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Strategies for low limit maintenance thresholds and condition states for bridge structures

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Abstract

The objectives of asset management are to ensure secure service of the objects and/or network, to preserve the infrastructure capital and to maintain the function through their life cycle. Maintenance activities should preserve the performance and future serviceability in such way that an adequate level of reliability with respect to performance requirements applicable to the structure under consideration is preserved. Hence adequate and low limit maintenance should guarantee reliability, safety functionality, availability, maintainability, health and security, as well as environmental and economic performance at the politically agreed level of service. In order to arrange resources, the concept of condition-states and minimum maintenance thresholds are widely used in context of maintenance planning in many European countries. However, there is no uniform approach defining and rating the condition-states and setting the low limit maintenance thresholds. In general, national authorities or individual operators are using their own developments which consequently lead to different levels of service. In many cases, the models and criteria used are based on country-specific experience with implementation of condition-based maintenance strategies. Moreover, in some European countries, preventive maintenance uses both condition-based and scheduled maintenance strategy, with certain maintenance measures carried out in a condition-based manner and some other measures are planned/fixed at certain intervals. In this contribution based on the outcomes of IM-SAFE project, maintenance concepts, condition-state definitions and low limit thresholds of maintenance strategies of European countries will be presented, discussed and compared. In addition, a special focus is given to apply sustainable measures and to develop maintenance strategies respecting the European green deal scopes.

Keywords

Maintenance concepts, Condition-state, Low limit maintenance threshold, Bridge structure

1 Introduction

Any structure is subject to degradation during its lifetime, depending on various factors such as environmental conditions, natural aging, material quality, workmanship, and planned maintenance [1]. Therefore, different design procedures based on the prediction of deterioration acting on the structure need to be characterized and defined, e.g., by using performance indicators for present and future structure conditions. The deterioration of a construction, during its life cycle, will face with on several factors such as the environmental condition, the natural aging, the quality of the material, the execution of works and the planned maintenance. Therefore, in context of Asset Management, transport infrastructure assets are usually assessed based on condition classification, which generally ranges from fully functional (new), good (functional/satisfactory), adequate (functional-/requiring minor intervention), poor (functional/requiring major intervention), to deficient (non-functional).

The sound safety assessment and maintenance decision-making process shall take into consideration the impact of the condition rating of the structures as part of the structural diagnosis process. In addition, both for new and for existing structures, the life cycle perspective should be considered. Therefore, the life cycle analysis methods are instrumental to determine the maintenance strategies and management systems that capture relevant degradation processes are often used in conjunction with such life cycle analyses [2].

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In order to identify the critical performance path, performance indicators (PIs) can be formulated to evaluate and to predict the development and the effect of deterioration for the material and structure (e.g. stiffness/flexibility/robustness, load bearing capacity, internal forces, stresses, deflections, accelerations, crack sizes, but also safety for people, energy consumption, usability, availability, etc.).

Usually, three main options for maintenance are to be considered, ranging from:

- doing nothing,
- performing regular maintenance, conducting minor repairs and, finally, major repair or
- reconstruction.

When the structure is in a deteriorated state, which can be determined from (the evolution of) its condition or performance level (it includes reliability aspects like structural safety, serviceability or durability), the maintenance options need to be considered with particular care. Maintenance activities bring benefits but come with associated costs and environmental impact [2] and [4]. The direct impacts are regularly calculated as owners' cost and will represent the economic performance aspects of the structure. Other impacts are often categorized as availability and environmental performance aspects. Traffic safety during the regular operation and the during maintenance activities is also one of the relevant performance aspects that is influenced by maintenance. The indirect impact, like traffic deviation, traffic jump etc. create very often much higher macro-economical costs and a multiple environmental impact.

Figure 1 provides an overview of multiple performance goals (objectives) and associated performance indicators/attributes related to process of maintenance planning.

When deciding about the maintenance, the rational way to proceed is to consider decision criteria expressed in terms of relevant thresholds. However, at present there is no uniform and generally adopted European approach to defining and rating the condition states and setting the low limit maintenance thresholds. In general, national authorities or individual operators are using their own developments and set low limit maintenance thresholds for their infrastructure assets that may substantially differ from each other, which consequently lead to different levels of service across Europe with regard to e.g. reliability and availability of infrastructures assets (in context of this discussion the reliability with regard to structural safety is perceived as an attribute of overall reliability of structures in the context of RAMS). In many cases, the condition states rating, the condition and performance evaluation models and the decision criteria used to determine maintenance decisions (such as e.g. the threshold levels) are based on the decades of country-specific experience with implementation of corrective maintenance for infrastructure assets. At the same time in a constantly increasing number of European countries preventive maintenance strategy are being used, both condition-based and predetermined (i.e. scheduled) maintenance, with certain maintenance measures (e.g. rehabilitation)

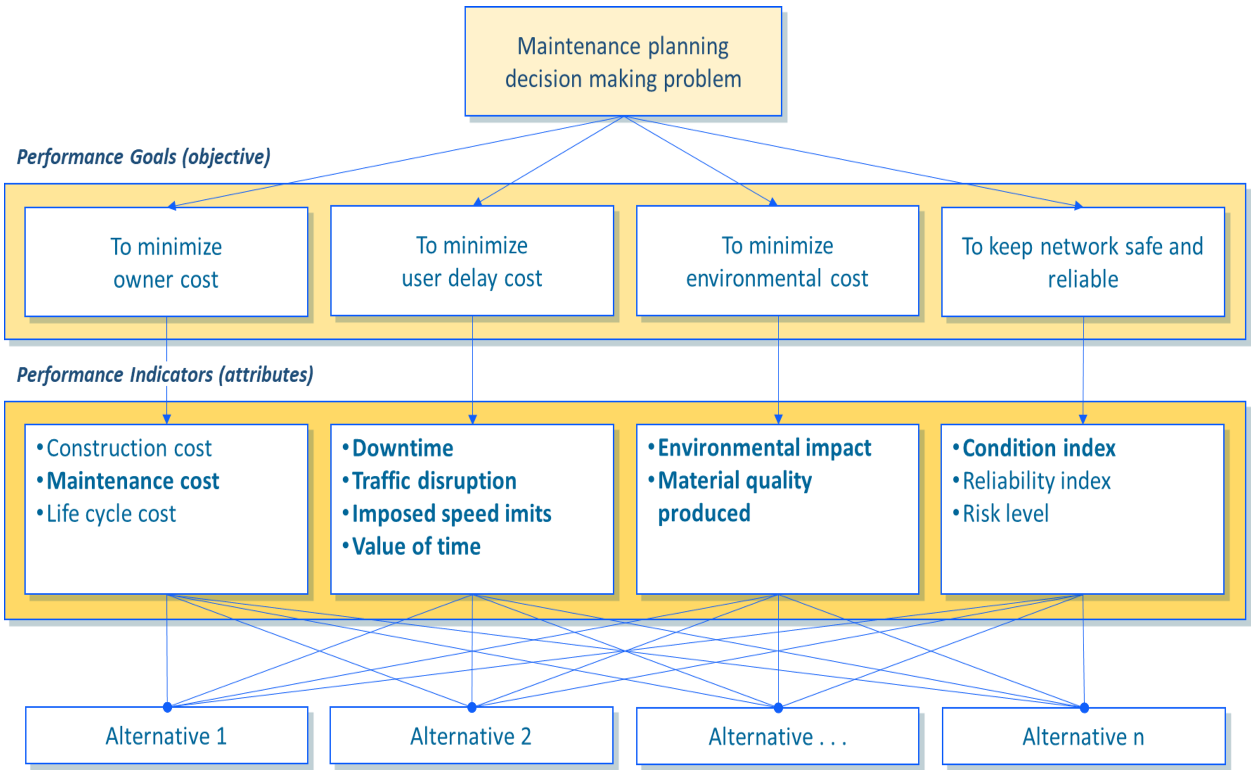

Figure 1 Linking multiple performance goals, objectives to performance indicators [5]

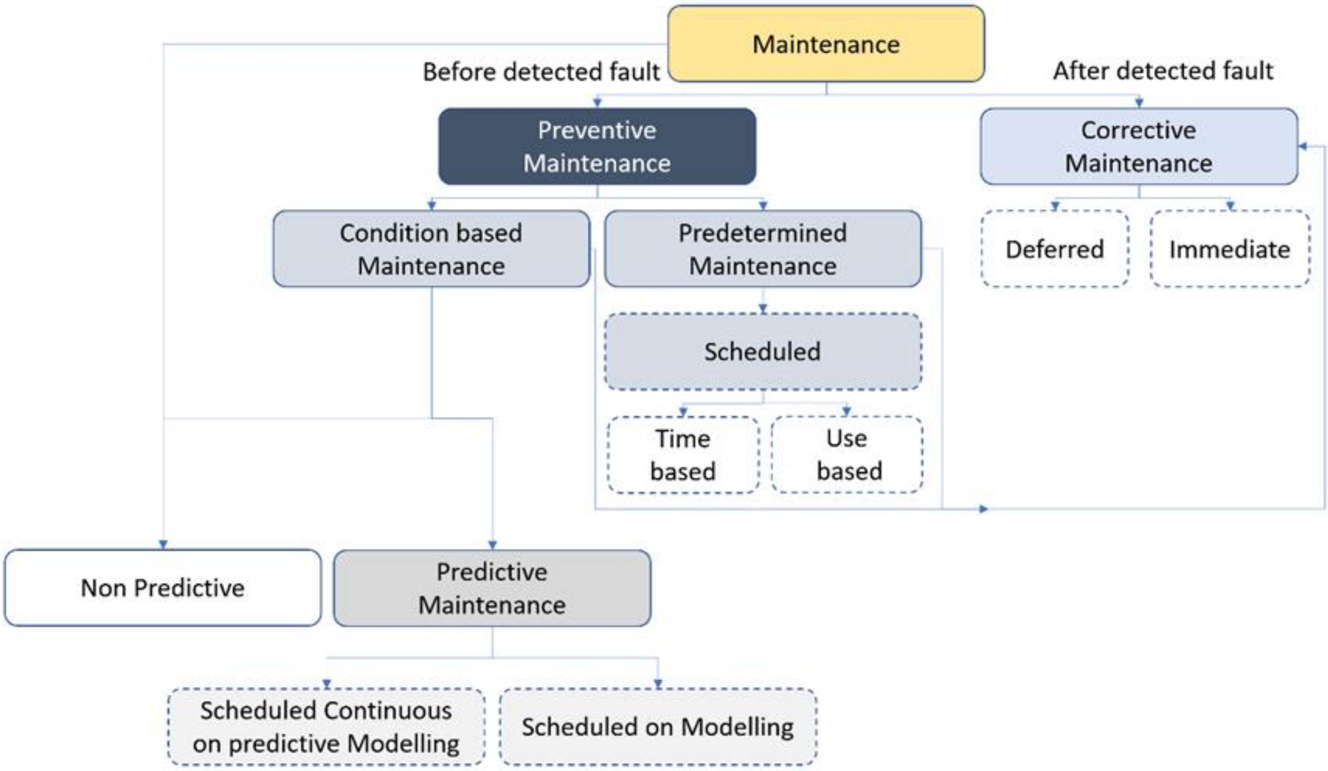

Figure 2 Maintenance strategies applied in engineering practice [6]

determined in a condition-based manner and some other measures (e.g. cleaning, deforestation) are planned/fixed at certain intervals. The minimum condition requirements associated with maintenance thresholds are frequently not clear or are variable over time.

Figure 2 shows a schematic overview of the maintenance approaches commonly used in engineering, such as (i) preventive maintenance and (ii) corrective maintenance, (iii) predictive maintenance and (iv) reliability/risk centred maintenance approach. Within the particular maintenance approaches number of individual strategies can be distinguished.

2 Maintenance in engineering practice

In the following sections the maintenance strategies are briefly discusses as applied in the engineering practice in case of various approaches to condition survey (i.e. routine monitoring, inspections, already set up in the individual countries and to provide an overview in form of a first simplified statistical evaluation of the methods implemented in the countries.

2.1 Routine monitoring

Rational behind: Routine monitoring serves to determine the functionality of infrastructures and the road safety of roadways and equipment. It covers the detection of gross damage and conspicuous changes, as far as they are visible from a vehicle when driving over infrastructures. In general, routine monitoring is processed during inspection trips by the roadway service employees or persons of equivalent competence. Routine monitoring is carried out on all structures to be maintained from the traffic level for visible defects and changes, as far as they are visible, when driving from the vehicle, such as: (a) Unusual changes to the structure, (b) Damage to the road surface including side beams, (c) Damage to equipment such as transition structures, railings, guard rails, noise protection devices, snow and spray protection devices, (d) Damage to drainage facilities, (e) Damage to embankments, (f) Damage to any existing object-related traffic signs and information signs.

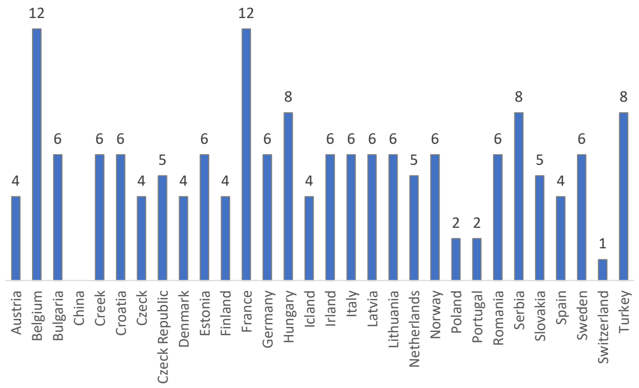

Figure 3 Time intervals between routine monitoring in month according to surveys in COST TU1406 [6]

Time intervals: As shown in figure 3, in the European countries the routine monitoring is performed every 2 to 8 months according to the COST TU1406 surveys [6].

These intervals were determined mostly based on expert estimation for occurring damages, depending on climatic conditions, traffic load and winter maintenance. In many cases, the available budget and manpower were also cited.

2.2 Inspections

Rational behind: The change in the state of preservation compared to the last inspection event (inspection/testing) is determined, documented and assessed. This is usually done by visual inspection and in the future with digital imaging technologies, unless components are to be inspected more closely in accordance with special inspection instructions. A trained engineer or experienced technical personnel should be entrusted with the execution.

Time intervals: In the European countries, inspections are mostly carried out at intervals of two to four years or, if the condition of the object requires it, at shorter intervals, see figure 4. After extraordinary events such as floods, earthquakes, avalanches or debris flows, landslides, accidents (fire or impact of vehicles), the affected structures are specifically checked for their possible impact.

The inspection intervals, as shown in figure 4, are more or less closely related to the routine monitoring considerations and the associated time intervals are determined based on the occurring damages, climatic conditions, traffic load and winter maintenance, the available budget and manpower, as described in the COST TU1406 surveys [6] and IM-SAFE project report [4] information.

Maintenance strategy: Inspection procedures can be assigned to the preventive maintenance strategy since there is the intention to a continuous observation of the condition class development. However, if the structure is already in a certain poor condition class, some countries prefer to apply a corrective maintenance strategy, see COST TU1406 WP1 survey [6] and IM-SAFE project report [2].

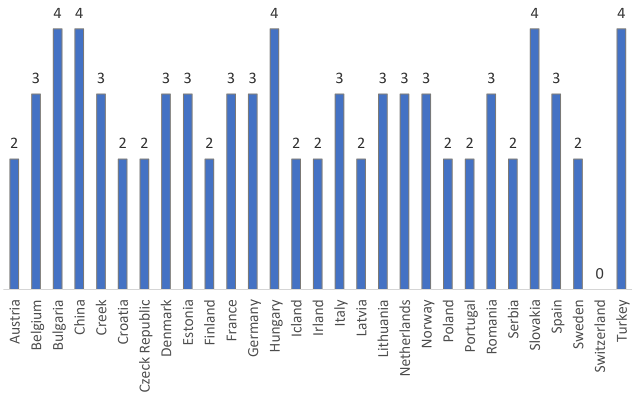

Figure 4 Time intervals between inspection in years according to surveys in COST TU1406 [6]

2.3 Main inspection

Rational behind: During the main inspection, the conservation status is surveyed based on a close inspection by hand, documented and evaluated. If needed, necessary measures are suggested. In consultation with the party responsible for maintenance, the documentation must also be in the form of meaningful visual material that can be clearly assigned to the inspected location on the object, e.g. on the basis of plan drawings. Only experienced engineer should carry out the main inspection. The expert must be able to assess the basic structural condition of the object, to estimate the influence of damage on the load-bearing capacity, robustness, serviceability and durability of the structure. In the course of the assessment, the evaluation of the following components should be planned:

- Substructure… Foundation elements, abutments, piers, wing walls, channels, embankments, etc.
- Superstructure… Supporting structure
- Surface course… pavement, sidewalk and cycle path pavement and their connections Bridge bearings
- Expansion joints… Expansion joint structure including elastic pavement expansion joints
- Sealing… drainage Bridge sealing and drainage facilities such as drains, drain pipes, fasteners
- Edge beams… edge beams including curbs and edge beam joints
- Other equipment… Railings, vehicle restraint systems, noise protection equipment, splash protection, drop guards, lighting, lines, general traffic signs, object related traffic signs (e.g. clearance, weight restriction), etc.

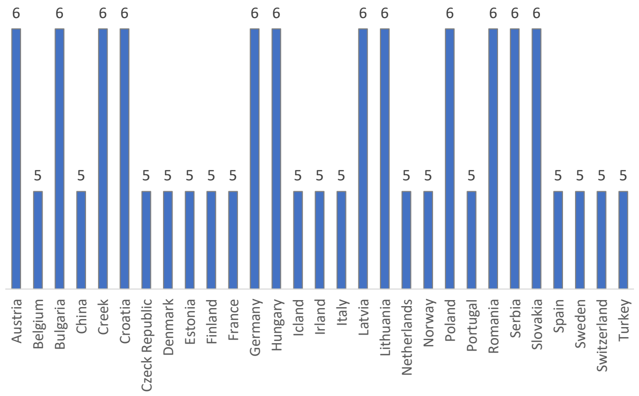

Figure 5 Time intervals between main inspection in years according to surveys in COST TU1406 [6]

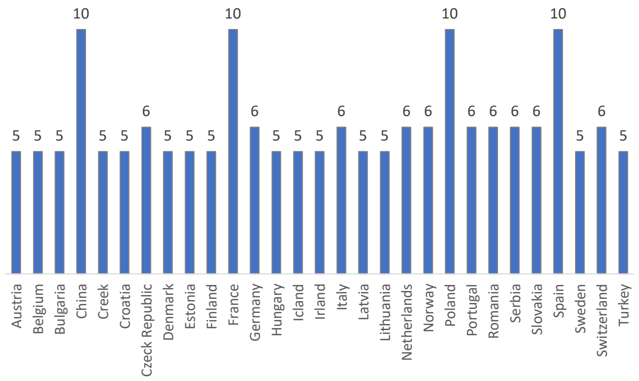

Figure 6 Number of condition classes of condition based monitoring strategies according to the surveys in COST TU1406 [6]

Measurement programs: If a bridge has a measurement program (geotechnical parameters, geodetic information, crack widths etc.) or monitoring system in place, the measurement results shall be included in the evaluation.

Time intervals: Structures such as bridges are usually inspected at intervals of about six years, see figure 5, or at shorter intervals if the condition of the object requires it. Some countries also allow an extension if there are no moving parts or with simple static conditions. The prerequisite for this is that the inspections are carried out properly and on time and that the serviceability of the object is confirmed to the previous extent. Figure 5 displays the outcome of the inspection interval studies from the COST TU1406 surveys.

Condition Classes: The number of condition classes of the condition based monitoring strategies handled in each individual countries are shown in figure 6.

3 Maintenance in context of structural assessment

Within the European IM-SAFE project a proposal was made for the implementation of performance indicators and key performance indicators in the various assessment phases. According to the IM-SAFE project report [2] breaking down the performance assessment of a structure or any other facility into a minimum of three phases is reasonable. In order to respect and include also the environmental impact within a maintenance concept, a fourth phase should be included. Figure 7 presents these phases in a schematic flow chart, which is herein explained in the context of the maintenance strategies.

3.1 Preliminary assessment (Condition assessment level I: visual inspection)

The purpose of Preliminary assessment or condition assessment level I visual inspection is to remove existing doubts about the performance using fairly simple but suitable methods.

The purpose of preliminary assessment (phase I) is to remove existing doubts about the performance using fairly simple methods, which must, however, be adequate. The information gained in phase I must be summarised in a report for the owner and must result in key performance requirement rating in terms of key performance requirement indexes (KPRs), which are required for the strategic asset management and budget allocation decisions. In this context key performance requirement are defined as: *Requirements set for the primary function(s) of an asset that further specify the functional requirement(s), usually in terms of reliability, availability, maintainability, safety, security, health, environment, economics and politics, aiming at meeting a specified functional requirement(s) during the service life at appropriate service level.* In COST TU1406 key performance requirements (KPRs) are referred to as key performance indicators (KPI).

The performance evaluation process illustrated in figure 7 is based on anomaly detection and aims to determine the KPR level. In case of unsatisfactory KPR level, assessment may be continued via phase II procedure, provided that the costs of phase II are justified. In this phase I, the following maintenance strategies are generally used, as outlined in table 1.

– Corrective maintenance (predominantly in those classes indicating bad condition)
– Preventive-condition based maintenance (predominantly in those classes indicating good condition)
– Preventive-predictive maintenance (hardly ever used)

Table 1 Maintenance strategies used in phase I, based on [2]

	Prev.-M.	Corr.-M.	Pred.-M.
Austria	+	+	O
Belgium	+	+	+
Bulgaria	O	+	O
China	+	+	O
Greek	+	+	O
Croatia	+	+	O
Czech Republic	+	+	O
Denmark	+	+	+
Estonia	+	+	O
Finland	+	+	O
France	+	+	O
Germany	+	+	O
Hungary	+	+	O
Iceland	+	+	O
Ireland	+	+	O
Italy	+	+	O
Latvia	+	+	O
Lithuania	+	+	O
Netherlands	+	+	+
Norway	+	+	+
Poland	O	+	+
Portugal	+	+	O
Romania	O	+	O
Serbia	O	+	O
Slovakia	+	+	O
Spain	+	+	O
Sweden	O	+	O
Switzerland	+	+	O
Turkey	+	+	O
United Kingdom	+	+	O
United States	+	+	O

3.2 Detailed investigations (Condition assessment level II: Detailed Inspection, testing and monitoring campaign)

Structural investigations and updating of information are typical of phase II Detailed investigations. Performance indicators or observations in this phase are mainly received from detailed inspection, testing and monitoring campaigns, see figure 7. The additional information gained e.g. from the performance indicators of these investigations can be introduced into confirmatory calculations with the aim of finally dispelling or confirming any doubts as to whether the structure is safe. In this phase II, the following maintenance strategies are generally used, as outlined in table 2.

– Corrective maintenance (is rarely in this phase II)
– Preventive-condition based maintenance (is frequently in this phase II)
– Preventive-predictive maintenance (partly initiated in this phase II)
– Corrective maintenance (is rarely in this phase II)
– Preventive-Condition based Maintenance (is frequently in this phase II)
– Preventive-Predictive Maintenance (partly initiated in this phase II)

Table 2 Maintenance strategies used in phase II, based on [2]

	Prev.-M.	Corr.-M.	Pred.-M.
Austria	+	O	+
Belgium	+	O	+
Bulgaria	O	O	O
China	+	O	O
Greek	+	O	O
Croatia	+	O	+
Czech Republic	+	+	O
Denmark	+	+	+
Estonia	+	O	O
Finland	+	O	O
France	+	O	+
Germany	+	O	+
Hungary	+	O	O
Iceland	+	O	O
Ireland	+	+	O
Italy	+	+	O
Latvia	+	O	O
Lithuania	+	O	O
Netherlands	+	O	+
Norway	+	O	+
Poland	O	+	O
Portugal	+	+	+
Romania	O	O	O
Serbia	O	O	O
Slovakia	+	+	O
Spain	+	+	+
Sweden	O	O	O
Switzerland	+	+	+
Turkey	+	O	O
United Kingdom	+	O	+
United States	+	O	+

Table 3 Maintenance strategies used in phase III, based on [2]

	Prev.-M.	Corr.-M.	Pred.-M.
Austria	+	O	+
Belgium	O	O	+
Bulgaria	O	O	O
China	+	O	+
Greek	+	O	+
Croatia	O	O	+
Czech Republic	O	+	+
Denmark	+	+	+
Estonia	O	O	+
Finland	O	O	+
France	O	O	+
Germany	+	O	+
Hungary	O	O	O
Iceland	O	O	+
Ireland	O	+	+
Italy	+	+	+
Latvia	O	O	O
Lithuania	O	O	+
Netherlands	+	O	+
Norway	+	O	+
Poland	O	+	+
Portugal	+	+	+
Romania	O	O	+
Serbia	O	O	O
Slovakia	+	+	+
Spain	+	+	+
Sweden	O	O	+
Switzerland	+	+	+
Turkey	O	O	O
United Kingdom	O	O	+
United States	+	O	+

3.3 Assessment and prediction by advanced analysis (condition assessment level III: structural health monitoring and modelling)

For problems with substantial consequences, an advanced analysis for performance assessment and performance prediction should be planned to carefully check the proposal for the pending decision that results from phase I and II. In assessing an existing structure, such an analysis acts to a certain extent as a substitute for the codes of practice, which for new structures constitute the rules to follow in a well-balanced and safe design, see Figure 7. In this phase III, extended surveys such as continuous monitoring or structural health monitoring are usually necessary for the in-depth analyses with regard to phases I and II for the determination of the analysis input variables. In this phase III, the following maintenance strategies are generally used, as outlined in Table 3.

- Corrective maintenance (is rarely in this phase III)
- Preventive-condition based maintenance (is generally applied in this phase III)
- Preventive-predictive maintenance (is increasingly in use in this phase II)

3.4 Maintenance concept including the environmental impact (condition assessment level IV: maintenance concepts, comparison in terms of cost, time and environmental impact, traffic deviation and their impact in terms of environment and traffic flow)

It is almost obligatory to include in the asset management of transport infrastructures also the environmental impact. The following concepts should be used:

- Evaluation of a multiple variety of maintenance concepts and their impact of the traffic flow in terms of (i) work progress, (ii) costs and (iii) environmental impact
- Decision to maintain, or to upgrade or to rebuild (by considering circular economy) the infrastructure

4 Visual representation of maintenance strategies

The performance graph shown in Figure 8 is a suitable for displaying, optimizing and evaluating the maintenance strategies and can be used as instrument to evaluate the effectiveness of the selected maintenance strategy. In these graphs, the actual condition of an asset is generally plotted along the horizontal time axis.

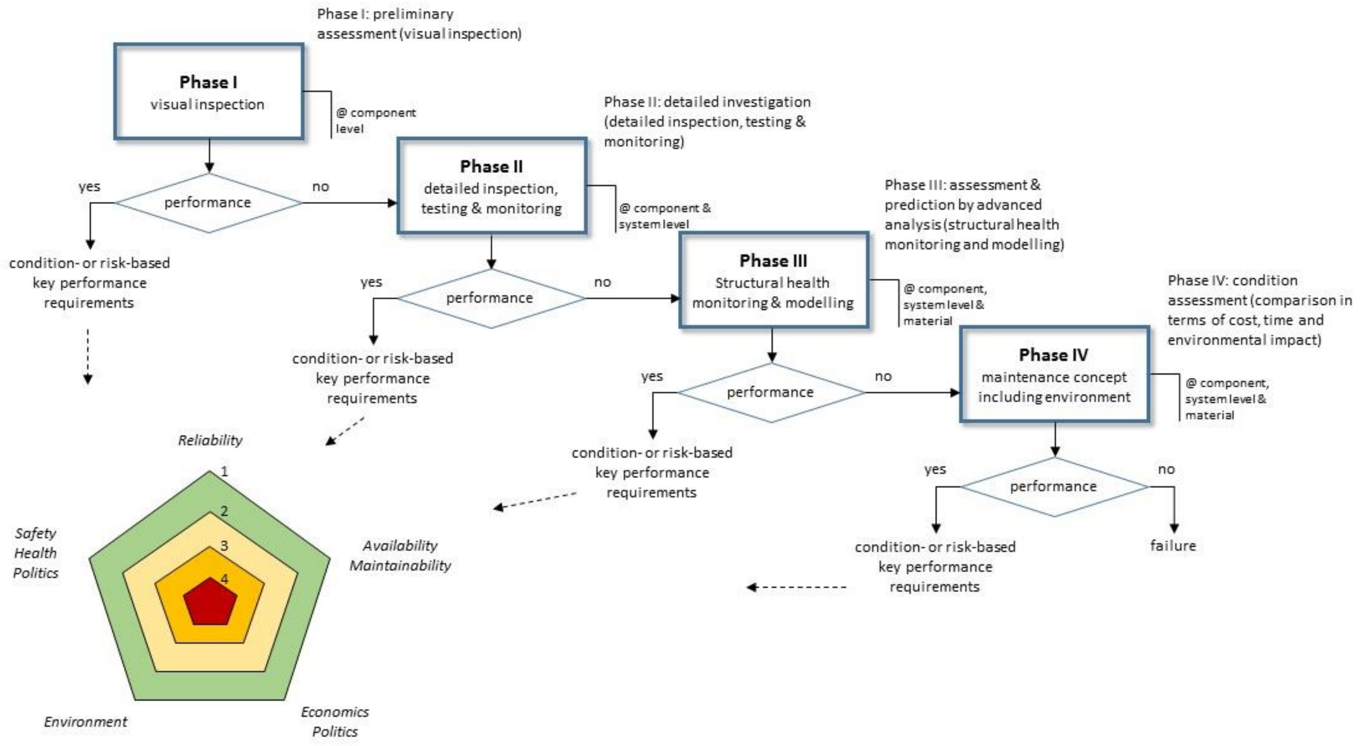

Figure 7 Performance assessment according to the different inspection levels (phase I: visual inspections; phase II: detailed inspections, testing and monitoring; phase III structural health monitoring and modelling) for the comparison with the key performance requirements and phase IV including environment [8]

As can be seen on the vertical axis of the graph, the actual condition of an asset can be represented in the form of condition classes, reliability measures or risk. The form of representation will also result according to the investigation phase of assessment phases outlined in the previous chapter. The graph itself can be divided into the following elements:

- horizontal progressions: stable condition periods (no existing degradation or
- degradation stopped by conservation measures)
- decreasing gradients: periods of time during which the condition deteriorates
- rising gradients: periods in which the condition is improved, e.g. by an intervention measure.

4.1 Preventive maintenance strategy graphs

The grey graph shown in Figure 8 as an example can be assigned to a preventive maintenance strategy. (in the graph condition levels are used as explained in previous section of this paper). After an initial horizontal progression at a condition level 3, a degradation process starts which is stopped by an intervention at level 4 (before the minimum level 5). After the intervention, which as can be seen is implemented over a certain period of time, the system remains at condition level 1 for a certain period of time. After this period of time a degradation process starts again and can be represented by a descending graph. Subsequently, a preventive maintenance is arranged on the condition level 2 which brings the degradation process to a standstill again. The same is done again on condition level 3. The following steps are a repetition of the previously sketched steps. This graph is called the Preventive Maintenance Graph because the graph is a documentation of the past state and the actual state. Each of the presented elements (progressions of the graphs) in Figure 8 and the associated activities implies costs. Therefore, in addition to the maintenance graphs, it is recommended to develop the related cost graphs as shown in Figure 9.

In the future also the environmental impact (expressed as CO2-impact) must be taken into account. For example, in this cost graph it can be seen that for the corrective maintenance strategy for the condition class worse than 4, there are already costs for e.g. the restricted traffic and then consequently for the closure of the asset. These considerations about the cost graphs are of course applicable for all presented maintenance strategies:

- Preventive maintenance strategies
- Preventive maintenance strategies with corrective elements
- Corrective maintenance strategies
- Predictive maintenance strategies

4.2 Availability optimized maintenance strategies:

The minimization of maintenance costs and the environmental impact over the lifetime can be used to optimize the adaptable elements of the strategies, as sketched in the section before. However, there are also situations or political constraints where cost optimization is not of primary importance but, for example, the availability of a structure of an infrastructure. For such cases, also the availability can be integrated.

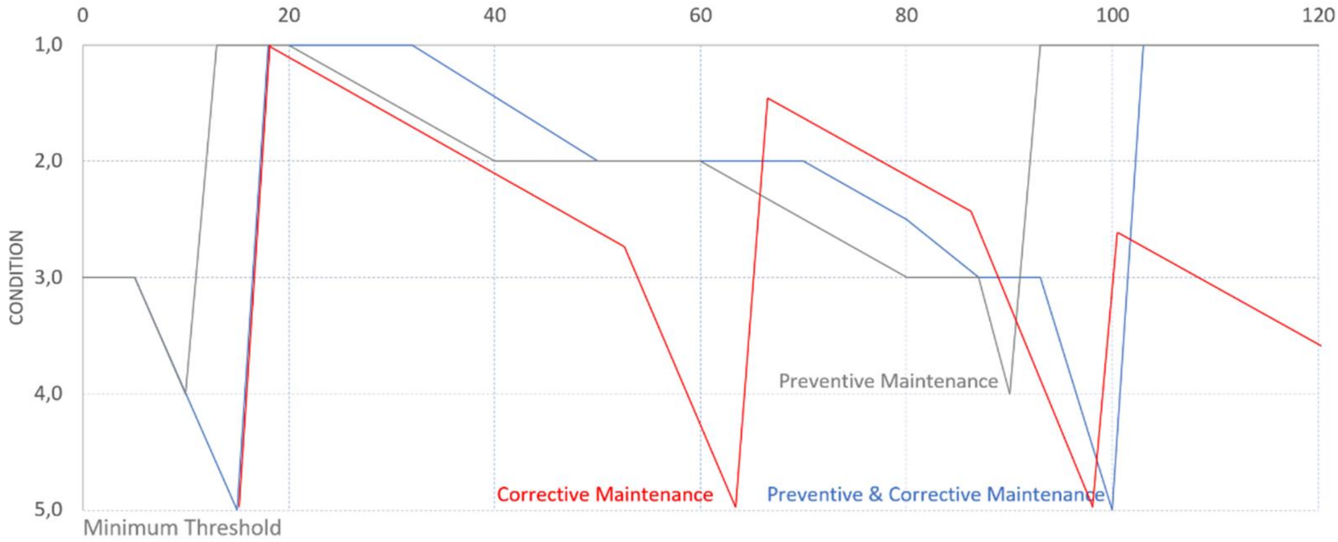

Figure 8 Condition based maintenance graphs; preventive and corrective strategies

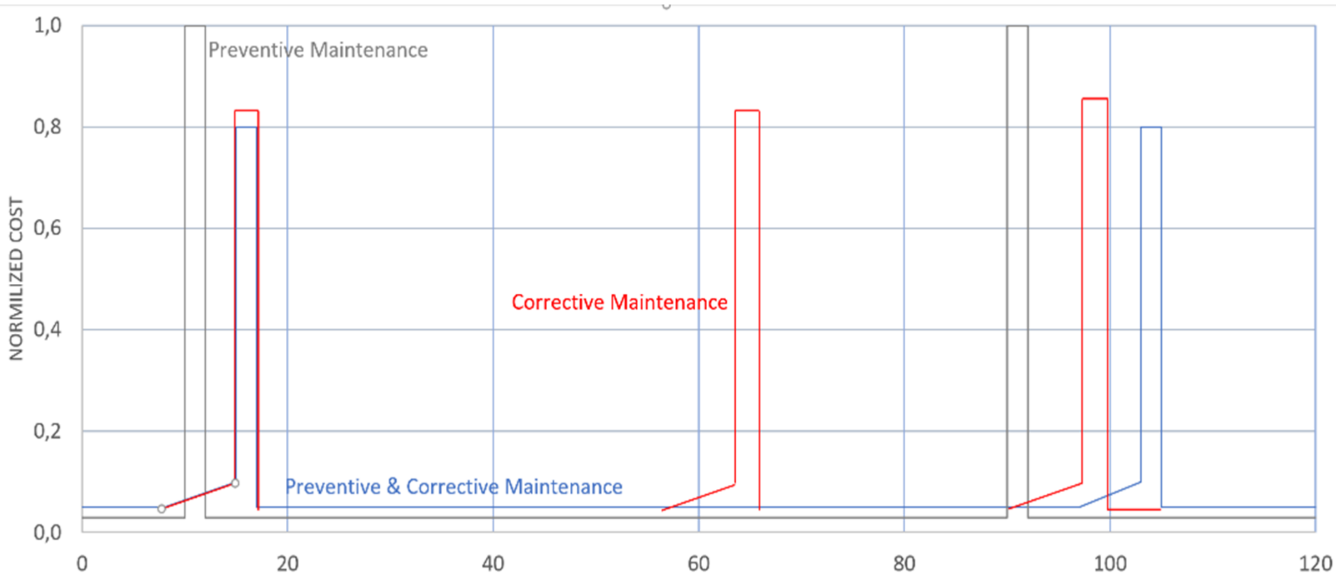

Figure 9 Condition based cost graphs associated with maintenance graphs as presented in figure 8

5 Conclusions

At present there is no uniform and generally adopted approach to defining and rating the condition states and setting the low limit maintenance thresholds. In general, national authorities or individual operators are using their own developments and set low limit maintenance thresholds for their infrastructure assets that may substantially differ from each other, which consequently lead to different levels of service across Europe and the world with regard to e.g. reliability and availability of infrastructures assets (in context of this discussion the reliability with regard to structural safety is perceived as an attribute of overall reliability of structures). The need of bridging the gap between implemented maintenance strategies, environmental impact and research is of paramount importance.

Quite often, these methods are not picked up by the industry. This can be due to various obstacles. This contribution as well as the IM-SAFE project has the goal to make this gap shorter and possibly even close it, especially as presented here for the topic of maintenance strategies.

Acknowledgement

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