à posteriori assessment can differ from the one for quantitative assessment.

Visual inspections are considered to be subjective and uncertain allowing only qualitative outcome such as condition rating. The connection to KPIs is therefore lost and it is sometimes reestablished after a detailed investigation and/or structural re-analysis. Although it is undeniable that observations made during visual inspection are often fuzzy, they can be useful if their inherent uncertainty is properly modeled. The observation “Reinforcement corrosion” is indeed not very informative and this fact has to be modeled adequately. The reinforcement corrosion can be anywhere on the bridge or its elements i.e. it has to be uniformly distributed. Likewise, a spalling area and a section loss can also be modeled with non-informative or slightly informative distributions. If, however additional information is available such as that the reinforcement corrosion is located in highly stressed i.e. “hot” areas, the uncertainty with regard to its influence on KPIs can be significantly reduced. The spalling area and section loss can further reduce uncertainty. This reasoning applies both for qualitative as well as quantitative assessment of KPIs.

The Bayesian network for qualitative à posteriori assessment is presented in FIGURE 8. The node “Load effect” is taken over from the à priori assessment. The force reduction in post-tensioning, the reinforcement corrosion in the hot area of superstructure and the dysfunctionality of bearings is observed during an inspection. These observations influence the resistance and serviceability limit resulting in updating of the safety and serviceability rating evaluated in à priori assessment. The observations can also include forecast and to this end the parameter “Time” is included in Bayesian network. The forecast can be deterministic or stochastic using e.g. Markov chains.

The observations can be uncertain as well: For instance, the reliability of the force measurement is often far from ideal, so that some false positives or some false negatives may occur. This can be also modeled with likelihood functions.

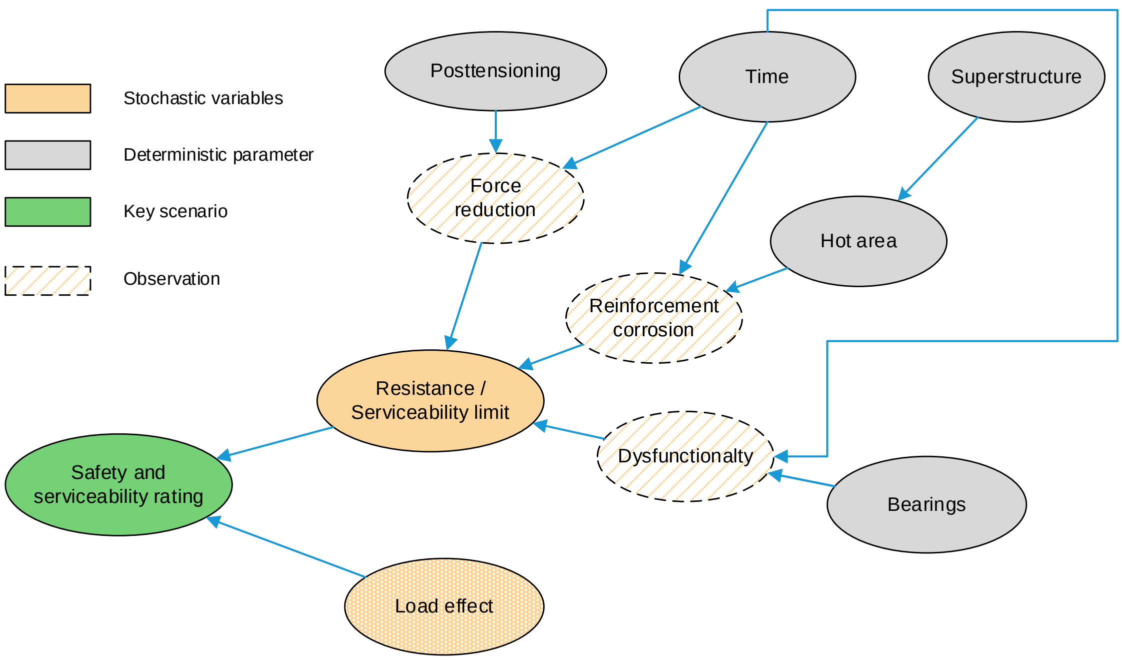

FIGURE 8 Simplified Bayesian network for qualitative à posteriori assessment of KPIs

Bayesian network for quantitative à posteriori assessment is presented in FIGURE 9. The only difference to the Bayesian network for qualitative à posteriori assessment is the replacement of the node “Hot areas” with the node “Location”. Furthermore, the joint distributions of the nodes in FIGURE 9 are not discrete but continuous and therefore quantitative. This also means that some observations e.g. dysfunctionality of bearings have to be transformed into quantitative distribution, which is indeed tedious and require expert knowledge.

If the location of the reinforcement corrosion is not known then one has to assume non-informative distribution of location variable over the whole superstructure.

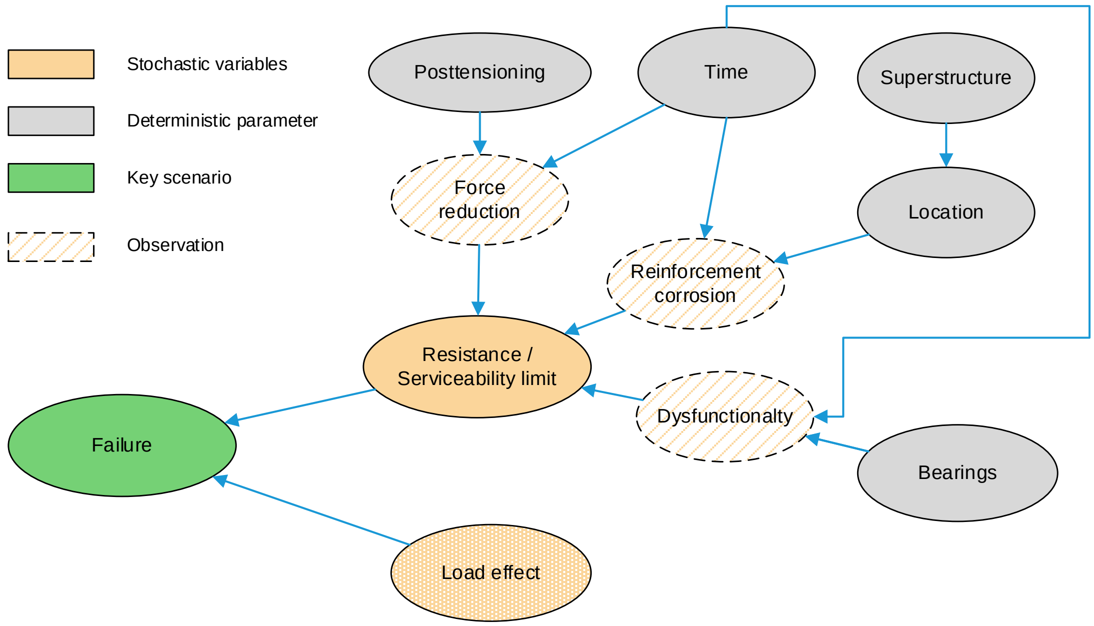

FIGURE 9 Example of a Bayesian network for quantitative à posteriori assessment of KPIs

In order to illustrate the à posteriori assessment of KPIs, the same example as for the à priori assessment is analyzed. The visual inspection revealed a spalling area with the reinforcement corrosion (node “Reinforcement corrosion” in FIGURE 9) with a section loss of 10%. This is a typical entry in numerous BMSs, in which defects are classified in so called knowledge catalogues. The location of the defect is not known and there is inherent uncertainty with regard to section loss. The experience has shown the likelihood of section loss can be expressed as in TABLE 1.

TABLE 1 Likelihood of indicating specific section loss

Section loss	5%	10%	15%	20%
Probability	60%	20%	10%	10%

In the first step one has to evaluate the safety index for the deterministic section loss with no information on its location. This means the safety index has to be computed for every possible location of a corroded reinforcement. The location of the corroded reinforcement is given with the distance *y*, as in FIGURE 10.

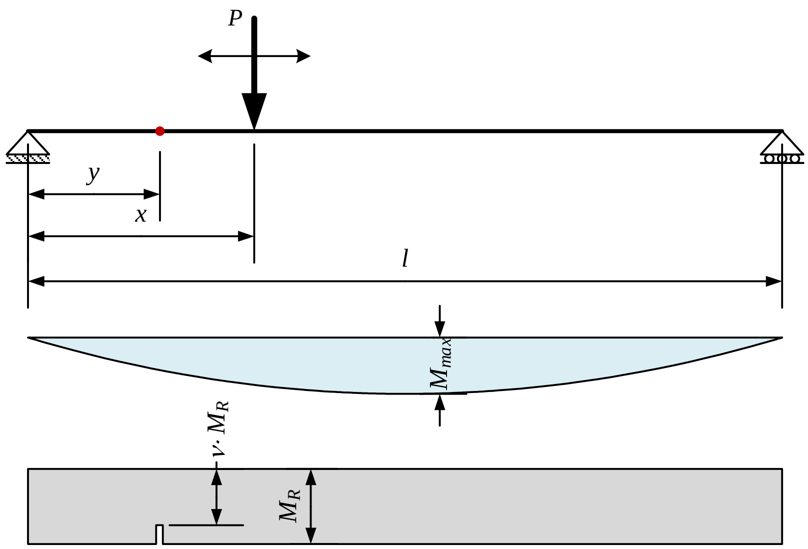

FIGURE 10 Resistance of the damaged structural system

The safety index cannot be larger than the one obtained in à priori assessment. It can be however lower if the section loss is in the area of high bending moments. This reasoning result in following expression for safety index.

$$\beta = Min\left(\frac{\nu \cdot \mu_{M_R} - \mu_P \cdot \xi \cdot (1-\xi) \cdot l}{\sqrt{\sigma_{M_R}^2 + \left(\sigma_P \cdot \xi \cdot (1-\xi) \cdot l\right)^2}}, 4\right) \tag{2}$$

$$P_f = \Phi(-\beta)$$

The safety index can be plotted as a function of location of corroded reinforcement. It can be seen in FIGURE 11 that for certain locations, the section loss has no influence on safety index. In the middle part, there is however a clear reduction of safety index indicating a “hot area”.

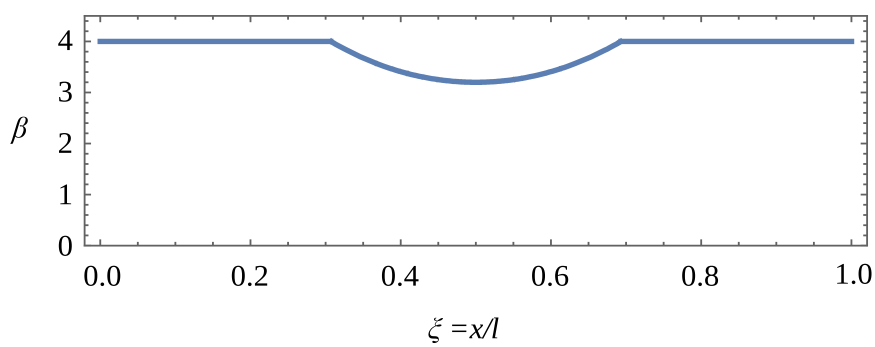

FIGURE 11 Safety index in function damage location

Assuming that there is an equal probability of corroded reinforcement being anywhere on the beam one has to integrate the probability of failure for all locations as in following expression:

$$P_f = \int_0^1 \Phi\left(-Min\left(\frac{\nu \cdot \mu_{M_R} - \mu_P \cdot \xi \cdot (1-\xi)\cdot l}{\sqrt{\sigma_{M_R}^2 + \left(\sigma_P \cdot \xi \cdot (1-\xi)\cdot l\right)^2}}, 4\right)\right)\cdot d\xi$$

$$= \int_0^1 \Phi\left(-Min\left(\frac{0.9 \cdot \mu_{M_R} - 100 \cdot \xi \cdot (1-\xi)\cdot 10}{\sqrt{20^2 + \left(15 \cdot \xi \cdot (1-\xi)\cdot 10\right)^2}}, 4\right)\right)\cdot d\xi = 15.69 \cdot 10^{-5} \tag{3}$$

$$\beta = -\Phi^{-1}\left(P_f\right) = 3.6$$

The probability of failure increased fivefold although the location of the crack is still not considered. In the second step the uncertainty of the observation can be also considered. Considering the likelihood values from TABLE 1 the probability of failure can be computed as follows:

$$\begin{aligned} P_f &= 0.6 \cdot \int_0^1 \Phi\left(-Min\left(\frac{0.95 \cdot \mu_{M_R} - 100 \cdot \xi \cdot (1-\xi)\cdot 10}{\sqrt{20^2 + \left(15 \cdot \xi \cdot (1-\xi)\cdot 10\right)^2}}, 4\right)\right)\cdot d\xi + \\ &+ 0.2 \cdot \int_0^1 \Phi\left(-Min\left(\frac{0.9 \cdot \mu_{M_R} - 100 \cdot \xi \cdot (1-\xi)\cdot 10}{\sqrt{20^2 + \left(15 \cdot \xi \cdot (1-\xi)\cdot 10\right)^2}}, 4\right)\right)\cdot d\xi + \\ &+ 0.1 \cdot \int_0^1 \Phi\left(-Min\left(\frac{0.85 \cdot \mu_{M_R} - 100 \cdot \xi \cdot (1-\xi)\cdot 10}{\sqrt{20^2 + \left(15 \cdot \xi \cdot (1-\xi)\cdot 10\right)^2}}, 4\right)\right)\cdot d\xi + \\ &+ 0.1 \cdot \int_0^1 \Phi\left(-Min\left(\frac{0.8 \cdot \mu_{M_R} - 100 \cdot \xi \cdot (1-\xi)\cdot 10}{\sqrt{20^2 + \left(15 \cdot \xi \cdot (1-\xi)\cdot 10\right)^2}}, 4\right)\right)\cdot d\xi \\ &= 0.6 \cdot 5.134 \cdot 10^{-5} + 0.2 \cdot 15.69 \cdot 10^{-5} + 0.1 \cdot 56.62 \cdot 10^{-5} + 0.1 \cdot 190.55 \cdot 10^{-5} = 30.94 \cdot 10^{-5} \end{aligned} \tag{4}$$

The probability of failure is doubled again and the safety index β dropped to 3.42. This means that the safety is not given any more as the probability of failure exceeds $5.0 \cdot 10^{-4}$.

CONCLUSIONS

In this paper, an approach is proposed to include results of visual inspections, which are oft fuzzy, into assessment of key performance indicators for bridges i.e. safety and serviceability. It makes extensive use of information from design phase, which needs to be merely updated based upon the results of visual inspections. The approach closes a gap characteristic for todays practice, in which different performance indicators are used during the service life of a bridge.

The proposed approach relies heavily on Bayesian networks that can yield both qualitative and quantitative results. The qualitative approach seems to be the next logical step given the current inspection practice worldwide. To this end the Bayesian networks has to be adapted to accommodate relevant types of observations that are common in different countries. In a further steps the quantitative approach can be gradually adopted, perhaps together with the introduction of BIM.

Finally, it should be noted that the visual appearance of a bridge is not addressed in this paper, although it may play important role in decision-making process. Spalling concrete, dripping joints and corrosion traces are not very appealing and the owner or operator is inclined to remedy them in order to protect its reputation. The commonly used condition rating is often strongly influenced by visual appearance and in fact it can be used to evaluate it. A decent visual appearance can therefore be regarded as a performance goal as well. It's up to an owner or operator and the social environment to set up criteria for the decent visual appearance.

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