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Condition-states and low limit maintenance thresholds of transport infrastructures in a European Context

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ABSTRACT
The objectives of Asset Management transport infrastructure are to ensure secure (reliable and safe) service of the individual objects and/or network, to preserve the infrastructure capital and to maintain infrastructure function through their life-cycle. Maintenance activities should preserve or modify the performance and future serviceability of a structure in such way that an adequate level of reliability with respect to performance requirements applicable to the structure under consideration is preserved or achieves. Hence adequate 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, anticipated by the designer and corresponding with the stakeholders needs. In order to arrange maintenance resources, the concept of condition-states and minimum maintenance thresholds are widely used in context of maintenance planning in many European countries for the maintenance of bridges and infrastructure systems. However, there is no uniform 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 which consequently lead to different levels of service with regard to e.g. safety, reliability and availability. In many cases, the models and criteria used are based on the 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 (e.g. rehabilitation) carried out in a condition-based manner and some other measures (e.g. cleaning, deforestation) are planned/fixed at certain intervals. Nevertheless, the minimum condition requirements associated with maintenance thresholds are frequently not clear or are variable over time. In this contribution based on the outcomes of H2020 IM-SAFE project, maintenance concepts, condition-state definitions and low limit thresholds of maintenance strategies of European countries will be presented, discussed and compared.

INTRODUCTION

Any structure is subject to degradation and undergoes condition change during its lifetime, depending on various factors such as environmental conditions, natural aging, material quality, workmanship, and planned maintenance. Therefore, in context of Asset Management, transport infrastructure assets are usually assessed based on condition classification, which generally spealing 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. Therefore, performance evaluation procedures capable of prediction of development and effect of deterioration for the structure need to be formulated, e.g., by using performance indicators (PIs) for present and future structure conditions that can be defined on various levels of abstraction, e.g. at the level structural characteristics (e.g. stiffness/flexibility, load bearing capacity), response parameters (e.g. internal forces, stresses, deflections, accelerations, crack sizes), utilization factors or functionalities (e.g. safety for people, energy consumption, robustness, usability, availability, failure probabilities) 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: the chosen maintenance strategy will have direct and indirect costs, such as direct expenses related to the maintenance activities and indirect impacts attributed to the maintenance activities and borne by the society, such as e.g. hindrance, user delays and environment impacts [3], [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. Figure 1 provides an overview of multiple performance goals (objectives) and associated performance indicators/attributes related to process of maintenance planning.

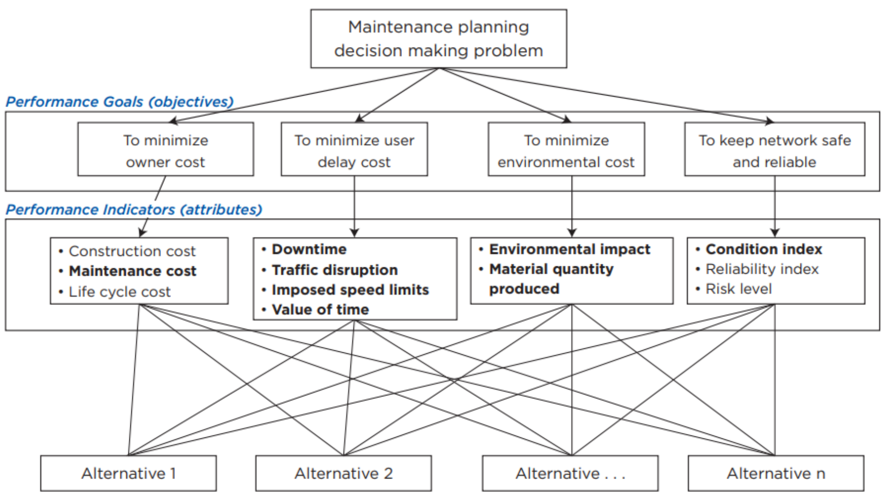

Figure 1: Linking multiple performance goals (objectives to performance indicators (attributes), (adapted from Rashidi [1])

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) 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.

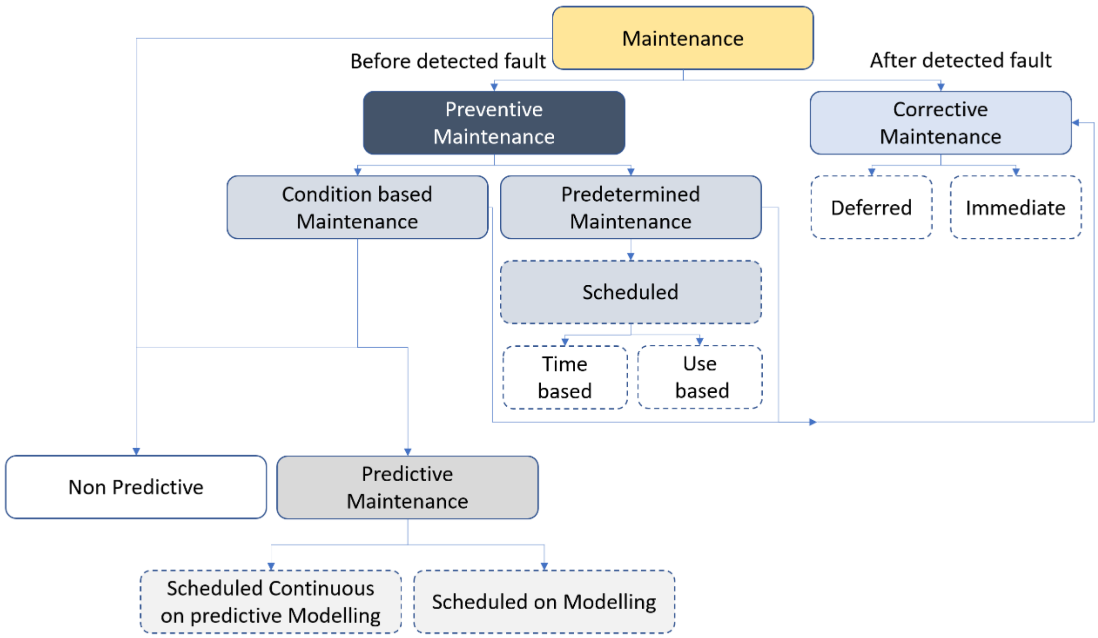

Figure 2: Maintenance strategies applied in engineering practice [2]

MAINTENANCE IN ENGINEERING PRACTICE

In the following sections the maintenance strategies are 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.

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, but at least every four months for structures in the course of roads and streets where no roadway service is established. 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. In addition, attention should be paid to impact damage, damage to ceiling and wall coverings, parts hanging down and damp spots on the underside. No written record of ongoing monitoring of individual structures will be made from the inspection trips. Any damage or conspicuous changes found shall be reported in writing to the person responsible for maintenance. Insofar as they affect traffic safety, the necessary measures are to be taken immediately.

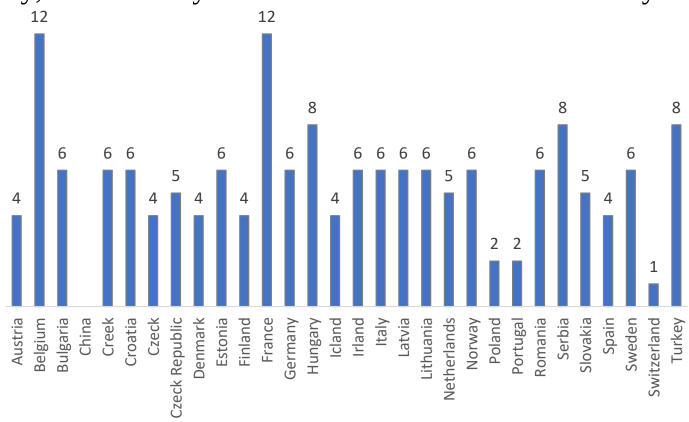

Figure 3: Time intervals between routine monitoring in years according to surveys in COST TU1406 [3]

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

Maintenance strategies: Routine monitoring can be seen primarily as relevant for corrective maintenance and is intended to eliminate large damage and conspicuous changes at an early stage, whereby in a broader sense the entire process can be counted as a preventive maintenance strategy – this means, for example, that minor elements or components that are not so important for the load capacity of a structure are replaced immediately, and these replacements have a significant influence on the longer system load capacity. These immediate corrections are generally carried out in a worse condition class as can be seen from the COST TU1406 survey [3].

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, unless components are to be inspected more closely in accordance with special inspection instructions. A competent engineer, appropriately trained (e.g. internal training of the owner, education and training) or experienced technical personnel (e.g. bridge foreman) is to 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 Fig 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 Fig. 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 [2] and IM-SAFE project report [3] information.

Based on the result of the inspection, the following is in general documented: (a) Condition of the object compared with the last finding, (b) Usability of the traffic route in the previous scope depending on the condition of the object, (c) Newly detected defects/damage, (d) Immediate measures based on the detected defects/damage, (e) Arrangement of an inspection, if defects/damage cannot be assessed in the course of the inspection, (f) Special instructions for the next inspection/testing, (g) Year of next inspection.

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 [3] and IM-SAFE project report [2].

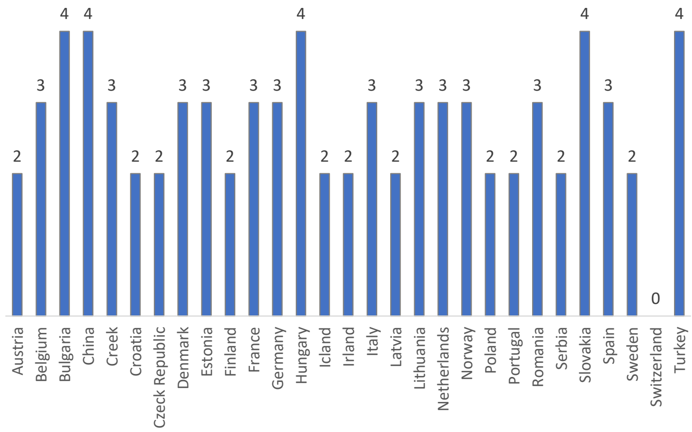

Figure 4: Time intervals between inspections in years according to the surveys in COST TU1406 [3]

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. A competent engineer with relevant experience in the inspection of structures or structural planning is to be entrusted with the management of the inspection. This person must be able to assess the basic structural condition of the object to be inspected and estimate the influence of damage on the load-bearing capacity, serviceability and durability of the structure. Depending on the size of the objects to be inspected, he must have personnel and suitable equipment. If the specified scope of testing is not sufficient, special tests must be arranged. 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
- Waterproofing, — drainage Bridge waterproofing and drainage facilities such as drains, drain pipes, fasteners
- Border beams — Border beams including curbs and border 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.

Measurement programs: If a bridge has a measurement program (geotechnical, geodetic, crack widths, etc.) or monitoring system in place, the measurement results shall be made available for inspection and included in the evaluation. In terms of relevant documentation, the results of the last test and/or inspection as well as general plans showing the as-built condition shall be made available for the bridge inspection. If required, necessary technical documents and supplementary plans are to be consulted.

Time intervals: Structures such as bridges are usually inspected at intervals of about six years, see Fig. 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.

Maintenance strategy: For the component assessment, condition grades are to be assigned for the individual components and, based on this, for the entire object. Assessment procedures can be assigned as before to the preventive maintenance strategy, in certain condition classes, a partially change to corrective maintenance strategies can also be identified, see [3].
Condition Classes: The number of condition classes of the condition base monitoring strategies handled in each individual countries are shown in Fig. 6.

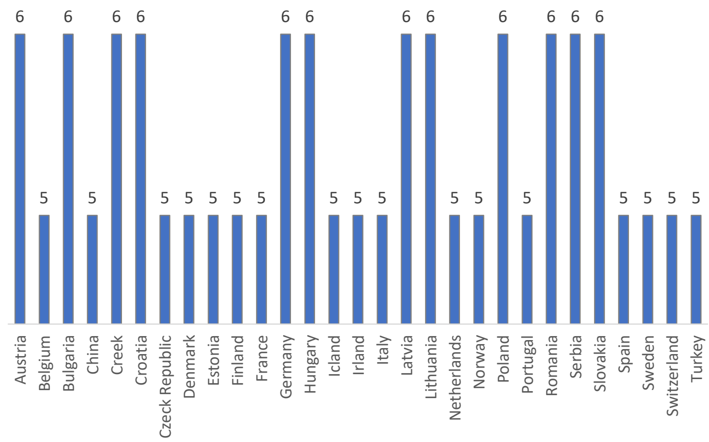

Figure 5: Time intervals between main inspections in years according to the surveys in COST TU1406 [3]

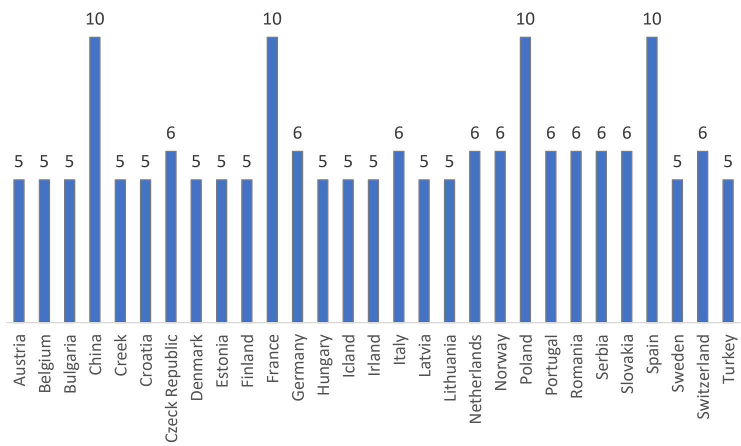

Figure 6: Number of Condition Classes of CBM strategies according to the surveys in COST TU1406 [3]

MAINTENANCE IN CONTEXT OF STRUCTURAL ASSESSMENT

In IM-SAFE project a proposal was made for the implementation of performance indicators and key performance indicators in assessment phases. According to IM-SAFE project report [4] breaking down the performance assessment of a structure or any other facility into a minimum of three phases is reasonable. Fig. 7 presents these phases in a schematic flow chart, which is herein explained in the context of the maintenance strategies.

Phase I: Preliminary assessment (*Condition assessment Level I : Visual inspection*)

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 Fig. 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)

	Prev.-M	Corr.-M	Pred.-M		Prev.-M	Corr.-M	Pred.-M		Prev.-M	Corr.-M	Pred.-M
Austria	+	+	o	France	+	+	o	Portugal	+	+	+
Belgium	+	+	+	Germany	+	+	o	Romania	o	+	o
Bulgaria	o	+	o	Hungary	+	+	o	Serbia	o	+	o
China	+	+	o	Icland	+	+	o	Slovakia	+	+	o
Creek	+	+	o	Irland	+	+	o	Spain	+	+	o
Croatia	+	+	o	Italy	+	+	o	Sweden	o	+	o
Czeck Republic	+	+	o	Latvia	+	+	o	Switzerland	+	+	o
Denmark	+	+	+	Lithuania	+	+	o	Turkey	+	+	o
Estonia	+	+	o	Netherlands	+	+	+	United Kingd	+	+	o
Finland	+	+	o	Norway	+	+	+	United State:	+	+	o
				Poland	o	+	o				

Table 1 Maintenance Strategies used in Phase I based on the surveys in COST TU1406 [3]

Phase II: 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 Fig. 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)

	Prev.-M	Corr.-M	Pred.-M		Prev.-M	Corr.-M	Pred.-M		Prev.-M	Corr.-M	Pred.-M
Austria	+	o	+	France	+	o	+	Portugal	+	+	+
Belgium	+	o	+	Germany	+	o	+	Romania	o	o	o
Bulgaria	o	o	o	Hungary	+	o	o	Serbia	o	o	o
China	+	o	o	Icland	+	o	o	Slovakia	+	+	o
Creek	+	o	o	Irland	+	+	o	Spain	+	+	+
Croatia	+	o	+	Italy	+	+	o	Sweden	o	o	o
Czeck Republic	+	+	o	Latvia	+	o	o	Switzerland	+	+	+
Denmark	+	+	+	Lithuania	+	o	o	Turkey	+	o	o
Estonia	+	o	o	Netherlands	+	o	+	United Kingd	+	o	+
Finland	+	o	o	Norway	+	o	+	United State:	+	o	+
				Poland	o	+	o				

Table 2 Maintenance Strategies used in Phase II based on the surveys in COST TU1406 [3]

Phase III: Assessment and prediction by advanced analysis (*Condition assessment Level III: Structural Health Monitoring (SHM) and Modelling*)

For problems with substantial consequences, an advanced analysis for performance assessment and performance prediction should be planned to check carefully the proposal for the pending decision that results from Phases I and II. In assessing an existing structure, such an analysis (see Fig. 7) 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. In Phase III, extended surveys such as continuous monitoring or SHM are usually necessary for the in-depth analyses with regard to Phases I and II for the determination of the analysis input variables. In 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 III)

	Prev.-M	Corr.-M	Pred.-M		Prev.-M	Corr.-M	Pred.-M		Prev.-M	Corr.-M	Pred.-M
Austria	+	o	+	France	o	o	+	Portugal	+	+	+
Belgium	o	o	+	Germany	+	o	+	Romania	o	o	+
Bulgaria	o	o	o	Hungary	o	o	o	Serbia	o	o	o
China	+	o	+	Icland	o	o	+	Slovakia	+	+	+
Creek	+	o	+	Irland	o	+	+	Spain	+	+	+
Croatia	o	o	+	Italy	+	+	+	Sweden	o	o	+
Czeck Republic	o	+	+	Latvia	o	o	o	Switzerland	+	+	+
Denmark	+	+	+	Lithuania	o	o	+	Turkey	o	o	o
Estonia	o	o	+	Netherlands	+	o	+	United Kingd	o	o	+
Finland	o	o	+	Norway	+	o	+	United State:	+	o	+
				Poland	o	+	+				

Table 3 Maintenance Strategies used in Phase III based on the surveys in COST TU1406 [3]

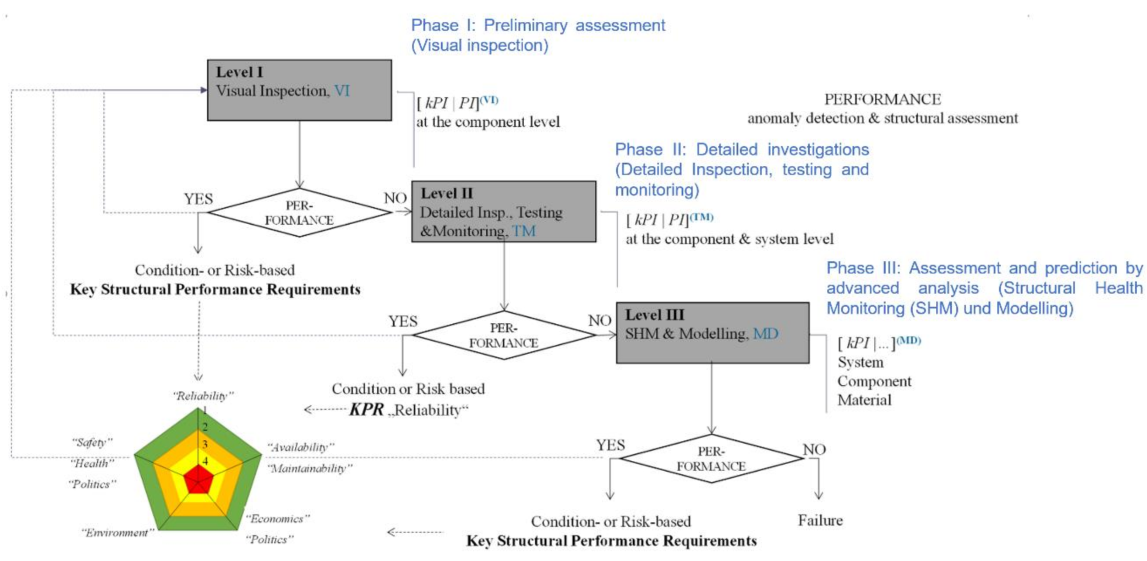

Figure 7 Performance assessment according to the different inspection levels (Phase I Visual Inspections; Phase II Detailed Inspections, Testing and Monitoring; Phase III SHM and Modelling) for the comparison with the Key Performance Requirements [2],[7]

VISUAL REPRESENTATION OF MAINTENANCE STRATEGIES

The performance graph shown in Fig. 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. 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.

Preventive maintenance strategy graphs

The gray graph shown in Fig. 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.

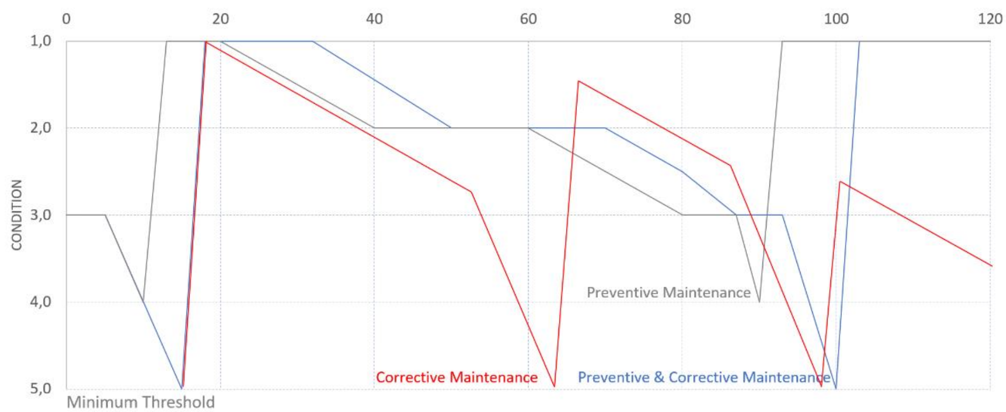

Figure 8: Condition based maintenance graphs; preventive and corrective strategies

Preventive & corrective maintenance graphs (strategies)

The blue graph shown in Fig. 8 can be assigned to the preventive strategy with corrective elements. The main difference to the grey strategy is that no preventive measures are taken in the poor condition classes (e.g. 4 to 5), but deterioration is allowed up to the minimum threshold – corrective is applied here.

Corrective maintenance graphs: The red graph of the pure corrective maintenance strategies reduce to three essential elements (a) stable horizontal areas, (b) descending degrading graphs running to the minimum threshold, and (c) the intervention graphs starting from the minimum threshold levels.

Predictive maintenance graphs: The preventive maintenance, preventive with corrective elements, and corrective maintenance graphs outlined above can be predicted using physical models, statistical models, stochastic models, etc. (see Fig.8), even beyond the time of evaluation, e.g., up to the end of a structure's service life. When these graphs are predicted, they are called predictive maintenance graphs. In other words, predictive maintenance strategies can include the basic concepts of preventive maintenance, preventive including corrective elements, and corrective maintenance.

Cost optimized maintenance strategies: Each of the presented elements (progressions of the graphs) in Fig. 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 Fig. 9. 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

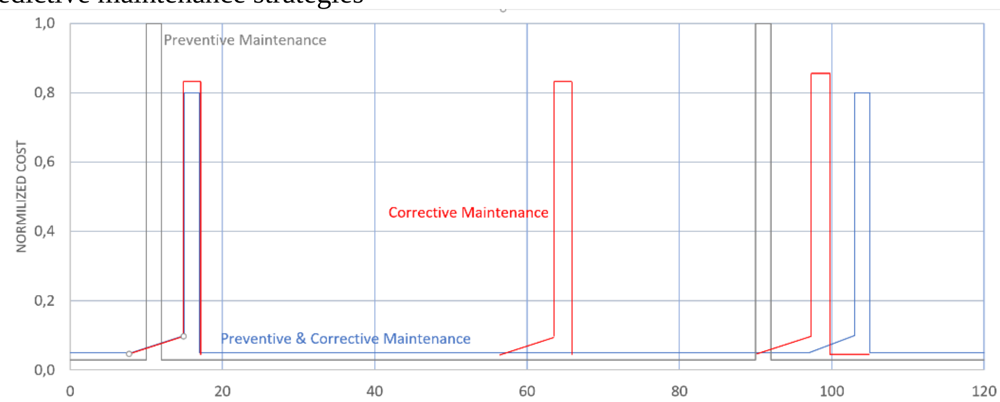

Figure 9: Condition based cost graphs associated with maintenance graphs as presented in Fig. 8

Availability optimized maintenance strategies: The minimization of maintenance costs 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, instead of the cost graphs, the availability graphs can be plotted over the maintenance graphs, see e.g. Fig. 10. In these graphs, 1 is associated with 100% availability and 4 with 0% availability or a lockout of the system. In the end, these graphs can be used to determine the time available during the lifetime of the system and subsequently this parameter can be used to optimize the maintenance strategy. In such case, maximization of availability over the lifetime can be used to optimize the adaptable elements of the strategies, as presented in previous sections

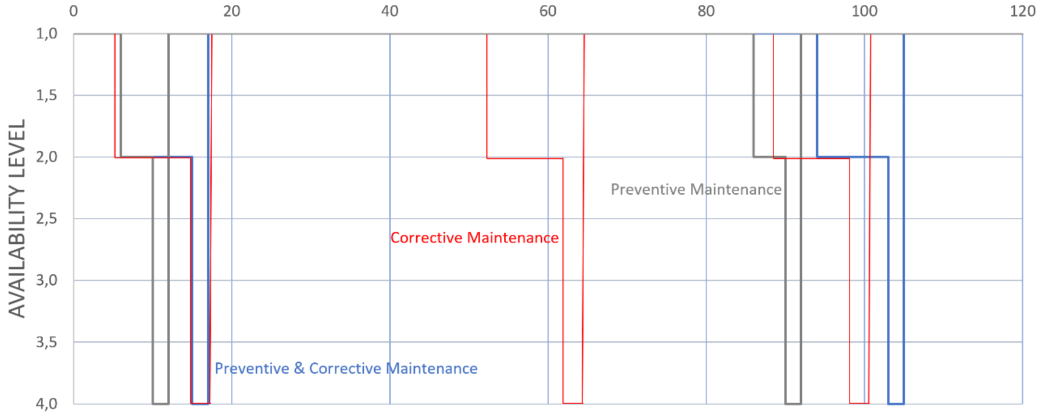

Figure 10: Condition based availability graphs associated with the condition-based maintenance graphs as presented in Fig. 8

SUMMARY

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 and research is of paramount importance. Quite often, these methods are not picked up by the industry. This can be due to various obstacles such as lack of data, reluctance to (or difficulties related to) deviate from their current modus operandi, lack of trust that these models really add to the specific engineering understanding, lack of skills within the infrastructure organisation, lack of standard provisions for their application, lack of technical background in new knowledge needed taken from other technical disciplines (big data, machine learning, sensor and image-based monitoring, etc.) This contribution as well as the IMSAFE project has the goal to make this gap shorter and possibly even close it, especially as presented here for the topic of maintenance strategies.

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