LESSONS LEARNED FROM PROACTIVE MAINTENANCE PRACTICES FOR CONCRETE BRIDGES

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ABSTRACT: Maintenance deficiency such as weak diagnostics of concrete bridges, suboptimal maintenance strategies and shortage of resources for renovation and replacement accelerates the structural deterioration and increases level of risk. There is a clear need of sound procedures to improve management of bridges and to optimize utilisation of the narrow resources for conservation through an efficient asset management process. Appropriate maintenance strategy shall be selected, with suitable activities such as (structural and operational) interventions being chosen for implementation. A condition-based maintenance strategy is desirable as it enables early identification of problems and risk issues following from the change of the condition of the structure or actions on the structure, potentially allowing early preventive actions to be taken, minimizing the overall cost of ownership. In the current practice, preventive maintenance strategies are increasingly used. However, current decision-making processes with respect to planning of maintenance activities are lacking a solid rational basis. Decisions are often taken ad-hoc without duly considering the actual condition data, performance level and risk profile of structures and/or networks since the use of results of condition surveys, and safety and risk evaluations is far from optimal. At the same time best practice in latest technologies and methodologies prove the feasibility of accurate and cost-efficient inspections, testing, monitoring and assessment of structural performance and risk. Providing a consistent and harmonized basis for decision-making concerning the implementation of maintenance strategies in asset management is becoming essential. The H2020 CSA IM-SAFE project explores the current best practice of preventive maintenance for concrete bridges across Europe. This contribution outlines the lessons learned and explores the vision developed in IM-SAFE project, which envisages the use of risk-based maintenance management system, employing condition-based maintenance strategies and using information from inspection, testing and monitoring to ensure reliability, safety, availability and economical operation over the assets' lifetime.

INTRODUCTION

The life cycle management of an infrastructure [1,2] is a process adopted during the whole lifetime of an asset, particularly during operation and use phase, to ensure the ongoing safe service of an individual asset or of a network of interconnected assets. The management strategy should be developed from the (predetermined) performance requirements set for the new, existing or altered assets. Performance requirements that are to be dealt with in the life cycle management process should be set for the primary function(s) of an asset and may be expressed by the Key Performance Requirements with the associated performance criteria. The RAMS (or RAMSSHE€P) analysis approach can be used to develop appropriate criteria for the identification of Key Performance Requirements. This is usually done in terms of reliability, availability, maintainability, safety requirements (often extended with requirements of security, health, environment, economics and politics). Further discussion regarding the Key Performance Requirements for transport infrastructure is to be found in [3,4]. The approach to performance-based asset management may benefit from establishing appropriate weightings or hierarchical order for the performance requirements, which is not further evaluated in this paper considering that the context of the main focus herein is on the life cycle management of the reliability of infrastructure assets. Due to limitations in the available resources or conflicting requirements, the life cycle management usually requires compromise and judgement about the action to be taken by the engineer or asset manager at each stage of planning, design, execution, use, etc. Successful implementation of asset management principles shall provide input to the processes of design, construction, use, interventions, and decommissioning of the structure to aid engineers and decision-makers in compromising and judging options and alternatives. In this context, interventions refer to both structural and operational actions and may include e.g. inspection, monitoring, maintenance as well as rehabilitation, repair or upgrading required for adaptation to changed performance requirements, together with those associated with improving the performance of structures in-service or extending the useful life, see Figure 1.

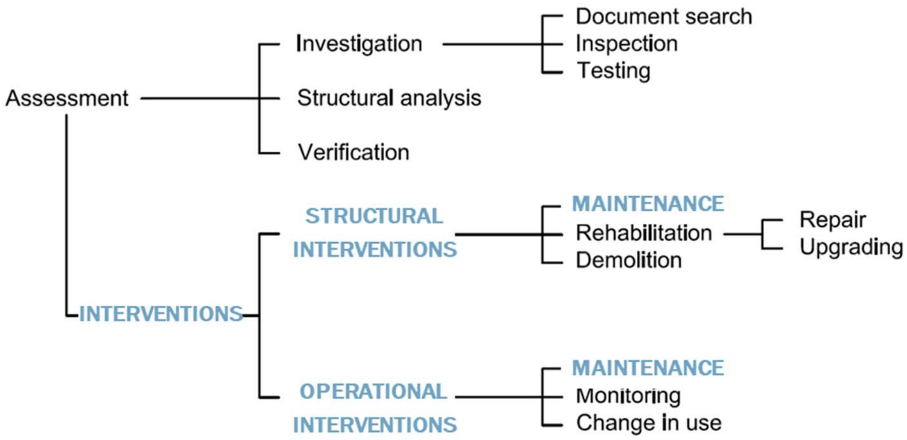


Figure 1- Hierarchy of terms and positioning of maintenance in context of the assessment of existing structures, according to [11]

Asset owners and road operators benefit from a rational, consistent and harmonized basis for decision-making processes with regards to maintenance approaches. This paper outlines the principles for optimal maintenance of infrastructures, focusing specifically on a condition-based maintenance management approach and risk-based decision-making with regard to setting up the maintenance strategy. Condition-based maintenance and condition control processes are presented, illustrating the benefits from the use of information gathered from inspection, testing and monitoring in ensuring reliability and economical operation of the transport infrastructure assets in general, and concrete bridges in particular. A decision-making proposal for optimized maintenance and interventions as part of a wider risk-based asset management framework is illustrated with practical example of application for a case study within the TEN-T corridors. For further applied case studies refer to [5].

PRINCIPLES OF MAINTENANCE OF INFRASTRUCTURES

The current European asset management for bridges is largely dominated by the legacy procedures, systems and approaches for regular manual/visual inspections, damage assessment and corrective maintenance. Although application of preventive and condition-based maintenance is steadily increasing, it did not yet become a common practice and those strategies are still used occasionally, in particular for critical assets. The IM-SAFE project deals with the key factors of resilience-oriented maintenance and risk management based on the “4R”: Robustness, Redundancy, Resourcefulness and Rapid response. To avoid sub-optimal decision making, life cycle management shall be based on a consistent concept for all phases of the life cycle of an asset, considering the risk of performance degradation of the asset during the lifespan, as well as the impact of the asset on the environment and economy. For this reason, a rational approach to life cycle management is very complex and optimisation of maintenance activities involves making trade-offs between competing objectives with due consideration of interdependencies between a wide range of factors, including risk, quality and costs. Therefore, a rational management necessitates performing risk assessment for the whole existence and use of the asset, as well as life-cycle cost (LCC) assessment and life-cycle analysis (LCA) of the environmental impacts and benefits. In this context it is essential to take into consideration various assessment levels (i.e. network-, asset-, component-level) and keep in mind differences in service lives for the various parts of the system. Moreover, during the service life, the management scenarios shall be appropriately updated to consider the consequences of on-going and anticipated changes in risks, costs and environmental impacts and benefits. During all phases of the life cycle, decisions regarding risk management and maintenance are made, however their objectives and the information required to support such decisions are changing. During the phase of project planning and design, the foreseen approach to maintenance management shall be defined, followed by the preliminary selection of the maintenance strategies. Information used during this stage comprise design files with the underlying data, and the outcomes of the decision making including the preliminary setup of maintenance management with the associated maintenance strategies. This as-design information is essential in the life cycle management activities and, therefore, it must be recorded and reflected upon during the construction and operation phases as it constitutes the pertinent basis for decision-making during these stages of the design life. During construction phase, the choice of the maintenance management approach and maintenance strategy must be confirmed (or adequately revised if needed) making use of the outcomes of the condition survey and evaluation performed after construction of the structure. For similar reasons as in for the previous phases, the as-built information shall be considered pertinent for recording. Examination of the appropriateness of the maintenance management approach and maintenance strategy must be continued during the operation phase to make sure that they remain relevant: during this stage of decision-making the previous evaluations should be regularly re-examined (and when needed revised) making use of the outcomes of the condition survey, condition judgement and performance assessment executed during operation phase. The examination of the appropriateness of the previous decisions and of the implemented setup of maintenance management and strategies is of essential importance if intervention works have been undertaken to change/improve the structural condition. In case of interventions, information related to applied interventions and performance change after interventions shall be gathered, evaluated, recorded and reflected upon during re-examination (and where relevant revision) of maintenance management approach and maintenance strategy during the post-intervention phase. After decision about decommissioning, maintenance activities are no longer relevant, however the records created during the life cycle management are of relevance for assessing the suitability of the structure for circular reuse of construction elements or components for recycling of construction materials. Therefore, it is of utmost importance to carefully plan how the transfer of information collected during the service life between different parties involved during the life cycle is managed and taken care off. In this respect, the responsibility rests with the owner of the asset, who should be aware that the lack of information about the structure (design, construction, interventions, alterations, and use) may severely impact the opportunities to maximise the circular use of the structure after its decommissioning. [1,6]

RISK-BASED MAINTENANCE MANAGEMENT FRAMEWORK

Maintenance is one of the intervention options to be considered for life cycle management of structures (see Figure 1) and plays a major role in seeking the optimum between maximizing performance and minimizing life cycle costs, with due consideration to the suitability perspective. Maintenance is defined as a combination of all technical, administrative and managerial activities performed during the lifespan of the structure in order to retain or restore its performance and future serviceability at/to the level at which it can perform the required function. In other words, maintenance aims to ensure that assets continue to be able to do what they are designed for and benefit its users, and society at large, now and in the future. The risk-based maintenance management of infrastructure assets [9] combines the risk-based approach to selection of the assets that should be targeted by a maintenance program, with the choice of maintenance strategy for implementation to an asset during its service life, assessing and evaluating risks on various levels (network, system and component). The risk-based maintenance management prioritises the maintenance of assets, system and component that carry the most risk if they were to fail, and allows engineers and maintenance managers to determine the most economical use of limited maintenance resources to minimise the total risk of failure across a facility. In line with [7], the failure is defined as a state in which assets, system and component under consideration does not meet the required performance objectives due to structural damage and/or loss of function. The risk-based approach to maintenance management shall apply a multicriteria analysis to ensure that all performance requirements relevant for the assets are satisfied i.e. all targets related to reliability, availability, maintainability and safety (eventually extended with requirements of security, health, environment, economics and politics) are met. These shall be achieved implementing inspection, monitoring and maintenance programs optimized on the basis of an appropriate risk-based methodology and complying with applicable legal or normative regulations and guidelines.

For new structures, the risk-based framework for maintenance management should be set up during the design stage. The approach to risk-based maintenance management and choice of the maintenance strategy must be confirmed (and in needed revised) based on the outcomes of the condition evaluation (and any associated intervention works) performed after construction of the structure, and then continued into the operation phase. For existing structures without a risk-based maintenance management framework in place, during the re-design stage the preliminary set-up of the maintenance management framework must be defined, followed by the selection of the appropriate maintenance strategy. During operation, the chosen risk-based maintenance management approach and the maintenance strategy must be confirmed on the basis of the condition evaluation and re-assessment of the (often revised during operation) performance requirements. In the particular case of revised performance requirements, the risk-based framework for maintenance management and the choice of the maintenance strategy must be re-evaluated and, if necessary, changed to meet the new performance requirements; during the re-design stage it must be confirmed (and if needed revised) on the basis of the outcome of the condition evaluation.

The process of setting out the risk-based framework for maintenance management shall consider:

- criticality assessment
- formulation of maintenance strategy and maintenance planning (discussed in the following section)
- development of risk-based inspection plans and - where relevant - testing and monitoring plans (for more information see [5])

A criticality assessment is a systematic approach to evaluate potential risks, therefore consequences that can impact the performance of the asset. In this context, criticality is the severity of a failure, or a fault combined with the probability or frequency of its occurrence. The severity of a failure or a fault reflects the potential or actual detrimental consequences while criticality is a measure of the severity of a failure or a fault combined with the probability or frequency of its occurrence, and should be evaluated for all performance categories considered, i.e. criticality assessment shall reveal potential risks with regard to reliability, availability, maintainability, safety, security, health, environment, economics and politics. By understanding which assets are the most important through a criticality assessment, engineers and maintenance managers can determine how to most effectively schedule maintenance activities of the right asset/system/component at the right time to reduce risk over the whole network. There are often many ways to conduct a criticality analysis. Which approach to use is dependent upon the size and complexity of the problem at hand. Although criticality assessment should not be confused with assessing the risk of failure, which is the product of the probability of failure and the consequence of that failure, risk analyses may very well contribute to criticality assessment [4]. The criticality assessment is only possible with the defined criteria, that enable to classify the potential consequences so that they can be objectively evaluated, categorized and prioritized. For further discussion reference is made to [5].

At present, the objective of developing the life cycle maintenance programs is often based on minimising of the economic costs of ownership, while satisfying minimum performance requirements for the networks/asset (the latter are frequently targeting reliability, availability, maintainability and safety). However, increasingly attempts are made to deal with life cycle management on the basis of rational risk analysis. Accordingly, the main principle for the development of the risk-based maintenance management programs for the infrastructure networks is to minimise the total risk of failure over the network. Rational optimisation of risk-based maintenance management programs requires an approach which weights the direct and associated indirect life-cycle costs against the benefits such as a longer service life, fewer faults or greater safety [7]. Hence:

- assets with a greater risk and consequence of failure are maintained and monitored more frequently to achieve tolerable risk criteria
- assets with a lower risk have a less stringent maintenance program

Next to considering those objectives and given the huge potential of existing structures to contribute during service life to achieving sustainability goals, it is essential to take into consideration environmental performance requirements and aim at enhancing the sustainability of the asset / structure with the adequate maintenance. Consequently, minimising the environmental impacts for the networks /asset during the life-cycle and maximizing its potential for circular reuse after decommissioning should be considered a part of life cycle maintenance management objectives.

MAINTENANCE STRATEGIES SELECTION

A maintenance strategy indicates the approach taken in relation to a particular risk that may affect the assets performance. A common typology of maintenance strategies highlights differences in terms of:

- acceptance of risk;
- the basis on which maintenance is planned and/or takes place;
- the type of activities required in the strategy (e.g. maintenance, inspection, monitoring).

Table 1 provides an overview of commonly used maintenance strategies [11].

Table 1: Overview of commonly used maintenance strategies, based on [11]

Typology of maintenance strategies		
Corrective	Failure-based (e.g. Run to failure)	
Preventive	Predetermined	Time based
		Use based
	Condition-based	Non-predictive
		Predictive

The selection of a particular maintenance strategy depends on various factors including: *risk level*, *changes of risks over time*, *predictability of failure, detectability of failure* and *costs.*

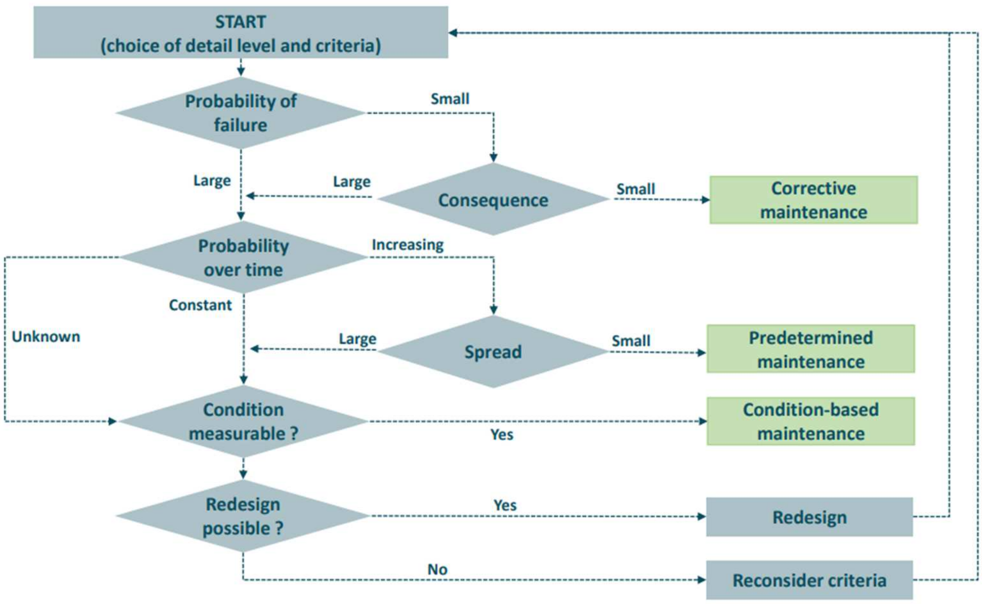


Figure 2 - Schematisation of process for determining an appropriate maintenance strategy

Figure 2 schematises a basic structure for determining an appropriate maintenance strategy and the following reasoning illustrates the considerations related to these criteria:

- *Risk level*: All relevant risks and the risk level shall be considered. In situations where the risk levels are considered unacceptable, a preventive maintenance strategy is typically sought after. In situations where the risk levels for the assets are considered acceptable, a corrective maintenance strategy may be regarded as (cost) effective.
- *Changes of risks over time:* The change of risks and the change of the risk level over time shall be considered. In situations where the probability of failure is increasing in time, a preventive maintenance strategy will likely be an effective maintenance strategy. In situations where probability of failure is considered constant over time (e.g. random failure), it will likely be ineffective to select a preventive maintenance strategy.

- *Predictability of failure:* The degree to which the moment of failure can be predicted accurately a priori shall be considered. In situations where such an estimate can be made, a predetermined maintenance strategy will likely be an effect maintenance strategy. In situations where such estimates are difficult to make, i.e. the probability of failure can vary, a predetermined maintenance strategy may likely be ineffective, and a condition based approach may be considered an better alternative.
- *Detectability of failure*: The degree in which failure can be detected and anticipated prior to occurring shall be considered. In situations where there are possibilities to e.g. measure condition, detect failure, or otherwise collect information in order to determine when failure is likely and maintenance is required, the condition based maintenance strategy may prove useful.
- *Costs*: The cost structure and cost level for maintenance strategies shall be considered. In situations where a condition-based strategy is employed, this entails investing in activities such as inspections and/or monitoring, to prevent costly failures and/or to postpone maintenance to the last moment possible. However, such maintenance strategies will result in maintenance being anticipated, thus making it easier to plan, which typically is more cost-effective that unplanned maintenance.

The best choice of maintenance strategies is case depended. However, some general trends such as aging assets (thus increasing probabilities of risk associated with age), increasing possibilities in data collection and analysis, decreasing costs of e.g. censoring, and increasing understanding of the effect of degradation on failure mechanisms in concrete structures allow the (predictive) condition based maintenance (CBM) strategies to become increasingly more relevant strategy for concrete bridges. For more details on application of CBM to concrete bridges reference is made to [12]. As shown in Figure 2, in some cases, no satisfying maintenance strategy can be found, in which case the initial criteria should be reconsidered, or it may become useful to explore other options such as asset modification (redesign). The latter may include for example modifying an asset to become more robust, or to ensure that the redundancies are in place, which can provide an interesting alternative in mitigating risk. It is essential to note that next to optimisation path, devising a maintenance plan will include seeking out synergies, which may be of particular importance if maintenance strategy alternatives are initially developed per risk identified. This leads to many specific tailor-made maintenance strategies for an asset. In practice, it is usually considered effective to combine various activities into larger jobs. For example, if a certain risk requires periodic inspections, the same inspection can be used to obtain other information as well. A maintenance plan, thus, entails a degree of clustering and further optimization. This can be done on a component, asset, portfolio, and network level. On context of selecting maintenance strategy, it should be kept in mind that there are situations where maintenance activities are not feasible. Such circumstances apply e.g. to parts of a structure such as foundations where inspection and the application of conservation measures is very difficult or not practical, or where it would be uneconomically and/or technically difficult to undertake preventative or remedial measures. It should be also noted that, in some cases, it may be feasible to obtain indirect indications of condition or performance of the non-inspectable parts of the structure from e.g. joint leakage detection, ground movement and land surveying or through ancillary behaviours such as relative displacements or local damage (e.g. cracking) of other parts of a structure.

DECISION-MAKING FOR OPTIMIZED MAINTENANCE AND INTERVENTIONS

The IM-SAFE project proposes a framework for the data-informed safety assessment [5] highly interrelated with the life cycle management of the transport infrastructure. The proposed flow describes the different stages of the assessment of new and existing structures, focusing on various levels (network, system and component) and taking into account the available data during the lifespan and maintenance process of the structure. It allows to consider both input information, data collection and storage necessities, as well as the possibility to have a BIM and/or Digital Twin model to support the analysis and the infrastructures management process. The aims of the proposed flow are: i) implement in practice the data-informed safety assessment methods; ii) rationalize the decision-making process with regards to interventions; iii) provide an efficient asset management tool as further guidance on the use of data.

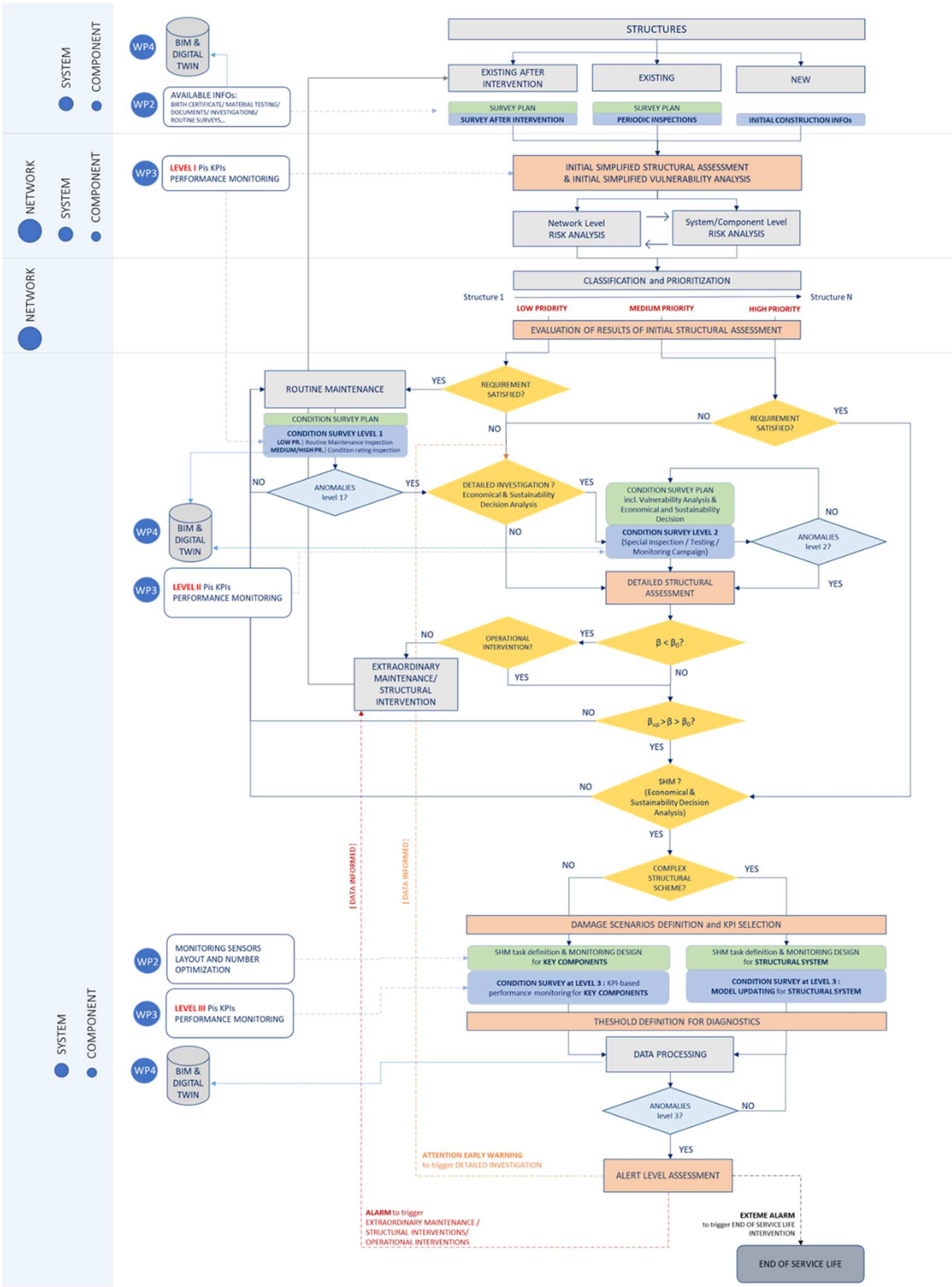
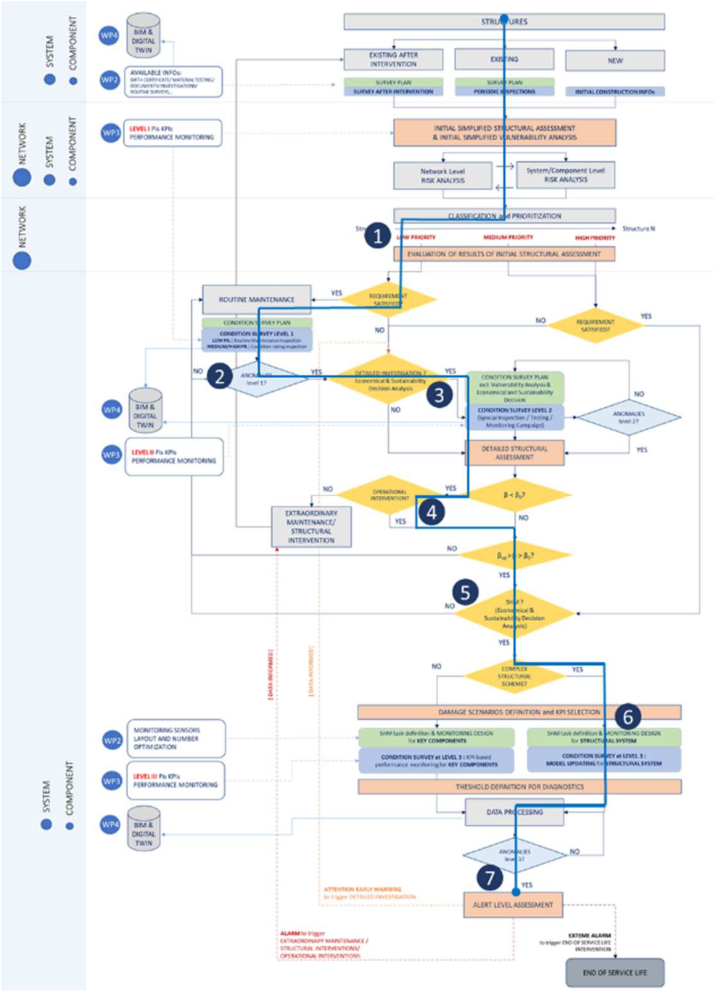


Figure 3 – Decision-making flow for optimized maintenance and interventions.

The assets have been subdivided and differentiated in 3 relevant classes: a) new structures; b) existing structures; c) existing structures after intervention. The first step of the framework consists of a simplified assessment of the structures that are part of the same road network. This analysis is based on the review of the available relevant information (such as design documents, as-bult information incl. Birth Certificate [8], inspection documents, condition surveys, structural investigations, material testing outcomes, data gathered from continuous monitoring re-deign documents, Re-birth Certificate and intervention reports, etc.) and can be supported by a vulnerability analysis [1,4], aiming to identify the critical elements of each asset, taking into account that some vulnerable areas can develop only with the aging of the structure or also the occurrence of degradation processes and cannot be assessed due to their inaccessibility. The simplified analysis is required as a prerequisite to perform a classification and prioritization of the assets that are part of the same road network based on a risk analysis [5,9,10], which can be performed either at the network level or at the system/component level. Risk analyses aims to define the priority list for optimized maintenance and interventions policies. Based on its outcomes, structures can be assigned to one of the following classes: **Low** Priority, **Medium** Priority or **High** Priority. Prioritization of intervention is not required in case a single structure is being analysed. Each of the classes defined above is characterized by a specific prioritization plan of interventions, based on the results of the preliminary assessment. "Low priority" structures undergo routine maintenance inspection plans and could change class based on the outcomes of the ordinary maintenance or eventually light monitoring. The specific maintenance strategy can be selected based on the risk analysis s and considerations as described in Figure 2. A detailed investigation plan as well as a detailed assessment might be considered in case of detected or suspected anomalies [16]. In this case, further condition survey plans can include special inspections, testing and monitoring campaigns. Structures in the "Medium priority" and "High priority" classes may be subjected to detailed assessment. Based on the gathered information about the condition of the structure, decisions regarding the use of inspections, monitoring and testing are evaluated. In particular, with respect to the reliability levels differentiation proposed for the assessment of existing structures, actions may vary based on the target levels β_0, which is the level below which the existing structure is considered unreliable and should be upgraded, and β_{up} [1,4,13,15], which is the level indicating an optimum upgrade strategy while upgrading of existing structures. If the reliability is lower than the minimum accepted β_0, the outcome of detailed assessment can result directly in extraordinary maintenance or interventions. In case operational interventions (e.g. traffic limitation) are needed before any structural intervention is performed, monitoring strategies might be applied as a step to prevent undesired events before the structural upgrade. If the reliability is between β_0 and β_{up}, the evaluation of the most suitable monitoring strategy is suggested, based on an optimization approach to either select increased visual inspection schedules, further additional testing and/or application of periodic, frequent, or continuous monitoring. The identification of the monitoring strategy can be made based on economical and sustainability decision making processes.

In case continuous SHM systems [14] are used, the approach to monitoring differs depending on the complexity of the structural scheme following an increasing level of approximation [1,4] in the analysis approach. Monitoring of the structural performance of key structural components is suggested for simple structural schemes, whilst non-linear FE modelling coupled with model updating approaches [17,18,19] is suggested for more complex structures. Complex structural schemes, as such, require a higher complexity of the analysis and performance monitoring, which implies numerical modelling, model updating processes and deeper analysis of the presence and localisation of damages. Regardless of the complexity of the structural system, the gathered data should feed appropriate key-performance indicators and should serve as input for structural diagnostics procedures, including the definition of thresholds, essential step to promptly identify potential anomalies or identify a sudden change of the behaviour of the structures. Structural diagnostics procedures have to be supported by a thorough data processing phase, which allows to identify potential anomalies (anomaly detection) with respect to the standard structural behaviour expected based on both the numerical models and the past performance (statistical evaluation of the data series over time). The presence and quantification of the extent of damage in a system based on the information extracted from the measured system response may be performed using ad-hoc damage detection algorithms. In more recent years, the big-data processing is increasingly supported by machine learning and AI routines, both supervised and unsupervised. The detection of anomalies may be considered as a trigger for decisions regarding the end of service life of the structure: in case of very extreme events or exceedance of the alarm levels, the end of the service life of the structures could potentially be reached, whilst for less severe thresholds levels exceedance, the monitoring system would be a trigger for further investigation levels or, eventually, for another detailed structural assessment to evaluate if a structural intervention or an upgrade is needed. A practical application of the decision-making process to a real case scenario located on TEN-T corridors is included below. The selected case study is representative of how the proposed decision-making flow is already applied, at different levels, in current practice. Further case studies are detailed in [5].

CASE STUDY: PRESTRESSED CONCRETE BRIDGE CONTINUOUS MONITORING



The case study under analysis [17,18,19] is a prestressed concrete bridge built in the early 60s, composed by two independent carriageways, each having nine simply supported spans. The structure is located along the A32 highway connecting Turin to Bardonecchia (Mediterranean TEN-T corridor). The typical span is 35m long with a cross section made by a prestressed concrete slab having constant height of 1.5m. The assessment and decision-making process is described here.

1) Based on the prior information available the bridge had been classified as a low priority structure, and, therefore, undergoing routine maintenance inspection plan.
2) Inspection outcomes pointed out the presence of cracks at the inner surface of the slab of one of the 9 spans of the bridge, due to the failure of a significant number of pre-stressing tendons caused by a diffuse corrosive phenomenon.
3) Additional detailed investigations were performed to evaluate the corrosion diffusion and the prestressing cables health status, to support the detailed structural assessment process.
4) The detailed analysis required operational intervention (traffic limitation) as well as the design of strengthening works, with the adoption of an external pre-stressing system.
5) A SHM system was required to monitor the structural response of the damage structure, during and after the repairing works. Each span was instrumented by Sacertis Ingegneria S.r.l. with 5 biaxial MEMS clinometers and 5 triaxial MEMS accelerometers, 2 two gateways, a powerline communication to connect the devices to the network.
6) A stable peak-picking analysis was performed to track the natural frequencies evolution in the long-term. Non-Linear Finite Element Analysis and a model updating procedure were used to simulate the bridge behaviour both in damaged and strengthened state. Static and dynamic load tests were performed to characterize the structural response before and after the strengthening works. The FE model was also used to simulate a set of possible damaged scenarios to calculate the thresholds for the long-term monitoring (plastic rotations, frequency shifts).
7) Continuous monitoring and diagnostics are active since 2019, on all the 9 spans of the bridge, with a real-time alerting system active to support proactive maintenance interventions.

CONCLUSIONS

Although application of preventive and condition-based maintenance is steadily increasing, a key challenge to be addressed in the short term is to stimulate and facilitate the transition from traditional maintenance approaches (corrective and time-based maintenance) towards the risk-based approach by standardising and harmonising the condition-based maintenance strategies and practices at local, national and EU level. Before this goal can be achieved, the existing large differences in methods and technologies for infrastructure monitoring and maintenance must be tackled. In the present paper, a thorough description of the principles for optimal selection of maintenance strategies of infrastructures have been presented, focusing specifically on a condition-based maintenance management approach and risk-based decision-making, illustrating the benefits from the use of information gathered from inspection, testing and monitoring in ensuring reliability and economical operation of the transport infrastructure assets. A decision-making flow for optimized maintenance and interventions as part of a wider risk-based and data-informed asset management framework is proposed, with a practical example of application at different levels in the current practice for a case study within the TEN-T corridors.

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