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**Research Paper**

# From quality control to decision-making on the management of bridges and structures: What's next?

***José C. Matos [a], Sérgio Fernandes [a], Hélder S. Sousa [a], Mário Coelho [a], Elisabete Teixeira [a], Yina Moscoso [a], Joaquim Tinoco [a]***

*[a] ISISE, University of Minho, Campus de Azurém, Av. da Universidade, 4800-058 Guimarães,, Portugal*

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The process of managing a stock of existing bridges and structures is extremely complex and challenging. At the same time, it is considered as one of the most relevant and important fields for civil engineers, involving academics, researchers, consultants, contractors, and owners. Indeed, in the recent years, several national and international R&D funded projects raised this topic, and many international associations, such as EuroStruct, IABSE& fib, started commissions and task groups on this field. This work consists on an overview of the most recent matters on this field, covering the whole cycle, from the quality control, addressing extreme events, to the decision making process. Also, it will be given a focus on the recent developments on the assessment and forecasting the performance of bridge and other structures. Finally, an overview will be made for different types of structures, specifically those related to transport infrastructures.

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## 1 Introduction

Quality Control is associated with systems development to ensure that products and services meet or exceed the expectations and needs of users and community [1]. Concerning bridges and structures the asset management and quality control are two sides of the same coin. However, there is agrowing need of developing approaches to ensure the quality of the entire structure, with the aim of reducing the risk of unexpected costs [1].

Numerous critical assets that ensure the mobility of goods and people are reaching their design lifetime. Of these structures, some show a more accelerated degree of deterioration as a result of man-made or natural hazards, but also due to poor design and/or poor construction enhanced by excessive traffic loads [2]. In order to keep these assets within acceptable performance levels, maintenance actions based on extensive life cycle approaches are required [2]. Moreover, is crucial the

* *Corresponding author. Tel.: +351965817678.*
E-mail address: jmatos@civil.uminho.pt

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definition of a holistic and integrative management approach capable of encompassing the following stages: i) condition monitoring and inspection; ii) modelling and assessment of performance; iii) adaptive interventions and retrofitting; iv) standardization of best practices in management and maintenance [2]. Additionally, the harmonization of various codes and standards to allow the definition of new guidelines is also required [1].

## 2 The quality control framework

### *2.1 Performance Indicators*

Significant research has been carried out in relation to the assessment of bridge condition, including the concept of performance indicators (PI) [3]. This concept allows the implementation of quality control (QC) plans which compare assessed PIs, with pre-specified performance goals (PG). PIs, in particular Key Performance Indicators (KPI), make it possible to express a set of objectives aimed to establish QC plans which ensure desired bridge quality service. By quantifying and assessing bridge performance, as well as quality specifications to assure an expected performance level, bridge management strategies can be significantly improved, enhancing asset management of ageing constructions [4].

Management systems, taking different degradation processes, are very often used in relation to lifecycle analyses methods. Such systems, developed for a structural condition assessment, are usually based on deterministic performance prediction models which describe the future condition by a functional correlation between structural condition characteristics, such as the structural age, and the mechanical, chemical and thermal loading processes. The practical implementation of such models needs detailed information about its variables, being important to analyse such indicators in terms of used assessment frameworks, and in terms of the quantification procedure itself [4].

### *2.2 Performance Goals*

The concept of efficient transport network management is the “process of maintaining and improving the existing road network to enable its continued use by traffic efficiently and safely, normally in a manner that is effective and environmentally sensitive; a process that is attempting to optimize the overall performance of the road network over time” [5]. Maintaining the national road network plays an important role in achieving strategic goals. However, the relationship between goals and network performance is not exclusive as, for example, network performance may be dependent on traffic patterns, weather conditions, economic growth and oil prices. It is therefore often not possible to derive PIs directly from network level goals [4].

A functioning transport infrastructure network requires structures such as bridges. To ensure bridge performance is in accordance with network level, individual bridge PGs must be set. However, the definition of bridge PIs can present difficulties. Since the estimated lifetime of a bridge is usually longer than the time scale for which network PGs defined, bridge PGs should ease life cycle optimization as well as to allow short term PGs to be met. In addition, while it is desired that the condition of the bridge be expressed in objectives that reflect the performance of the network, bridge management is focused on condition assessment [4].

A clear definition of the required performance forms the start of the process of risk based inspections. The demands on a network level will be translated to demands for parts of the network and subsequently to demands for single infrastructures. The terminology criteria can be related to performance and sub-criteria to PG. These criteria can be applied during inspection and maintenance processes [6, 7], but the link from PIs obtained and the exact criteria addressed, doesn’t necessarily have to be direct. However, to assess PGs, KPIs determined from a number of PIs collected at an operational level need to be defined at strategic and tactical level [4].

Bridge inspections are generally carried out on the bridge component level and often are divided into subsystem groups, i.e. substructure, superstructure, roadway. Through bridge inspections a number of PIs are collected and analysed (processed), in order to determine the aggregated KPI at the system level. Those PIs are usually related to technical aspects of the bridge performance, mostly defined as structural performance or reliability [4].

When the reliability level is in a deteriorated state, maintenance options need to be considered for each bridge below the threshold. Usually three main options are considered: (i) do nothing; (ii) do minor repair; (iii) do major repair or reconstruction. The chosen maintenance option will have both direct and indirect impacts, such as direct costs related to the maintenance activity and indirect costs caused by maintenance activities borne by society (e.g. user delay, environmental impacts). The direct impacts are regularly determined as owner costs and will represent economy performance aspects of the bridge. Other impacts can be categorized as availability and environmental aspects. Traffic safety is also a performance aspect which can be quantified at two periods, during the regular operation and during maintenance activities [4].

From this intricacy between inputs can be concluded that multiple bridge PGs should be set as a multi-objective system, taking into account different aspects of bridge and network performance [4].

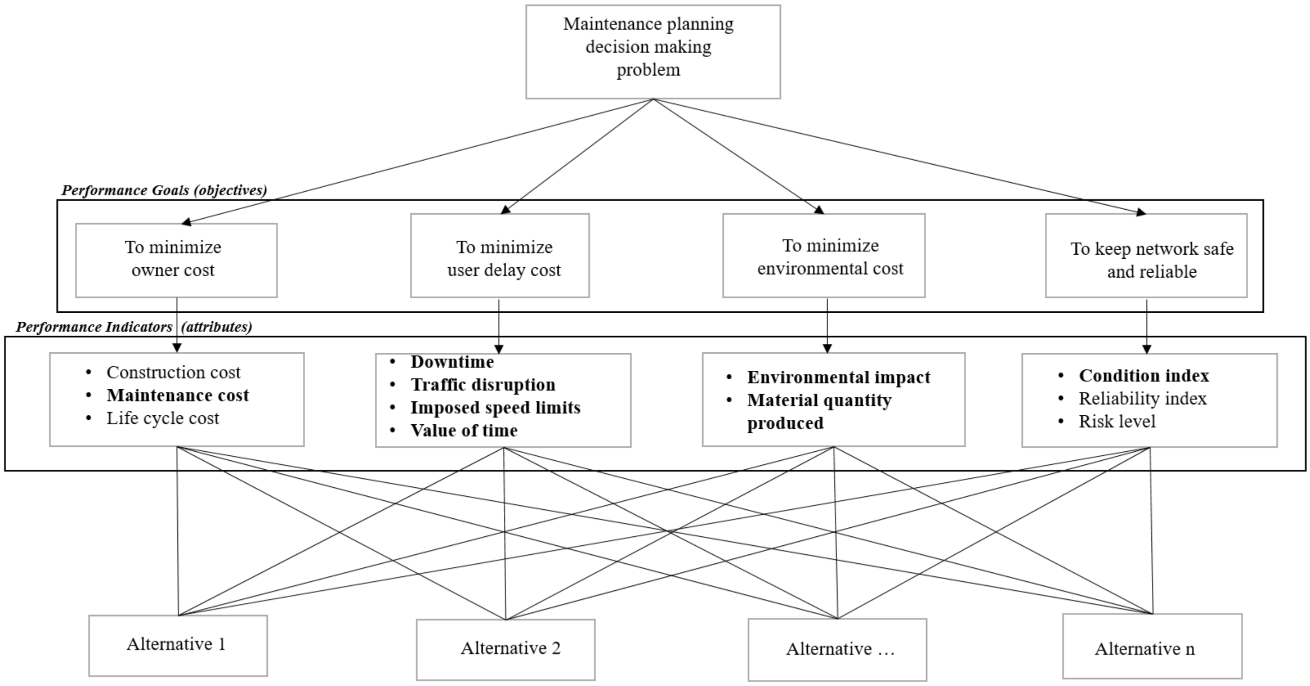


***Fig. 1 – Linking multiple PGs (called multiple objective) to PIs (adapted from [8]).***

Multi-criteria decision-making (MCDM) provides a systematic approach to combine these inputs with cost/benefit information and decision-maker or stakeholder views to rank alternatives. Hierarchy structure for linking multi-objective bridge PGs, covering most of the before mentioned aspects with PIs is shown in figure 1 (adapted from [8]).

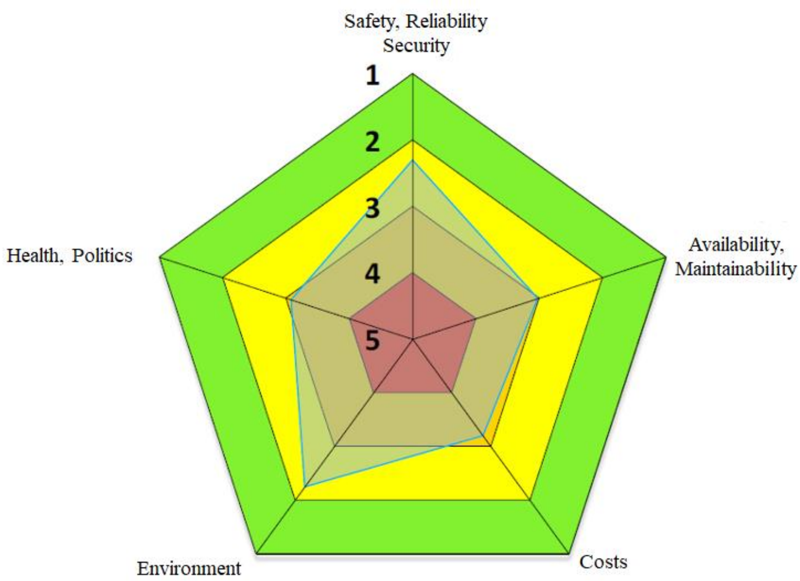


***Fig. 2 – Spider diagram for multi-criteria assessment.***

MCDM is used to identify and quantify decision-maker and stakeholder considerations about various (mostly) non-monetary factors in order to compare alternative courses of action. Hierarchy structure for linking multi-objective bridge PGs with PIs is required. Possible result of multi-criteria assessment of different bridge maintenance alternatives can be depicted in a spider diagram (Fig. 2) to be used for a decision making about the optimal maintenance or design solution. Alternatively, multiple performance criteria can be combined into a so-called utility function, in which all the criteria are brought into a single scale [4]. In doing so, the best decision can be found as a formal optimized process, in which the selected option has the maximum "utility" [4].

Multi-attribute utility theory (MAUT) make available a systematic approach to reduce the qualitative values of various attributes (i.e. PIs) into utility functions. The obtained utility scores are then aggregated based on the relative importance of attributes. The final score assigns a ranking to each alternative based on either minimization or maximization function [4].

### *2.3 Quality Control Plan*

Quality specifications or QC frameworks aim to provide a methodology with detailed step-by-step explanations for the establishment of QC plans for different bridge types. These plans relate user/society goals, such as: (i) Reliability: including the probability of structural failure (structural safety) or operational failure (serviceability); (ii) Availability: the proportion of time a system is in a functioning condition. In our case is the additional travel time due to imposed traffic regime on the bridge; (iii) Safety (not structural safety): minimize or eliminate people harm during the service life; (iv) Economy: minimize life-cycle cost; (v) Environment: minimize the harm to environment during the service life of a bridge. Fig. 3 shows the structure that supports bridge QC plans.

Quality control plans are also divided in 2 groups: (i) Static (snap shot) control: to inspect and investigate the bridge and determine whether reliability (structural safety and serviceability) and safety are met. This is fundamentally the basis for the decision making on actions; (ii) Dynamic control: based on the static control and including the plan and actions to execute in order to ensure the long-term fulfilment of safety and serviceability goals. The goals to achieve are related to availability, economy and sustainability as it includes the feasible maintenance scenarios that define costs and availability over a certain time frame by using reliability and safety forecasts.

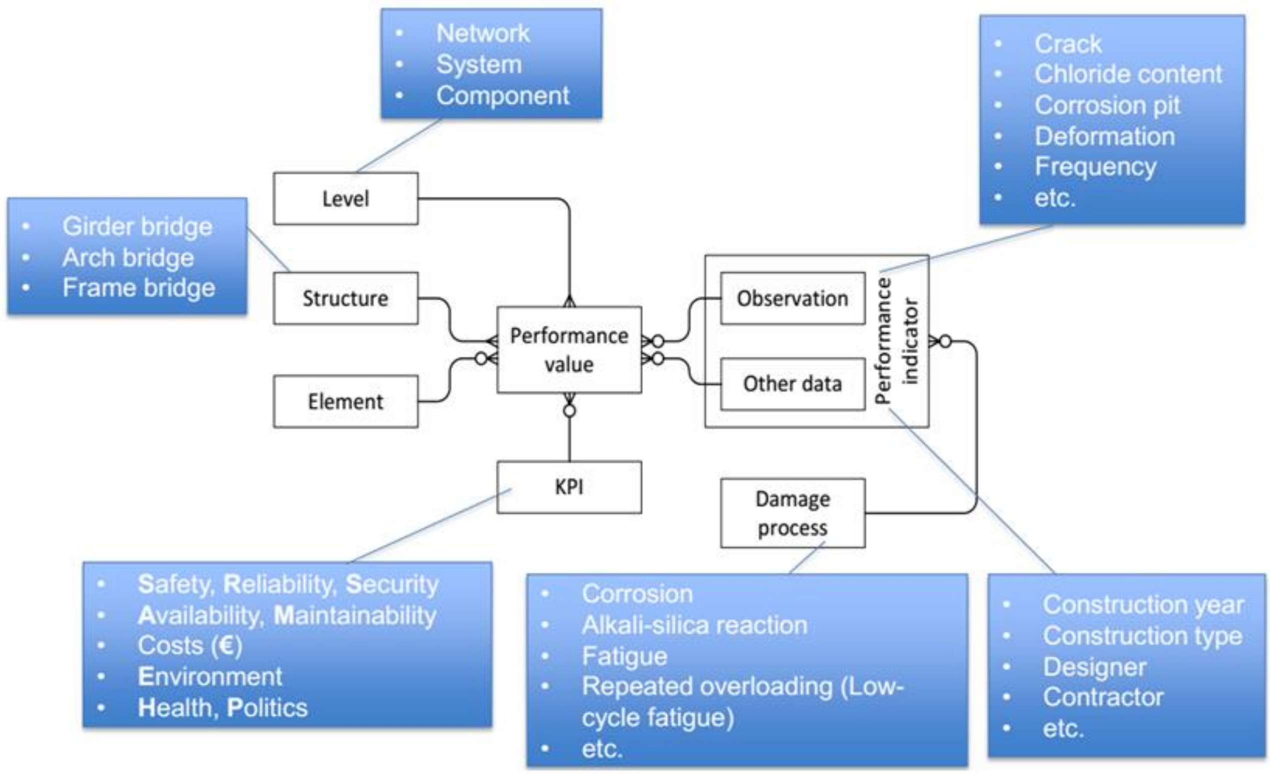


*Fig. 3 – Quality control plan structure.*

As the reliability target must be verified in relation to feasible failures, the practical application of the method requires the categorization of the global group of bridges in types: frame, arch, continuous beam. For each of these bridge types the most vulnerable zones can be identified and the corresponding PIs related to reliability observed and/or quantified. This division also helps in the process of selecting the best maintenance policy. The goals of availability, economics and sustainability are governed by maintenance scenarios. In fact, the snapshot assessment of availability and costs are of none or little interest. Therefore, the feasible maintenance scenarios (do nothing, preventive and corrective) are defined (figure 4).

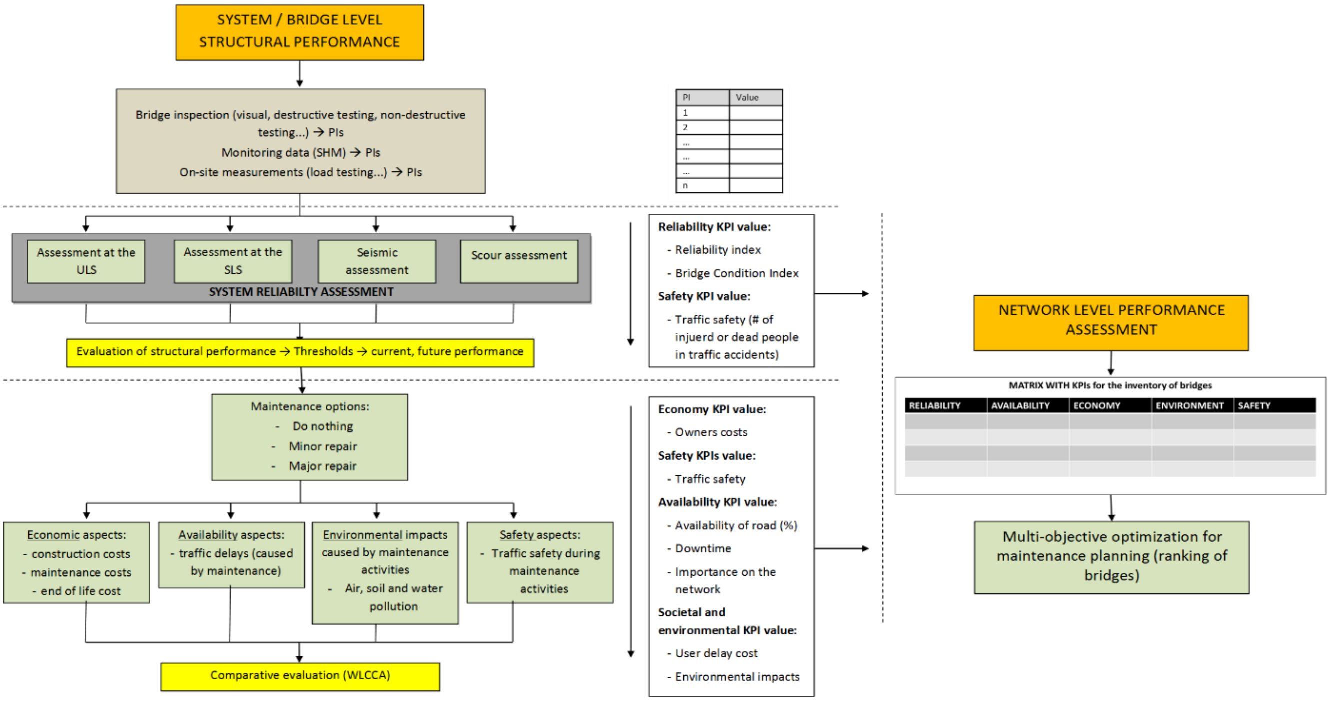


***Fig. 4 – Quality control procedure and maintenance scenarios.***

Regarding the availability indicator, each maintenance intervention requires certain traffic regime, which may include closure for certain type of vehicles or lane closure or narrower lanes. The normal traffic regime can be assigned with the maximum performance value. The other traffic regimes can be ranked by the additional travel time they cause for the road users. This additional travel time can be also monetized. The selected intervention scenario is obtained through MAUT based on the results presented in the diagrams as in 5 [4].

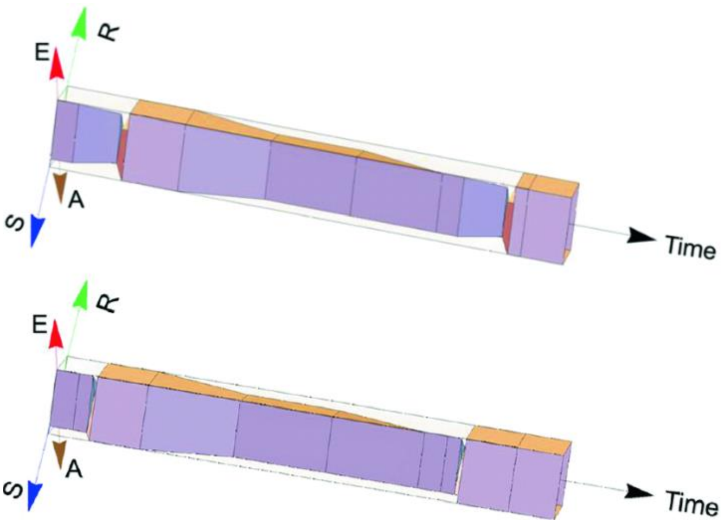


***Fig. 5 – Reference and preventative scenarios. KPI through time [4].***

## 3 From quality control to decision-making

### *3.1 Performance predictive models*

In the past, different models have been used to predict bridges' performance evolution. Depending on the approach adopted, these models can be grouped into five major categories [9, 10], namely:

- Physical models: this type of models considers the mechanical behavior of the bridge components, as well as the deterioration mechanism undergoing and influencing the performance evolution. Some examples of physical models include carbonation-induced corrosion, chloride-induced corrosion, alkali-aggregate reaction and freeze/thaw attack, among other;

- Deterministic models: likewise, physical models, deterministic models are based on a set of analytical expressions. However, deterministic category includes models that are deduced essentially in a mathematical fashion. This category includes multiple linear regressions, polynomial regressions and ordinal logistic regressions, and similar regression-based models;

- Stochastic models: in this category can be found all those models that include uncertainty, regardless to its source, in the prediction process. Majority of bridge management systems available worldwide use predictive models of this category. Particularly, Markov models (including pure, semi and hidden versions) are the most widely used;

- Artificial intelligence (AI) models: this category has been increasingly used in the last years, benefiting from the widespread of AI algorithms and tools. These models aim at exploring the large amounts of data available from multiple monitoring sources existing nowadays, which is not possible using previous models. Models based in artificial neural networks (ANN), machine learning, fuzzy logic and case-based reasoning, are just few examples of what can be found recently in the literature;

- Other: besides the four categories mentioned before, there can be also found some other prediction models. These, even though used with promising results in many cases, do not fall within a single category thus are grouped in this last and generic category. Bayesian networks and Petri nets are two examples of such king of prediction models.

Some interesting and novel studies, comparing these different tools were developed such as that provided in figure 6 [10]. In this case the ANN is compared to pure, semi and hidden Markov. The analysis is made for the NBI data system and for a hundred years of lifetime analysis. The results showed that, in this case, the ANN provide a much higher efficiency when compared with the other three models [10].

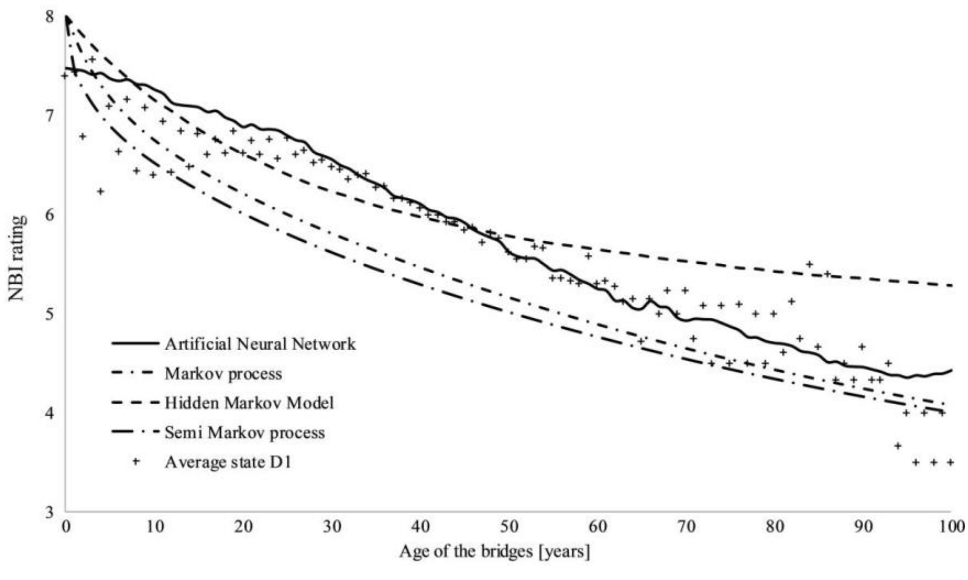


***Fig. 6 – Comparative studies of different performance predictive models [10].***

The predictive models used for bridges and transportation infrastructures, can also be used to determine the behaviour of other infrastructures. Accordingly, for this reason, they will be used in the R&D project Intelligent Port Infrastructures Management (GIIP), in which it seeks to implement sensors in a selected infrastructure of the port of Leixões, located in North Portugal, analyse its evolution in a certain time and then foresee the behaviour of the structure in a future time. The main objective of the GIIP project is to develop a modular decision support system for integrated asset management, based on new functional and infrastructural degradation models for different asset types, and taking into account operational, economic, and environmental criteria. The decision support system to be developed under this project represents an innovative solution both at national and international levels, by allowing a truly integrated approach for asset management, promoting maritime transportation inter-modality and interoperability.

## 4 Management of bridges and structures: What's next?

Maritime infrastructures are essential for a sustainable development of any country. However, some of them present important cliff stability problems, either in their road access, or in the interface with the sea. In fact, these geotechnical assets present significant threats to land use and development, namely due to cliff recession or coastal land-sliding. Occasional injuries and deaths due to cliffs falls and the cumulative loss of land, cliff top properties, services and infrastructures are problems that have long been experienced on unprotected cliff lines. Therefore, due to its natural characteristics, together with the strong exposition to erosive factors (e.g. wave exposure or rainfall), the cliffs require a continuum and detailed observation since its failure can have severe constraints for social and economic activities. Accordingly, it is important the development of integrated systems for cliffs management over the sea front, namely in the harbor zones. Such system will allow a more efficient management of these geotechnical assets, by improving the quality of available data in each moment, improving the future performance forecasts, and take better decisions regarding the need of mitigation/repair interventions.

Nowadays, it is also known that, critical civil infrastructures during their service life are subject to gradual deterioration such as corrosion and fatigue as well as deterioration caused by natural hazards such as: earthquakes, hurricanes, floods, and fire [11]. To fulfil their functionality, intervention actions such as inspections, maintenance and repair are needed, and this inevitably leads to life-cycle costs of the infrastructures [11]. So, it is important to develop a risk assessment framework focused on Urban Critical Infrastructures vulnerability and their interdependencies against multiple natural hazards. This risk models need to take into consideration: (i) the Urban Critical Infrastructure definition; (ii) the risk assessment modelling; (iii) the predictive models; (iv) validation of these models with the creation of risk scenarios and applied in study cases; and, finally, the (v) development of a definition matrix of priorities.

More important than the risk assessment analysis, is its incorporation in an innovative technological solution for protection and management of these critical infrastructures. This technological solution intends that the management, protection, and prediction of the risk related to a certain event is made in an integrated and real time, as well as in a collaborative, modular and prepared Geographic Information System (GIS) platform to work with large volume of data, in order to: manage the registration of critical infrastructures, achieve maps of criticality, monitor the evolution of the degree of criticality of the infrastructures under analysis, crossing it with a map of vulnerability for different types of events and determine the zones affected by an event and its consequences, from the results generated by the simulation of those events, to which are associated vulnerability maps [11].

In this sense, a hazard map is a map that highlights areas that are affected by, or are vulnerable, to a particular hazard. They are normally created for natural hazards, such as earthquakes, volcanoes, landslides, flooding and tsunamis. Meanwhile, a vulnerability map gives the exact location of sites where people, the natural environment or property are at risk due to a potentially disastrous event, that could result in death, injury, pollution and/or other destruction. Such maps are made in conjunction with material about different risk types.

Already now and tending to increase, is the decision making process based on network resilience, not only assuming structural issues but also relating to societal recovery. In this concern, the study of resilience is associated to with the society's response to sudden unwanted events, involving social, political, economic and environmental aspects.

This performance bases management, includes the strategies to reduce impact prior to an extreme event, as well as strategies to reduce the consequences of an extreme event both during and post event. Thus, the post event is also characterized by the selection and adoption of proper strategies that will affect and measure the response and recovery of society. In this scenario both empirical and analytical recovery functions may be used to characterize this response, as well as short and long-term recovery models (figure 7).

This is often the way to go, but it is needed to assume that this analysis will be dictated by the chosen KPI. Society may react and recover adequately with respect to a given KPI and may have a poor answer to another. Attending to this, decision supporting systems (DDS) must consider a multi-objective optimization problem, where the aim is to obtain an optimal scheduling of risk mitigation actions for a given period of time attending. Some interesting works concerning the novel application of optimization algorithms within a DSS can be seen in [12, 13].

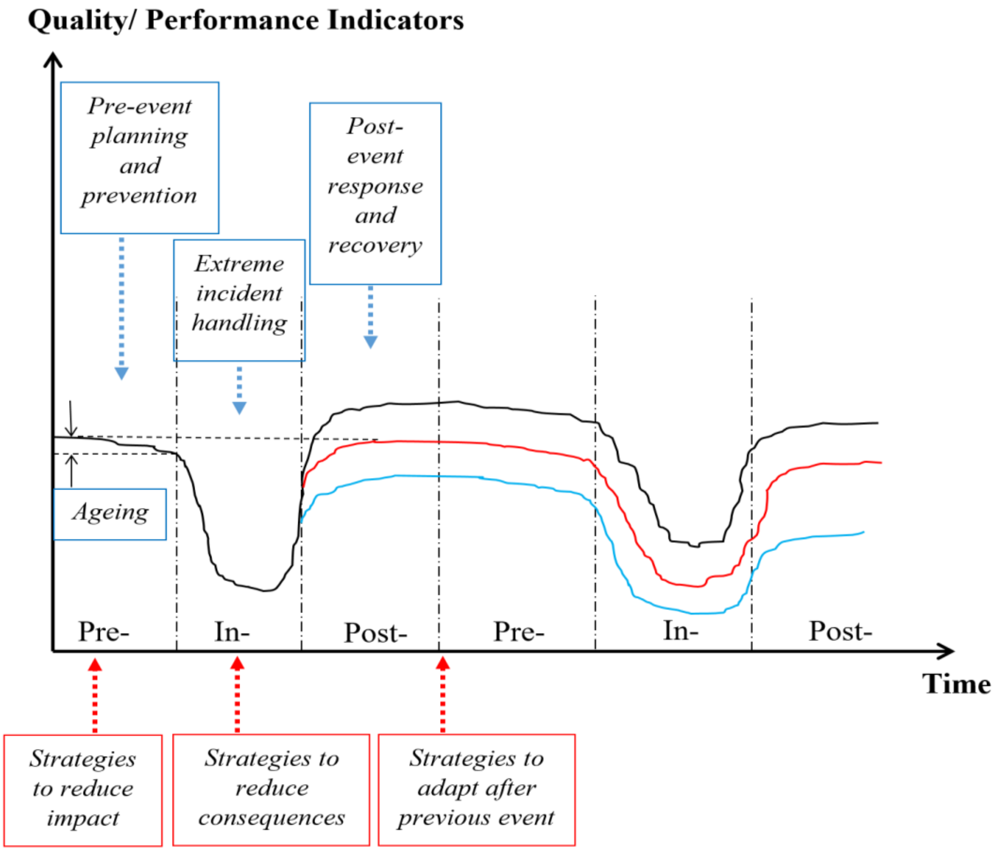


*Fig. 7 – Combining ageing with extreme events on the management of infrastructures.*

## 5 Conclusion

This paper proposed on an overview of the most recent matters on this field, covering the whole cycle, from the quality control, addressing extreme events, to the decision making process. Also, show that in the recent developments on the assessment and forecasting the performance of bridge and other structures, more important than the risk assessment analysis, is its incorporation in an innovative technological solution for protection and management of these infrastructures.

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