The Indicator Readiness Level for the classification of Research Performance Indicators for road bridges

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ABSTRACT: National road owners are required to monitor the condition and performance of infrastructure elements through an effective inspection and assessment regime as part of an overall asset management strategy. Performance Indicators are parameters used to characterize the present and future structural conditions accounting for the goals specified by the codes, the owners or the operators. In Europe there is a large disparity regarding the way these parameters are quantified and the goals specified. In this context, COST action TU 1406 aims at providing quality specifications for roadway bridges standardized at a European level. In particular, one goal is to investigate the practical implementation of innovative condition assessment. In particular, this COST action collected the input from 36 countries in Europe, based on research-based performance indicators related to bridge maintenance, assessment and management. This paper introduces an Indicator Readiness Level (IRL) framework to rank the maturity level of those performance indicators at the research stage. In this paper the first results of the application of the IRL to the performance indicators collected in the context of the COST Action are reported

1 INTRODUCTION

Most of the roadway bridges, built prior to adoption of modern principles of sustainable planning and seismic design, are today at the end of their design lifetime. The volume and loading of the heavy freight vehicles that they are carrying today is considerably larger than anticipated at the time of their construction. In most cases, these bridges are structurally deficient and degraded due to the aging effects and/or inadequate maintenance, and as such require reliable assessment of their safety to seismic and increased operational loads before deciding on their optimal management. Efficient maintenance of the infrastructure is a process that exerts great economic pressure on their owners and managers. In deciding on further remedial or rehabilitation measures, it is therefore necessary to look for solutions that follow the concept of intelligent maintenance so that interventions or maintenance actions are optimally scheduled along the life cycle of the structure. In Europe there is a large disparity regarding the way performance indicators are quantified and goals specified. In the realm of the networking project COST action TU1406 research-based performance indicators related to bridge maintenance, assessment and management have been collected from 36 countries in Europe. At the time the survey has been limited to indicators related to safety, serviceability and reliability. In the further development of the project it will be extended to other performance indicators related to the effects of climate change, natural hazards, sustainability and resilience.

Differently form the operational performance indicators that are already used in quality checks of bridges, the research performance indicators (RPIs) can be at different levels of maturity and need still investigations to be ready for practical applications. In order to quantify the level of maturity of RPIs, in reference (Limongelli und Orcesi 2017) was introduced a scale to measure their level of maturity

This scale is meant to serve as a supporting tool for a twofold aim:

1) to check the eligibility of a performance indicator for quality check and related decision making on roadway bridges based on its maturity.
2) to select research needs on performance indicators that is to underpin the indicators on which more research is needed in order to bring them to the level of full applicability for quality checks.

Performance Indicators related to safety and serviceability are computed based on the available knowledge on the structural state. This knowledge is collected in the form of performance Parameters (measures or observations) that can b e directly used to compute the Performance Indicators or used to calibrate a model that can then be employed for the computation of Performance Indicators.

In this paper, after a description of the methods for collecting the performance parameters and a definition of different types of performance Indicators, the IRL scale will be briefly described. Some examples of its application to parameters related to corrosion conclude the paper.

1.1 *Inspection and monitoring: collection of Performance parameters (PPs)*

Performance Parameters (PP) may be defined as information (measure or expert opinion) collected using visual inspections, off-site tests on materials (Destructive Tests), on-site investigation using the Non Destructive Tests (NDT), or Structural Health Monitoring systems (SHM). These parameters support the procedures for bridge assessment and their collection should be in line with the pre-defined Key Performance Indicators KPIs. An obvious bottleneck in bridge assessment lies in the treatment of qualitative information retrieved usually through periodical visual inspections, which strongly rely on expert subjective opinion for assessment of structural condition. An objective assessment ought to be instead put in place, which in turn heavily relies on the availability, ease of implementation and resolution of monitoring and inspection methods.

Current inspection procedures adopted in Europe for collecting structural information may be classified into four main categories, at an increasing level of accuracy in the quantification of the Performance Parameters, along with an accompanying increase in costs:

- Visual inspections
- Destructive Testing
- Non Destructive Testing
- Structural Health Monitoring techniques

1.1.1 *Visual inspections*

Visual inspection forms the “de-facto” tool of structural assessment in both Europe and the rest of the world. For many European countries, no official procedure is offered for bridge condition assessment, while no official regulations are further established on the inspections needed for the collection of performance parameters. European Bridge condition assessment is for the most part traditionally based on a rating system, specifying a certain number of condition levels corresponding to different levels of degradation, usually from 0 (no damage) to the maximum level. The latter corresponds to defects that may jeopardize safety and thus require immediate intervention and limitation or shutdown of traffic. The rating is assigned based on the results of visual inspections, which are regularly carried out by technicians, with the goal to detect local damage parameters mainly related to cracks, concrete spalling or loss, delamination, steel corrosion. Based on the extent of such damages a rating is assigned on the basis of the afore-mentioned scale. The shortcomings related to the information retrieved from visual inspection may be mainly summarized as:

- They form local information related to the single structural section or structural element not allowing the condition rating of the structure as a whole;
- They are more often qualitative and not quantitative information, leaving room for subjective interpretations of experienced bridge engineers, rather than leading to objective evaluation of the structural conditions.

1.1.2 *Destructive Testing (DT)*

Destructive testing carried out by extracting samples from the structure, and follow-up laboratory tests, renders quantitative information on material parameters (e.g. strength of materials and /or elastic modulus) and structural integrity (corrosion ingress). The drawback is the invasive character of these type of tests and the local character of the information they provide, which depends on the location of the sample used for the laboratory test.

1.1.3 *Non-destructive Testing (NDT)*

NDT methods aim in providing information on structural condition, without harming the structure itself, i.e., in a non-invasive manner since they do not require samples of material taken from the structure. A wide variety of non-destructive technologies are available for bridge structure such as Ground Penetrating Radar, Acoustic emission, Thermographic methods, Magnetic flux leakage and may provide local information on the conditions of both individual structural elements (e.g. rebar, post-tensioning) and on non-structural elements (such as location of voids, pipes, pavement thickness). Detection of zones with increased chloride contents and moisture is also possible and provides a warning on deterioration through corrosion. This list is not exhaustive and the interested reader is referred to the work of (Ayswarya, et al. 2016) for further information. NDTs offer a more rigorous quantitative characterization of the structure with respect to visual inspections. Their shortcoming is related to the local character of the information they provide that requires expensive testing campaigns in order to achieve a global description of the structure. In addition, static proof loading tests using loaded trucks may be considered a particular family of NDTs and constitute one of the standard means of structural testing for determining structural capacity. Shortcomings of these tests are related to the prohibitive costs, limitations related to the maximum size of truck, the maximum load these are allowed to carry, the rather long interval within which the operation of the bridge needs to be suspended, and more.

1.1.4 *Structural Health Monitoring (SHM)*

The state-of-the-art in retrieving performance parameters relies on use of monitoring systems, namely sensor network deployed on the structure, able to record the structural response to operational loads, ambient vibrations or seismic excitations. This may be applied in the static or dynamic sense, allowing assessing or characterizing the system using inverse or system identification techniques. The great advantage with respect to the previous technique is that they allow computing global performance parameters, thus rendering an objective evaluation of the structural condition of the bridge as a whole.

The use of monitoring systems for bridge structures is lately becoming more and more established (Wenzel 2009). The implementation of such systems can be classified in two main categories depending on the duration of the instrumentation, which may vary from short term (typically up to few days) or mid-term (few days to few weeks), to long term (few months to few years), and perhaps throughout the lifespan of the structure (Glisic, Posenato und Inaudi 2007). A noteworthy example of short term monitoring for condition assessment and immediate decision making processes is the non-destructive dynamic field testing (from vibration response data) conducted in three Cincinnati bridges for the rating of those specimens (Aktan, et al. 1994). The testing methods utilized in that case included impact tests as well as proof-load level truck-load tests.

A main issue in damage identification and condition assessment through monitoring data is the fact that environmental effects also play a major role in the properties of the system. In this sense, long-term monitoring (from cradle-to-grave) is advisable for continually tracking the evolution of the system's properties under environmental, operational and deterioration effects. Long-term monitoring systems have already been implemented on a number of bridges in Europe (Casciati 2003) the United States (Pines und Aktan 2002) and elsewhere. An example of a state-of-the-art implementation is the long term monitoring system deployed on the Tsing Ma bridge in Hong Kong (Chung, et al. 2003), involving a network of more than 350 sensor channels including GPS and Fiber Bragg Grating (FBG) sensors. A further pioneering monitoring initiative is the one initiated by the Californian Department of Transportation (Caltrans 2006) and the California Strong Motion Instrumentation Program (CSMIP) for instrumenting Caltrans bridges throughout the state, recording their response during earthquakes. This data is assimilated with a larger data stream from further infrastructure components, for identifying the areas of greatest potential damage for use by the Office of Emergency Services and other emergency response personnel in the event of a damaging earthquake. Although still relatively rare, such schemes are becoming more and more available. As the necessary technology becomes increasingly cheaper and software systems become more and more spread, such schemes are envisioned as the future of monitoring, eventually to be required by code to accompany traditional assessment methods such as visual inspection.

2 PERFORMANCE ASSESSMENT

The Performance Indicators are quantities aimed to synthetically represent the condition of the structure based on the available knowledge. The process that goes from knowledge to information useful for decision making is represented in

Figure 2.1. Knowledge comes from measures and observations retrieved from monitoring systems, testing and visual inspections. This knowledge is represented by the values of the so-called performance parameters. In order to transform this knowledge in information for decision making there are two steps that need to be taken namely the definition of the performance indicators and the definition of the performance goals. Herein the focus is on the definition of the Performance Indicators and on the proposal of a metric to rate the maturity level of Indicators that are still at the research stage (Research performance Indicators).

2.1 *From Performance Parameters (PPs) to Performance Indicators (PIs)*

The knowledge (Performance Parameters) stemming from monitoring, testing and inspections may be exploited in two major ways:

1. For direct computation of the Performance Indicators and check of performance goals (thresholds), where this is feasible (e.g. crack length, load/strain thresholds). Performance Indicators are computed as variation of the Performance Parameters with respect to a reference state. For example in the case of crack length or width the reference value is zero so the values of the Performance Parameter and of the Performance Indicator coincide. A different example is that of modal parameters retrieved form the response to vibration. Their variation with respect to the undamaged condition – which is the performance Indicator - gives an indication about the existence of a damage state in the structure. More refined Indicators can even give information about the location of damage in a structure (Limongelli, 2010). In this case we talk about Diagnostic Performance Indicators able to describe the changes

in the state of the system with respect to a reference state (e.g. intact structure)

2. For the updating and calibration of structural or analytical models of the structural behaviour in order to obtain a proxy of the true structure to use for the computation of different performance indicators. This is the case for example of modal parameters (frequencies, damping factors and modal shapes) retrieved from dynamic tests or continuous monitoring systems, which are often used to calibrate and update structural models. These calibrated models can then be used to compute for example displacements to compare with limit values. In this sense the model is used to obtain Diagnostic Performance Indicators. Furthermore if the models are able to simulate the future behaviour of the structure (i.e. both the future actions and the evolution of the structural parameters) the values of Prognostic Performance Indicators can be also obtained. For example using a Markov chain - fitted to data collected on the structure - to model the future degradation of some structural parameters, a prediction of the inspection score can be obtained (see Orcesi et al, 2011).

A flowchart for the definition and computation of different types of Performance Indicators is reported in Figure 2.1

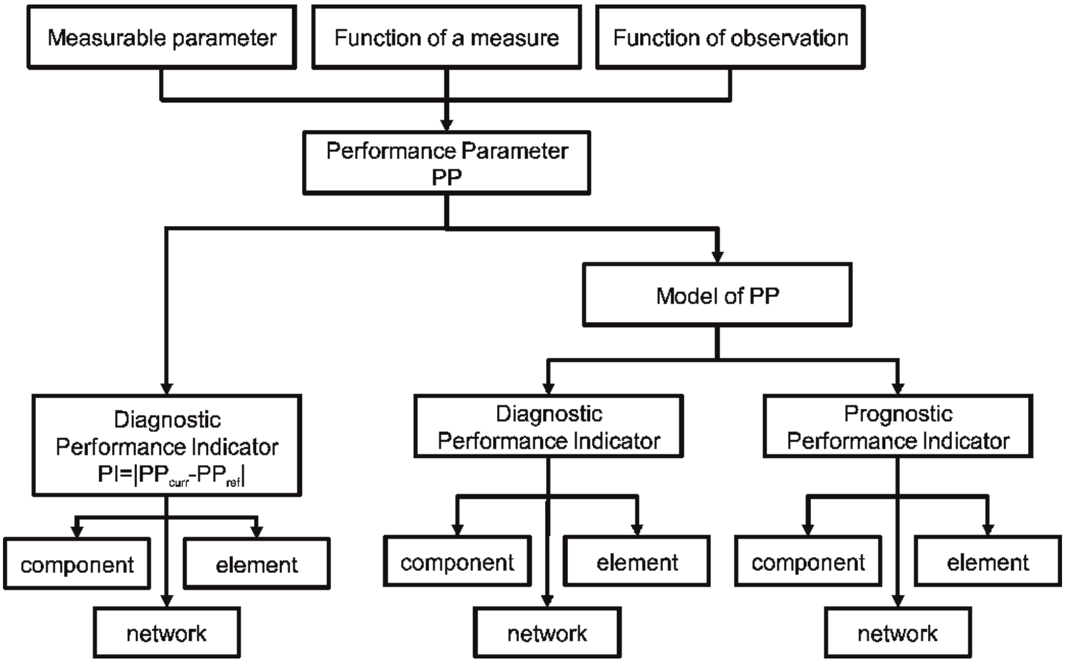

Figure 2.1 Definition and computation of Performance Indicators

2.2 *From Component PIs to Element PIs*

When the PIs need to be computed at the element level (one bridge), the importance of each component of the bridge (beams, piers, abutments, ecc.) for the bridge functionality should be properly taken into account (COST TU1406 2016). Based on the computational approach used, the methods for developing element PIs from component PIs can be grouped into the following four approaches (Chase, et al. 2016):

- The weighted averaging approach, which estimates the condition of the whole structure by combining condition ratings of all individual bridge elements weighted by their significance or contribution to the structural integrity of the bridge. This approach is common in systems that rely on element-level inspection data. Bride Condition Index (BCI) used in Australia (BCN), the United Kingdom (BCI), South Africa (BCI), and Austria (BCI)
- In the worst-conditioned component approach the BCI is approximated to the condition index of the component in the worst condition. The German and Japanese BCIs are the examples of this approach that is common in systems that carry out inspections on key bridge components.
- Qualitative methods do not report the condition of the bridge on a numerical scale. They describe a structure as either “Poor,” “Fair,” or “Good,” based on the condition and importance of the elements under investigation. In the United States, Washington, Florida, and other States use this type of methods.
- Ratio-based methods assign a BCI or bridge condition number (BCN) based on the ratio of the PPs in the current condition with respect to the value of the same PP measured in the structure when it was first built.

2.3 *From Element PIs to Network PIs*

In order to comply with safety requirements, each element (bridge) of the network has to be assessed according to codes enforced in the different European countries, or at the European level (Eurocodes), in accordance to prescribed standards and guidelines. However, for safety and reliability assessment a competing requirement exists between codes on one side, requiring the structure to be safe under design actions, and the limited resources on the other side. Owners and concessionaries in charge of bridge maintenance are thus led to establish a hierarchy of interventions, accounting for the importance of the bridge in the network in order to prioritize investments. In this respect, it is of strategic importance to define Performance Indicators at the network level that can guide both the choice between maintenance options for bridges that do not comply with Code safety requirements, as well as the prioritization of interventions in bridges of the network. Therefore, the network Performance Indicators are usually linked to costs related to the maintenance activity, indirect costs caused by maintenance activities and borne by the society, such as user delay (availability) and environmental impacts and not least aspects related to Traffic safety (COST TU1406 2017).

3 RESEARCH PERFORMANCE INDICATORS

A number of Performance Indicators have been proposed and their potentialities are currently being studied by researchers. By definition these indicators are not Operational that is they are not yes used for quality checks of bridges. This may depend by several issues that the efforts of researchers try to tackle and overcome. In the following a scale to classify the Research Performance Indicators based on their maturity level is proposed.

4 INDICATOR READINESS LEVEL (IRL)

The IRL scale takes basis on the scale of Technology Readiness Level (TRL) that was proposed in the 70s by the NASA (National Aeronautics and Space Administration) to assess the stage of development (maturity) of new technologies and to compare different technologies in terms of the maturity level from idea to application (EARTO 2014) to classify new technologies in terms of their maturity level. The TRL scale has been adapted to take into account that in our case we have to rank indicators and not technologies. The definitions of the different maturity levels are reported in Table 4.1.

In order to clarify its meaning and use in the following sections the IRL scale is applied to both Operational and Research Performance Indicators related to corrosion and loss of stiffness.

Table 4.1 Indicator Readiness Level (IRL).

IRL1	Basic principles observed	The **principles** underlying the indicator are known
IRL2	Indicator concept formulated	The indicator is computed using an **analytical/numerical model**
IRL3	Experimental proof of concept	The indicator is computed for **laboratory specimen tested indoor**
IRL4	Indicator validated in laboratory	The indicator is computed for a **reduced scale model** of a component tested **indoor**
IRL5	Indicator validated in laboratory in simulated environment	The indicator is computed for a **reduced scale model** of a component tested **outdoor**
IRL6	Indicator demonstrated in relevant environment	The indicator is computed for a **full-scale model** of a component tested outdoor
IRL7	Indicator demonstrated in operational environment	The indicator is computed for a **real structure**
IRL8	System complete and qualified	The indicator can be used for quality checks. (**performance goals and testing protocols are defined**)
IRL9	Actual system proven in operational environment	The indicator is **sistematically used** for quality checks and related decision making

For an each indicator a table with 3 columns is presented. In the first column are reported the IRL levels, in the second a “Y” if the level has been already achieved by the considered indicator or a “N” if this is not the case and in the third column a brief explanation of the reason why yes or no is chosen.The achievement of a certain level is documented by publication of results in technical reports or scientific papers.

4.1 *RPIs related to corrosion*

Corrosion can be detected capturing rust or other corrosion products during the visual inspection of a bridge or measured through parameters related to the different phases of corrosion development: initiation and propagation phase. During the first phase, corrosion is induced by either chloride or carbon dioxide penetration. Carbonation depth and chloride content can be assumed as quantifiable indication of corrosion. Since the reference value of both parameters – i.e. their value for the intact structure – is zero, in this case the numerical values of the Performance Parameter and of the Performance indicator coincide. These indicators give information about the current state of the structure so they are Diagnostic

Performance Indicators (DPIs). In order to use them for quality checks their values corresponding to limit states (performance goals) have to be defined. Based on the comparison between the performance indicator and its limit value it could be estimated for example that depassivation limit state has been reached and that propagation period, i.e. corrosion, may start or has already started. This may allow a decision on possible reactive or proactive intervention measures.

This was an example of Diagnostic Performance Indicator directly computed from the available knowledge (measures and observations).

In several cases, research efforts focus on the development of analytical and/or numerical models of the degradation phenomena and of their evolution.

In these cases, as mentioned in section 2.1, the performance parameters (measured and observations) are used just to calibrate the model. The Performance Indicators are computed using the calibrated model. For example the calibration of the model can be performed using the measured modal parameters and the Performance Indicator can be the displacement at a given location computed from the calibrated numerical or analytical model. If the model is able to simulate the future performance of the structure, Prognostic Performance Indicators can be computed. For instance, remaining service life can be estimated from a numerical model where a model of corrosion evolution is implemented. The Prognostic Performance Indicator (remaining service life) will be of course a function of the model used for corrosion.

IRL scale is herein applied to chloride content at the reinforcing steel as Diagnostic Indicator and to the remaining service life as Prognostic Performance Indicator. Both indicators need as basic knowledge (performance parameter) the Chloride content at the reinforcing steel.

4.1.1 *DPI - Chloride content*

Chloride content measured during inspections is a performance parameter that depends on the total amount of chloride ion in concrete, including bound in the solid phases and free chlorides in the pore solution. The corresponding Diagnostic Performance Indicator coincides in this case with the Performance Parameter. Chloride concentration is already used for quality checks of bridges therefore this indicator is an Operational Performance Indicator that reaches the level 9 in the IRL scale.

Table 4.2 IRL applied to chloride content (DPI) based on measured chloride content (PP)

IRL	Level achieved	Explanation
1	Y	The critical free chloride concentration in pore solution in contact with the rebar surface causes depassivation of the steel rebar leading to its corrosion.
2	Y	It is possible to calculate change of the chloride content in concrete by various developed mathematical models, such as those from (fib 2006).
3	Y	It is possible to perform laboratory tests on concrete specimens, in order to determine chloride concentration in hardened concrete.
4	Y	It is possible to perform laboratory tests on reduced scale models, in order to determine chloride concentration in hardened concrete.
5	Y	It is possible to perform experimental studies on a reduced scale model of the structure in real environment.
6	Y	It is possible to determine chloride content on a full-scale model of the structure/element in real environment.
7	Y	It is possible to measure chloride concentration in concrete on real bridge/element of a bridge. Determination of chlorides on case studies after 13 years (Kuster Maric, et al. 2017), and 14, 20, 25 years of exposure are recorded (M. Kuster Maric 2013).
8	Y	Determination of chloride content in hardened concrete is a well-established procedure and prescribed in EN 14629 (CEN 2007). Threshold values are defined (CEN 2005)), (Ozbolt, et al. 2010). There are no issues in applying the indicator in quality checks and related decision-making.
9	Y	Chloride content measurements are regularly used in quality checks and intervention plans (Kuster Maric, et al. 2017), (M. Kuster Maric 2013).

4.1.2 *PPI – Remaining service life based on a model of the chloride content*

In this case the Performance Parameter chloride content is used to calibrate a model that is then used to the predicted service life. This latter is a Prognostic Performance Indicator. Currently this indicator reaches level 8 in the IRL scale.

Table 4.3 IRL applied to service life prediction (PPI) computed based on measured (PP)

IRL	Level achieved	Explanation
1	Y	Increase of chloride concentration near rebar leads to corrosion and decrease of bridge load carrying capacity and its service life.
2	Y	It is possible to obtain the relationship between the chloride content and service

		life (fib 2006), (Gode and Paeglitis 2014).
3	Y	It is possible to perform laboratory tests on concrete specimens, in order to determine chloride content in hardened concrete, necessary for estimation of the service life.
4	Y	It is possible to perform laboratory tests on reduced scale model of the structure/element in order to determine chloride concentration in hardened concrete, necessary for estimation of the service life
5	Y	It is possible to perform experimental studies on reduced scale model of the structure/element in real environment, in order to determine chloride concentration in hardened concrete, necessary for estimation of the service life
6	Y	It is possible to perform experimental studies on a full-scale model of a structure/element in real environment, in order to determine chloride concentration in hardened concrete necessary for estimation of the service life
7	Y	It is possible to perform experimental studies on specimen drilled out from a real bridge or a component , in order to determine chloride concentration in hardened concrete necessary for estimation of the service life (M. Kuster Maric 2013), (Kuster Maric, et al. 2017), (Gode and Paeglitis 2014).
8	N	It is possible to use estimation of service life in decision-making, but applicability issues still exist.

5 CONCLUSIONS

A scale defined Indicator Readiness Level is herein proposed to rank performance indicators proposed for quality checks of road bridges. This scale is meant to serve as a supporting tool for a twofold aim:

1) to check the eligibility of a performance indicator for quality check and related decision making on roadway bridges based on its maturity.
2) to select research needs on performance indicators that is to underpin the indicators on which more research is needed in order to bring them to the level of full applicability for quality checks.

Example of the application of the IRL to indicators that are at the operational level as well to indicators still at the research level have been presented and discussed.

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