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State-Of-Research on Performance Indicators for Bridge Quality Control and Management

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The present study provides a review of the most diffused technical and non-technical performance indicators adopted worldwide by infrastructure owners. This work, developed within the European COST Action TU 1406—"Quality specifications for roadway bridges, standardization at a European level," aims to summarize the state-of-art maintenance scheduling practices adopted by bridge owners, mainly focusing on the identification and classification of the most diffused performance indicators (*PIs*). *PIs* are subdivided in technical and non-technical ones: for this latter subclass, *PIs* are classified in environmental, social and economic-targeted. The study aims to be a reference for researchers dealing with performance-based assessments and bridge maintenance and management practices.

Keywords: bridge maintenance, infrastructure planning, management methods, performance indicators, quality control

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INTRODUCTION

Roadway infrastructure asset management aims at define the optimal maintenance strategies required in order to ensure the fulfillment of a desired performance level, thus achieving a pre-defined performance goal. Performance levels are usually assessed with the so-called performance indicators (*PI*s), representing an objective technical-based metric wherewith a rational ranking of maintenance intervention needs can be derived. *PI*s can be currently derived from visual examination, or based on results coming from the execution of non-destructive tests or the installation of temporary/permanent monitoring systems. In addition, *PI*s can be defined at different levels (i.e., component, system and network level) and can be classified in qualitative- or quantitative-based.

Once a *PI* has been assessed, it has to be subsequently compared with its related performance goal (*PG*), to evaluate if, for the analyzed bridge, the quality control (*QC*) plan is accomplished. Different approaches for the quantification and use of *PI*s are currently adopted in European countries regarding the quality control plans for roadway bridges. For this reason, the main aim of COST TU 1406 Action is to develop an overall homogenization among Countries, bringing together research and practicing communities, to establish a unified European guideline in this field.

Hence, the present study provides an extensive review about operational *PI*s currently in use for bridges, and research *PI*s under investigation by several research groups worldwide, that may have a feasible application for developing *QC* plans of roadway administrators in the next future. In particular, a special focus is given to not-purely technical *PI*s (e.g., environmental, social, economic) that might be considered in the development of a sustainable *QC* plan. **Figure 1** shows how this paper is organized, where red text and numbers indicate the section and subsection labels. A total of 263 were surveyed to extract key information used to depict the present state-of-research: **Table 1** lists the subdivision of documents by type, showing how more than two thirds of references come from international journal papers.

The first part of the work is devoted to describe tools currently used to quantify the technical *PI*s for existing bridges. The second part deals with a comprehensive review of the technical and non-technical *PI*s, used both in practical and research activities. Lastly, an overview of decision-making approaches currently in use for handling different types of *PI*s is detailed, and a discussion on present literature gaps and future developments in this field of research is addressed.

PERFORMANCE INDICATORS' ASSESSMENT TOOLS

As we are mainly interested at reviewing those *PI*s that can be objectively quantified, it is first necessary to give some insights on the tools currently adopted for the assessment of technical *PI*s for bridge management. Four different macro groups can be identified: visual surveys, probing, non-destructive techniques (*NDT*s) and structural health monitoring (*SHM*). **Figure 2** shows a sketch of the four categories of NDTs that may be used for assessing technical *PI*s of existing bridges.

Visual Surveys

The use of visual surveys is the most diffused method for assessing structural damage among Bridge Management Systems (*BMS*s). Indeed, traditional *BMS*s are based on condition rating systems combining information from visual inspections on bridge components into overall bridge condition rates. Usually, trained technicians carry out inspections, compiling handwritten records during field surveys.

As reported in Moore et al. (2001), Caner et al. (2008), Avsar et al. (2012), and Tenzera et al. (2012), visual inspections suffer for important variability in the results due to subjectivity. Subjectivity in visual inspection outcomes may be mainly attributed to different experience levels among trained inspectors that lead to varying perception of the severity of an observed damage. In addition, environmental conditions that can be present at the time of the survey execution may also affect its outcomes, e.g., due to differences in light intensity and visual resolution of different colors.

Some efforts were carried out in this context to improve the effectiveness and accuracy of visual inspections. Sunkpho and Garrett (2003) illustrated the benefits coming from the use of speech recognition in the execution of visual inspections in snowy cold regions, instead of classic handwriting on paper, showing how it may reduce the risk that inspectors will meet with accidents. Kim et al. (2008) proposed other robotic solutions for damage detection, also with the combined use of wall-climbing and flying robots: such techniques allow carrying out safer damage detection operations, and are powerful tools when dealing with large bridges and hardly accessible viaducts. Oh et al. (2009) presented an interesting application of a robotic system able to detect automatically cracks, demonstrating the effectiveness of this solution able to overpass the problem of subjectivity of bridge inspectors. Koch et al. (2015) and Omar and Nehdi (2017) detailed interesting and up-to-date review of computer vision-based defect detection techniques for bridges.

Probing

Probing is required when a quantitative characterization of main material properties is required, and it commonly consists in the extraction of samples, to be subsequently characterized via laboratory tests (e.g., when dealing with the characterization of steel or concrete stress-strain curves) or with *in-situ* tests (e.g., single-double flat jack systems, see Pellegrino et al., 2014). Depending on the material of each structural element, different types of probing should be carried out. Reinforced concrete members may be investigated with pull-out tests, with concrete cover removal to check the presence of corrosion on steel reinforcement rebars, with concrete coring for assessing both mechanical and durability-related properties, and extraction of steel rebars. Masonry bridges can be investigated via the execution of mortar penetration tests, *in-situ* single/double flat jacks, and endoscopic tests. Probing for existing steel bridges consists in the extraction of dog-bone samples from steel profiles, and the removal of bolts to be further tested with laboratory tests.

Non-destructive Techniques

Non-destructive techniques (*NDT*s) are another tool that can be used for the detection of cracks and deterioration from steel corrosion, providing information that cannot be derived with a simple visual examination of the structural elements. Nevertheless, they are usually less adopted, since they are more cost- and time-consuming with respect to visual inspections, especially due to the need of lane closures (Hiasa et al., 2017). In addition, sometimes difficulties may arise in data interpretation as evidenced in Kee and Gukunski (2016). More in general, it is of crucial importance to know the implicit uncertainties in the implementation of *NDT*s, since such issue can severely impact on a reliability of a risk-based inspection plan (see Hesse et al., 2015). In few countries, existing bridge condition assessment procedures include *NDT* surveys, but their periodical execution is still rare. *NDT*s results are generally used to assess in a more reliable way the most suitable condition state of a deteriorated component (Pushpakumara et al., 2017). In this regard, Gucunski et al. (2012), evidenced how *NDT*s can be used for a proper segmentation of a bridge structure in subparts characterized by similar condition states, with the final aim of helping inspectors to make a more objective rating. Omar et al. (2017a) presented an interesting study providing a procedure

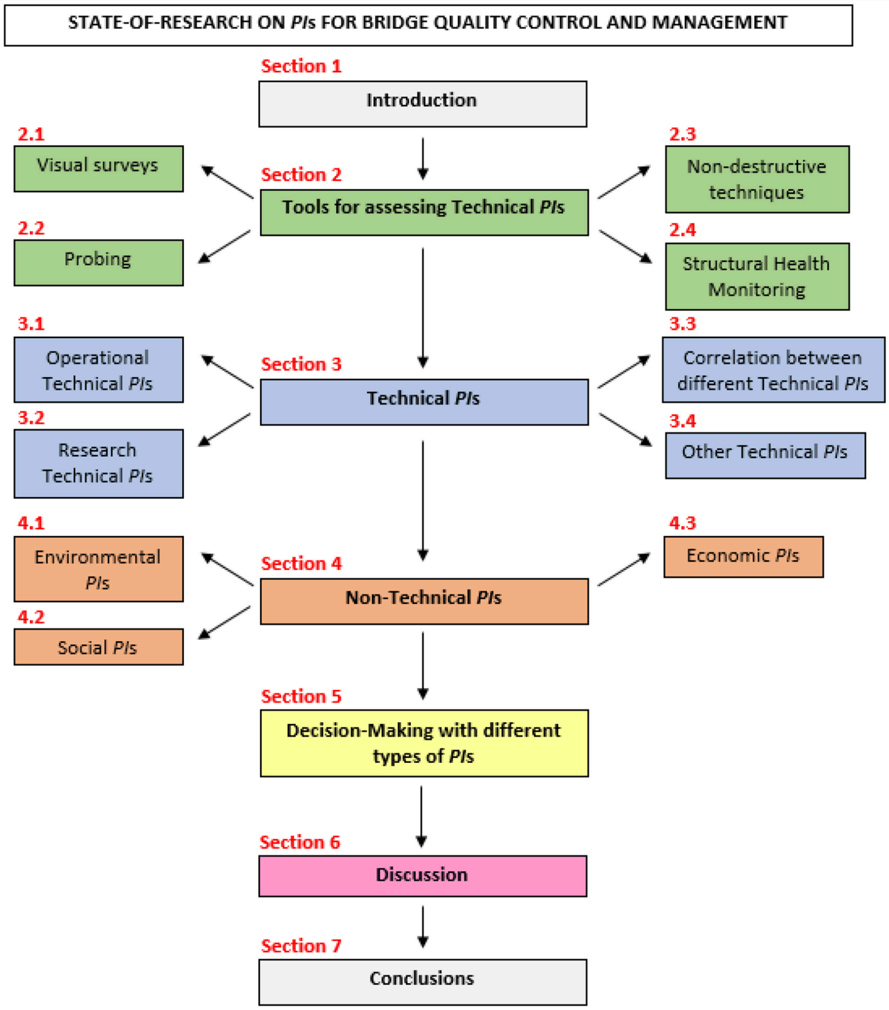

FIGURE 1 | Workflow of the presented review on *PIs* for bridge *QC* and management.

TABLE 1 | Type of sources analyzed in the present review.

Type	International journal papers	International conference papers	Reports	Books/Book chapters	Technical standards	Total
Number	196	36	19	10	2	263

for an integrated defect-based condition rating procedure for RC bridges able to integrate information derived from the implementation of *NDTs* in terms of extent and severity of damage into a rating system via the use of a fuzzy approach.

However, *NDTs* are often badly correlated with material properties (like in the case of probing), and therefore their outcomes cannot be easily used in a further quantitative reliability assessment (Breysse et al., 2011; Breysse, 2012; Sbartai et al., 2012). A review of *NDTs* and strategies for the optimization of their implementation in *BMS* can be found in the results of the *EC* funded project "Sustainable Bridges" with particular emphasis to automatized solutions (Sustainable Bridges, 2007). In Jensen et al. (2006), a general discussion with possible implementation of *NDTs* in the framework of principal, general and special inspections was presented. In recent literature, Rehman et al. (2016) presented an interesting review of existing *NDTs* applied for defect detection in reinforced concrete bridges. Several comparative studies were conducted to emphasize merits and drawbacks of alternative *NDTs*. Among others, Yehia et al. (2007) conducted comparative tests on specimens using the three most commonly diffused *NDTs* in United States [i.e., Ground Penetrating Radar (*GPR*), Impact Echo (*IE*) and Infrared Thermography (*IT*)] evidencing how *GPR* seemed to be the most promising technique in terms of accuracy and time consumption. Oh et al. (2013) illustrated the results of an overpass condition assessment via the use of three *NDTs* (i.e., *IE*, *IT*, and chain drag) with the aim to compare their practicality and ability in detecting shallow lamination. Omar et al. (2017b) proposed a fuzzy methodology for assisting bridge stakeholders in a rational appraising of the most suitable *NDT* to be used given time- and cost-constraints. Some efforts were recently oriented in the development of automatized solutions. The US Federal Highway

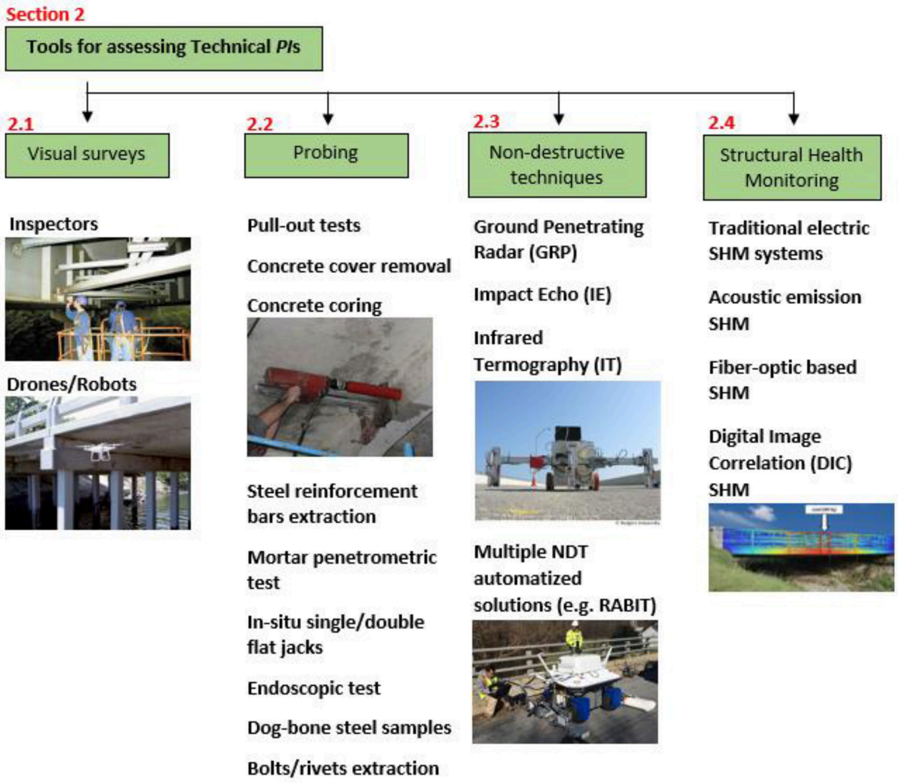

FIGURE 2 | Sketch of the tools currently in use for the assessment of technical *PI*s.

Administration in the framework of its Long Term Bridge Performance (*LTBP*) Program, developed a robotic assisted bridge inspection tool called *RABIT* (Gucunski et al., 2015), able to provide a comprehensive condition assessment of concrete bridge decks via the adoption of different *NDT*s integrated into a robotic platform.

Structural Health Monitoring

Structural Health Monitoring (*SHM*) is the most advanced type of *NDT* and it is usually implemented with the aim to characterize the main modal parameters, that will be following linked to a structural model in order to assess the safety level of an existing bridge against static and dynamic loading (Tecchio et al., 2013; Morbin et al., 2014; Prendergast et al., 2018). Extensive literature on *SHM* techniques and related algorithms can be found with reference to damage detection for bridges. Salawu (1997) presented a first review of existing *SHM* methods, followed by other state-of-art works (Carden and Fanning, 2004): among others, Hsieh et al. (2006) and Fan and Qiao (2011) reviewed different types of vibration sources and damage identification methods discussing in detail merits and drawbacks. Farrar and Jauregui (1998) compared the use of five alternative damage identification algorithms for a bridge case study. Over the last decade, a significant number of innovative sensors were introduced in civil engineering applications in order to implement continuous monitoring and real-time assessment of bridge performances. Among others, Nair and Cai (2010), Elfergani et al. (2013), and Behnia et al. (2014) illustrated the state-of-art on acoustic emission monitoring of bridges. Lopez-Higuera et al. (2011) and Ye et al. (2014) presented comprehensive reviews in the use of fiber optic-based sensors in *SHM* systems, Casas and Cruz (2003) described the application of intensity modulated and spectrometric fiber optic sensors for monitoring temperature, load measurements, as well as strain, corrosion and cracking of a pre-stressed bridge case study. Barrias et al. (2016) reviewed the current applications of distributed fiber optics for bridges and civil engineering structures. Lynch and Kenneth (2006) presented a review of different wireless sensors adopted in civil engineering applications. Digital image correlation (*DIC*) can also be used as alternative to traditional sensors in *SHM* applications, and consists in an optical measurement technique able to record tridimensional deformation via digital photography. One of the main advantages of *DIC* is that it does not require any equipment for the installation of components as well as wirings like in traditional *SHM* systems. Some applications of *DIC* in *SHM* applications can be found in Stephen et al. (1993), Bell et al. (2012), Nonis et al. (2013), Dworakowski et al. (2015), and Pan et al. (2016).

However, *SHM* systems are often costly, and therefore their application has to be carefully designed and justified in case of strategic bridges: in this regard, Guo et al. (2004) illustrated a possible use of genetic algorithms for the definition of the optimal placement of sensors in *SHM* applications. In addition, modern long-term *SHM* systems collect huge amounts of data that have to be adequately post-processed (Soyoz and Feng, 2009): the development of fast algorithms and new metrics represents therefore a relevant topic of research for advancing in this field. Among others, genetic algorithms and machine learning techniques (Nick et al., 2015; Liang et al., 2016) can be used to handle huge amount of data deriving from long-term *SHM*s, also taking into account effects of incomplete measurements (Marano et al., 2011) and operational/environmental variability over time (Figueiredo et al., 2011). Results of *SHM* are usually too linked to quantitative condition assessment: in this regard, interesting case study applications were presented by Catbas et al. (2008), Frangopol et al. (2008), Orcesi and Frangopol (2010), Liu et al. (2010), Orcesi et al. (2010) considering the reliability index as quantitative measure to be linked with monitoring data.

TECHNICAL PERFORMANCE INDICATORS

Once classified tools available for assessing bridge condition, a detailed overview on existing technical *PI*s is presented. In the framework of a modern *BMS*, one of the key steps is damage assessment: usually it is expressed adopting suitable technical *PI*s, a metric for defining a qualitative/quantitative judgment via the use of the abovementioned tools on the bridge component/system condition state. In general terms, technical *PI*s can be subdivided in two main categories: operational and research indicators. While operational technical *PI*s are commonly used in practice by engineers of road agencies dealing with large stocks of bridges, research technical *PI*s are more refined metrics developed by academics, and whose practical application is still ongoing. Patidar et al. (1991) first gave a clear definition of technical *PI* in *BMS* applications, highlighting how it should have the following properties:

- Appropriateness: *PI* "*should be an adequate reflection of at least one agency goal or objective*" (Patidar et al., 1991);
- Comprehensible and defensible: *PI "should be clear, simple, and concise in its definition"* (Patidar et al., 1991) as well as in its method of computation;
- Comprehensive: *PI* levels *"should cover the full range of possible consequences"* (Patidar et al., 1991);
- Dimensionality: *PI "should be able to capture the required level of each dimension associated with the decision-making problem, and it should be comparable across different time periods or geographic regions"* (Patidar et al., 1991);
- Measurability: *PI* should be objectively measured;
- Predictable: it *"should be possible to reliably determine future PI levels"* (Patidar et al., 1991) like with the use of forecasting models;
- Realistic and operational: *PI* should be reliably measured without excessive effort or time;
- Unambiguous: *PI*s should be clearly defined and their metric should be directly related to the consequences.

A detailed overview of the operational and research technical *PI*s actually available is reported in the following, describing in detail all *PI*s reported in **Figure 3**.

Operational Technical Performance Indicators

Regarding operational technical *PI*s, the most commonly adopted *PI* is a qualitative condition rating (also called condition state or condition value, in a numerical scale, e.g., 0–5 or 0–9), and usually assigned during a visual survey (Gattulli and Chiaramonte, 2005). Several *BMS*s, like BRIME in Europe or PONTIS and BRIDGIT in the United States, were thus developed in past decades based on data mainly collected during visual surveys and adopting mathematical and statistical forecasting models for maintenance planning (Austroads, 2002). Several researchers (e.g., Catbas and Aktan, 2002; Mishalani and Madanat, 2002; Suksuwan and Hadikusumo, 2010; Adey and Hajdin, 2011; Aflatooni et al., 2013; Fernando et al., 2013; Nasrollahi and Washer, 2015; Denysiuk et al., 2016; Zanini et al., 2016a, 2017a; Quirk et al., 2017) proposed frameworks for the optimal maintenance planning on the basis of visual-inspection data, mainly considering environmental deterioration, and in some cases also consequences of natural hazards (e.g., Valenzuela et al., 2010; Fernando et al., 2015). Critical issues of condition rating-based *BMS*s are represented by the subjectivity in the judgments provided by the inspectors, non-linear relationships in damage progression over time, unbalanced availability of records, missing data. Visual inspections are highly subjective as noted by Tenzera et al. (2012), who pointed out that inspectors with different expertise levels can label the same bridge with a different rating. Hence, this implies that the same judgment from different bridge inspectors may result in a significant dispersion of condition rating results. Moore et al. (2001) analyzed this aspect, i.e., the reliability of visual inspection methods in USA, highlighting how external environmental aspects (e.g., presence of traffic, accessibility of the bridge members and connections, wind speed) can significantly affect dispersion in condition ratings. These observations highlight the need for improving inspector training programs and condition rating procedures. In addition, as explained in Wang et al. (2007), even with perfectly trained inspectors, different assessments can be obtained depending on weather conditions (inspection performed during sunny, cloud or rainy days). In this regard, Vanderzee (2004) evidenced how future *BMS* will tend to substitute a subjective process with an objective one, by switching the assessment tools from the classical visual survey to more sophisticated mixed *NDT*/*SHM* solutions. The use of probabilistic approaches (Zambon et al., 2017), also able to link the probability of damage detection with a certain condition rating (Frangopol et al., 1997; Kim et al., 2013), might represent viable solutions for properly handling such type of uncertainties. In this context, the implementation of fuzzy-logic tools (Zhao and Chen, 2002; Kawamura and Miyamoto, 2003; Sasmal et al., 2006; Pan, 2007; Sasmal and Ramanjaneyulu, 2008; Tarighat and Miyamoto, 2009; Liu et al., 2017) or evidential reasoning approaches (Wang and Elhag, 2008; Ayati et al., 2012; Bolar et al., 2013) were also explored in recent scientific literature, as alternative approaches for accounting uncertainties in a simpler way than via fully probabilistic analyses. Li and Burgueno (2010) presented and interesting study where different soft computing

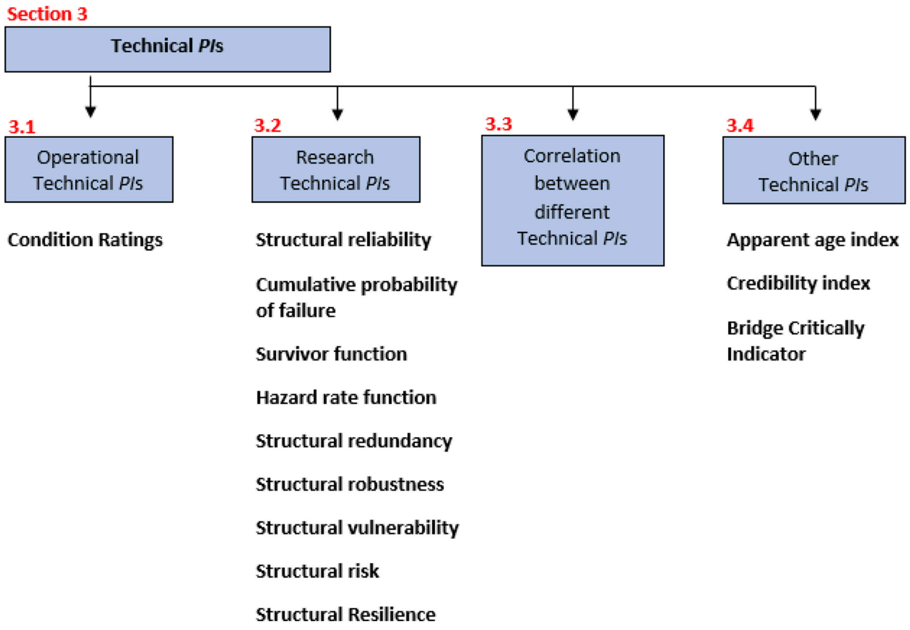

FIGURE 3 | Sketch of the investigated technical *PI*s.

methods were applied to visual surveys, in order to reduce uncertainties and thus calibrating reliable deterioration forecast models. In addition, condition-rating systems cannot provide a clear structural safety judgment, since no quantitative evaluation is done both from resistance and loading sides. For this reason, it should be necessary to couple them with safety indicators in a process of multi-variate optimization, as proposed in Neves and Frangopol (2005).

Research Technical Performance Indicators

Several research technical *PI*s were proposed in the last decades, with the aim to optimize maintenance planning of aging bridges, mainly based on the quantitative evaluation of the structural safety, usually expressed in terms of probability of failure for a given limit state function, considering both load and resistance characteristics. Saydam and Frangopol (2011) and Zhu and Frangopol (2012) proposed reviews of the most valuable research technical *PI*s, also taking into account their time-dependency. Among the various proposals, main research technical *PI*s are:

- Structural reliability: it is one of the most common research technical *PI*s, quantifying the probability of failure for an investigated component/system (Tabsh and Nowak, 1991; Estes and Frangopol, 1998; Frangopol et al., 2001). Reliability can quantitatively take into account load models and resistance of structural elements, also considering deterioration phenomena that may affect safety over time (Val and Melchers, 1997; Stewart and Rosowsky, 1998; Vu and Stewart, 2000; Kong and Frangopol, 2003). Reliability can also be adopted when dealing with natural hazards like earthquakes (Choi et al., 2004; Duenas-Osorio and Padgett, 2011), flooding (Johnson and Ayyub, 1992; Muzzammil et al., 2008), hurricanes (Padgett et al., 2012; Ataei and Padgett, 2013). A comprehensive review of the reliability-based *PI*s is provided by Ghosn et al. (2016a);
- Cumulative probability of failure: a *PI* that quantifies the probability that the time to failure of a component is less than a generic time interval value *t*, and is calculated starting from the probability density function of the time to failure (Hoyland and Rausand, 1994; Okasha and Frangopol, 2010a);
- Survivor function: this *PI* estimates the complement of the cumulative probability of failure, and provides an estimation of the availability, i.e., the value of the probability that a component will not fail before a generic time instant *t* (Leemis, 1995);
- Hazard rate function: a *PI* providing a measure of the instantaneous failure rate of a structural component (Ramakumar, 1993), defined as the conditional probability that the component will fail in a future time interval, given the fact that it has survived until the present time instant (Mauch and Madanat, 2001);
- Structural redundancy: this *PI* represents an estimate of warning prior to system collapse (Okasha and Frangopol, 2010a), or in other terms, the ability of a structural system to continue carrying load after the failure of one structural component, e.g., like a column (Frangopol et al., 1992). Several literature works presented formulations for assessing redundancy, but no agreement has been reached in the most suitable metric to be used for such *PI*. Frangopol and Curley (1987) first proposed to adopt reliability metric for quantifying redundancy. Hendawi and Frangopol (1994) defined redundancy as the ratio between the reliability index of the intact system in a generic time instant and the

difference of reliability indexes calculated for the intact and damaged system at the same time instant (see also Okasha and Frangopol, 2009, 2010b). Such difference can be seen as a measure of the availability of system warning before the entire structural system failure (Anitori et al., 2013). Ghosn et al. (2016b) extended the field of application of structural redundancy also at the network-level;

- Structural robustness: *PI* quantifying the ability of a structural system to suffer damage induced by the occurrence of an extreme action (Ghosn and Moses, 1998; Liu et al., 2000; Saydam and Frangopol, 2011; Sorensen et al., 2012). Starossek and Haberland (2011), Anitori et al. (2013) and Cavaco et al. (2013) summarized different measures (deterministic, probabilistic and risk-based) for this indicator. Recently the concept of robustness has been extended to the case of systems under deterioration occurring progressively due to aging and environmental effects (Baker et al., 2008). For instance, Biondini (2009) proposed a time-dependent measure of robustness intended to quantify the susceptibility to damage increases at during the service-life of a structural system. On the other hand, Cavaco et al. (2013, 2017, 2018) proposed a time-independent measure of robustness with the aim to quantify the susceptibility to damage in the whole service life of the structure. According to Maes et al. (2006) present three robustness measures: one related to the residual system strength, one to the residual structural reliability and the third one taking into account the risks of all the system consequences of failure. A practical application of the first approach considering the system capacity as the performance objective to the case of a railway bridge is presented in Wisniewski et al. (2006);
- Structural vulnerability: this *PI* is a key-measure used to define the susceptibility of a structural component or a system to some external natural or man-made action (Agarwal et al., 2003; Haimes, 2006). Different approaches for quantifying this *PI* were proposed in literature: Lind (1995) proposed a structural vulnerability index based on the ratio between the failure probability of the damaged system and the failure probability of the intact system; The concept of vulnerability is often treated in literature studies focusing on the structural response of bridges subject to natural hazardous actions like floods, earthquakes, hurricanes (e.g., see Morbin et al., 2015; Zampieri et al., 2016). Some research in this field was oriented on the assessment of the interaction between natural aging and structural vulnerability, with the aim to quantify the increase of vulnerability related to the development of natural deterioration phenomena (Choe et al., 2009; Ghosh and Padgett, 2010; Simon et al., 2010; Choine et al., 2012; Zanini et al., 2013; Kumar and Gardoni, 2014);
- Structural risk: a *PI* quantifying the combined effect of actions, probability of failures and related consequences or disaster in a given context (Adey et al., 2003; Ellis et al., 2016). Saydam et al. (2013) presented a risk-based methodology able to take into account direct and indirect losses for highway bridges considering a Markov model for the prediction of bridge performances over time. Many efforts were done in recent years in assessing risk for bridges, in particular with reference to the occurrence of natural hazardous actions. As examples, considering seismic events, Ghosh and Padgett (2011), Alipour and Shafei (2016) and Zanini et al. (2016b, 2017b) investigated the time-dependent variation of structural risk due to seismic actions;
- Structural resilience: this *PI* estimates the ability of a system to recover its original functionality after the occurrence of a hazardous event. With specific reference to seismic events, Bruneau et al. (2003) defined seismic resilience as *"the ability of social units (e.g., organizations, communities) to mitigate hazards, contain the effects of disasters when they occur, and carry out recovery activities in ways that minimize social disruption and mitigate the effects of future earthquakes,"* illustrating also a framework for quantitatively assessing it. Other approaches to quantify resilience can be found in Cimellaro et al. (2010), Zobel (2011), and Bocchini et al. (2013). Recently, Zhang et al. (2017) have proposed two resilience metrics, namely the total recovery time (TRT) representing the rapidity of the restoration process and the skew of the recovery trajectory (SRT), directly linked to the efficiency of the restoration process. The latter aims to capture the characteristics of the recovery trajectory that relates to the efficiency of those restoration strategies considered. Based on them, the optimal restoration schedules of a bridge network following extreme events are decided. It is worth mentioning that not only the total time to recover is important, but also the sequence of recovering activities that should prioritize the repair and, hence, put into service the critical nodes of the network at the early stages after the extreme event.

Also for research technical *PI*s, probabilistic approaches are required for accounting uncertainties in the definition of the main input parameters. Several researchers stressed the importance of using a probabilistic approach when dealing with the assessment of bridge performances: among others, Ellingwood (2005) highlighted how probabilistic risk analysis methods allow estimating and thus managing uncertainties when dealing with structural safety. Knowledge of the probability of satisfactory performance over a certain time interval is a key *PI*, and it needs to be compared with some performance objectives. However, the definition of acceptance criteria is still not adequately investigated, since also performance goals have to be expressed in terms of probabilities, losses, or some combinations of these metrics. In this regard, an interesting fully probabilistic reliability analysis taking into account also deterioration forecasts and synthetizing results in terms of different reliability indexes through the use of radar charts was carried out by Strauss et al. (2014).

Correlation Between Different Technical Performance Indicators

Given the substantial differences between operational and research technical indicators, many researchers tried to find correlations between them. Anitori et al. (2014), as example, analyzed potential relationships between robustness and condition ratings of existing bridges, with the aim to correct rating with data derived by robustness assessment to make it dependent on the system behavior. Deco and Frangopol (2010) proposed a condition-based approach describing lifetime deterioration of reinforced concrete (*RC*) bridge decks. The study evidenced how the combined use of condition and reliability indices is a powerful tool, especially when it is applied to *RC* bridge decks under corrosion. Furthermore, in the case of *RC* decks under corrosion, the correlation between condition and reliability was demonstrated. Load rating factor is also a commonly used operational performance indicator for bridge capacity and not only condition. Estes and Frangopol (2005) performed both a load rating analysis and a reliability analysis on the same highway bridge, concluding how a direct correlation between the two methods is lacking, since reliabilities are strongly dependent by assumed failure modes and load models, whereas load ratings do not account for redundancy in a structure or correlation between failure modes. In the research presented in Estes and Frangopol (2003), it was shown how routine visual information related to condition rating of composite highway bridges and used in the PONTIS bridge management system can be used to update the reliability of these bridges subject to corrosion, demonstrating a clear interaction between operational and research performance indicators.

Other Technical Performance Indicators

Other types of technical *PI*s could be mentioned as not fully belonging to operational/scientific subclasses, rather mainly based on statistical theories applied on pure operational/scientific technical *PI*s. Among others, condition indexing based on the concept of apparent age can be associated with operational technical *PI*s, whereas the credibility index can be proposed on the research technical *PI*s. The condition index based on the concept of the apparent age was proposed by Zonta et al. (2008), based on the underlying theory that *"the apparent age of a standard element is the most likely age of the element given its condition state, assuming theoretical age distributions that are consistent with the normal deterioration model adopted for the element."* Biondini et al. (2010) proposed the adaptation of a statistical estimator called "credibility indicator," and originally proposed by Grandori et al. (1998), to the case of the deterioration modeling of bridge structures. In particular, the effect of the epistemic uncertainty associated with deterioration modeling on the bridge service life prediction was evaluated through the calculation of the credibility indicator, comparing two models (quantitative and qualitative) and identifying the most reliable one. Avsar et al. (2012) proposed a prioritization index based on the combination of visual inspection results and vulnerability estimates. Lastly, McCarten (2016) presented a review of bridge failures, showing how risk events whether by natural causes or man-made have the greatest impact on bridge performance and highlighting the need to have risk-based indicators as well as condition indicators: the study proposed a Bridge Critically Indicator (BCI) reflecting four basic indicators: risk, robustness, redundancy, and resilience.

NON-TECHNICAL PERFORMANCE INDICATORS

Technical *PI*s are also considered for the prediction of deterioration over time and thus plan future restoration interventions and their effectiveness over time (Zhu et al., 2017). Given a certain observed/predicted condition, the owner can define the optimal restoration strategy to be implemented. Technical *PI*s allow quantifying the effectiveness of a restoration strategy: however, its implementation involves a series of social, environmental and economic consequences that may significantly affect the decision-making process. In addition, more solutions can be developed (e.g., with different techniques, materials, costs, Gantt charts), and thus there is the need of identifying the best one, not only focusing on technical *PI*s, but analyzing also a set of non-technical *PI*s to rationally find the best restoration strategy. In the following, an extensive review of non-technical *PI*s retrievable in literature is provided. **Figure 4** illustrates a sketch of the investigated environmental, social and economic *PI*s currently retrievable in scientific literature.

Environmental Performance Indicators

Regarding environmental *PI*s, many parameters, including energy consumption, use of non-renewable resources, traffic disruption, durability and the reuse or recycling of components and materials have to be considered (Wallbank et al., 1999). In order to make sense of all these different factors, Life Cycle Assessment (*LCA*) was defined as a methodology for quantifying environmental impacts and burdens associated with an item over its entire life (ISO, 2006a,b). Depending on the systems boundaries, analyses may be carried with a cradle-to-gate or cradle-to-cradle approach, thus integrating all the life phases of the structure, i.e., material manufacture, construction, maintenance and operation, and lastly the end of life, with its alternative solutions being dismantling and landfilling or materials recovery and recycling. *LCA* concentrates on environmental aspects—resource use, ecological consequences and human health—and does not normally address economic or most social aspects (Klöpffer and Grahl, 2009). Rodrigues et al. (2017) presented an application to evaluate the environmental friendliness of TCC bridges with respect to traditional solutions. Pang et al. (2015), Penadés-Plà et al. (2016), and Dabous et al. (2017) presented comparative *LCA* analyses between alternative bridge maintenance scenarios. Some researchers proposed probabilistic *LCA* approaches able to account for uncertainties in main input parameters (Shen and Lepech, 2017). Regarding reinforced concrete systems, some studies were also conducted with the aim to highlight the sustainability potential paying attention to the composition of the mix-design and its environmental implications (Hammervold et al., 2013; Hooton and Bickley, 2014; Muller et al., 2014; Ali et al., 2015) performed *LCA* on Norway bridge types highlighting how main environmental impacts can be related to the production of materials for bridge decks and abutments, as these components require large quantities of materials. The following environmental indicators, that practically cover some of the main

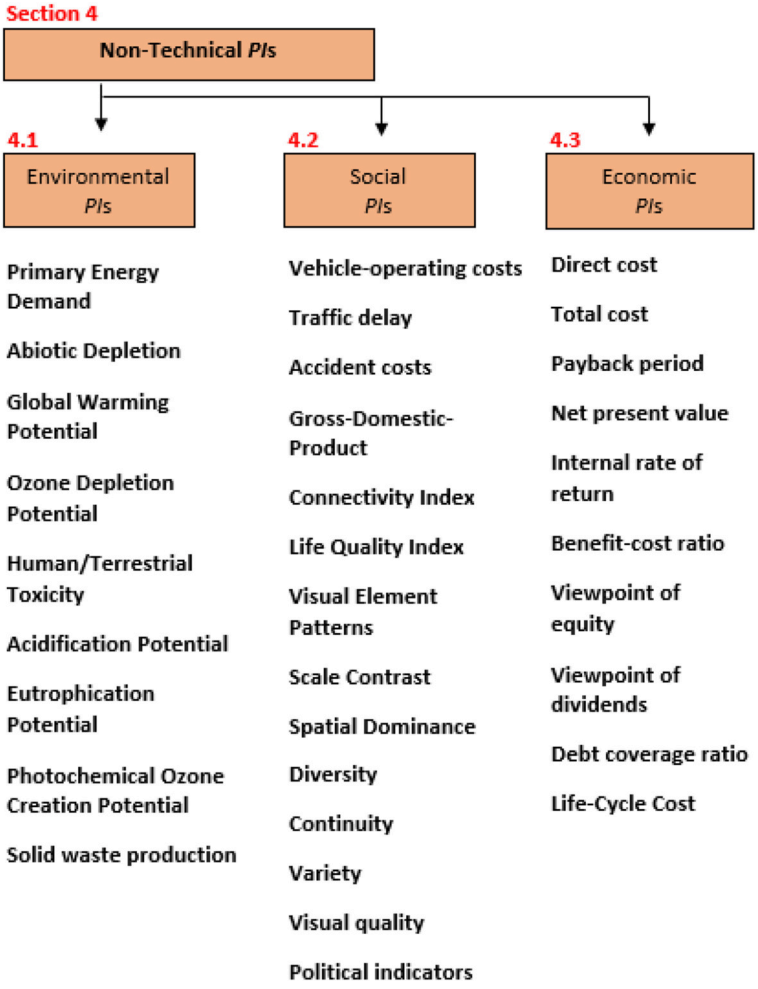

FIGURE 4 | Sketch of the investigated non-technical *PI*s.

mid-point indicators of the CML2002 method (Guinée et al., 2002) and energy demand, were proposed:

- Primary Energy Demand: a *PI* quantifying the amount of energy directly withdrawn from the hydrosphere, atmosphere or geosphere (Keoleian et al., 2005a), that derive from the CED (cumulative energy method) method (Boustead and Hancock, 1979). It is distinguished from non-renewable and renewable resources: for the former (i.e., fossil fuels and uranium), the amount is expressed in MJ- equivalents, whereas in case of the latter it is quantified in biomass kg- equivalents. For hydropower, Primary Energy is instead assessed as the amount of energy needed for an equivalent change in the potential energy of the water (Kreißig and Kümmel, 1999). According to Du et al. (2014), it has been shown that CED is largely dominated by the material manufacture phase, regardless of the structural type analyzed, and it is responsible for 68–80% of the overall energy demand during bridge life cycle. Maintenance phase instead is highly dependent on the bridge type, given the same deteriorating scenario;
- Abiotic depletion: this *PI* represents one of the most discussed impact categories since currently a reliable method for its assessment is still lacking (van Oers and Guinee, 2016). The issue of depletion of abiotic resources can be viewed as a decrease of the resource itself, or, an incremental change in the environmental impact of extraction processes at some point in the future (Heijungs et al., 1997; Guinée et al., 2002). The impact category of "abiotic depletion" is measured in kg Sb-equivalents/kg extraction, and is estimated as the product between the amount of extractions/fossil fuels and some characterization factors (ADPs). It is worth recalling that this indicator is mostly used to evaluate mineral resources, whereas it still do not find large applications when dealing with the extraction of virgin bulk resources, e.g., aggregates used for concrete manufacture (Habert et al., 2010). For the above reasons, it is not typically included in LCA analysis when dealing with RC structures analysis. Recently, this indicator has been used as a basis to capture also the influences on land occupation and transformation, associated to degradation

problems related to soil depletion, topography alteration and visual damage to landscape (Milà i Canals et al., 2007);

- Global Warming Potential: this *PI* is probably the most well-known, on which the communities and hence decision makers put more attention, and it describes the mechanism of the greenhouse effect, measured in kg CO_2- equivalents (Padgett and Tapia, 2013; Mara et al., 2014). Greenhouse gases that are considered to be caused or increased anthropogenically are for example carbon dioxide, methane, and chlorofluorocarbons (CFCs), which are converted into equivalent of CO_2 by well-known conversion factors, e.g., $1\,\text{kg}\ CH_4 = 25\,\text{kg}\ CO_2$. For a bridge 320 m long and 22.5 m wide, carrying two traffic lanes in each direction located in Västra Götaland, Sweden, Du et al. (2014) have analyzed five alternatives realized with steel box girder composite bridge, a steel I-girder composite bridge, two solutions with post-tensioned concrete box girder bridges, and a balanced cantilever concrete box girder bridge. In all the cases, the order of magnitude of GWP indicator was about 6×10^6 kg CO_{2-eq}, along the whole service life of the structure. Particularly, the maintenance operations are responsible for <10% of such emissions, whereas material production still remains by far the main contribution, in a range between 72 and 94%, depending on the analyzed solution;
- Ozone Depletion Potential: this *PI* quantifies anthropogenic emissions, such as fluorine-chlorine-hydrocarbons (CFCs) and nitrogen oxides (NOX), and it is measured in kg R11-equivalents. These emissions are considered responsible of potential ozone depletion, and main factors of the increase of the hole in the stratosphere layer (Habert et al., 2012). For the above case-studies, Du et al. (2014) have estimated that a range between 2 and 3×10^{-1} kg CFC-11_{eq} may be produced during the entire life cycle of a structure;
- Human/Terrestrial Toxicity: this *PI* estimates the Human Toxicity Potential (HTP), i.e., the potential harm of a unit of chemical released into the environment (Habert et al., 2012). HTP includes both inherent toxicity and generic source-to-dose relationships for pollutant emissions, and it is measured in kg 1.4-DB equivalents. The overall HTP score of an emissions' profile is calculated as the sum of the release of each chemical multiplied by the respective equivalency factor (McKone and Hertwich, 2001). For the above case-studies, Du et al. (2014) have estimated that a range between 1 and 2×10^6 kg DB_{eq} may be produced during the whole life cycle of a bridge structure, and particularly the solutions with post-tensioned concrete box girders with a balanced cantilever concrete box girder promote a reduction by 30% of the impacts, due to the reduced impacts of selecting concrete instead of steel as main structural materials. Although this reduction, within the whole life cycle, the impact of maintenance operations seems still negligible if compared to the materials manufacture phase, but it worth recalling not negligible in terms of absolute values;
- Acidification Potential: this *PI* quantifies the acidification of soils and waters originated by the transformation of air pollutants, such as sulfur dioxide and nitrogen oxide into acids (H_2SO_4 und HNO_3), and it is measured in kg SO_2- equivalents (Kim et al., 2013). This leads to a decrease in the pH-value of rainwater (i.e., "acid rain") and fog, harming ecosystems and causing forest dieback. As an indicative example, LCA analysis carried out on Mälkiä Canal Bridge by Rantala (2010), one of the biggest bridge under construction in Finland at year 2009 (a continuous composite girder bridge with steel girders as main bearing structure and reinforced concrete deck, with seven spans and total length of 318.8 meters), has estimated that operation, repair and maintenance operations will be responsible for 6.5% of whole SO_2 emissions, thus being 2,500 kg of $SO_{2,eq}$. Within maintenance operations, waterproofing renovation, zinc coating of steel girders, bearing and expansion joints reparation and substitution are examples of the operations that were considered;
- Eutrophication Potential: this *PI* describes the enrichment of nutrients in a defined place, either aquatic or terrestrial, and it is measured in kg PO_{4^-} equivalents (Kim et al., 2013). It is caused by waste water, air pollutants and fertilization in agriculture. In the analyzed case of Mälkiä Canal Bridge by Rantala (2010), 300 kg $PO^-_{4\ eq}$ are estimated to be released during operation, repair and maintenance operations, thus representing about 4% of the overall emission within this category;
- Photochemical Ozone Creation Potential: this *PI* quantifies the photochemical ozone production in the troposphere, commonly known as summer smog, and it is measured in kg $C_2H_4{}^-$ equivalents (Du and Karoumi, 2013). Ground-level ozone is produced by combination of radiation from the sun and the presence of nitrogen oxides and hydrocarbons. Rantala (2010) estimated that operation, repair and maintenance may lead to 10.8% of the overall emissions in this category for the Mälkiä Canal Bridge, being about 160 kg $C_2H^-_{4\ eq}$, compared to steel parts manufacturing that are responsible for more than 30% of the emissions alone;
- Solid waste production: this *PI* estimates potential impacts due to the production of construction and demolition waste (Keoleian et al., 2005a). The value of this indicator is sensible dependent on the end-of-life (EOL) scenario that might be experienced by the structure. If recycling/reuse strategies are adopted, such emissions can be highly reduced, and are caused by the sole transportation ones. However, typical, concrete parts might be contaminated for instance by chlorides, due to the use of de-icing salts during winter or in cold climates; hence, it is necessary to evaluate carefully the amount that could not be re-used, or that should be used for low-value applications.

Specific software programs containing suitable dataset for the *LCA* analysis (e.g., SimaPro7, 2008) can be used for the assessment of the abovementioned environmental *PI*s.

Social Performance Indicators

Regarding existing social *PI*s, they can be subdivided in quantitative and qualitative ones. Among quantitative social *PI*s, the most significant social effects associable with bridge deterioration and consequent maintenance works and/or bridge failures are linked to indirect consequences like traffic delays with related increase of traveling times for roadway users and potential human losses due to accidents (Keoleian et al., 2005b). Delays during maintenance works to bridges on busy roads can be relevant, with economic impacts many times outweighing the pure rehabilitation costs: Koch et al. (2002) estimate the user costs due to traffic delays and lost productivity to be more than ten times the direct cost of maintenance, repair, and rehabilitation of bridges. For this reason, the owners have to minimize such effects, thus reflecting in a substantial improvement in the level of sustainability of the rehabilitation (Wallbank et al., 1999; Wallbank, 2002; Liu and Frangopol, 2006). An interesting discussion on user cost models was provided by Thoft-Christensen (2009), in which the author also explained how to estimate user costs associated to the repair activities of a deteriorated bridge structure. The quantification of user costs is often a hard task, since in most of the cases several aspects have to be accounted for: user costs can be estimated as the sum of different components (Wilde et al., 2001). Goh and Yang (2010) tried to give a categorization of cost components via the execution of a questionnaire survey in Australia. In general terms, three main categories can be identified: vehicle operating costs (*VOC*, including the costs of fuel, tires, engine oil, maintenance, and depreciation), traffic delay (*TD*, considering speed delay, detour time and consequent loss of opportunities) and accident costs (*AC*, fatal accidents, non-fatal injury accidents, property damage accidents) (Najafi and Soares, 2001). *VOC* estimation models are usually based on the definition of main road characteristics (e.g., roughness, geometry, traffic rates), vehicle attributes (e.g., weight, age, horse power, price of maintenance works) and environmental climate characteristics (Ben-Akiva and Gopinath, 1995). *TD* is often the most relevant component and must be differentiated when dealing with cars or trucks (Sobanjo and Thompson, 2004): its estimation is based on the product between the increase in travel time and the travel time cost per hour (Gao and Zhang, 2013). Travel time cost represents a measure of value of time to road users, and usually it is based on average hourly wage and income level in a city or region, with differentiated values for passenger cars and commercial trucks (Matthews and Allouche, 2010). *AC* cost models try instead to capture social impact related to the potential increase of vehicle accidents during the period in which rehabilitation is taking place, disrupting normal traffic flow and reducing the vehicle capacity of a bridge (Ehlen, 1997). Some studies dealt with the calibration of models taking into account main bridge parameters: among others, Thompson (2002) presented a user annual accident count model taking also into account geometrical and traffic flow characteristics of a generic road link; Lounis and Daigle (2010) considered average accident costs and the normal accident rate taken from statistics published by Wilson et al. (1994); Transport Canada (2006). Considering the lack of statistical data on accident in work zones, a rule of thumb of three times the normal accident rates is used as suggested by Walls and Smith (1998). Bai et al. (2010) presented a framework for comprehensive estimation of user cost for bridge management, synthesizing the existing state of practice of user cost estimation and techniques to address a number of considerations in such estimation. Chen et al. (2017) recently calibrated multivariate models able to quantify accident rates in relation to road-surface condition state.

In case of the occurrence of natural hazards like earthquakes, tornadoes, etc., damage can affect multiple bridge structures, thus influencing the functionality of the transportation network itself. In such cases, social *PI*s that can be monitored are related to the variation of gross domestic product due to the occurrence of the natural hazard (Carturan et al., 2014). At the network-level, it is also important to take into account the potential residual functionality of the transportation network due to bridge damage/failures and also buildings like in the case of historical centers (Zanini et al., 2017c). In this context, connectivity indexes are usually considered as social *PI*s for the evaluation of the functionality of the infrastructure both for analyzing issues related to the accessibility by rescuing operations and the safe evacuation of citizens (Hadas et al., 2015; Nahum et al., 2017).

Other quantitative research-based social indicators can be used: among others, Pandey et al. (2006) proposed the use of the so-called Life Quality Index (*LQI*) as a rigorous basis for program evaluation to assist decision-makers in directing expenditures where they may most effective. The *LQI* is equivalent to a multi-attribute utility function being consistent with the principles of rational decision analysis. It is further refined to consider the issues of discounting of life years, competing background risks, and population age and mortality distribution. Rackwitz et al. (2005) expanded the *LQI* framework and applied it to determine optimal safety levels in civil engineering infrastructures. Maes et al. (2003) applied *LQI* for optimizing the life-cycle cost of structures.

The above-mentioned Social *PI*s requires a higher level of analysis, moving from the so-called system-level (i.e., focused on the single bridge) to the network-level: such type of analyses, allow to capture the impact of a bridge damage/failure/restoration on the overall transportation system accounting for reliable traffic demand models and detailed network topology transportation graphs. In this way, it is possible to identity those bridges that can mainly impact at the network-level and thus give priority to them in the following implementation of restoration/replacement actions.

With reference to qualitative social *PI*s, aesthetic impact, prestige and historic value and political implications can be evaluated. One important point is in fact that bridges are often located directly in the urban space or are seen as prestigious landmarks. Therefore, their aesthetic impact and acceptance is another important performance aspect (Barelli et al., 2006). Furthermore, historic bridges can constitute a part of the cultural heritage and hence, preservation can become an important aspect. Dette and Sigrist (2011) proposed an aesthetic indicator for concrete bridges called time of unsatisfactory appearance (*RTUA*), which is defined as the fraction of the service lifetime in which the condition of the concrete surface is below a certain aesthetic threshold and thus the appearance is impaired. Other visual quality characteristics can be considered as aesthetic indicators (Smardon and Hunter, 1983; FHWA, 1988; Rahman, 1992), as:

- Visual Pattern Elements: this *PI* describes *"how well the bridge fits into the overall landscape on the basis of primary visual attributes"* (Patidar et al., 1991) of objects like color, form, line, texture;
- Scale Contrast: this *PI* describes *"the extent to which a bridge blends into its environment on the basis of its relative size with respect to those of other features in its environment"* (Patidar et al., 1991);
- Spatial Dominance: this *PI* is similar to the previous, *"but pertains to a larger dimension; is the extent to which the bridge elements would be dominant in views of larger landscape and cityscape"* (Patidar et al., 1991);
- Diversity: this *PI* describes *"a function of the frequency, variety, and intermixing of the visual pattern elements of the bridge with its setting. Also termed as setting contrast (the extent to which project's visual pattern elements contrast with or blends in with its existing natural or man-made background)"* Patidar et al. (1991);
- Continuity: this *PI* evaluates *"the uninterrupted flow of pattern elements in a landscape and the maintenance of visual relationships between landscape components that are immediately connected or related"* (Patidar et al., 1991);
- Variety: this *PI* estimates *"the richness/diversity of physical objects and interrelationships within the landscape"* (Patidar et al., 1991);
- Visual quality: this *PI* rates *"the excellence of the viewing experience. Visual quality may be assessed using one of several approaches, e.g., via using opinion surveys of viewers, or judgments of visual quality metrics like vividness, intactness, unity"* (Patidar et al., 1991).

From the abovementioned list of visual quality attributes, an owner can select a set of *PI*s to evaluate alternative bridge projects and rehabilitation solutions.

Regarding politics, no clear indicator was found in literature. However, some suggestions are herein reported on how to define it in a consistent way. In the authors' opinion, the aim of a political indicator is to try to measure benefits associated with the implementation of a rehabilitation intervention on a bridge in terms of improvement of the social consensus for a politician. Hence, when dealing with the comparison of different solutions, the one characterized by the highest consensus is the best one. For the assessment of this indicator, the most suitable tool is represented by opinion polls via interviews or other ways: the key issue in this context is to define a proper sample of citizens to be queried, reflecting the real distribution of population potentially interested/afflicted in case of adoption of a specific decision.

Economic Performance Indicators

Bridge owners can also use economic *PI*s to assess economic efficiency of alternative bridge projects and rehabilitation strategies (Virtala, 1997; Pitonak and Pepucha, 2016). Among others, Robert et al. (2004) evidenced the role of economic analysis in engineering and political decisions regarding transportation investments, focusing on the use of computer systems in the execution of systematic economic analyses for United States roadway projects. In the context of *BMS*s, it seems evident that the main economic *PI* is the direct cost of a rehabilitation intervention, i.e., the sum of all costs associated with the material execution of the intervention (Zanini et al., 2016c). Zanini et al. (2016d) presented an extensive cost analysis for an asset of reinforced-concrete and masonry bridges with the aim to derive some relationships between restoration and seismic retrofitting costs with condition ratings obtainable from visual surveys. However, when dealing with the identification of the optimal rehabilitation strategy among different alternatives, direct cost cannot has to be integrated also with an economic quantification of social and environmental impacts estimated with respective *PI*s, in order to obtain the total cost for a given decision-making.

After estimating the total cost of a certain rehabilitation strategy, other economic *PI*s that can be used to capture the entire financial dimension of an investment (Valuch and Pitonak, 2015), as:

- Payback period: this *PI* estimates the number of years needed for equalizing benefits and costs for restoration of bridges;
- Net present value: this *PI* represents the actualized difference between social benefits and costs. In case of more sophisticated build-operate-transfer contracts, usually developed when dealing with the identification of the best solution among a set of alternative projects, other additional terms related to royalties, business income taxes and earnings must be subtracted to the net value (Chang and Po-Han, 2001);
- Internal rate of return: this *PI* quantifies the value of the rate of return required for obtaining a net present value equal to zero;
- Benefit-cost ratio: this *PI* compares *"the economic net present value of all the social benefits and costs of the project life cycle and its cost of acquisition"* (Chang and Po-Han, 2001), quantifying in such a way the profitability (Hofer et al., 2018) of a rehabilitation investment;
- Viewpoint of equity: this *PI* accounts for *"the equity invested in the construction period and the total net profit before dividends are given to stockholders in the operating period. The total net profit here comes from the statement of cash flows, which considers financing-related items, such as loans, interest, stocks, dividends, and so forth. In this way, the concessionaire will know how long it will take for their investment to be recovered with the total net profit in the operating period"* Chang and Po-Han (2001);
- Viewpoint of dividends: this *PI* considers *"the equity invested in the construction period and the dividends paid to stockholders in the operating period. This viewpoint also provides information to stockholders about the period of time during which the dividends given to stockholders in the operating period can recover the equity investment in the construction period"* (Chang and Po-Han, 2001);
- Debt coverage ratio: this *PI* computes *"the ratio between earnings before interest and taxes (EBIT), including depreciation. However, depreciation is not a real cash outflow. It represents the wearing-out of the equipment. Therefore, to present the concessionaire's available capital to pay debt,*

> *depreciation is added back to EBIT. Debt coverage ratio shows the concessionaire's ability to pay debt. The debt coverage ratio influences the willingness of banks to loan money to the concessionaire*" (Chang and Po-Han, 2001). Generally speaking, a debt coverage ratio at least equal to or larger than 1.0 is acceptable (Brigham and Gapenski, 1997).

Many researchers deal with another *PI* called Life-Cycle Cost (*LCC*) (Chang and Shinozuka, 1996; Frangopol et al., 1997, 2001; Kong and Frangopol, 2003; Soliman and Frangopol, 2014; Wessels et al., 2014; Biondini and Frangopol, 2016; Rossi et al., 2017), i.e., the sum of all the costs that an owner has to sustain during the entire service-life of a bridge structure. *LCC* seems to be a promising economic *PI* in bridge management practices, even if some cautions have to be used when actualizing future cash flows if the time horizon is too long.

DECISION-MAKING WITH DIFFERENT TYPES OF *PI*S

As illustrated above, different types of *PI*s can be used in ordinary bridge maintenance practice, each characterized by a specific qualitative or quantitative metric. Therefore, there is the need to rationally handle various metrics accounting for different aspects in the identification of the optimal rehabilitation strategy for a bridge structure. In this regard, some researchers proposed indicators to comprehensively accounting for such different aspects: Hendy and Petty (2012) presented the so-called "Sustainability index" based on radar charts ranging between 0 and 1, and used it for comparing different solutions for a new bridge project. Radar charts are often used when dealing with qualitative/quantitative indicators characterized by different metrics, as in the case of sustainability analyses (Rezayat, 2009): Umer et al. (2016) presented an index called "Sustainometer" based on radar charts and able to incorporate uncertainties with a fuzzy logic toolbox for the evaluation of sustainability of roadway projects. Yadollahi et al. (2016) presented a fuzzy factor analysis aimed at identifying the most significant factors involved in the definition of bridge rehabilitation projects with the aim to improve sustainability of bridge maintenance operations. Radar charts allow also considering the contribution of each individual impact to the overall rating via the use of weighting systems. In general terms, there is the need of refined decision-making approaches in order to use a rational approach in the selection of the optimal restoration strategy accounting for all the different economic, social and environmental aspects. Penadés-Plà et al. (2017) presented an interesting review of previous literature studies dealing with the implementation of methods based on the Multiple-Attribute-Decision-Making (MADM) for a sustainable bridge design: among others, scoring methods (Podvezko, 2011), distance-based methods (Tamiza et al., 1998; Ballestero, 2007), pairwise comparison approaches like analytic hierarchy/network processes (Gorener, 2012; Ali et al., 2015; Rashidi et al., 2016), outranking methods (Behzadian et al., 2010; Govindan and Jepsen, 2016; Jajac et al., 2017), multi-attribute utility/value theory (Sarabando and Dias, 2010; Sabatino et al., 2015) can be viable solutions for a rational decision-making process. Recently Yoon and Hastak (2017) presented a multitiered prioritizing method based on urgency scales able to take into account two hierarchical selection steps based on urgency and total prioritization scales. Another interesting work was proposed by Lounis and McAllister (2016) that illustrated the proposal of a risk-based decision-making framework for bridges subject to different hazards able to account both technical and sustainability requirements.

DISCUSSION

The issue of bridge quality control and management has been significantly deepened in past and recent literature studies, and has been widely addressed in the present review. Looking to the current state-of-research on this field, some considerations can be carried out with the aim to highlight present gaps and potential future research developments.

In particular, significant efforts are still required in order to try to find reliable correlations between visual inspections and NDTs, as well as between the latter and probing outcomes. As regards SHM techniques, one open issue is related to develop smart algorithms able to handle big data coming from SHM systems, and more generally, trying to reduce as possible the amount of data collected and costs for the implementation of SHM. Given the substantial standardization of the bridge types, it would be desirable in the near-future to develop low-cost and less-computationally onerous permanent SHM systems to be directly installed at the time of construction of the bridge.

As regards technical *PI*s, one challenge is represented by the conversion of the current visual-inspection based *BMS*s, adopted by the majority of public/private infrastructure owners, to more refined quantitative technical *PI*s, like those reported in section Operational Technical Performance Indicators. This passage it is not an easy task, and for this reason, scientific community may contribute with more research activities aimed to investigate correlations between qualitative and quantitative technical *PI*s. Another relevant issue that may be addressed deals with the integration of the existing *BMS*s, mainly focused on the collection of reports on surveyed damage due to deterioration phenomena, with *PI*s like vulnerability and risk that are usually related to sudden natural or man/made events. In particular, more research is required on the combined effect of natural aging and sudden events in order to prevent potential relevant damage/failures.

Lastly, the field of non-technical *PI*s as well as that of decision-making approaches are still little known among infrastructure owners, and currently no relevant research presents a detailed and comprehensive application of all technical, socio-environmental and economic *PI*s to a bridge case study. It is therefore strongly recommended to scientist dealing with research in bridge quality control and management to put efforts in developing case-study applications with a multidisciplinary approach in order to allow engineers and infrastructure owners to familiarize with such issues.

CONCLUSIONS

This work focused on the identification and classification of the most diffused technical, environmental, social and economic performance indicators (*PI*s) adopted in existing Bridge Management Systems, and those still under progress and that could be eventually included in the next future. A wide literature review was, therefore, performed, with the aim to provide a comprehensive state of the research actually available in the identification of *PI*s to be used in the development of sustainable *QC* plans for roadway administrators in the near future. First, a focus on tools actually adopted for the quantification of *PI*s for existing bridges was presented with emphasis on visual surveys, probing, non-destructive techniques and structural health monitoring, reporting related advantages and drawbacks. In the following, a detailed overview of technical and non-technical *PI*s used both in practical and research activities was carried out, explaining their quantitative/qualitative metrics, and providing references to literature studies in which are presented realistic applications. In the last part, a section illustrating a wide selection of decision-making methods able to take into account different types of *PI*s and related metrics is illustrated. The present work can therefore be considered as a useful support for researchers and practitioners involved with bridge maintenance operations and development of *QC* plans, providing a global perspective to the issue of measuring the performance of existing bridges via the use of suitable *PI*s.

AUTHOR CONTRIBUTIONS

MZ performed the review of technical indicators and social and economic non-technical indicators. FF reviewed the environmental non-technical indicators currently in use. JC analyzed method for taking into account multiple indicators and organized the structure of the manuscript.

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REFERENCES

Adey, B., Hajdin, R., and Bruhwiler, E. (2003). Risk-based approach to the determination of optimal interventions for bridges affected by multiple hazards. *Eng. Struct.* 25, 903–912. doi: 10.1016/S0141-0296(03)00024-5

Adey, B. T., and Hajdin, R. (2011). Methodology for determination of financial needs of gradually deteriorating bridges with only structure level data. *Struct. Infrastruct. Eng.* 7, 645–660. doi: 10.1080/15732479.2010.501568

Aflatooni, M., Chan, T. H. T., Thambiratnam, D. P., and Thilakarathna, I. (2013). Synthetic rating system for railway bridge management. *J. Civil Struct. Health Monit.* 3, 81–91. doi: 10.1007/s13349-013-0035-6

Agarwal, J., Blockley, D., and Woodman, N. (2003). Vulnerability of structural systems. *Struct. Saf.* 25, 263–286. doi: 10.1016/S0167-4730(02)00068-1

Ali, M. S., Aslam, M. S., and Mirza, M. S. (2015). A sustainability assessment framework for bridges – a case study: Victoria and Champlain Bridges, Montreal. *Struct. Infrastruct. Eng.* 12, 1381–1394. doi: 10.1080/15732479.2015.1120754

Alipour, A., and Shafei, B. (2016). Assessment of post-earthquake losses in a network of aging bridges. *J. Infrastruct. Syst.* 22:04015023-1-12. doi: 10.1061/(ASCE)IS.1943-555X.0000253

Anitori, G., Casas, J. R., and Ghosn, M. (2013). Redundancy and robustness in the design and evaluation of bridges: European and North American perspectives. *J. Bridge Eng.* 18, 1241–1251. doi: 10.1061/(ASCE)BE.1943-5592.0000545

Anitori, G., Casas, J. R., and Ghosn, M. (2014). "Condition rating of concrete bridges based on structural robustness," in *IABMAS2014, Seventh International Conference on Bridge Maintenance, Safety and Management* (Shanghai), July 7–11, 2014. doi: 10.1201/b17063-255

Ataei, N., and Padgett, J. E. (2013). Probabilistic modeling of bridge deck unseating during Hurricane events. *J. Bridge Eng.* 18, 275–286. doi: 10.1061/(ASCE)BE.1943-5592.0000371

Austroads (2002). *Bridge Management Systems: The State of the Art*. Rep. No. AP-R198, Australian and New Zealand Road Transport and Traffic Authorities (Sidney, NSW).

Avsar, O., Marianos, W. N., and Caner, A. (2012). Identifying bridge rehabilitation needs using an analytical method developed for interpretation of visual inspection data. *ASCE J. Perform. Const. Facil.* 26, 312–319. doi: 10.1061/(ASCE)CF.1943-5509.0000233

Ayati, E., Neghab, M. P., Sadeghi, A. A., and Moghaddam, A. M. (2012). Introduction roadside hazard severity indicator based on evidential reasoning approach. *Saf. Sci.* 50, 1618–1626. doi: 10.1016/j.ssci.2012.03.023

Bai, Q., Labi, S., Ong, G. P., Bhargava, A., Sinha, K. C., and Thompson, P. D. (2010). "A framework for comprehensive estimation of user costs for bridge management: a synopsis of existing practices and discussion of new considerations," in *IABMAS2010, Fifth International Conference on Bridge Maintenance, Safety and Management* (Philadelphia, PA), July 11–15, 2010.

Baker, J. W., Schubert, M., and Faber, M. (2008). On the assessment of robustness. *Struct. Saf.* 30, 253–267. doi: 10.1016/j.strusafe.2006.11.004

Ballestero, E. (2007). Compromise programming: a utility-based linear-quadratic composite metric from the trade-off between achievement and balanced (non-corner) solutions. *Eur. J. Oper. Res.* 182, 1369–1382. doi: 10.1016/j.ejor.2006.09.049

Barelli, M., White, J., and Billington, D. P. (2006). History and aesthetics of the Bronx-Whitestone bridge. *J. Bridge Eng.* 11, 230–240. doi: 10.1061/(ASCE)1084-0702(2006)11:2(230)

Barrias, A., Casas, J. R., and Villalba, S. (2016). A review of distributed optical fiber sensors for civil engineering applications. *Sensors* 16:748. doi: 10.3390/s16050748

Behnia, A., Chai, H. K., and Shiotani, T. (2014). Advanced structural health monitoring of concrete structures with the aid of acoustic emissions. *Constr. Build. Mater.* 65, 282–302. doi: 10.1016/j.conbuildmat.2014.04.103

Behzadian, M., Kazemzadeh, R. B., Albadvi, A., and Aghdasi, M. (2010). PROMETHEE: a comprehensive literature review on methodologies and applications. *Eur. J. Oper. Res.* 200, 198–215. doi: 10.1016/j.ejor.2009.01.021

Bell, E. S., Peddle, J. T., and Goudreau, A. (2012). "Bridge condition assessment using digital image correlation and structural modeling," in *IABMAS2012, Sixth International Conference on Bridge Maintenance, Safety and Management* (Stresa), July 8–12, 2012. doi: 10.1201/b12352-41

Ben-Akiva, M., and Gopinath, D. (1995). Modeling infrastructure performance and user costs. *J. Infrastruct. Syst.* 1, 33–43. doi: 10.1061/(ASCE)1076-0342(1995)1:1(33)

Biondini, F. (2009). "A measure of lifetime structural robustness," in *Structures Congress 2009, SCE/SEI* (Austin, TX). doi: 10.1061/41031(341)193

Biondini, F., and Frangopol, D. M. (2016). Life-cycle performance of deteriorating structural systems under uncertainty: review. *J. Struct. Eng.* 142:F4016001. doi: 10.1061/(ASCE)ST.1943-541X.0001544

Biondini, F., Garavaglia, E., and Frangopol, D. M. (2010). "Credibility indicator for bridge service life prediction," in *IABMAS2010, Fifth International Conference on Bridge Maintenance, Safety and Management* (Philadelphia, PA), July 11–15, 2010. doi: 10.1201/b10430-198

Bocchini, P., Frangopol, D. M., Ummenhofer, T., and Zinke, T. (2013). Resilience and sustainability of civil infrastructure: toward a unified approach. *J. Infrastruct. Syst.* 20:04014004. doi: 10.1061/(ASCE)IS.1943-555X.0000177

Bolar, A., Tesfamariam, S., and Sadiq, R. (2013). Condition assessment for bridges: a hierarchical evidential reasoning (HER) framework. *Struct. Infrastruct. Eng.* 9, 648–666. doi: 10.1080/15732479.2011.602979

Boustead, I., and Hancock, G. F. (1979). *Handbook of Industrial Energy Analysis*. New York, NY: John Wiley and Sons Inc., 391 p.

Breysse, D. (2012). Nondestructive evaluation of concrete strength: an historical review and a new perspective by combining NDT methods. *Constr. Build. Mater.* 33, 139–163. doi: 10.1016/j.conbuildmat.2011.12.103

Breysse, D., Larget, M., Sbartai, Z. M., Lataste, J. F., and Balayssac, J. P. (2011). Quality of NDT measurement and accuracy of concrete physical properties quantitative assessment. *Eur. J. Environ. Civil Eng.* 15, 619–632. doi: 10.1080/19648189.2011.9693351

Brigham, E. F., and Gapenski, L. C. (1997). *Financial Management—Theory and Practice. 8th Edn.* Fort Worth, TX: Dryden Press.

Bruneau, M., Chang, S. E., Eguchi, R. T., Lee, G. C., O'Rourke, T. D., Reinhorn, A. M., et al. (2003). A framework to quantitatively assess and enhance the seismic resilience of communities. *Earthq. Spectra* 19, 733–752. doi: 10.1193/1.1623497

Caner, A., Yanmaz, A. M., Yakut, A., Avsar, O., and Yilmaz, T. (2008). Service life assessment of existing highway bridges with no planned regular inspections. *ASCE J. Perform. Constr. Facil.* 2, 108–114. doi: 10.1061/(ASCE)0887-3828(2008)22:2(108)

Carden, E. P., and Fanning, P. (2004). Vibration based condition monitoring: a review. *Struct. Health Monit.* 3, 355–377. doi: 10.1177/1475921704047500

Carturan, F., Zanini, M. A., Pellegrino, C., and Modena, C. (2014). A unified framework for earthquake risk assessment of transportation networks and gross regional product. *Bull. Earthq. Eng.* 12, 795–806. doi: 10.1007/s10518-013-9530-8

Casas, J. R., and Cruz, P. J. S. (2003). Fiber optic sensors for bridge monitoring. *J. Bridge Eng.* 8, 362–373. doi: 10.1061/(ASCE)1084-0702(2003)8:6(362)

Catbas, F. N., and Aktan, A. E. (2002). Condition and damage assessment: issues and some promising indices. *J. Bridge Eng.* 128, 1026–1036. doi: 10.1061/(ASCE)0733-9445(2002)128:8(1026)

Catbas, F. N., Susoy, M., and Frangopol, D. M. (2008). Structural health monitoring and reliability estimation: long span truss bridge application with environmental monitoring data. *Eng. Struct.* 30, 2347–2359. doi: 10.1016/j.engstruct.2008.01.013

Cavaco, E., Casas, J. R., Neves, L., and Huespe, A. (2013). Robustness of corroded reinforced concrete structures. A structural performance approach. *Struct. Infrastruct. Eng.* 9, 42–58. doi: 10.1080/15732479.2010.515597

Cavaco, E., Neves, L., and Casas, J. R. (2017). Reliability-based approach to the robustness of corroded RC structures. *Struct. Concrete*. 18, 316–325. doi: 10.1002/suco.201600084

Cavaco, E., Neves, L., and Casas, J. R. (2018). On the robustness to corrosion in the life-cycle assessment of an existing reinforced concrete bridge. *Struct. Infrastruct. Eng.* 14, 137–150. doi: 10.1080/15732479.2017.1333128

Chang, L. M., and Po-Han, C. (2001). BOT financial model: Taiwan high speed rail case. *J. Constr. Eng. Manage.* 127, 214–222. doi: 10.1061/(ASCE)0733-9364(2001)127:3(214)

Chang, S. E., and Shinozuka, M. (1996). Life-cycle cost analysis with natural hazard risk. *J. Infrastruct. Syst.* 2, 118–126. doi: 10.1061/(ASCE)1076-0342(1996)2:3(118)

Chen, S., Saeed, T. U., and Labi, S. (2017). Impact of road-surface condition on rural highway safety: a multivariate random parameters negative binomial approach. *Anal. Methods Accident Res.* 16, 75–89. doi: 10.1016/j.amar.2017.09.001

Choe, D., Gardoni, P., Rosowsky, D., and Haukaas, T. (2009). Seismic fragility estimates for reinforced concrete bridges subject to corrosion. *Struct. Saf.* 31, 275–283. doi: 10.1016/j.strusafe.2008.10.001

Choi, E., DesRoches, R., and Nielson, B. (2004). Seismic fragility of typical bridges in moderate seismic zones. *Eng. Struct.* 26, 187–199. doi: 10.1016/j.engstruct.2003.09.006

Choine, M. N., O'Connor, A., and Padgett, J. E. (2012). "Impact of corrosion on the seismic vulnerability of multi-span integral concrete bridges," in *Proceedings of the 6th International Conference on Bridge Maintenance, Safety and Management (IABMAS 2012)* (Stresa), London: Taylor and Francis Group.

Cimellaro, G. P., Reinhorn, A. M., and Bruneau, M. (2010). Framework for analytical quantification of disaster resilience. *Eng. Struct.* 32, 3639–3649. doi: 10.1016/j.engstruct.2010.08.008

Dabous, S. A., Ghenai, C., Shanableh, A., and Al-Khayyat, G. (2017). Comparison between major repair and replacement options for a bridge deck life cycle assessment: a case study. *MATEC Web Conf.* 120:02017. doi: 10.1051/matecconf/201712002017

Deco, A., and Frangopol, D. M. (2010). "Deterioration and maintenance of RC bridge decks under uncertainty: condition and reliability indexes," *IABMAS2010, Fifth International Conference on Bridge Maintenance, Safety and Management* (Philadelphia, PA), July 11–15, 2010. doi: 10.1201/b10430-481

Denysiuk, R., Fernandes, J., Matos, J., Neves, L. C., and Berardinelli, U. (2016). A computational framework for infrastructure asset maintenance scheduling. *Struct. Eng. Int.* 26, 94–102. doi: 10.2749/101686616X14555428759046

Dette, G., and Sigrist, V. (2011). "Performance indicators for concrete bridges," in *Proceedings of the Fib Symposium Prague 2011* (Prague).

Du, G., and Karoumi, R. (2013). Life cycle assessment of a railway bridge: comparison of two superstructure designs. *Struct. Infrastruct. Eng.* 9, 1149–1160. doi: 10.1080/15732479.2012.670250

Du, G., Safi, M., Petterson, L., and Karoumi, R. (2014). Life cycle assessment as a decision support tool for bridge procurement: environmental impact comparison among five bridge designs. *Int. J. Life Cycle Assess.* 19, 1948–1964 doi: 10.1007/s11367-014-0797-z

Duenas-Osorio, L., and Padgett, J. E. (2011). Seismic reliability assessment of bridges with user-defined system failure events. *J. Eng. Mech.* 137, 680–690. doi: 10.1061/(ASCE)EM.1943-7889.0000272

Dworakowski, Z., Kohut, P., Gallina, A., Holak, K., and Uhl, T. (2015). Vision-based algorithms for damage detection and localization in structural health monitoring. *Struct. Control Health Monit.* 23, 35–50. doi: 10.1002/stc.1755

Ehlen, M. A. (1997). Life-cycle costs of new construction materials. *J. Infrastruct. Syst.* 3, 129–133. doi: 10.1061/(ASCE)1076-0342(1997)3:4(129)

Elfergani, H. A., Pullin, R., and Holford, K. M. (2013). Damage assessment of corrosion in prestressed concrete by acoustic emission. *Constr. Build. Mater.* 40, 925–933. doi: 10.1016/j.conbuildmat.2012.11.071

Ellingwood, B. (2005). Risk-informed condition assessment of civil infrastructure: state of practice and research issues. *Struct. Infrastruct. Eng.* 1, 7–18. doi: 10.1080/15732470412331289341

Ellis, R. M., Evans, D. J., and McElhinney, C. (2016). "Practical performance measures for bridge management," in *IABMAS2016, Eighth International Conference on Bridge Maintenance, Safety and Management* (Foz do Iguacu), June 26–30, 2016.

Estes, A. C., and Frangopol, D. M. (1998). RELSYS: a computer program for structural system reliability. *Struct. Eng. Mech.* 6, 901–918. doi: 10.12989/sem.1998.6.8.901

Estes, A. C., and Frangopol, D. M. (2003). Updating bridge reliability based on bridge management systems visual inspection results. *J. Bridge Eng.* 8, 374–382. doi: 10.1061/(ASCE)1084-0702(2003)8:6(374)

Estes, A. C., and Frangopol, D. M. (2005). Load rating versus reliability analysis. *J. Struct. Eng.* 131, 843–847. doi: 10.1061/(ASCE)0733-9445(2005)131:5(843)

Fan, W., and Qiao, P. (2011). Vibration-based damage identification methods: a review and comparative study. *Struct. Health Monit.* 10, 83–111. doi: 10.1177/1475921710365419

Farrar, C. R., and Jauregui, D. A. (1998). Comparative study of damage identification algorithms applied to a bridge: I. Experiment. *Smart Mater. Struct.* 7:704. doi: 10.1088/0964-1726/7/5/013

Fernando, D., Adey, B. T., and Lehtanh, N. (2015). A model for the evaluation of intervention strategies for bridges affected by manifest and latent deterioration processes. *Struct. Infrastruct. Eng.* 11, 1466–1483. doi: 10.1080/15732479.2014.976576

Fernando, D., Adey, B. T., and Walbridge, S. (2013). A metholodgy for the prediction of structure level costs based on element condition states. *Struct. Infrastruct. Eng.* 9, 735–748. doi: 10.1080/15732479.2011.609176

FHWA (1988). *Visual Impact Assessment for Highway Projects*. Washington, DC: U.S. Department of Transportation.

Figueiredo, E., Park, G., Farrar, C. R., Worden, K., and Figueiras, J. (2011). Machine learning algorithms for damage detection under operational and environmental variability. *Struct. Health Monit.* 10, 559–572. doi: 10.1177/1475921710388971

Frangopol, D. M., and Curley, J. P. (1987). Effects of damage and redundancy on structural reliability. *J. Struct. Eng.* 113, 1533–1549. doi: 10.1061/(ASCE)0733-9445(1987)113:7(1533)

Frangopol, D. M., Iizuka, M., and Yoshida, K. (1992). Redundancy measures for design and evaluation of structural systems. *J. Offshore Mech. Arctic Eng.* 114, 285–290. doi: 10.1115/1.2919982

Frangopol, D. M., Kong, J. S., and Gharaibeh, E. M. (2001). Reliability-based life-cycle management of highway bridges. *J. Comput. Civil Eng.* 15, 27–34. doi: 10.1061/(ASCE)0887-3801(2001)15:1(27)

Frangopol, D. M., Lin, K. Y., and Estes, A. C. (1997). Life-cycle cost design of deteriorating structures. *J. Struct. Eng.* 123, 1390–1401. doi: 10.1061/(ASCE)0733-9445(1997)123:10(1390)

Frangopol, D. M., Strauss, A., and Kim, S. (2008). Bridge reliability assessment based on monitoring. *J. Bridge Eng.* 13, 258–270. doi: 10.1061/(ASCE)1084-0702(2008)13:3(258)

Gao, H., and Zhang, X. Q. (2013). A Markov-based road maintenance optimization model considering user costs. *Comput. Aided Civil Infrastruct. Eng.* 28, 451–464. doi: 10.1111/mice.12009

Gattulli, V., and Chiaramonte, L. (2005). Condition assessment by visual inspection for a bridge management system. *Comput. Aided Civil Infrastruct. Eng.* 20, 95–107. doi: 10.1111/j.1467-8667.2005.00379.x

Ghosh, J., and Padgett, J. E. (2010). Aging considerations in the development of time-dependent seismic fragility curves. *J. Struct. Eng.* 136, 1497–1511. doi: 10.1061/(ASCE)ST.1943-541X.0000260

Ghosh, J., and Padgett, J. E. (2011). Probabilistic seismic loss assessment of aging bridges using a component-level cost estimation approach. *Earthq. Eng. Struct. Dyn.* 40, 1743–1761. doi: 10.1002/eqe.1114

Ghosn, M., Dueñas-Osorio, L., Frangopol, D. M., McAllister, T. P., Bocchini, P., Manuel, L., et al. (2016b). Performance indicators for structural systems and infrastructure networks. *J. Struct. Eng.* 142:F4016003. doi: 10.1061/(ASCE)ST.1943-541X.0001542

Ghosn, M., Frangopol, D. M., McAllister, T. P., Shah, M., Diniz, S. M. C., Ellingwood, B. R., et al. (2016a). Reliability-based performance indicators for structural members. *J. Struct. Eng.* 142:F4016002. doi: 10.1061/(ASCE)ST.1943-541X.0001546

Ghosn, M., and Moses, F. (1998). *Redundancy in Highway Bridge Superstructures NCHRP Report 406*. Washington, DC: Transportation Research Board.

Goh, K. C., and Yang, J. (2010). "Responding to sustainability challenge and cost implications in highway construction projects," in *Proceedings of CIB 2010 World Congress* (Lowry, Salford Quays), May 10–13, 2010.

Gorener, A. (2012). Comparing AHP and ANP: an application of strategic decisions making in a manufacturing company. *Int. J. Bus. Social Sci.* 3, 194–208. Available online at: https://pdfs.semanticscholar.org/d93e/48d7fa1cde465aced6251943b37284ad0f49.pdf

Govindan, K., and Jepsen, M. B. (2016). ELECTRE: a comprehensive literature review on methodologies and applications. *Eur. J. Oper. Res.* 250, 1–29. doi: 10.1016/j.ejor.2015.07.019

Grandori, G., Guagenti, E., and Tagliani, A. (1998). A proposal for comparing the reliabilities of alternative seismic hazard models. *J. Seismol.* 2, 27–35. doi: 10.1023/A:1009779806984

Gucunski, N., Kee, S. H., and Basily, B. (2015). "Implementation of a fully autonomous platform for assessment of concrete bridge decks RABIT," in *Structures Congress 2015, April 23–25, 2015* (Portland, OR).

Gucunski, N., Maher, A., Ghasemi, H., and Ibrahim, F. S. (2012). "Segmentation and condition rating of concrete bridge decks using NDE for more objective inspection and rehabilitation planning," in *IABMAS2012, Sixth International Conference on Bridge Maintenance, Safety and Management, July 8–12, 2012* (Stresa). doi: 10.1201/b12352-83

Guinée, J. B., Gorée, M., Heijungs, R., Huppes, G., Kleijn, R., de Koning, A., et al. (2002). *Handbook on Life Cycle Assessment: Operational Guide to the ISO Standards*. Dordrecht: Kluwer Academic Publisher.

Guo, H. Y., Zhang, L., Zhang, L. L., and Zhou, J. X. (2004). Optimal placement of sensors for structural health monitoring using improved genetic algorithms. *Smart Mater. Struct.* 13:528. doi: 10.1088/0964-1726/13/3/011

Habert, G., Arribe, D., Dehove, T., Espinasse, L., and Le Roy, R. (2012). Reducing environmental impact by increasing the strength of concrete: quantification of the improvement to concrete bridges. *J. Clean. Prod.* 35, 250–262. doi: 10.1016/j.jclepro.2012.05.028

Habert, G., Bouzidi, Y., Chen, C., and Jullien, A. (2010). Development of a depletion indicator for natural resources used in concrete. *Resourc. Conserv. Recycl.* 54, 364–376. doi: 10.1016/j.resconrec.2009.09.002

Hadas, Y., Rossi, R., Gastaldi, M., Pellegrino, C., Zanini, M. A., and Modena, C. (2015). Optimal critical infrastructure retrofitting model for evacuation planning. *Transport. Res. Proc.* 10, 714–724. doi: 10.1016/j.trpro.2015.09.025

Haimes, Y. Y. (2006). On the definition of vulnerabilities in measuring risk to infrastructures. *Risk Anal.* 26, 293–296. doi: 10.1111/j.1539-6924.2006.00755.x

Hammervold, J., Reenaas, M., and Brattebo, H. (2013). Environmental life cycle assessment of bridges. *J. Bridge Eng.* 18, 153–161. doi: 10.1061/(ASCE)BE.1943-5592.0000328

Heijungs, R., Guinée, J., and Huppes, G. (1997). *Impact Categories for Natural Resources and Land Use*. CML-report 138. Leiden: Leiden University.

Hendawi, S., and Frangopol, D. M. (1994). System reliability and redundancy in structural design and evaluation. *Struct. Saf.* 16, 47–71. doi: 10.1016/0167-4730(94)00027-N

Hendy, C., and Petty, R. (2012). "Quantification of sustainability principles in bridge projects," in *IABMAS2012, Sixth International Conference on Bridge Maintenance, Safety and Management* (Stresa), July 8–12, 2012. doi: 10.1201/b12352-263

Hesse, A. A., Atadero, R. A., and Ozbek, M. E. (2015). Uncertainty in common NDE techniques for use in risk-based bridge inspection planning: existing data. *J. Bridge Eng.* 20:04015004. doi: 10.1061/(ASCE)BE.1943-5592.0000733

Hiasa, S., Catbas, F. N., Matsumoto, M., and Mitani, K. (2017). Considerations and issues in the utilization of infrared thermography for concrete bridge inspection at normal driving speeds. *J. Bridge Eng.* 22:04017101. doi: 10.1061/(ASCE)BE.1943-5592.0001124

Hofer, L., Zanini, M. A., Faleschini, F., and Pellegrino, C. (2018). Profitability analysis for assessing the optimal seismic retrofit strategy of industrial productive processes with business-interruption consequences. *J. Struct. Eng. ASCE* 144:4017205. doi: 10.1061/(ASCE)ST.1943-541X.0001946

Hooton, R. D., and Bickley, J. A. (2014). Design for durability: the key to improving concrete sustainability. *Constr. Build. Mater.* 67, 422–430. doi: 10.1016/j.conbuildmat.2013.12.016

Hoyland, A., and Rausand, M. (1994). *System Reliability Theory: Models and Statistical Methods*. New York, NY: Wiley-Interscience Publication, John Wiley and Sons.

Hsieh, K. H., Halling, M. W., and Barr, P. J. (2006). Overview of vibrational structural health monitoring with representative case studies. *J. Bridge Eng.* 11, 707–715. doi: 10.1061/(ASCE)1084-0702(2006)11:6(707)

ISO (2006a). *ISO 14040: Environmental Management? Life Cycle Assessment? Principles and Framework*. Geneva: International Organization for Standardization.

ISO (2006b). *ISO 14040: Environmental Management? Life Cycle Assessment? Requirements and Guidelines*. Geneva: International Organization for Standardization.

Jajac, N., Rogulj, K., and Radnic, J. (2017). Selection of the method for rehabilitation of historic bridges – a decision support concept for the planning of rehabilitation projects. *Int. J. Archit. Herit.* 11, 261–277. doi: 10.1080/15583058.2016.1207113

Jensen, B. B., Frolund, T., and Pedersen, T. (2006). "Current use of NDT in bridge condition assessment," in *IABMAS2006, Third International Conference on Bridge Maintenance, Safety and Management* (Porto), July 16–19, 2006. doi: 10.1201/b18175-398

Johnson, P. A., and Ayyub, B. M. (1992). Assessing time-variant bridge reliability due to pier scour. *J. Hydraul. Eng.* 118, 887–903. doi: 10.1061/(ASCE)0733-9429(1992)118:6(887)

Kawamura, K., and Miyamoto, A. (2003). Condition state evaluation of existing reinforced concrete bridges using neuro-fuzzy hybrid system. *Comput. Struct.* 81, 1931–1940. doi: 10.1016/S0045-7949(03)00213-X

Kee, S. H., and Gukunski, N. (2016). Interpretation of flexural vibration modes from impact-echo testing. *J. Infrastruct. Syst.* 22:04016009. doi: 10.1061/(ASCE)IS.1943-555X.0000291

Keoleian, G. A., Kendall, A., Dettling, J. E., Smith, V. M., Chandler, R. F., Lepech, M. D., et al. (2005a). Life cycle modeling of concrete bridge design: comparison of engineered cementitious composite link slabs and conventional steel expansion joints. *J. Infrastruct. Syst.* 11, 51–60. doi: 10.1061/(ASCE)1076-0342(2005)11:1(51)

Keoleian, G. A., Kendall, A., Dettling, J. E., Smith, V. M., Chandler, R. F., Lepech, M. D., et al. (2005b). "Life-cycle cost model for evaluating the sustainability of bridge decks," in *Proceedings of the 4th International Workshop on Life-Cycle Cost Analysis and Design of Civil Infrastructures Systems* (Cocoa Beach, FL), May 8–11, 143–150.

Kim, S., Frangopol, D. M., and Soliman, M. (2013). Generalized probabilistic framework for optimum inspection and maintenance planning. *J. Struct. Eng.* 139, 435–447. doi: 10.1061/(ASCE)ST.1943-541X.0000676

Kim, S., Lee, J. S., Choi, Y., and Shik Moon, Y. (2008). "Intelligent bridge management system based on the image data from robotic devices," in *IABMAS2008, Fourth International Conference on Bridge Maintenance, Safety and Management* (Seoul), July 13–17, 2008.

Kim, S. H., Choi, M. S., Mha, H. S., and Joung, J. Y. (2013). Environmental impact assessment and eco-friendly decision-making in civil structures. *J. Environ. Manage.* 126, 105–122. doi: 10.1016/j.jenvman.2013.03.045

Klöpffer, W., and Grahl, B. (2009). *Ökobilanz (LCA) Ein Leitfaden für Ausbildung und Beruf*. Weinheim: WILEYVCH.

Koch, C., Georgieva, K., Kasireddy, V., Akinci, B., and Fieguth, P. (2015). A review on computer vision based defect detection and condition assessment of concrete and asphalt civil infrastructure. *Adv. Eng. Inform.* 29, 196–210. doi: 10.1016/j.aei.2015.01.008

Koch, G. H., Brongers, M. P., Thompson, N. G., Virmani, Y. P., and Payer, J. H. (2002). *Corrosion Cost and Preventive Strategies in the United States (No. FHWAQ18 RD-01-156)* (Houston, TX), 77084–4906.

Kong, J. S., and Frangopol, D. M. (2003). Life-cycle reliability-based maintenance cost optimization of deteriorating structures with emphasis on bridges. *J. Struct. Eng.* 129, 818–828. doi: 10.1061/(ASCE)0733-9445(2003)129:6(818)

Kreißig, J., and Kümmel, J. (1999). Baustoff-Ökobilanzen. *Wirkungsabschätzung und Auswertung in der Steine-Erden-Industrie*. Berlin: Bundesverband Baustoffe Steine + Erden e.V.

Kumar, R., and Gardoni, P. (2014). Effect of seismic degradation on the fragility of reinforced concrete bridges. *Eng. Struct.* 79, 267–275. doi: 10.1016/j.engstruct.2014.08.019

Leemis, L. M. (1995). *Reliability, Probabilistic Models and Statistical Methods.* Englewood Cliffs, NJ: Prentice Hall, 288.

Li, Z., and Burgueno, R. (2010). Using soft computing to analyze inspection results for bridge evaluation and management. *J, Bridge Eng.* 15, 430–438. doi: 10.1061/(ASCE)BE.1943-5592.0000072

Liang, Y., Wu, D., Liu, G., Li, Y., Gao, C., Ma, Z. J., et al. (2016). Big data-enabled multiscale serviceability analysis for aging bridges. *Digital Commun. Netw.* 2, 97–107. doi: 10.1016/j.dcan.2016.05.002

Lind, N. C. (1995). A measure of vulnerability and damage tolerance. *Reliabil. Eng. Syst. Saf.* 43:1–6. doi: 10.1016/0951-8320(95)00007-O

Liu, H., Wang, X., Jiao, Y., He, X., and Wang, B. (2017). Condition evaluation for existing reinforced concrete bridge superstructure using fuzzy clustering improved by particle swarm optimization. *Struct. Infrastruct. Eng.* 13, 955–965. doi: 10.1080/15732479.2016.1227854

Liu, M., and Frangopol, D. M. (2006). Optimizing bridge network maintenance management under uncertainty with conflicting criteria: life-cycle maintenance, failure, and user costs. *J. Struct. Eng.* 132, 1836–1845. doi: 10.1061/(ASCE)0733-9445(2006)132:11(1835)

Liu, M., Frangopol, D. M., and Kim, S. (2010). Bridge system performance assessment from structural health monitoring: a case study. *J. Struct. Eng.* 135, 733–742. doi: 10.1061/(ASCE)ST.1943-541X.0000014

Liu, W. D., Ghosn, M., Moses, F., and Neuenhoffer, A. (2000). *Redundancy in Highway Bridge Substructures*, NCHRP Report 458, Washington, DC: Transportation Research Board.

Lopez-Higuera, J. M., Cobo, L. R., Incera, A. Q., and Cobo, A. (2011). Fiber optic sensors in structural health monitoring. *J. Lightw. Technol.* 29, 587–608. doi: 10.1109/JLT.2011.2106479

Lounis, Z., and Daigle, L. (2010). "Towards sustainable design of highway bridges," in *IABMAS2010, Fifth International Conference on Bridge Maintenance, Safety and Management* (Philadelphia, PA), July 11–15, 2010.

Lounis, Z., and McAllister, T. P. (2016). Risk-based decision making for sustainable and resilient infrastructure systems. *J. Struct. Eng.* 142:F4016005. doi: 10.1061/(ASCE)ST.1943-541X.0001545

Lynch, J. P., and Kenneth, J. L. (2006). A summary review of wireless sensors and sensor networks for structural health monitoring. *Shock Vib. Digest.* 38, 91–130. doi: 10.1177/0583102406061499

Maes, M. A., Fritzsons, K. E., and Glowienka, S. (2006). Structural robustness in the light of risk and consequence analysis. *Struct. Eng. Int.* 16, 101–107. doi: 10.2749/101686606777962468

Maes, M. A., Pandey, M. D., and Nathwani, J. S. (2003). Harmonizing structural safety levels with life-quality objectives. *Can. J. Civil Eng.* 30:500–510. doi: 10.1139/l02-112

Mara, V., Haghani, R., and Harryson, P. (2014). Bridge decks of fibre reinforced polymer (FRP): a sustainable solution. *Constr. Build. Mater.* 50, 190–199. doi: 10.1016/j.conbuildmat.2013.09.036

Marano, G. C., Quaranta, G., and Monti, G. (2011). Modified genetic algorithm for the dynamic identification of structural systems using incomplete measurements. *Comput. Aided Civil Infrastruct. Eng.* 26, 92–110. doi: 10.1111/j.1467-8667.2010.00659.x

Matthews, J. C., and Allouche, E. N. (2010). "A social cost calculator for utility construction projects," in *North American Society for Trenchless Technology (NASTT) No-Dig Conference* (Chicago, IL), May 2–7, 2010.

Mauch, M., and Madanat, S. (2001). Semiparametric hazard rate models of reinforced concrete bridge deck deterioration. *J. Infrastruct. Syst.* 7, 49–57. doi: 10.1061/(ASCE)1076-0342(2001)7:2(49)

McCarten, P. S. (2016). "Bridge performance measures: robustness – redundancy," in *IABMAS2016, Eighth International Conference on Bridge Maintenance, Safety and Management* (Foz do Iguacu), June 26–30, 2016.

McKone, T. E., and Hertwich, E. G. (2001). The human toxicity potential and a strategy for evaluating model performance in life cycle impact assessment. *Int. J. LCA* 6, 106–109. doi: 10.1007/BF02977846

Milà i Canals, L., Bauer, C., Depestele, J., Dubreuil, A., Knuchen, R. F., Gaillard, G., et al. (2007). Key elements in a framework for land use impact assessment within LCA. *Int. J. LCA* 12, 5–15. doi: 10.1065/lca2006.05.250

Mishalani, R. G., and Madanat, S. (2002). Computation of infrastructure transition probabilities using stochastic duration models. *J. Infrastruct. Syst.* 8, 139–148. doi: 10.1061/(ASCE)1076-0342(2002)8:4(139)

Moore, P. M., Graybeal, B. A., Rolander, D. D., and Washer, G. A. (2001). "Chapter 2: Literature review-Visual inspection of highway structures," in *Reliability of Visual Inspection for Highway Bridges* (McLean, VA: U.S. Department of Transportation-Federal Highway Administration), 22101–2296.

Morbin, R., Faleschini, F., Zanini, M. A., Caldon, M., Marchesini, F. P., Maiorana, E., et al. (2014). "Improvement of dynamic behaviour of the Varesine-Garibaldi footbridge (Milan, Italy) with TMD," in *Civil-Comp Proceedings, Vol. 106, Proceedings of the 12th International Conference on Computational Structures Technology CST2014* (Naples), 2–5 September 2014.

Morbin, R., Zanini, M. A., Pellegrino, C., Zhang, H., and Modena, C. (2015). A probabilistic strategy for seismic assessment and FRP retrofitting of existing bridges. *Bull. Earthq. Eng.* 13, 2411–2428. doi: 10.1007/s10518-015-9725-2

Muller, H. S., Haist, M., and Vogel, M. (2014). Assessment of the sustainability potential of concrete and concrete structures considering their environmental impact, performance and lifetime. *Constr. Build. Mater.* 67, 321–337. doi: 10.1016/j.conbuildmat.2014.01.039

Muzzammil, M., Siddiqui, N. A., and Siddiqui, A. F. (2008). Reliability considerations in bridge pier scouring. *Struct. Eng. Mech.* 28, 1–18. doi: 10.12989/sem.2008.28.1.001

Nahum, O. E., Hadas, Y., Zanini, M. A., Pellegrino, C., Rossi, R., and Gastaldi, M. (2017). Stochastic multi-objective evacuation model under managed and unmanaged policies. *Transport. Res. Proc.* 27, 728–735. doi: 10.1016/j.trpro.2017.12.156

Nair, A., and Cai, C. S. (2010). Acoustic emission monitoring of bridges: review and case studies. *Eng. Struct.* 32, 1704–1714. doi: 10.1016/j.engstruct.2010.02.020

Najafi, F. T., and Soares, R. (2001). User costs at the work zone. *Can. J. Civil Eng.* 28, 747–751. doi: 10.1139/l01-025

Nasrollahi, M., and Washer, G. (2015). Estimating inspection intervals for bridges based on statistical analysis of national bridge inventory data. *J. Bridge Eng.* 20:04014104. doi: 10.1061/(ASCE)BE.1943-5592.0000710

Neves, L. C., and Frangopol, D. M. (2005). Condition, safety and cost profiles for deteriorating structures with emphasis on bridges. *Reliabil. Eng. Syst. Saf.* 89, 185–198. doi: 10.1016/j.ress.2004.08.018

Nick, W., Asamene, K., Bullock, G., Esterline, A., and Sundaresan, M. (2015). A study of machine learning techniques for detecting and classifying structural damage. *Int. J. Mach. Learn. Comput.* 5:313. doi: 10.7763/IJMLC.2015.V5.526

Nonis, C., Niezrecki, C., Yu, T. Y., Ahmed, S., Su, C. F., and Schmidt, T. (2013). "Structural health monitoring of bridges using digital image correlation," in *Proceedings, Vol. 8695, Health Monitoring of Structural and Biological Systems 2013*. 869507. doi: 10.1117/12.2009647

Oh, J., Jang, G., Oh, S., Lee, J. H., Yi, B., Moon, Y. S., et al. (2009). Bridge inspection robot system with machine vision. *Autom. Constr.* 18, 929–941. doi: 10.1016/j.autcon.2009.04.003

Oh, T., Kee, S. H., Arndt, R. W., Popovics, J. S., and Zhu, J. (2013). Comparison of NDT methods for assessment of a concrete bridge deck. *J. Eng. Mech.* 139, 305–314. doi: 10.1061/(ASCE)EM.1943-7889.0000441

Okasha, N. M., and Frangopol, D. M. (2009). Lifetime-oriented multi-objective optimization of structural maintenance considering system reliability, redundancy and life-cycle cost using GA. *Struct. Saf.* 31, 460–474. doi: 10.1016/j.strusafe.2009.06.005

Okasha, N. M., and Frangopol, D. M. (2010a). Redundancy of structural systems with and without maintenance: an approach based on lifetime functions. *Reliabil. Eng. Syst. Saf.* 95, 520–533. doi: 10.1016/j.ress.2010.01.003

Okasha, N. M., and Frangopol, D. M. (2010b). Time-variant redundancy of structural systems. *Struct. Infrastruct. Eng.* 6, 279–301. doi: 10.1080/15732470802664514

Omar, T., and Nehdi, M. L. (2017). "Automated data collection for progress tracking purposes: a review of related techniques," in *Facing the Challenges in Structural Engineering. GeoMEast 2017. Sustainable Civil Infrastructures*, eds H. Rodrigues, A. Elnashai, and G. Calvi (Cham: Springer).

Omar, T., Nehdi, M. L., and Zayed, T. (2017a). Integrated condition rating model for reinforced concrete bridge decks. *J. Perform. Constr. Facil.* 31:04017090. doi: 10.1061/(ASCE)CF.1943-5509.0001084

Omar, T., Nehdi, M. L., and Zayed, T. (2017b). Performance of NDT techniques in appraising condition of reinforced concrete bridge decks. *J. Perform. Constr. Facil.* 31:04017104. doi: 10.1061/(ASCE)CF.1943-5509.0001098

Orcesi, A. D., and Frangopol, D. M. (2010). Inclusion of crawl tests and long-term health monitoring in bridge serviceability analysis. *J. Bridge Eng.* 15, 312–326. doi: 10.1061/(ASCE)BE.1943-5592.0000060

Orcesi, A. D., Frangopol, D. M., and Kim, S. (2010). Optimization of bridge maintenance strategies based on multiple limit states and monitoring. *Eng. Struct.* 32, 627–640. doi: 10.1016/j.engstruct.2009.11.009

Padgett, J. E., Spiller, A., and Arnold, C. (2012). Statistical analysis of coastal bridge vulnerability based on empirical evidence from Hurricane Katrina. *Struct. Infrastruct. Eng.* 8, 595–605. doi: 10.1080/15732470902855343

Padgett, J. E., and Tapia, C. (2013). Sustainability of natural hazard risk mitigation: life cycle analysis of environmental indicators for bridge infrastructure. *J. Infrastruct. Syst.* 19, 395–408. doi: 10.1061/(ASCE)IS.1943-555X.0000138

Pan, B., Tian, L., and Song, X. (2016). Real-time, non-contact and targetless measurement of vertical deflection of bridges using off-axis digital image correlation. *NDTE Int.* 79, 73–80. doi: 10.1016/j.ndteint.2015.12.006

Pan, N. F. (2007). Forecasting bridge deck conditions using fuzzy regression analysis. *J. Chin. Inst. Eng.* 30, 593–607. doi: 10.1080/02533839.2007.9671288

Pandey, M. D., Nathwani, J. S., and Lind, N. C. (2006). The derivation and calibration of the life-quality index (LQI) from economic principles. *Struct. Saf.* 28, 341–360. doi: 10.1016/j.strusafe.2005.10.001

Pang, B., Yang, P., Wang, Y., Kendall, A., Xie, H., and Zhang, Y. (2015). Life cycle environmental impact assessment of a bridge with different strengthening schemes. *Int. J. Life Cycle Assess.* 20, 1300–1311. doi: 10.1007/s11367-015-0936-1

Patidar, V., Labi, S., Sihna, K. C., Thompson, P. D., Shirole, A., and Hyman, W. (1991). Performance measures for enhanced bridge management. *Transport. Res. Rec. J. Transport. Res. Board* 1991, 43–53. doi: 10.3141/1991-06

Pellegrino, C., Zanini, M. A., Zampieri, P., and Modena, C. (2014). Contribution of *in situ* and laboratory investigations for assessing seismic vulnerability of existing bridges. *Struct. Infrastruct. Eng.* 11, 1–16. doi: 10.1080/15732479.2014.938661

Penadés-Plà, V., Garcìa-Segura, T., Martì, J. V., and Yepes, V. (2016). A review of multi-criteria decision-making methods applied to the sustainable bridge design. *Sustainability* 8:1295. doi: 10.3390/su8121295

Penadés-Plà, V., Martì, J. V., Garcìa-Segura, T., and Yepes, V. (2017). Life-cycle assessment: a comparison between two optimal post-tensioned concrete box-girder road bridges. *Sustainability* 9:1864. doi: 10.3390/su9101864

Pitonak, M., and Pepucha, L. (2016). "Economic indicators to assess the bridges of rehabilitation," in *IABMAS2016, Eighth International Conference on Bridge Maintenance, Safety and Management* (Foz do Iguacu), June 26–30, 2016.

Podvezko, V. (2011). The comparative analysis of MCDA methods SAW and COPRAS. *Eng. Econ.* 22, 134–146. doi: 10.5755/j01.ee.22.2.310

Prendergast, L. J., Limongelli, M. P., Ademovic, N., Anzlin, A., Gavin, K., and Zanini, M. A. (2018). Structural health monitoring for performance assessment of bridges under flooding and seismic actions. *Struct. Eng. Int.* 28, 296–307. doi: 10.1080/10168664.2018.1472534

Pushpakumara, J., De Silva, S., and De Silva, S. (2017). Visual inspection and non-destructive tests-based rating method for concrete bridges. *Int. J. Struct. Eng.* 8, 74–91. doi: 10.1504/IJSTRUCTE.2017.081672

Quirk, L., Matos, J., Murphy, J., and Pakrashi, V. (2017). Visual inspection and bridge management. *Struct. Infrastruct. Eng.* 14, 320–332. doi: 10.1080/15732479.2017.1352000

Rackwitz, R., Lentz, A., and Faber, M. (2005). Socio-economically sustainable civil engineering infrastructures by optimization. *Struct. Saf.* 27, 187–229. doi: 10.1016/j.strusafe.2004.10.002

Rahman, O. M. A. (1992). Visual quality and response assessment: an experimental technique. *Environ. Plan.* 19, 689–708. doi: 10.1068/b190689

Ramakumar, R. (1993). *Engineering Reliability: Fundamentals and Applications*. 1st Edn. Englewood Cliffs, NJ: Prentice Hall, 482.

Rantala, T. (2010). *Life Cycle Analysis of Mälkiä Canal Bridge*. Helsinki: Liikennevirasto, 25p.

Rashidi, M., Samali, B., and Sharafi, P. (2016). A new model for bridge management: part B: decision support system for remediation planning. *Aust. J. Civil Eng.* 14, 46–53. doi: 10.1080/14488353.2015.1092642

Rehman, S. K. U., Ibrahim, Z., Memon, S. A., and Jameel, M. (2016). Nondestructive test methods for concrete bridges: a review. *Constr. Build. Mater.* 107, 58–86. doi: 10.1016/j.conbuildmat.2015.12.011

Rezayat, M. (2009). *System and Method for Sustainability Analysis.* U.S. Patent Application No 12/630,900. Terrace Park, OH.

Robert, W. E., Weinblatt, H. B., and Pradhan, A. A. (2004). "The role of economic analysis in making engineering and political decisions," in *IABMAS2004, Second International Conference on Bridge Maintenance, Safety and Management* (Kyoto), October 18–22, 2004.

Rodrigues, J. N., Providencia, P., and Dias, A. M. P. G. (2017). Sustainability and lifecycle assessment of timber-concrete composite bridges. *J. Infrastruct. Syst.* 23:04016025. doi: 10.1061/(ASCE)IS.1943-555X.0000310

Rossi, B., Marquart, S., and Rossi, G. (2017). Comparative life cycle cost assessment of painted and hot-dip galvanized bridges. *J. Environ. Manage.* 197, 41–49. doi: 10.1016/j.jenvman.2017.03.022

Sabatino, S., Frangopol, D. M., and Dong, Y. (2015). Sustainability-informed maintenance optimization of highway bridges considering multi-attribute utility and risk attitude. *Eng. Struct.* 102, 310–321. doi: 10.1016/j.engstruct.2015.07.030

Salawu, O. S. (1997). Detection of structural damage through changes in frequency: a review. *Eng. Struct.* 19, 718–723. doi: 10.1016/S0141-0296(96)00149-6

Sarabando, P., and Dias, L. C. (2010). Simple procedures of choice in multicriteria problems without precise information about the alternatives' values. *Comput. Oper. Res.* 37, 2239–2247. doi: 10.1016/j.cor.2010.03.014

Sasmal, S., and Ramanjaneyulu, K. (2008). Condition evaluation of existing reinforced concrete bridges using fuzzy based analytic hierarchy approach. *Expert Syst. Appl.* 35, 1430–1443. doi: 10.1016/j.eswa.2007.08.017

Sasmal, S., Ramanjaneyulu, K., Gopalakrishnan, S., and Lakshmanan, N. (2006). Fuzzy logic based condition rating of existing reinforced concrete bridges. *J. Perform. Constr. Facil.* 20, 261–273. doi: 10.1061/(ASCE)0887-3828(2006)20:3(261)

Saydam, D., Bocchini, P., and Frangopol, D. M. (2013). Time-dependent risk associated with deterioration of highway bridge networks. *Eng. Struct.* 54, 221–233. doi: 10.1016/j.engstruct.2013.04.009

Saydam, D., and Frangopol, D. M. (2011). Time-dependent performance indicators of damaged bridge superstructures. *Eng. Struct.* 33, 2458–2471. doi: 10.1016/j.engstruct.2011.04.019

Sbartai, Z. M., Laurens, S., Elachachi, S. M., and Payan, C. (2012). Concrete properties evaluation by statistical fusion of NDT techniques. *Constr. Build. Mater.* 37, 943–950. doi: 10.1016/j.conbuildmat.2012.09.064

Shen, B., and Lepech, M. D. (2017). Probabilistic design of environmentally sustainable reinforced-concrete transportation infrastructure incorporating maintenance optimization. *J. Infrastruct. Syst.* 23:04016038. doi: 10.1061/(ASCE)IS.1943-555X.0000345

SimaPro7 (2008). *Software and Database Manual*. Amersfoort: PRé Consultants.

Simon, J., Bracci, J. M., and Gardoni, P. (2010). Seismic response and fragility of deteriorated reinforced concrete bridges. *J. Struct. Eng.* 136, 1273–1281. doi: 10.1061/(ASCE)ST.1943-541X.0000220

Smardon, R. C., and Hunter, M. (1983). "Procedures and methods for wetland and coastal areas visual impact assessment," in *The Future of Wetlands: Assessing Visual–Cultural Values*, ed R. C. Smardon (Totowa, NJ: Allanheld Osmun Publishers), 171–206.

Sobanjo, J. O., and Thompson, P. D. (2004). *Project Planning Models for Florida's Bridge Management System*. Tallahassee, FL: Florida State University.

Soliman, M., and Frangopol, D. M. (2014). Life-cycle cost evaluation of conventional and corrosion-resistant steel for bridges. *J. Bridge Eng.* 20:06014005. doi: 10.1061/(ASCE)BE.1943-5592.0015g100647

Sorensen, J. D., Rizzuto, E., Narasimhan, H., and Faber, M. H. (2012). Robustness: theoretical framework. *Struct. Eng. Int.* 22, 66–72. doi: 10.2749/101686612X13216060213554

Soyoz, S., and Feng, M. Q. (2009). Long-term monitoring and identification of bridge structural parameters. *Comput. Aided Civil Infrastruct. Eng.* 24, 82–92. doi: 10.1111/j.1467-8667.2008.00572.x

Starossek, U., and Haberland, M. (2011). Approaches to measures of structural robustness. *Struct. Infrastruct. Eng.* 7, 625–631. doi: 10.1080/15732479.2010.501562

Stephen, G. A., Brownjohn, J. M. W., and Taylor, C. A. (1993). Measurements of static and dynamic displacement from visual monitoring of the Humber Bridge. *Eng. Struct.* 15, 197–208. doi: 10.1016/0141-0296(93)90054-8

Stewart, M. G., and Rosowsky, D. V. (1998). Structural safety and serviceability of concrete bridges subject to corrosion. *J. Infrastruct. Syst.* 4, 146–155. doi: 10.1061/(ASCE)1076-0342(1998)4:4(146)

Strauss, A., Grossberger, H., Bergmeister, K., Zimmermann, T., Ralbovsky, M., Alten, K., et al. (2014). "Comprehensive infrastructure life-cycle assessment," in *IABMAS2014, Seventh International Conference on Bridge Maintenance, Safety and Management* (Shanghai), July 7–11, 2014. doi: 10.1201/b17618-25

Suksuwan, N., and Hadikusumo, H. W. (2010). Condition rating system for Thailand's concrete bridges. *J. Constr. Dev. Ctries.* 15, 1–27. Available online at: http://eprints.usm.my/42187/1/JCDC_Vol_15(1)_ART_1_(1-27).pdf

Sunkpho, J., and Garrett, J. H. (2003). Java inspection framework: developing field inspection support systems for civil systems inspection. *J. Comput. Civil Eng.* 17, 209–218. doi: 10.1061/(ASCE)0887-3801(2003)17:4(209)

Sustainable Bridges (2007). *Guideline for Inspection and Condition Assessment of Existing European Railway Bridges, Including Advices on the Use of Nondestructive Testing*. WG3 Project Report, (Luleå), 259.

Tabsh, S. W., and Nowak, A. S. (1991). Reliability of highway girder bridges. *J. Struct. Eng.* 117, 2372–2388. doi: 10.1061/(ASCE)0733-9445(1991)117:8(2372)

Tamiza, M., Jonesa, D., and Romerob, C. (1998). Goal programming for decision making: an overview of the current state-of-the-art. *Eur. J. Oper. Res.* 111, 569–581. doi: 10.1016/S0377-2217(97)00317-2

Tarighat, A., and Miyamoto, A. (2009). Fuzzy concrete bridge deck condition rating method for practical bridge management system. *Expert Syst. Appl.* 36, 12077–12085. doi: 10.1016/j.eswa.2009.04.043

Tecchio, G., Donà, M., Casarin, F., Islami, K., Zanini, M. A., Pellegrino, C., et al. (2013). "Monitoring fatigue effects in an orthotropic steel bridge deck," in *International IABSE Conference on Assessment, Upgrading and Refurbishment of Infrastructures* (Rotterdam), 6–8 May 2013. doi: 10.2749/222137813806521270

Tenzera, D., Puz, G., and Radic, J. (2012). Visual inspection in evaluation of bridge condition. *Gradevinar* 64, 717–726. Available online at: https://hrcak.srce.hr/87717

Thoft-Christensen, P. (2009). Life-cycle cost-benefit (LCCB) analysis of bridges from a user and social point of view. *Struct. Infrastruct. Eng.* 5, 49–57. doi: 10.1080/15732470701322818

Thompson, P. D. (2002). "User cost of accident risk in bridge management systems," in *IABMAS2002, First International Conference on Bridge Maintenance, Safety and Management* (Barcelona), July 14–17, 2002.

Transport Canada (2006). *Safety in Canada*. Report no TP11875E. Transport Canada-2003. Transport Canada (Ottawa, ON).

Umer, A., Hewage, K., Haider, H., and Sadiq, R. (2016). Sustainability assessment of roadway projects under uncertainty using Green Proforma: an index-based approach. *Int. J. Sustain. Built Environ.* 5, 604–619. doi: 10.1016/j.ijsbe.2016.06.002

Val, D. V., and Melchers, R. E. (1997). Reliability of deteriorating RC slab bridges. *J. Struct. Eng.* 123, 1638–1644. doi: 10.1061/(ASCE)0733-9445(1997)123:12(1638)

Valenzuela, S., de Solminihac, H., and Echaverugen, T. (2010). Proposal of an integrated index for prioritization of bridge maintenance. *J. Bridge Eng.* 15, 337–343. doi: 10.1061/(ASCE)BE.1943-5592.0000068

Valuch, M., and Pitonak, M. (2015). Economic analysis of bridges project rehabilitation. *Proc. Eng.* 111, 828–833. doi: 10.1016/j.proeng.2015.07.153

van Oers, L., and Guinee, J. (2016). The abiotic depletion potential: background, updates, and future. *Resources* 5:16. doi: 10.3390/resources5010016

Vanderzee, P. J. (2004). "The role of objective condition assessment for bridge asset management systems," in *IABMAS2004, Second International Conference on Bridge Maintenance, Safety and Management* (Kyoto), October 18–22, 2004.

Virtala, P. (1997). *Finnish PMS Expertise to Hungary Poland and Sweden. Newsletter of the Finnish Highway Transportation Technology Transfer Center 5*. Helsinki.

Vu, K. A. T., and Stewart, M. G. (2000). Structural reliability of concrete bridges including improved chloride-induced corrosion models. *Struct. Saf.* 22, 313–333. doi: 10.1016/S0167-4730(00)00018-7

Wallbank, E. J. (2002). "The application of sustainability to bridge management," in *IABMAS2002, First International Conference on Bridge Maintenance, Safety and Management* (Barcelona), July 14–17, 2002.

Wallbank, E. J., Tailor, P., and Vassie, P. R. (1999). "Strategic planning of future structures' maintenance needs," in *Management of Highway Structures*, ed P. C. Das (London: T. Telford), 163–172.

Walls, J., and Smith, M. R. (1998). *Life Cycle Cost Analysis in Pavement Design*. Pavement Division Interim Technical Bulletin, Publication No. FHWA-SA-98-079, (Washington, DC), 107.

Wang, X., Nguyen, M., Foliente, G., and Ye, L. (2007). An approach to modeling concrete bridge condition deterioration using a statistical causal relationship based on inspection data. *Struct. Infrastruct. Eng.* 3, 3–15. doi: 10.1080/15732470500103682

Wang, Y. M., and Elhag, T. M. S. (2008). Evidential reasoning approach for bridge condition assessment. *Expert Syst. Appl.* 34, 689–699. doi: 10.1016/j.eswa.2006.10.006

Wessels, J. F. M., Schoenmaker, R., van Meerveld, H., Bakker, J., and Schavemaker, J. (2014). "Introducing LCC in maintenance decision making on network level," in *Life-Cycle of Structural Systems: Design, Assessment, Maintenance and Management–Proceedings of the 4th International Symposium on Life-Cycle Civil Engineering, IALCCE 2014* (Tokyo), 16 November 2014. doi: 10.1201/b17618-232

Wilde, W., Waalkes, S., and Harrison, R. (2001). *Life Cycle Cost Analysis of Portland Cement Concrete Pavements*. Austin, TX: Center for Transportation Research, University of Texas at Austin.

Wilson, G., Blanchard, G., Laprade, D., Moore, K., O'Keefe, D., Wilson, K., et al. (1994). *Guide to Benefit-Cost Analysis in Transport Canada.* Report no TP11875E. Transport Canada (Ottawa, ON).

Wisniewski, D., Casas, J. R., and Ghosn, M. (2006). Load capacity evaluation of existing railway bridges based on robustness quantification. *Struct. Eng. Int.* 16, 161–166. doi: 10.2749/101686606777962440

Yadollahi, M., Nazari, R., Spanos, N. J., and Minner, N. (2016). An application of fuzzy factor analysis for sustainable bridge maintenance and retrofit projects. *Int. J. Manage. Sci. Eng.* 12, 225–236. doi: 10.1080/17509653.2016.61205528

Ye, X. W., Su, Y. H., and Han, J. P. (2014). Structural health monitoring of civil infrastructure using optical fiber sensing technology: a comprehensive review. *Sci. World J.* 2014:652329. doi: 10.1155/2014/652329

Yehia, S., Abudayyeh, O., Nabulsi, S., and Abdelqader, I. (2007). Detection of common defects in concrete bridge decks using nondestructive evaluation techniques. *J. Bridge Eng.* 12, 215–225. doi: 10.1061/(ASCE)1084-0702(2007)12:2(215)

Yoon, Y., and Hastak, M. (2017). Multitiered prioritizing method using urgency scale for bridge deck rehabilitation. *J. Infrastruct. Syst.* 23:04017020. doi: 10.1061/(ASCE)IS.1943-555X.0000381

Zambon, I., Vidovic, A., Strauss, A., Matos, J., and Amado, J. (2017). Comparison of stochastic prediction models based on visual inspections of bridge decks. *J. Civil Eng. Manage.* 23, 553–561. doi: 10.3846/13923730.2017.1323795

Zampieri, P., Zanini, M. A., and Faleschini, F. (2016). Derivation of analytical seismic fragility functions for common masonry bridge types: methodology and application to real cases. *Eng. Fail. Anal.* 68, 275–291. doi: 10.1016/j.engfailanal.2016.05.031

Zanini, M. A., Faleschini, F., Hofer, L., Franchetti, P., and Pellegrino, C. (2016c). "Maintenance and seismic retrofit cost assessment of existing bridges," in *8th International Conference on Bridge Maintenance, Safety and Management IABMAS2016* (Foz do Iguacu), 26–30 June 2016.

Zanini, M. A., Faleschini, F., and Pellegrino, C. (2016a). "Bridge life-cycle prediction through visual inspection data updating," in *5th International Symposium on Life-Cycle Civil Engineering IALCEE2016* (Delft), 16–19 October 2016.

Zanini, M. A., Faleschini, F., and Pellegrino, C. (2016b). "Seismic loss assessment of deteriorating bridge networks," in *8th International Conference on Bridge Maintenance, Safety and Management IABMAS2016* (Foz do Iguacu), 26–30 June 2016.

Zanini, M. A., Faleschini, F., and Pellegrino, C. (2016d). Cost analysis for maintenance and seismic retrofit of existing bridges. *Struct. Infrastruct. Eng.* 12, 1411–1427. doi: 10.1080/15732479.2015.1133661

Zanini, M. A., Faleschini, F., and Pellegrino, C. (2017a). Bridge residual service-life prediction through Bayesian visual inspection and data updating. *Struct. Infrastruct. Eng.* 13, 906–917. doi: 10.1080/15732479.2016.1225311

Zanini, M. A., Faleschini, F., and Pellegrino, C. (2017b). Probabilistic seismic risk forecasting of aging bridge networks. *Eng. Struct.* 136, 219–232. doi: 10.1016/j.engstruct.2017.01.029

Zanini, M. A., Faleschini, F., Zampieri, P., Pellegrino, C., Gecchele, G., Gastaldi, M., et al. (2017c). Post-quake urban road network functionality assessment for seismic emergency management in historical centers. *Struct. Infrastruct. Eng.* 13, 1117–1129. doi: 10.1080/15732479.2016.1244211

Zanini, M. A., Pellegrino, C., Morbin, R., and Modena, C. (2013). Seismic vulnerability of bridges in transport networks subjected to environmental deterioration. *Bull. Earthq. Eng.* 11, 561–579. doi: 10.1007/s10518-012-9400-9

Zhang, W., Wang, N., and Nicholson, C. (2017). Resilience-based post-disaster recovery strategies for road-bridge networks. *Struct. Infrastruct. Eng.* 13, 1404–1413. doi: 10.1080/15732479.2016.1271813

Zhao, Z., and Chen, C. (2002). A fuzzy system for concrete bridge damage diagnosis. *Comput. Struct.* 80, 629–641. doi: 10.1016/S0045-7949(02)00031-7

Zhu, B., and Frangopol, D. M. (2012). Reliability, redudancy and risk as performance indicators of structural systems during their life-cycle. *Eng. Struct.* 41, 34–49. doi: 10.1016/j.engstruct.2012.03.029

Zhu, W., Setunge, S., Gamage, N., Gravina, R., and Venkatesan, S. (2017). Evaluating time-dependent reliability and probability of failure of reinforced-concrete bridge components and predicting residual capacity after subsequent rehabilitation. *J. Perform. Constr. Facil.* 31:04017005. doi: 10.1061/(ASCE)CF.1943-5509.0000975

Zobel, C. W. (2011). Representing perceived tradeoffs in defining disaster resilience. *Decis. Support Syst.* 50, 394–403. doi: 10.1016/j.dss.2010.10.001

Zonta, D., Bortot, F., and Zandonini, R. (2008). "A condition index based on the concept of apparent age," in *IABMAS2008, Fourth International Conference on Bridge Maintenance, Safety and Management* (Seoul), July 13–17, 2008.

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